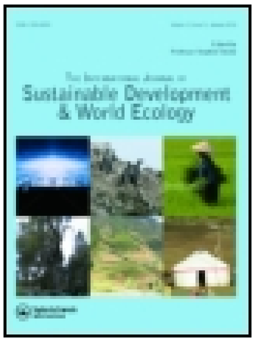

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Collaborative decision-making in sustainable mobility: identifying possible consensuses in the multi-actor multi-criteria analysis based on inverse mixed-integer linear optimization

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ABSTRACT

Sustainability is a key word in modern transportation and logistics. It requires not only economic development but also environmental and social actions. The involvement of multiple stakeholders can express different perspectives and interests to achieve the balance between these three pillars. The multi-actor multi-criteria analysis (MAMCA) is a methodology that can include multiple stakeholders in the process of decision-making. It is important in the field of transport and logistic project appraisal, as many projects fail to be implemented because of a lack of support from one or more stakeholders. In MAMCA, multiple stakeholders can use different criteria trees and express their own preferences. At the end of the analysis, the advantages and disadvantages of each of the proposed scenarios are highlighted. Possible consensuses are then being discussed. However, this last step often turns out to be a difficult task. The purpose of this paper is to propose a way to help the facilitator to identify this (these) consensus(es). This will be based on the use of a weight sensitivity analysis model that was recently developed in the context of the PROMETHEE methods and which is based on inverse mixed-integer linear optimization. This approach allows finding the minimum weight modification for each stakeholder in order to improve the position of a given alternative in the individual rankings and, in an ideal case, to the first position of all the rankings simultaneously. This approach is illustrated on two real MAMCA logistic project cases to seek sustainable mobility solutions.

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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 Aid (MCDA) helps decision-makers to rank or to sort different alternatives based on several conflicting criteria (Clmaco and Craveirinha 2005). MCDA 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 (Purvis et al. 2019). In practical transport cases, more than one individual or group of individuals which can influence the decision are involved. They are called the stakeholders (Freeman 2010). In considering the perspectives and interests of different stakeholders, it is easier to find a sustainable solution which satisfies 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 MCDA methods, was proposed for transport project evaluations (Macharis et al. 2012), which has been applied in various domains of application, especially in the area of mobility and logistics (Macharis and Baudry 2018), transport policy measures evaluation (Crals et al. 2004), transport technologies (Macharis et al. 2004), etc. During the decision-making process, different stakeholders are explicitly taken into account. Instead of the single criteria tree, MAMCA allows the different stakeholders having their own (and so possibly different) criteria trees. The concept of stakeholder is involved at the early stage of 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 stakeholders has been proven to be a difficult task.

In this paper, we will investigate how to identify one or a few possible consensuses by assuming that the different stakeholders accept limited modifications of their criteria weights. By doing so, we adopt an inverse

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optimization approach. We determine the minimal weight modification a given stakeholder 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 stakeholders 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 paper 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 4, we illustrate the integration of this approach in the MAMCA methodology. In section 5, we apply the proposed model on two real case studies which seek cost-effective and sustainable mobility solutions. Finally, we conclude and give directions for future research.

2. Multi-actor multi-criteria analysis

In this section, a brief literature review about group-decision support methodologies is presented. This emphasizes the importance of involving multiple stakeholders 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.

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 (Bulckaen et al. 2016). 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 (Jelassi et al. 1990). For instance, Dyer and Forman (Dyer and Forman 1992) 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 (Macharis et al. 1998) and ELECTRE (Leyva-Lopez and Fernandez-Gonzalez 2003) were also studied. In the context of transportation, Kannan et al. applied Fuzzy-TOPSIS to group decision (Kannan et al. 2009). Bana e Costa applied MCDA as a methodological framework on the basis of expert judgments to support the search for less conflicting policy options transportation services (Bana E Costa 2001). 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 stakeholders and policymakers (Keshkamat et al. 2009). Mousseau et al. proposed a conceptual and methodological framework which involves massive stakeholders for examining ticket pricing reform in public transport (Mousseau et al. 2001). 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 (Labbouz et al. 2008).

The concept of sustainability is by nature multi-dimensional, with most of the time conflicting interests among stakeholders. The involvement of multiple stakeholders 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, stakeholders 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 stakeholders' 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 paper under the assumption that stakeholders accept to slightly modify the weights they associate to their criteria.

2.2. MAMCA methodology

MAMCA strengthens the legitimacy and relevance of the decision-making process by engaging the stakeholders at the early stage. Multi-Stakeholder involvement helps in structuring the scope of the problems by identifying their conflicting perspectives concerning their own sustainability criteria (Macharis and Baudry 2018). MAMCA has often been used in the context of sustainable development. For instance, it successfully supports the assessment of low-carbon transport policy (Sun et al. 2015), long-term decision-making process on mobility, logistics (Macharis et al. 2010) and land-use (Vermote et al. 2014).

The steps of a classic MCDA process include problem statement, alternatives and criteria definition, alternatives screening, scores determination, scores analysis, and conclusions drawing (Nijkamp et al. 2013). Unlike classical MCDA 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 (Macharis and Baudry 2018). The overall methodology of MAMCA is shown in Figure 1.

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 stakeholders are identified. It is a crucial step in MAMCA as for each stakeholder there is a different criteria tree and an in-depth analysis to understand each stakeholder's objectives is conducted.

Next, criteria are defined for each group of stakeholders. These criteria can be pre-defined by the decision-makers/experts with respect to the considered objectives and the purposes of identified stakeholders. As already said, it is also possible for the stakeholders 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 paper: the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) (Brans et al. 1986; Brans and De Smet 2016).

The results of the analysis are shown in step 6. The ranking of each stakeholder is visualized. The multi-actor view chart illustrates the performance scores of the alternatives among all stakeholders. However, there is not a final ranking of alternatives for all stakeholders as they manage different criteria (indeed the sum of performance scores from different stakeholders will reduce the individual information). A discussion is needed between the decision-makers and stakeholders to reach a consensus on the final solution. However, as the stakeholders 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.

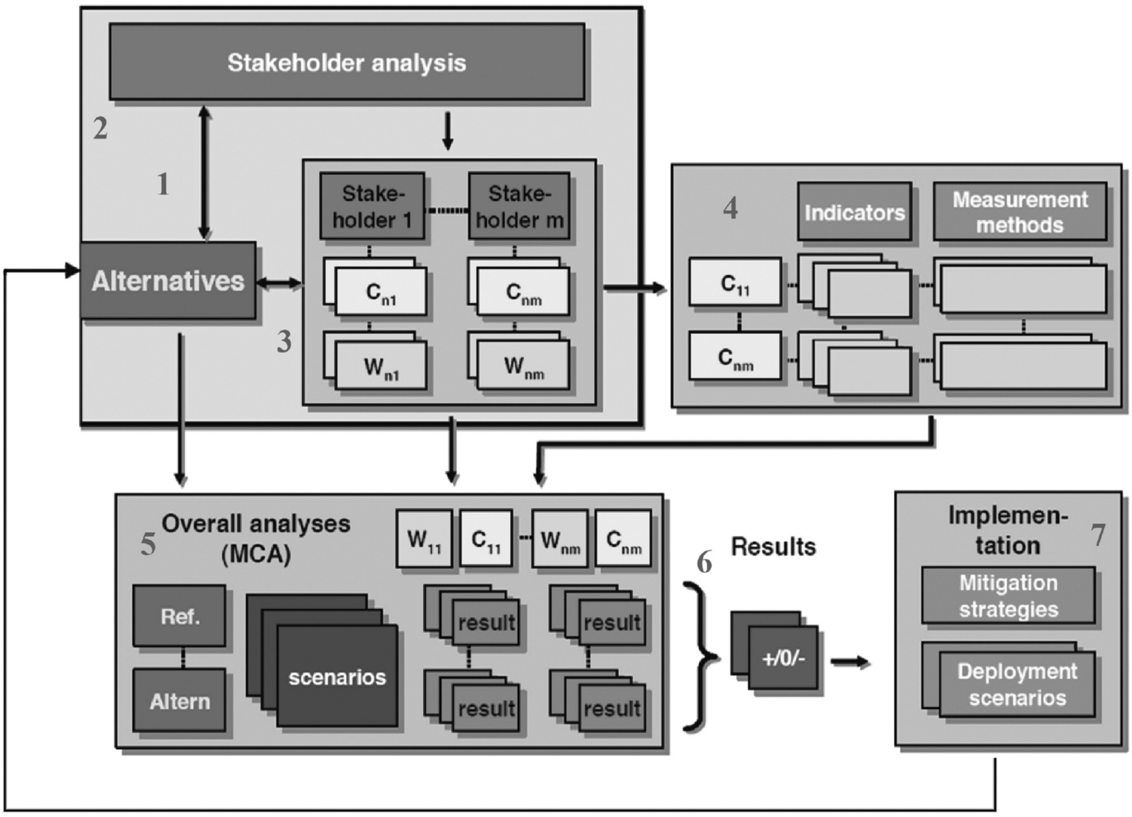

Figure 1. The methodology of MAMCA (Macharis 2004).

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.

3.1. Short description of PROMETHEE

Let us consider a set of criteria $\mathcal{F} = \{f_1, f_2, \ldots, f_m\}$ which are used to evaluate a finite set of alternatives $\mathcal{A} = \{a_1, a_2, \ldots, a_n\}$. 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:

$$P_k(a_i, a_j) = H_k(d_k(a_i, a_j)), \tag{1}$$

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 (Brans et al. 1986). Then we have:

$$\begin{cases} P_k(a_i, a_j) = 0, \text{means no preference of } a_i \text{ over } a_j, \\ P_k(a_i, a_j) \sim 0, \text{means weak preference of } a_i \text{ over } a_j, \\ P_k(a_i, a_j) \sim 1, \text{means strong preference of } a_i \text{ over } a_j, \\ P_k(a_i, a_j) = 1, \text{means strict preference of } a_i \text{ over } a_j. \end{cases} \tag{2}$$

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:

$$P(a_i, a_j) = \sum_{k=1}^{m} w_k \cdot P_k(a_i, a_j), \tag{3}$$

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

$$\begin{cases} \mathcal{W} = \{w_1, w_2, w_3, \ldots, w_m\}, \\ \sum_{k=1}^{m} w_k = 1. \end{cases} \tag{4}$$

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

$$\phi^+(a_i) = \frac{1}{n-1} \cdot \sum_{a_j \in \mathcal{A}, j \neq i} P(a_i, a_j), \tag{5}$$

$$\phi^-(a_i) = \frac{1}{n-1} \cdot \sum_{a_j \in \mathcal{A}, j \neq i} P(a_j, a_i), \tag{6}$$

$$\phi(a_i) = \phi^+(a_i) - \phi^-(a_i). \tag{7}$$

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:

$$\begin{cases} a_i P^+ a_j & \Leftrightarrow & \phi^+(a_i) > \phi^+(a_j), \\ a_i I^+ a_j & \Leftrightarrow & \phi^+(a_i) = \phi^+(a_j). \end{cases} \tag{8}$$

$$\begin{cases} a_i P^- a_j & \Leftrightarrow & \phi^-(a_i) < \phi^-(a_j), \\ a_i I^- a_j & \Leftrightarrow & \phi^-(a_i) = \phi^-(a_j). \end{cases} \tag{9}$$

$$\begin{cases} a_i P_I a_j \ (a_i \text{ outranks } a_j) \Leftrightarrow \begin{cases} a_i P^+ a_j & \text{and } a_i P^- a_j, \\ a_i P^+ a_j & \text{and } a_i I^- a_j, \\ a_i I^+ a_j & \text{and } a_i P^- a_j; \end{cases} \\ a_i I_I a_j \ (a_i \text{ is indifferent to } a_j) \Leftrightarrow a_i I^+ a_j \text{ and } a_i I^- a_j; \\ aRb \ (a_i \text{ and } a_j \text{ are incomparable}) \Leftrightarrow \begin{cases} a_i P^+ a_j \text{ and } a_j P^- a_i, \\ a_j P^+ a_i \text{ and } a_i P^- a_j. \end{cases} \end{cases} \tag{10}$$

The PROMETHEE I partial ranking is established by considering the intersection of the two preorders: PROMETHEE II complete ranking is based on net flow score ϕ (which does not support incomparability relations):

$$\begin{cases} a_i P_{II} a_j \ (a_i \text{ outranks } a_j) \Leftrightarrow \phi(a_i) > \phi(a_j), \\ a_i I_{II} a_j \ (a_i \text{ is indifferent to } a_j) \Leftrightarrow \phi(a_i) = \phi(a_j). \end{cases} \tag{11}$$

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

$$\begin{aligned} \phi(a_i) &= \frac{1}{n-1} \sum_{k=1}^{m} \sum_{a_j \in \mathcal{A}} [P_k(a_i, a_j) - P_k(a_j, a_i)] \cdot w_k \\ &= \sum_{k=1}^{m} \phi_k(a_i) \cdot w_k, \end{aligned} \tag{12}$$

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

$$\phi_k(a_i) = \frac{1}{n-1} \sum_{a_j \in \mathcal{A}, i \neq j} [P_k(a_i, a_j) - P_k(a_j, a_i)]. \tag{13}$$

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.

3.2. An alternative weight sensitivity analysis based on inverse MILP for PROMETHEE

In MCDM, the definition of weights is not very precise, nor are the values given by a decision-maker (Mareschal 1988). 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 (Doan and De Smet 2018). 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 stakeholders $\mathcal{S} = \{s_1, s_2, s_3, \ldots, s_q\}$. Each of them has his own set of weights and is assumed to accept small changes on these values. Let us consider stakeholder s_p with $p \in \{1, \ldots, q\}$. This stakeholder considers m_p criteria. The set of initial weights is denoted $\mathcal{W}_p = \{w_{1,p}, w_{2,p}, w_{3,p}, \ldots, w_{m_p,p}\}$, while the new set of weights is denoted $W'_p = \{w\prime_{1,p}, w\prime_{2,p}, w\prime_{3,p}, \ldots, w\prime_{m_p,p}\} W'_p = \{w\prime_{1,p}, w\prime_{2,p}, w\prime_{3,p}, \ldots, w\prime_{m_p,p}\}$.

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

For a given stakeholder 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:

$$\sum_{k=1}^{m_p} \left| w_{k,p} - w'_{k,p} \right| \tag{14}$$

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

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

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

$$w_{k,p} - w'_{k,p} = \begin{cases} d_{k,1,p} & \text{if } w_k - w\prime_k \geq 0 \\ -d_{k,2,p} & \text{otherwise} \end{cases}, \quad d_{k,1,p}, d_{k,2,p} \geq 0 \tag{15}$$

$d_{k,1,p}$ (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, $p \in \{1, \ldots, q\}$; $k \in \{1, 2, \ldots, m_p\}$:

$$\gamma_{k,p} = \begin{cases} 0 & \text{if } d_{k,1,p} + d_{k,2,p} = 0 \\ 1 & \text{otherwise} \end{cases}, \quad \gamma_{k,p} \in \{0, 1\} \tag{16}$$

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

The MILP model can then be formalized as follows:

$$\min z = \sum_{k=1}^{m_p} \left| w_{k,p} - w'_{k,p} \right| = \sum_{k=1}^{m_p} (d_{k,1,p} + d_{k,2,p}) \tag{17}$$

s.t.

$$\sum_{k=1}^{m_p} w'_{k,p} = 1, \quad p = 1, 2, \ldots, q \quad \text{(weights constraint)} \tag{18}$$

$$w_{k,p} - w'_{k,p} = d_{k,1,p} - d_{k,2,p}, , \quad p \in \{1, \ldots, q\}, \quad k \in \{1, 2, \ldots, m_p\} \tag{19}$$

$$\gamma_{k,p} \geq d_{k,1,p} + d_{k,2,p} - \tau, \quad p \in \{1, \ldots, q\}, \quad k \in \{1, 2, \ldots, m_p\} \quad \text{(number of modified criteria)} \tag{20}$$

$$\gamma_{k,p} \leq M(d_{k,1,p} + d_{k,2,p}), \quad p \in \{1, \ldots, q\}, \quad k \in \{1, 2, \ldots, m_p\} \tag{21}$$

$$\sum_{k=1}^{m_p} \gamma_{k,p} \leq N_p, \quad p \in \{1, \ldots, q\} \tag{22}$$
(N_p allowed modified criteria)

$$\phi_p^{'}(a_i) = \sum_{k=1}^{m} w_{k,p}^{'} \phi_{k,p}(a_i), \quad p \in \{1, \ldots, q\} \tag{23}$$
(net flow scores computation)

$$\phi_p^{'}(a_i) > \phi_p^{'}(a_j), \quad j \neq i; \quad p \in \{1, \ldots, q\} \tag{24}$$
(rank change of a_i)

$$w_{k,p}, d_{k,1,p}, d_{k,2,p} \geq 0, , \quad p \in \{1, \ldots, q\}, \quad k \in \{1, 2, \ldots, m_p\} \tag{25}$$
(domain)

$$\gamma_{k,p} \in \{0, 1\}, \quad p \in \{1, \ldots, q\}, \quad k \in \{1, 2, \ldots, m_p\} \tag{26}$$

4. Integration of the MILP in MAMCA to reach consensus

In practice, it is most of the time observed that different stakeholders 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 stakeholders 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 stakeholders. In an ideal case, we could study the minimum weight modifications that should be imposed to the different stakeholders, 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 individually and for all the alternatives. For the sake of simplicity, let us consider the case of alternative a_i and stakeholder s_p. First, we need to define new binary variables denoted r_j^p as follows:

$$\phi_p^{'}(a_i) - \phi_p^{'}(a_j) \leq M.\, r_j^p \tag{27}$$

$$\phi_p^{'}(a_j) - \phi_p^{'}(a_i) \leq M.\, (1 - r_j^p) \tag{28}$$

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 s_p. First, we will run the MILP for each stakeholder individually and for all the alternatives. Therefore, constraint ((24)) has to be changed to:

$$\sum_{j=1, j\neq i}^{n} r_j^p = n - g, \quad g = 1, 2, \ldots, n-1 \tag{29}$$

Once this has been computed for all stakeholders, 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 stakeholders which have to be as limited as possible;
- the ranking positions for all stakeholders 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 stakeholders). 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 stakeholders beforehand.

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

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 (CITYLAB 2018). 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

Table 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
Shopping center owner	Financial viability, attractive shopping environment, high quality service
Last-mile carrier and electric vans	Reduction of distance and energy, empty distance reduction
Common logistics in shopping center	Reduction of dwell times for delivery vehicles, fewer individual transport inside the shopping center, 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

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 1 lists the evaluated alternatives and the advantages comparing to the base line, business as usual. Stakeholder 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.

Five stakeholder groups were involved in the local stakeholder meeting, each stakeholder group had different criteria for evaluation, which can be found in Table 2. Based on Table 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 stakeholders to reach the consensus.

5.1. Case Oslo

The original first ranked alternatives for the stakeholders in case Oslo are listed in Table 3. Figure 2 illustrates the Multi-Actor view for this case (which is

Table 2. Criteria of different stakeholder group.

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 center 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 3. Original first ranked alternative and weights for stakeholders 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 center owner	[0.3333, 0.3333, 0.3333]	Common logistics in shopping center
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 center

generated by the MAMCA software). It can be noted that different alternatives are ranked first for different stakeholders. 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.

Therefore, the MILP model is applied and the weight modifications for alternatives rank at different positions among all stakeholders 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 stakeholders of one alternative, denoted Z, along with the corresponding sum of new rank distances O is obtained. Table 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 stakeholders, 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.

To find the possible consensual solution of the case, Pareto-efficient solutions are found by treating the results as a set of unsorted data (Pareto 1964). Figure 3 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 stakeholders of alternatives. The lines with markers illustrate the rank changes of the alternatives with the weight modification. The grey 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

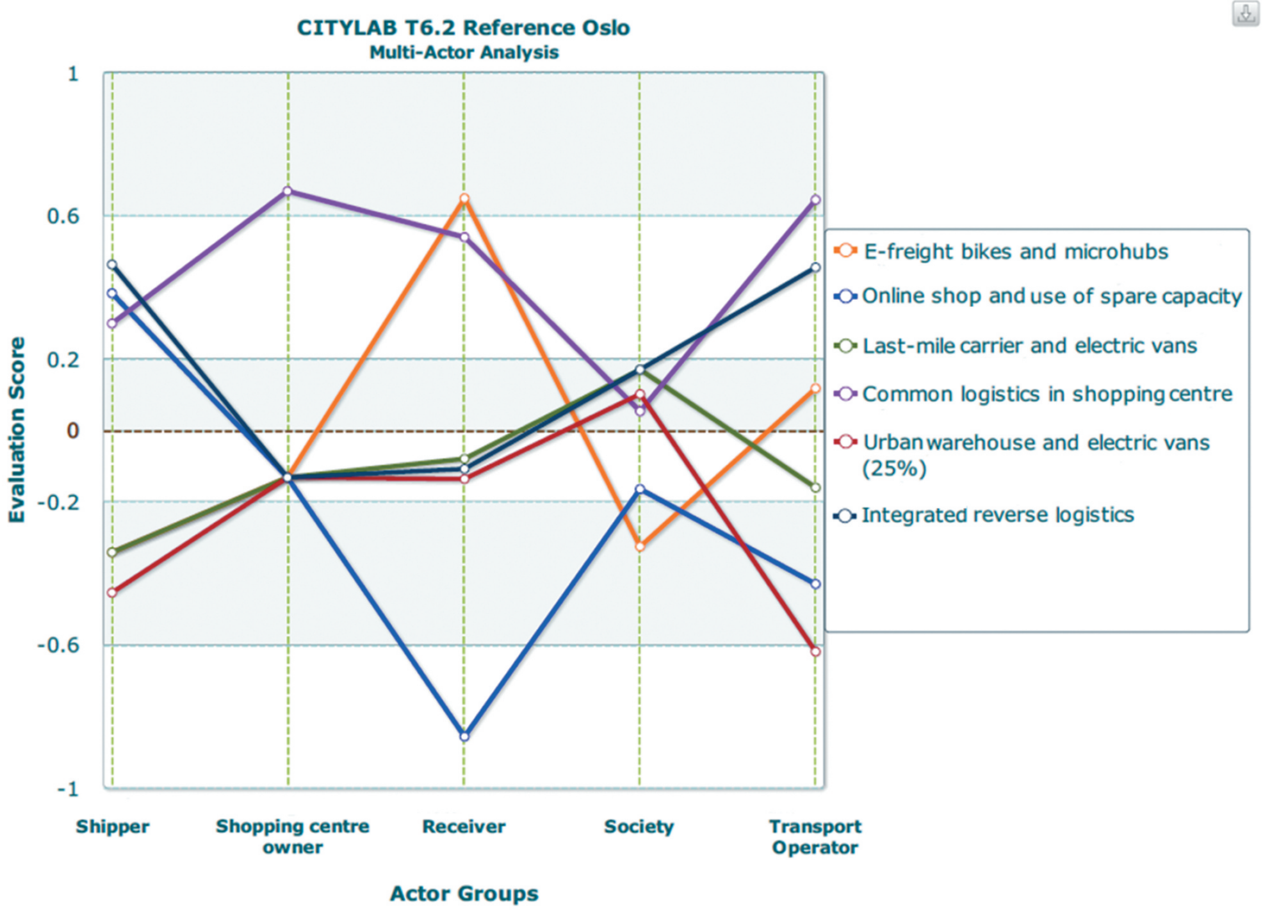

Figure 2. Multi-actor view in case Oslo.

Table 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

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 stakeholders.

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 is taken from CITYLAB D5.4. The original first ranked alternatives and weights are listed in Table 5.

The case of Brussels is more complex than that of Oslo. Based on Figure 4, 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 5 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.

6. Conclusion

Finding a sustainable solution normally requires a compromise of the different needs and interests from different stakeholders. The MAMCA methodology can include multiple stakeholders in the process of evaluation and decision-making. However, it is sometimes

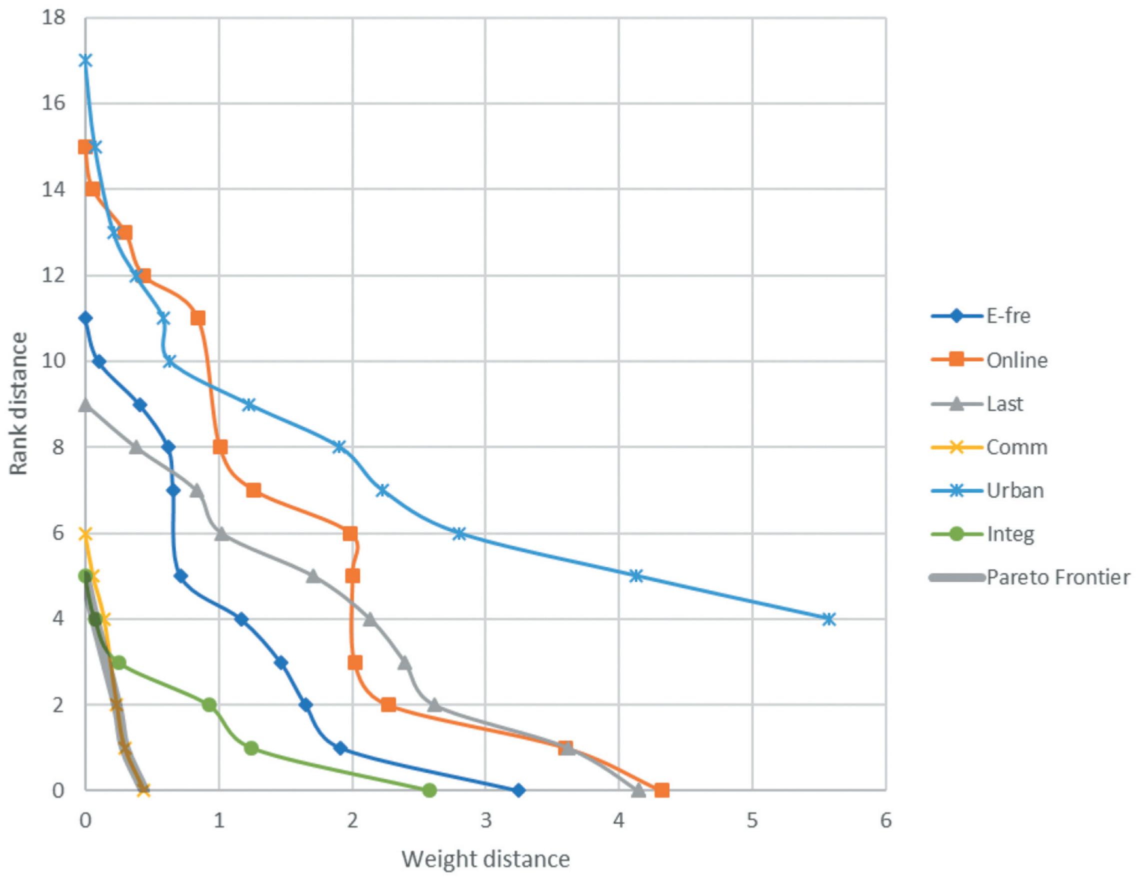

Figure 3. MILP result of case Oslo.

Table 5. Original first ranked alternative and weights for stakeholders 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 center owner	[0.4100, 0.4100, 0.1800]	Common logistics in shopping center
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

difficult to reach a consensus among all the stakeholders 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 stakeholders to converge to a common acceptable solution.

The outcome of MILP model is illustrated in the two MACMA case studies of CITYLAB. CITYLAB cases reveal the fact that even though the proposed options are all toward sustainable mobility, different stakeholders 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 one or two alternatives. This will help analysts to focus their work on these options but also give (visual) arguments that could be communicated to the stakeholders 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).

In the MAMCA methodology, all stakeholders 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 stakeholders. Of course, this implies compensatory effects leading to situations where one or several stakeholders 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 stakeholders. This could be done by adding an objective that will limit the weight deviation *efforts* among all stakeholders. In addition, constraints can be added to limit the possible weight modifications. From

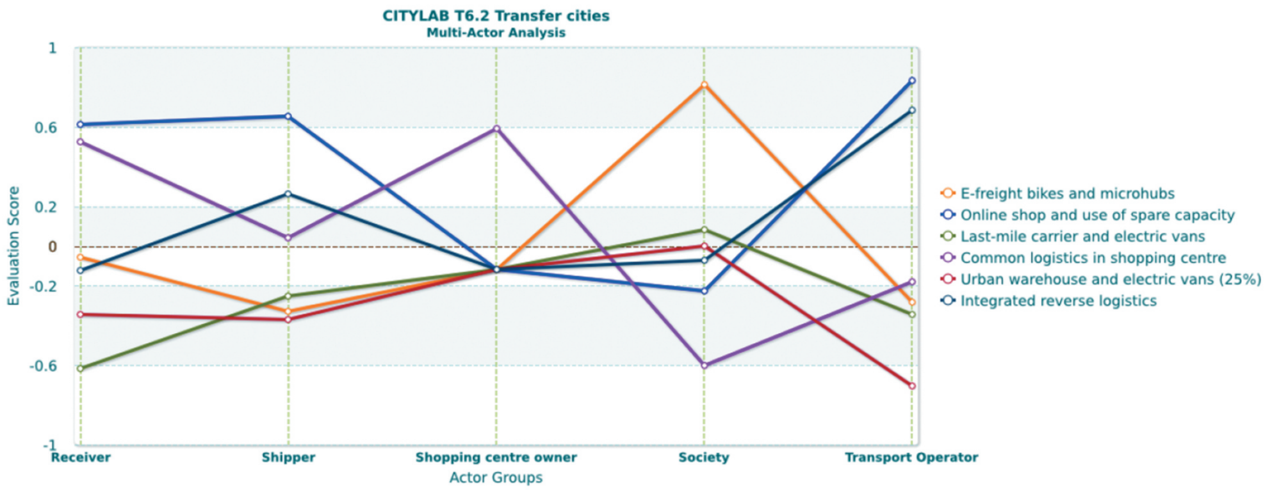

Figure 4. Multi-actor view in case Brussels.

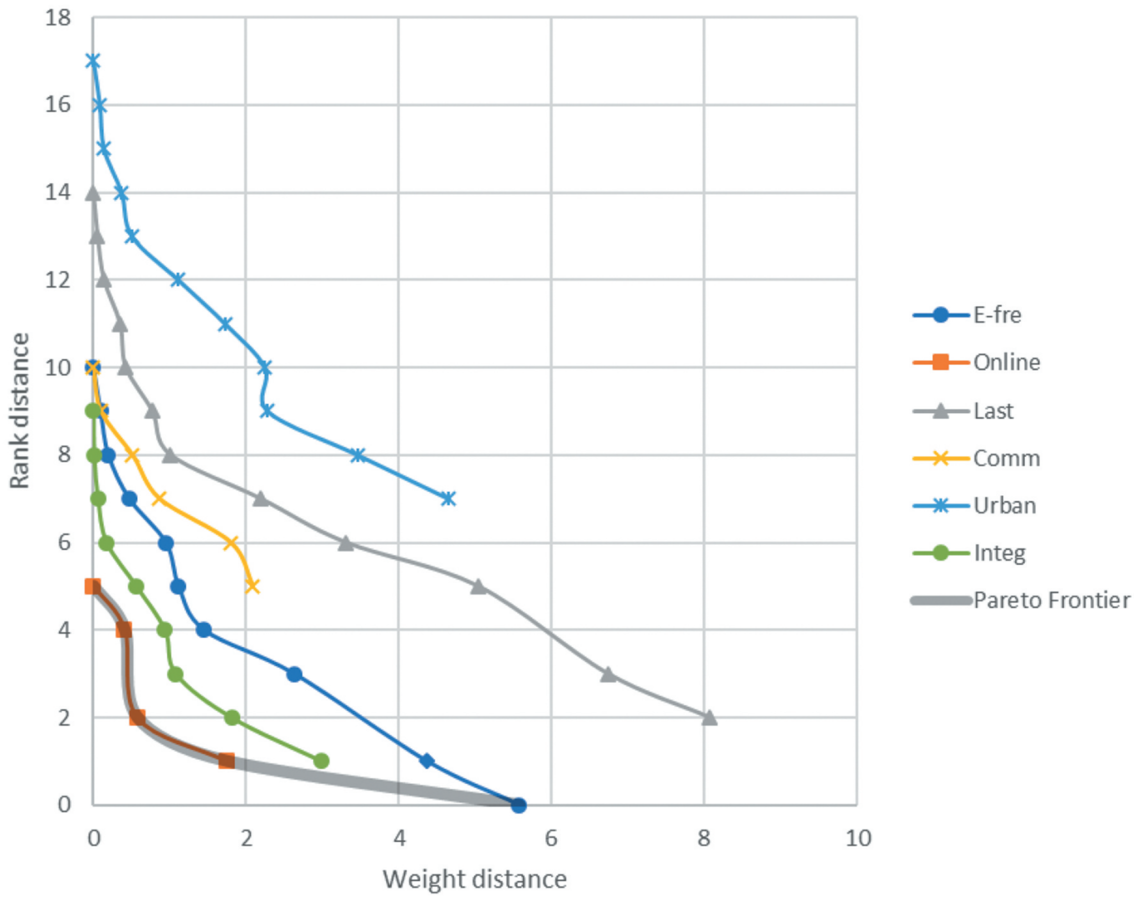

Figure 5. MILP result of case Brussels.

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.

Note

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

Disclosure statement

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References

Bana E Costa CA. 2001. The use of multi-criteria decision analysis to support the search for less conflicting policy options in a multi-actor context: case study. J Multi-Criteria Decis Anal. 10(2):111–125. doi:10.1002/mcda.292.

Brans JP, De Smet Y. 2016. PROMETHEE methods. Multiple criteria decision analysis. New York: Springer; p. 187–219.

Brans JP, Vincke P, Mareschal B. 1986. How to select and how to rank projects: the PROMETHEE method. Eur J Oper Res. 24(2):228–238.

Bulckaen J, Keseru I, Macharis C. 2016. Sustainability versus stakeholder preferences: searching for synergies in urban and regional mobility measures. Res Transp Econ. 55:40–49.

CITYLAB. 2018. D6.2 – minutes of local stakeholder meetings. [accessed Jul Wed Jul 15]. http://www.citylab-project.eu/deliverables/D6_2.pdf.07:34:29 2020.

Clmaco J, Craveirinha J. 2005. Multiple criteria decision analysis – state of the art surveys.New York: Springer.

Crals E, Keppens M, Macharis C, Ramboer R, Vereeck L, Vleugels I. 2004. Too many questions and too few options. Results of research into tradable mobility rights. Traffic Specialist. 110:15–18.

Doan NAV, De Smet Y. 2018. An alternative weight sensitivity analysis for PROMETHEE II rankings. Omega. 80:166–174.

Dyer RF, Forman EH. 1992. Group decision support with the analytic hierarchy process. Decis Support Syst. 8 (2):99–124.

Freeman RE. 2010. Strategic management: a stakeholder approach. Cambridge: Cambridge university press.

Jelassi T, Kersten G, Zionts S. 1990. An introduction to group decision and negotiation support. In: Costa CAB, editor. Readings in multiple criteria decision aid. Berlin: Springer; p. 537–568.

Kannan G, Murugesan P, Senthil P, Noorul Haq A. 2009. Multicriteria group decision making for the third party reverse logistics service provider in the supply chain model using fuzzy topsis for transportation services. Int J Serv Technol Manage. 11(2):162–181.

Keshkamat SS, Looijen JM, Zuidgeest MH. 2009. The formulation and evaluation of transport route planning alternatives: a spatial decision support system for the via Baltica project, Poland. J Transport Geogr. 17(1):54–64.

Labbouz S, Roy B, Diab Y, Christen M. 2008. Implementing a public transport line: multi-criteria decision-making methods that facilitate concertation. Oper Res. 8 (1):5–31.

Leyva-Lopez JC, Fernandez-Gonzalez E. 2003. A new method for group decision support based on Electre III methodology. Eur J Oper Res. 148(1):14–27.

Macharis C. 2004. The importance of stakeholder analysis in freight transport. Eur Transport Trasporti Europei. 25-26: 114–126.

Macharis C, Baudry G. 2018. Decision-making for sustainable transport and mobility: multi actor multi criteria analysis. Cheltenham: Edward Elgar Publishing.

Macharis C, Brans JP, Mareschal B. 1998. The GDSS PROMETHEE procedure. J Decis Syst. 7(4):283–307.

Macharis C, De Witte A, Turcksin L. 2010. The multi-actor multi-criteria analysis (MAMCA) application in the flemish long-term decision making process on mobility and logistics. Transport Policy. 17(5):303–311.

Macharis C, Turcksin L, Lebeau K. 2012. Multi actor multi criteria analysis (MAMCA) as a tool to support sustainable decisions: state of use. Decis Support Syst. 54 (1):610–620.

Macharis C, Verbeke A, De Brucker K. 2004. The strategic evaluation of new technologies through multicriteria analysis: the advisors case. Res Transp Econ. 8:443–462.

Mareschal B. 1988. Weight stability intervals in multicriteria decision aid. Eur J Oper Res. 33(1):54–64.

Mousseau V, Roy B, Sommerlatt I 2001. Development of a decision aiding tool for the evolution of public transport ticket pricing in the Paris region. A-MCD-A aide multicritère à la décision—multiple criteria decision aiding: 213–230.

Nijkamp P, Rietveld P, Voogd H. 2013. Multicriteria evaluation in physical planning. North Holland: Elsevier.

Pareto V. 1964. Cours d'économie politique. Vol. 1. Geneva: Librairie Droz.

Purvis B, Mao Y, Robinson D. 2019. Three pillars of sustainability: in search of conceptual origins. Sustainability Sci. 14(3):681–695.

Sun H, Zhang Y, Wang Y, Li L, Sheng Y. 2015. A social stakeholder support assessment of low-carbon transport policy based on multi-actor multi-criteria analysis: the case of Tianjin. Transport Policy. 41:103–116.

Vermote L, Macharis C, Hollevoet J, Putman K. 2014. Participatory evaluation of regional light rail scenarios: a flemish case on sustainable mobility and land-use. Environ Sci Policy. 37:101–120.