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Application of a novel PROMETHEE-based method for construction of a group compromise ranking to prioritization of green suppliers in food supply chain

Kannan Govindan[1a], Miłosz Kadziński[2], R.Sivakumar[3]
[1] Center for Engineering Operations Management, Department of Technology and Innovation, University of Southern Denmark, Denmark
[2] Institute of Computing Science, Poznan University of Technology, Poland
[3] Department of Mechanical Engineering, SSM Institute of Engineering and Technology, India

ABSTRACT

The food sector has a prodigious focus and is constantly gaining in importance in today's global economic marketplace. Due to an increasing global population, society faces a greater challenge for sustainable food production, quality, distribution, and food safety in the food supply chain. Adopting green supply chain management (GSCM) elements is essential for utilizing the food supply chain in an environmentally benign way. As a solution to the above challenge, the economic and green characteristics for supplier selection in green purchasing are studied in this paper. For an organization, the evaluation and selection of the green supplier is a vital issue due to several tangible and intangible criteria involved. Accordingly, we apply multiple criteria decision aiding techniques.

We propose a hybrid approach that combines the revised Simos procedure, PROMETHEE methods, algorithms for constructing a group compromise ranking, and robustness analysis. At first, the revised Simos procedure is applied to derive the criteria weights. Next, the PROMETHEE method is applied to rank the suppliers according to each Decision Maker's (DM's) preferences. Then, the compromise ranking is constructed to minimize the distance of the individual's rankings from the solution adopted by the whole group. For this purpose, we introduce and apply some original procedures based on Binary Linear Programming. Finally, the results are validated against the outcomes of robustness analysis. The applicability and efficiency of the proposed approach is endorsed with a case study in an Indian food industry.

Keywords: Green supplier selection, Multiple criteria decision analysis, PROMETHEE, Compromise ranking, Robustness analysis, Food industry

1. Introduction

A food supply chain is a grid used to move the final food product from the manufacturer through pre- and post-production activities to the customers under quality and time-conscious work. This linked chain is important because low quality and/or delayed delivery make the product useless or expired. The food supply chain has a significant importance in the global marketplace and it creates growth opportunities for society and the economy in many countries. It connects three main sectors: agriculture, food processing, and distribution, which are arguably the cornerstone of any economy while being directly connected to the environment.

[a]Corresponding Author (kgov@iti.sdu.dk)

Numerous activities are covered under a food supply chain. Typically, food processing has been considered as a key activity among them (Bukeviciute et al., 2009). An enormous burden on the food processing industry arises due to the increasing demand for high-quality, safe, and nutritious processed food (Sellahewa and Martindale, 2010). To ensure that the food processing industry is economically and environmentally sustainable, it is important to monitor the internal and external factors such as cost, quality, transport energy, labour and food safety regulation, public policy, and the macroeconomic environment (Bukeviciute et al., 2009). Moreover, to effectively use the supply chain in a food processing industry, one needs to adopt the green supply chain management (GSCM) elements such as green purchasing, green production, green presentation, and inverse logistics (Beamon,1999; Büyüközkan and Çapan,2007; Sarkis et al.,2005; Van Hoek,1999; Valton et al.,1998; Zhu et al.,2008).

Green purchasing refers to reducing or preventing waste and pollution by considering environmental impacts along with cost, quality, performance, and other traditional factors when making decisions on product purchase from the suppliers (Eltayeb et al., 2011). Apart from its notable environmental benefits, it also builds a green relationship between organizations and suppliers. This is attained by providing green design instructions to suppliers to embed the environmental requirements in green purchased materials (Govindan et al., 2015a). Thus, the main role of green purchasing involves choosing the suppliers while considering environmental criteria and procuring environmentally friendly raw materials. By procuring the green product from the suppliers, a firm can improve both customer satisfaction and competitive advantages in products with respect to cost and quality.

The current supply chain strategies in most organizations are facing critical upward trends of environmental awareness and sustainable growth (Yeh and Chuang, 2011; Kuo et al., 2010). This enforces incorporation of the environmental competencies into the supply chain operations (Diabat and Govindan, 2011). In the recent years, firms have become increasingly pressured to follow green environmental practices (e.g., controlling environmental emissions, hazardous substances, harmful waste (Awasthi et al., 2010)) so they may withstand current market competitions (Lee et al., 2009). Hence, food industry firms have to consider relevant environmental factors like energy consumption, solid waste generation, or food safety (airborne diseases) along with the traditional economic factors in the evaluation and selection process of suitable green suppliers (Davies and Konisky, 2000; Lee et al., 2009). It is also necessary to implement the appropriate control and assurance measures to prevent foodborne outbreaks (Lahou et al., 2015). According to Liao et al., 2012 and Prusak et al., 2013, evaluation and selection of the supplier in the food industry supply chain is a sensitive and critical issue for many firms.

Many decision making techniques and their hybrids have been used for evaluating and selecting suppliers while still accounting for multiple relevant criteria. In their extensive literature reviews, Ho et al., 2010, Chai et al., 2013, and Kannan et al.,2013 indicate that the most prevailing methods in this context are: Analytic Hierarchy Process (AHP) (Akarte et al., 2001) and its extensions (e.g., AHPSort (Ishizaka et al., 2012) or AHP coupled with clustering (Ishizaka, 2012)), TOPSIS (Chai et al., 2013), Case-Based Reasoning (CBR) (Choy and Lee, 2002), Analytic Network Process (ANP) (Gencer and Gürpinar, 2007), Fuzzy Set Theory, and SMART (Barla, 2003). The most popular hybrid approaches include the combinations of:

- AHP with Goal Programming (GP), Analytic Neural Network (ANN), Data Envelopment Analysis (DEA), grey rational analysis, or multi-objective programming (MOP), and
- ANP with Fuzzy PROMETHEE (Tuzkaya et al., 2009) or DEA and ANN (Kuo et al., 2010).

The extensive literature on traditional supplier evaluation and selection (Ho et al., 2010) confirms that comparatively little research has focused on green supplier selection and, in particular, employing outranking methods in this context although they have proven their usefulness in other application domains (for a review, see Behzadian et al., 2010 and Govindan and Jepsen, 2016).

In this paper, we introduce an integrated framework combining several outranking-based Multiple Criteria Decision Making (MCDM) approaches to help a firm evaluate and select the most preferred green supplier. The developed model incorporates various economic and environmental criteria for food industry supply chain. Its practical use is illustrated with a case study concerning a food processing industry situated in India. The study accounts for the preferences of several Decision Makers (DMs) representing conflicting viewpoints with regard to the purchase, production, and food safety departments.

Within the implemented approach, we first apply the revised Simos procedure (Figueira and Roy, 2002) to derive the relative weights of the selected criteria. Then, these weights are incorporated within the PROMETHEE method to construct, for each DM, a ranking of suppliers. We employ both PROMETHEE I, which provides the partial ranking, and PROMETHEE II, which constructs the complete ranking (Brans and Mareschal, 1994). Let us emphasize that this paper is the first to apply PROMETHHE (Brans et al., 1986) for green supplier selection in the field of food supply chain.

The individual DMs' rankings are combined into a compromise ranking using the novel algorithms proposed in this paper. These procedures construct group-consensus ranking by minimizing the distance from the individual rankings coming from different points of view. They are based on Binary Linear Programming (BLP). We introduce a few variants of the procedures oriented towards construction of a partial or complete ranking, both of which can be either utilitarian or egalitarian with respect to the entire group of DMs. Finally, the obtained results are validated against the outcomes of robustness analysis for group decision making (Greco et al., 2012, Kadziński et al., 2012) which is suitably adapted to the PROMETHEE methods.

This paper is organized in the following way. Section 2 discusses the comprehensive literature review of supplier selection methods and supplier selection criteria. An integrated PROMETHEE-based multiple criteria ranking approach for group decision making is presented in Section 3. In

Section 4, the proposed method is illustrated with a case study in an Indian food industry. Section 5 provides the managerial implication, while the last section concludes the paper.

2. Literature review

2.1. Food supply chain and green supply chain

The food supply chain occupies an important position in the global supply chain due to the fulfilment of human needs, employment opportunities, economic growth, and environmental effects (Yakovieva, 2009). Today's food sector is more highly pressured from socially aware organizations and governments due to various impacts involved in food production and ecological consumptions (Maloni and Brown, 2006; Matos and Hall, 2007; Yakovieva, 2009). This implies the need for utilizing the supplier chain management in an active manner (Diabat and Govindan, 2011) and for adopting the elements of GSCM within food establishments effectively (Büyüközkan and Çapan, 2007).

Sarkis, 1999, defined GSCM as the process of purchasing, producing, marketing, and performing various packaging and logistic activities while considering the ecological balance. The green supply chain differs from the traditional supply chain in the following aspects: (i) *goal* w.r.t. minimising the energy consumption and emission of pollutants, (ii) *management structure* w.r.t. inclusion of environmental performance in internal and external management, (iii) *business model* w.r.t. implementing environmental protection and low carbon supply chain from raw material purchase to end product, (iv)*business process* w.r.t. recycle implementation, (v) *consumption pattern* w.r.t. raising green government procurement, corporate social responsibility, sustainable consumption education and practice (CCICED, 2011). Overall, GSCM is based on an environmentally sensitive approach at every stage of the system (Sheu et al., 2005). It develops the strategies to involve environmental factors or concerns within organization's purchasing decisions and to establish consistent relationships with green suppliers.

To acknowledge the green supply chain, governments and organizations implement environmental policies concerning pollution and traffic control as well as establishing regulations for food contamination prevention and monitoring systems. For example, some of the major environmental regulations adopted in the European Union (EU) for promoting the GSCM include:

- general food law regulations (Official Journal of the European Communities, No 178/2002) which provide a basis for the assurance of a high level of protection of human health related to food products; they also cover all sectors of the food chain to include production, processing, storage, delivery, and sale;
- Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances regulations which have strongly influenced the electrical appliance manufacturers and helped to establish the electronics waste management;
- the European *Ecolabel* launched in 1992 to encourage the development and marketing of environmentally friendly products and services in the private sector (CCICED, 2011).

2.2. Supplier selection methods

Typically, food manufacturers select an ingredient supplier based on price, flavour, or the supplier's location. As governments and industry place a stronger emphasis on qualitative and quantitative criteria like food safety and quality, the evaluation and selection of the supplier has become more complex (Prusak et al., 2013).

Over the last few decades, several MCDM methods have been applied effectively to manage the supplier selection problem (Zeydan et al., 2011). These applications have been summarized in many review papers. In particular, De Boer et al., 2001, performed an extensive analysis concerning decision methods, Aissaoui et al., 2007, reviewed the models of supplier selection combined with order lot sizing, Ho et al., 2010 and Chen, 2011, systematically reviewed the individual and hybrid MCDM approaches for vendor evaluation, while Tahriri et al., 2008 reviewed the supplier selection approaches in manufacturing industries.

In the recent years, many researchers have adopted and developed suitable decision making methods for green supplier selection problems. In particular, Bai and Sarkis, 2010, applied Rough Set Theory for green supplier development; Tseng, 2011, used grey theory under fuzzy logic to evaluate green criteria and select the supplier under GSCM of the electronics industry, and Handfield et al., 2002, illustrated the case with AHP to help managers understand the trade-offs among environmental dimensions. Further, Büyüközkan and Çifçi, 2011, applied ANP for green supplier selection to incorporate interdependencies among decision structure components, whereas Lee and Kim, 2000, integrated ANP and GP for project selection. Finally, many researchers have coupled Fuzzy AHP (FAHP) with other approaches to effectively deal with green supplier evaluation and order allocation (see, e.g., Lee et al., 2009 and Kannan et al., 2013). Nevertheless, only limited literature has discussed the formal reference frameworks for supplier selection problem in food industry (see Magdalena, 2012 (Taguchi loss function combined with FAHP), Shenet al., 2012 (Cluster-Weighted DEMATEL with ANP), Agarwal and Vijayvargy, 2011 (ANP), and Liao et al., 2012 (Fuzzy TOPSIS integrated with Multi Segment Goal Programming)).

2.3. Supplier selection criteria

2.3.1. Economic criteria for supplier selection

The evaluation of suppliers based on the selected criteria is the primary attention in purchasing activity since the 1960s (Raut and Bhasin, 2012). Generally, cost, quality, and service have been considered as effective factors in the traditional supplier selection. Dickson, 1966, concluded from his survey carried through 273 purchasing agents that quality, delivery, and performance history were the most relevant criteria in supplier selection. This was subsequently confirmed by Chang et al., 2011. While reviewing

Dickson's work, Weber et al., 1991, concluded that price, delivery, quality, production capacity, and localization were relevant factors. Recently, Ho et al., 2010, identified quality, delivery, price/cost, manufacturing capability, service, management, and technology as the most dominant criteria applied in the supplier selection problems.

2.3.2. Green criteria for supplier selection

In the recent years, substantial interest has been shown by the researchers in the GSCM literature (Lee et al., 2009). The influential activity of green supply chain in an organization is to encourage or engage their suppliers in green projects and to make them better green performers in the supply chain (Hall, 2001). In the recent purchasing decisions under GSCM, supplier selection shows the noticeable significance (Seuring and Muller, 2008). Incorporation of objective environmental criteria in the evaluation systems ensures better environmental performance in the collaborative supply chains.

Many researchers have studied and incorporated the green decision variables in supplier evaluation. These are summarized in Table 1. In their reviews, Igarashi et al., 2013, indicated that considering the environmental certification, policy, regulation, control of hazardous substances, recycling, and labelling is required for greener supplier evaluation and selection, while Govindan et al., 2015b, found that the most widely considered criteria in this context relate to the environmental management system.

Table 1: Green supplier selection criteria from the literature review.

Reference	Approach	Application	Evaluating criteria	
Noci, 1997	AHP	Automobile Industry	Green Competencies Current Environmental efficiency	Supplier's Green Image Image Net Life cycle cost
Handfieldet al., 2002	AHP	Automotive, Apparel and Paper Manufacturer	Waste management Labelling/certification	Compliance to Government Regulations Environmental Programs
Chiouet al., 2008	FAHP	Electronic Industry	Green competencies Environmental management Systems	Environmental performance Corporate social responsibilities & Risk factor
Lee et al., 2009	Fuzzy Extended AHP	Electronics Industry	Green image Green product	Pollution control Green competencies
Grisi et al., 2010	FAHP		Environmental competencies Green image	Environmental management system Current environmental impact
Büyüközkan and Çifçi, 2011	FANP	Manufacturing Industry	Green Logistics Dimension Alternative green supply chain systems, projects, practices, etc.	Green organizational activities dimension
Awasthiet al., 2010	Fuzzy TOPSIS	Logistics	Use environment friendly Technology Green market share	Use of environmental friendly material Partnership with green Organization

		Adherence to environmental policies	Green R&D Projects
Humphreys et al.,2003	Knowledge based system	Green Image Environmental management systems	Design for Environment Environmental Competencies
Bai and Sarkis, 2010	Rough Set Theory	Green Knowledge Transfer	Management and organizational practices

With respect to the foodservice and food retail industries, Davies and Konisky, 2000, surveyed the relevant environmental effects. They indicated energy use, solid waste generation, air and water emissions as well as food safety concerns as the direct environmental impacts for these industries. In an Indian scenario, the food processing sector faces acute environmental and economic issues in the supply chain such as food safety, environmental pollution, energy consumption, infrastructure facilities, skilled manpower, etc. A survey conducted by the Federation of Indian Chambers of Commerce and Industry identified that the major challenges hampering the growth of the food sectors in India are: insufficient infrastructural facilities (inadequate cold storage, warehousing facilities, customized transportation, technology adoption), a comprehensive national level policy on food processing sector, food safety laws, and lack of trained manpower (FICCI, 2010).

Sahu and Narayanan, 2010, summarized the cumulative average growth rate (CAGR) changes in the energy consumption of Indian manufacturing industries from 1990-2008 and calculated CAGR for the food and beverage sector as 10.38%. In this way, it was found as the fourth most energy-consuming industrial sector in Indian manufacturing. According to Rai et al., 2013, up to 40% of vegetables and fruits and 10% of food grains are wasted in India due to inadequate storage facilities and those waste products cause environmental pollution like solid waste generation, air emission, etc. Suryawanshi et al., 2013, estimated that the waste in solid and liquid form that was generated by Indian food processing industries was 4.5 million tonnes per year. Vemula et al., 2012, reviewed the past 29 year reports of foodborne diseases outbreaks in India and found that 37 outbreaks involving 3485 people were affected due to food poisoning in India. Thus, it is the responsibility of the food industry to develop and implement a Hazard Analysis & Critical Control Point (HACCP) system. It is a management system for measuring food safety by analysis and prevention of physical, chemical, and organic hazards throughout the whole operation of the food industry (Lositoet al.,2011). Through proper implementation of the HACCP system, food industries and health authorities can prevent foodborne diseases in the supply chain (Ramírez Vela and Martín Fernández, 2003). Rais et al., 2013, stated that Indian food processing sector had a vast opportunity for science and technology capability, research, and development. Besides, improving the green supply chain in an Indian food processing sector by developing the infrastructure (like the cold supply chain) and by incorporating food safety regulations and HACCP system will strengthen the sector.

3. An integrated PROMETHEE-based multiple criteria ranking approach for group decision making

In this section, we discuss an integrated MCDM approach for evaluation and selection of a green supplier. We combine the revised Simos procedure (Figueira and Roy, 2002), PROMETHEE methods (Brans et al., 1986), original algorithms for constructing the compromise ranking, and robustness analysis (Greco et al., 2012, Kadziński et al., 2012). The main steps of the proposed approach are presented in Figure 1.

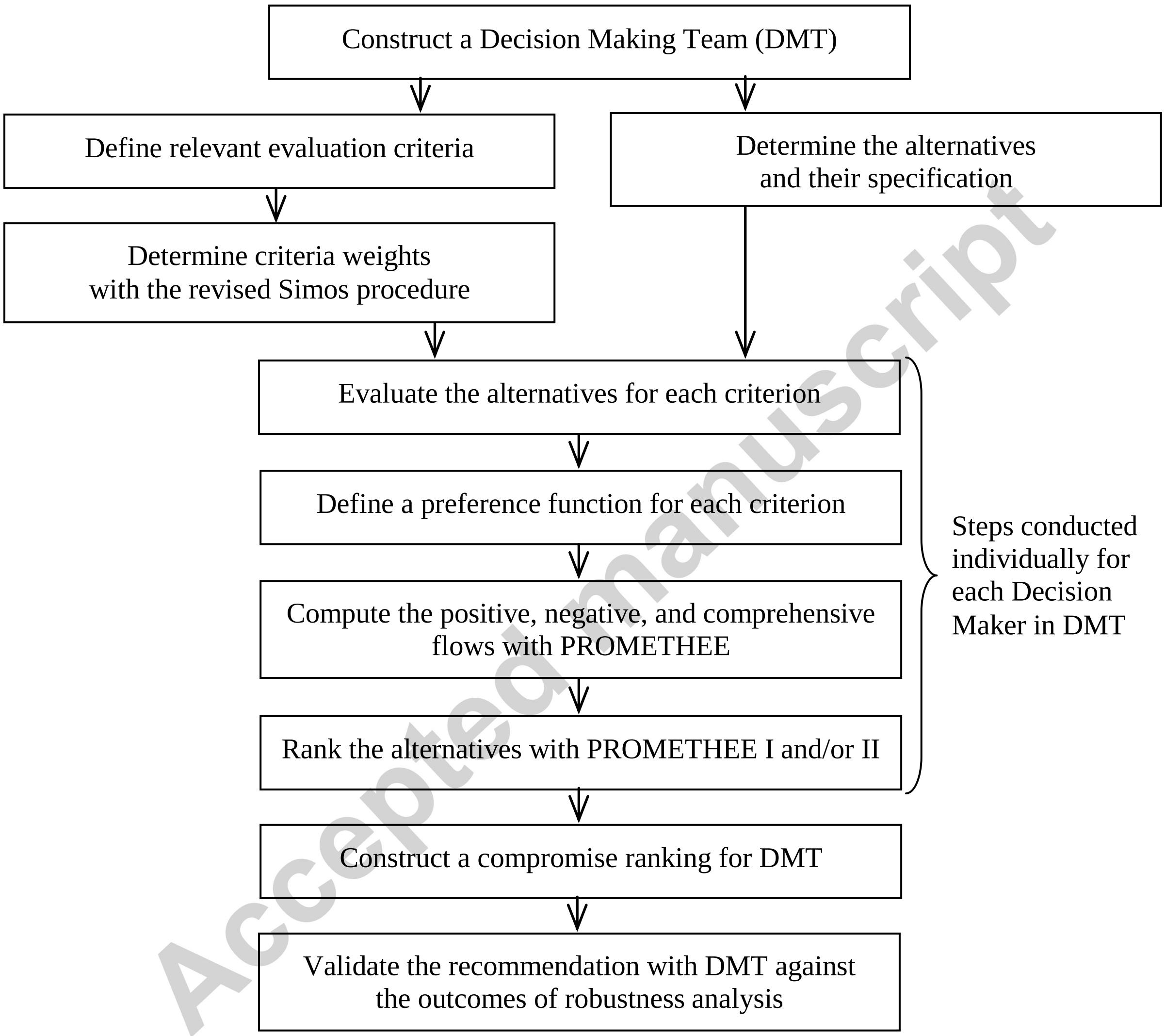

Figure 1: The integrated PROMETHEE-based framework for green supplier selection.

The considered problem can be expressed in a matrix format as presented in Table 2. It is an n x m matrix where $g_j(a_i)$ indicates the performance of alternative $a_i \in A$, $i = 1,2,\ldots,n$, evaluated in terms of the decision criterion g_j, $j = 1,2,\ldots,m$. We assume that the weights of the criteria are denoted with w_j, $j = 1,2,\ldots, m$. Without loss of generality, whenever not explicitly stated, we assume that all criteria are of gain type.

Table 2: Evaluation table.

a	$g_1(\,)$	$g_2(\,)$	...	$g_j(\,)$	...	$g_m(\,)$
a_1	$g_1(a_1)$	$g_2(a_1)$	...	$g_j(a_1)$	...	$g_m(a_1)$
.	.	.	...	.	...	.
a_i	$g_1(a_i)$	$g_2(a_i)$	...	$g_j(a_i)$	...	$g_m(a_i)$
.	.	.	...	.	...	.
a_n	$g_1(a_n)$	$g_2(a_n)$	...	$g_j(a_n)$	...	$g_m(a_n)$

3.1. The revised Simos procedure

In this section, we recall the revised Simos procedure for determining the criteria weights (Figueira and Roy, 2002). This approach has been used with the outranking methods in the context of many real-world applications (Shanian et al., 2008; Fontana et al., 2011; for a review, see Siskos and Tsotsolas, 2015). It assumes the DM is provided with m cards with the criteria names as well as a set of white (empty) cards. (S)he is asked to rank the cards from the least to the most important, while clustering together the criteria with the same importance. The number of white cards inserted between the subsets of criteria deemed indifferent can be used to control the difference of importance between these subsets.

Let us follow the notation proposed by Corrente et al., 2016b, and compute the non-normalized weight for each criterion g_j as follows:

$$w_j^{'} = 1 + \frac{(z-1)\left[l(j) - 1 + \sum_{s=1}^{l(j)-1} e_s\right]}{v - 1 + \sum_{s=1}^{v-1} e_s}.$$

where: $l(j)$ is the rank of importance to which criterion g_j belongs, $L_{l(j)}$ is the subset of criteria with rank $l(j)$, e_s is the number of white cards between the following sets of indifferent criteria L_s and L_{s+1}, and z is a ratio between the weights of criteria assigned to the most L_v and the least L_1 important groups. Then, the normalized weight w_j of g_j is defined in the following way (Corrente et al., 2016b):

$$w_j = \frac{w_j^{'}}{\sum_{k=1}^{m} w_k^{'}}.$$

Due to the simplicity of revised Simos procedure, its little computational effort, and providing effective results, we will use this approach to derive the weights of criteria employed within the PROMETHEE method.

3.2. The PROMETHEE method

In this section, we recall the PROMETHEE method (Brans et al., 1986) that will be used to rank the alternatives according to each DM's preference information. The main steps of PROMETHEE can be described as follows:

Step 1: Development of the alternatives' performance matrix as presented in Table 2.

Step 2: Specification of the marginal preference function. For criterion g_j this function translates the difference between the evaluations of two alternatives:

$$d_j(a_i, a_k) = g_j(a_i) - g_j(a_k)$$

into a marginal preference index $\pi_j(a_i, a_k)$ ranging from 0 to 1. Although PROMETHEE admits the use of several preference functions with pre-defined shapes, in this study we will refer to the one presented in Figure 2. When comparing the alternatives, this function implies that one alternative is preferred to another on g_j if its performance is strictly better.

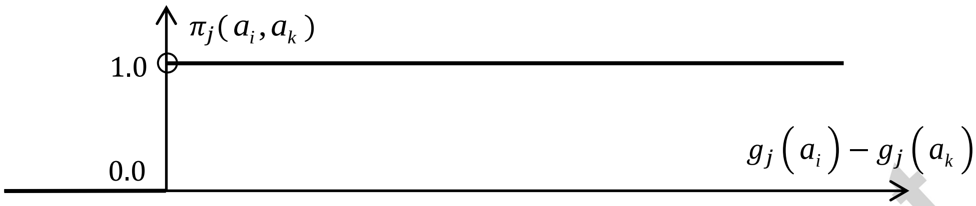

Figure 2: The marginal preference function for PROMETHEE used in the case study.

Note that this function is best suited for the qualitative criteria. Moreover, its employment in the context of all relevant viewpoints with the performances of alternatives expressed on a 10-point scale (see Section 4) has been motivated by the will of exploiting their ordinal character, i.e., comparing the alternative subject to the "the more, the better" rule.

Step 3: Specify or define the relative importance of each criterion (i.e., its weight w_j). In this study, the weights are determined using the revised Simos procedure described in Section 3.1.

Step 4: Determine the comprehensive preference index for the preference of a_i over a_k for all pairs of alternatives $a_i, a_k \in A$:

$$\pi(a_i, a_k) = \sum_{j=1}^{m} w_j \pi_j(a_i, a_k).$$

This index measures how strongly a_i is preferred to a_k in view of all criteria considered jointly on a scale between 0 and 1.

Step 5: Aggregatethe preference indices into the positive $\Phi^+(a_i)$ and negative $\Phi^-(a_i)$ outranking flows which express how much a_i, respectively, outranks all other *n-1* alternatives and is outranked by them:

$$\Phi^+(a_i) = \frac{1}{n-1}\sum_{a_k \in A} \pi(a_i, a_k) \text{ and } \Phi^-(a_i) = \frac{1}{n-1}\sum_{a_k \in A} \pi(a_k, a_i) .$$

These indices can be interpreted as the comprehensive strength and weakness of a_i. Finally, the net outranking flow $\Phi(a_i)$ reflects the difference between the positive and negative flows of a_i:

$$\Phi(a_i) = \Phi^+(a_i) - \Phi^-(a_i).$$

Step 6a: The PROMETHEE I partial ranking is determined through positive and negative outranking flows by constructing the relations of preference *P*, indifference *I*, and incomparability *R*. Precisely, a_i is preferred to a_k if one of its flows (i.e., positive or negative one) is strictly better while the other flow is not worse:

$$a_i P a_k \ \ if \ : \Phi^+(a_i) > \Phi^+(a_k) \text{ and } \Phi^-(a_i) < \Phi^-(a_k) \text{ or}$$
$$\Phi^+(a_i) > \Phi^+(a_k) \text{ and } \Phi^-(a_i) = \Phi^-(a_k) \text{ or}$$
$$\Phi^+(a_i) = \Phi^+(a_k) \text{ and } \Phi^-(a_i) < \Phi^-(a_k).$$

The indifference between a_i and a_k occurs if they have the same positive and negative flows:

$$a_i I a_k \ \ if \ : \Phi^+(a_i) = \Phi^+(a_k) \text{ and } \Phi^-(a_i) = \Phi^-(a_k).$$

Finally, two alternatives are considered incomparable if the results of a comparison between their positive and negative flows are contradictory:

$$a_i R a_k \ \ if \ : \Phi^+(a_i) > \Phi^+(a_k) \text{ and } \Phi^-(a_i) > \Phi^-(a_k) \text{ or}$$
$$\Phi^+(a_i) < \Phi^+(a_k) \text{ and } \Phi^-(a_i) < \Phi^-(a_k).$$

Step 6b: PROMETHE II provides the complete ranking of alternatives through comprehensive net flows $\Phi(a_i)$. Obviously, the higher the flow, the better. Note that in this approach only the preference *P* and indifference *I* relations are possible for the comparison of each pair of alternatives.

In the proposed framework PROMETHEE I and II can be employed jointly, or PROMETHEE II can be used when PROMETHEE I leaves too many alternatives to compare.

3.3. Construction of the compromise ranking for group decision making

In this section, we introduce a procedure for deriving a compromise ranking of alternatives based on the rankings constructed individually for each DM. The proposed algorithm can be used with both PROMETHEE and ELECTRE ranking methods.

When it comes to PROMETHEE, it has been first generalized to group decision in PROMETHEE-GDSS (Group Decision Support System) (see Macharis et al., 1998). This method permits to rank alternatives according to several DMs, considering each individual ranking given by the new flows as a criterion. In this way, the group ranking can be obtained by aggregating the individual flows (possibly incorporating weights assigned to the DMs). Moreover, one can perceive the flows as arguments of the different actors and display them in the geometrical analysis for interactive aid (GAIA) plane. This approach has been extensively used in real-world decision making (see, e.g., Alencar and de Almeida, 2010, Morais and de Almeida, 2007, Ishizaka and Nemery, 2011; for a review, see Macharis et al., 2015). PROMETHEE-GDSS has been subsequently extended in several ways. Firstly, one has introduced a procedure for grouping DMs with similar preferences using a hierarchical clustering (Ishizaka and Nemery, 2013). Secondly, the method has been adapted to multiple criteria sorting in FlowSort-GDSS (Lolli et al., 2015). Thirdly, one has proposed a fuzzification procedure to reflect an intrinsic dispersion of individual judgments. Finally, comparing alternatives by means of positive and negative flows has been implemented in the NAIADE (Novel Approach to Imprecise Assessment and Decision Environments) method which is capable of taking into account different interest groups (Munda, 2006).

Our approach differs from the majority of group decision making methods so far proposed in the context of PROMETHEE in that it derives a compromise recommendation from an analysis of the pairwise relations in the DMs' rankings rather than an aggregation of individual flows, criteria weights, or alternatives' performances. We discuss its several variants oriented towards construction of a partial or complete ranking, both of which can be either utilitarian or egalitarian with respect to the entire group of D DMs (thus, D is the number of DMs in DMT). On one hand, the utilitarian principle asserts that the best group policy is the one which maximizes the sum of utilities (or equivalently minimizes the sum of regrets) for all individuals (Myerson, 1981; Harsanyi, 1978). On the other hand, the egalitarian principle is equivalent to the maxmin (or minmax) principle, which maximizes the utility (or minimizes the regret) of the most unfortunate individual in the group (Rawls, 1999; Kalai, 1977; Myerson, 1981).

The introduced procedures build on the notion of distance between two rankings. Roy and Słowiński, 1993, defined such a distance function for partial rankings, justifying it by a set of logical and significance conditions. For each ordered pair (a_i, a_k), one and only one of the following relations is true: a_iPa_k, a_kPa_i, a_iRa_k, or a_iIa_k. For the sake of convenience, we shall substitute a_iPa_k and a_kPa_i with, respectively, $a_iP^+a_k$ and $a_iP^-a_k$.

Let $S_{ik}^{'}$ and $S_{ik}^{''}$ indicate the relations holding between a_i and a_k in the rankings O' and O'', respectively. Thus, $S_{ik}^{'}$ or $S_{ik}^{''}$ can be instantiated as one of the four relations: P^+, P^-, I, or R. Then, the distance $\delta(S_{ik}^{'}, S_{ik}^{''})$ between $S_{ik}^{'}$ and $S_{ik}^{''}$ can be derived from Table 3.

Table 3: Definition of distances $\delta(S_{ik}^{'}, S_{ik}^{''})$ between different pairwise relations.

$S_{ik}^{'} \setminus S_{ik}^{''}$	$a_iP^+a_k$	$a_iP^-a_k$	a_iIa_k	a_iRa_k
$a_iP^+a_k$	0	4	2	3
$a_iP^-a_k$	4	0	2	3
a_iIa_k	2	2	0	2
a_iRa_k	3	3	2	0

The distance between the same relations is zero (e.g., $\delta(P_{ik}^{+}, P_{ik}^{+})$=0). The greatest distance is attributed to the comparison of preference P^+ and inverse preference P^-. It is twice as big as for the indifference I and either preference (P^+ or P^-) or incomparability R. The value adopted for the comparison of preference and incomparability is intermediate. The comprehensive distance between two rankings O' and O'' that can be decomposed into relations $S_{ik}^{'}$ and $S_{ik}^{''}$, respectively, for all pairs of alternatives a_i, $a_k \in A$, such that $i > k$ (e.g., $O' = \{S_{ik}^{'} \text{ for } a_i, a_k \in A, i > k\}$), can be computed as follows:

$$\sum_{i,k:i>k} \delta(S'_{ik}, S''_{ik}).$$

3.3.1. Construction of a compromise partial ranking

In this section, we present a Binary Linear Program for constructing a compromise partial ranking based on individual DMs' rankings. Let us first focus on constructing the utilitarian ranking which minimizes the sum of distances from *D* individual rankings.

For each ordered pair of alternatives, we introduce five binary variables (see constraint [R6] in $E_{partial}^{utilitarian}$) representing the relations imposed for its comparison:

- r_{ik} - when instantiated with one, it indicates a weak preference of a_i over a_k; in this regard, r_{ik} and r_{ki} are used to instantiate one of the following four relations P^+,P^-, R, or I, for the comparison between a_i over a_k in the final ranking (see constraints [R1]-[$R4$]);
- P_{ik}^+ - when instantiated with one, it indicates a strict preference of a_i over a_k (i.e., $a_iP^+a_k$); it occurs if $r_{ik} = 1$ and $r_{ki} = 0$ (i.e., when a_i is weakly preferred to a_k (iff $a_iP^+a_k$ or a_iIa_k), while the inverse relation is not true; see constraint [R1]);
- P_{ik}^- - when instantiated with one, it indicates a strict preference of a_k over a_i (i.e., $a_iP^-a_k$); it occurs if $r_{ik} = 0$ and $r_{ki} = 1$ (see constraint [R2]);
- I_{ik} - when instantiated with one, it indicates indifference between a_i and a_k (i.e., a_iIa_k); it occurs if $r_{ik} = 1$ and $r_{ki} = 1$ (see constraint [R3]);
- R_{ik} - when instantiated with one, it indicates incomparability between a_i and a_k (i.e., a_iRa_k); it occurs if $r_{ik} = 0$ and $r_{ki} = 0$ (see constraint [R4]).

Only one of the four relations P^+,P^-, R, or I can hold for a given pair of alternatives (see constraint [R5]). For example, if $r_{ik} = 1$ and $r_{ki} = 0$, then $P_{ik}^+ \geq 1$ [R1], $P_{ik}^- \geq -1$ [R2], $I_{ik} \geq 0$ [R3], $R_{ik} \geq 0$ [R4], and $P_{ik}^+ + P_{ik}^- + I_{ik} + R_{ik} = 1$ [R5], and, thus, $P_{ik}^+ = 1$ and $P_{ik}^- = I_{ik} = R_{ik} = 0$; whereas if $r_{ik} = 0$ and $r_{ki} = 0$, then $P_{ik}^+ \geq 0$, $P_{ik}^- \geq 0$, $I_{ik} \geq -1$, $R_{ik} \geq 1$, and $P_{ik}^+ + P_{ik}^- + I_{ik} + R_{ik} = 1$, and thus $R_{ik} = 1$ and $P_{ik}^+ = P_{ik}^- = I_{ik} = 0$.

Moreover, a weak preference relation needs to be transitive (see constraint [T]). Thus, if a_i is weakly preferred to a_p and a_p is weakly preferred to a_k, the weak preference needs to hold also for a_i and a_k. For example, if $r_{ip} = 1$ and $r_{pk} = 1$, then $r_{ik} \geq 1 + 1 - 1.5 = 0.5$, and, thus, $r_{ik} = 1$, whereas if $r_{ip} = 1$ and $r_{pk} = 0$, then $r_{ik} \geq -0.5$, and, thus, r_{ik} can be either 0 or 1.

Let us denote the relation observed for a_i and a_k in the ranking of d-th DM by S_{ik}^d. Then, the comprehensive distance between relations S_{ik} adopted for different pairs of alternatives a_i, $a_k \in A$, $i > k$, in the final ranking and these observed in all individual DMs' rankings (d=1,...,D) can be expressed as follows:

$$\sum_{i,k:i>k} \sum_{d=1}^{D} \delta(S_{ik}^d, S_{ik}),$$

where $\delta(S_{ik}^d, S_{ik})$ are constants indicating the distance between relation S_{ik}^d and $S_{ik} \in \{P_{ik}^+, P_{ik}^-, I_{ik}, R_{ik}\}$ (see Table 3). Let us emphasize that we treat S_{ik}^d and S_{ik} within $\delta(S_{ik}^d, S_{ik})$ as symbols of the relations rather than variables.

Since S_{ik} is unknown a priori, when computing the overall distance, we need to consider its potential instantiation as one of the four relations: P_{ik}^+, P_{ik}^-, I_{ik} or R_{ik}, i.e.:

$$\sum_{i,k:i>k} \left[P_{ik}^+ \sum_{d=1}^{D} \delta(S_{ik}^d, P_{ik}^+) + P_{ik}^- \sum_{d=1}^{D} \delta\left(S_{ik}^d, P_{ik}^-\right) + I_{ik} \sum_{d=1}^{D} \delta\left(S_{ik}^d, I_{ik}\right) + R_{ik} \sum_{d=1}^{D} \delta\left(S_{ik}^d, R_{ik}\right) \right]$$
$$= \sum_{i,k:i>k} \sum_{S_{ik} \in \{P_{ik}^+, P_{ik}^-, I_{ik}, R_{ik}\}} S_{ik} \sum_{d=1}^{D} \delta(S_{ik}^d, S_{ik}).$$

As noted above, this instantiation is conducted by assigning one to the respective binary variable (e.g., $P_{ik}^+ = 1$) and zero to the remaining ones (e.g., $P_{ik}^- = I_{ik} = R_{ik} = 0$). As a result, only the distance associated with the instantiated relation is taken into account (e.g., $\delta(S_{ik}^d, P_{ik}^+)$), while the distances involving other relations (e.g., $\delta\left(S_{ik}^d, P_{ik}^-\right)$, $\delta\left(S_{ik}^d, I_{ik}\right)$, and $\delta\left(S_{ik}^d, R_{ik}\right)$), being multiplied by zero, are neglected.

In view of all above remarks, the compromise utilitarian partial ranking can be constructed by solving the following BLP:

$$min \sum_{i,k:i>k} \sum_{S_{ik} \in \{P_{ik}^+, P_{ik}^-, I_{ik}, R_{ik}\}} S_{ik} \sum_{d=1}^{D} \delta(S_{ik}^d, S_{ik})$$

$$\left.\begin{array}{c} \text{[R] for all } i,k = 1,2,\dots,n: i \neq k: \\ [R1]\ r_{ik} - r_{ki} \leq P_{ik}^+, \\ [R2]\ r_{ki} - r_{ik} \leq P_{ik}^-, \\ [R3]\ r_{ik} + r_{ki} - 1 \leq I_{ik}, \\ [R4]\ 1 - r_{ik} - r_{ki} \leq R_{ik}, \\ [R5]\ P_{ik}^+ + P_{ik}^- + I_{ik} + R_{ik} = 1 \\ [R6]\ r_{ik}, P_{ik}^+, P_{ik}^-, I_{ik}, R_{ik} \in \{0,1\} \\ \text{[T] for all } i,k,p = 1,2,\dots,n: i \neq k \neq p: \\ r_{ik} \geq r_{ip} + r_{pk} - 1.5, \end{array}\right\} E_{partial}^{utilitarian}$$

Instead of optimizing the sum of distances of individual rankings from the compromise one, we can minimize the greatest distance for any DM. To construct such egalitarian partial ranking, the objective function needs to be as follows:

$$min\, \alpha,$$

where α is not less than the distance of each DM's individual ranking from the compromise one. Thus, the set of constraints $E_{partial}^{utilitarian}$ has to be enriched with the following conditions, for $d = 1, \dots, D$:

$$\alpha \geq \textstyle\sum_{i,k:i>k} \sum_{S_{ik} \in \{P_{ik}^+, P_{ik}^-, I_{ik}, R_{ik}\}} S_{ik} \cdot \delta(S_{ik}^d, S_{ik}).$$

To support comprehension of the introduced procedures, in the e-Appendix (available online) we present and discuss in detail the mathematical programming models that need to be solved to construct a compromise ranking for the case study discussed in Section 4.

3.3.2. Construction of a compromise complete ranking

In this section, we present a BLP for constructing a compromise complete ranking based on individual DMs' rankings. Again, we will first focus on the utilitarian ranking. For each ordered pair of alternatives, we introduce two binary variables:

- r_{ik} - when instantiated with one, it indicates a weak preference of a_i over a_k; in this regard, r_{ik} and r_{ki} are used to instantiate one of the three relations P^+,P^-, or I, for the comparison between a_i over a_k in the final ranking; if $r_{ik} = 1$ and $r_{ki} = 0$, then $a_i P^+ a_k$, whereas if $r_{ik} = 0$ and $r_{ki} = 1$, then $a_i P^- a_k$;
- z_{ik} - when instantiated with one, it indicates indifference between a_i and a_k (i.e., $a_i I a_k$); it occurs if $r_{ik} = 1$ and $r_{ki} = 1$ (see constraint [R2'] in $E^{utilitarian}_{complete}$); for example, if $r_{ik} = 1$ and $r_{ki} = 1$, then $z_{ik} = 1 + 1 - 1 = 1$, whereas if $r_{ik} = 1$ and $r_{ki} = 0$, then $z_{ik} = 0$.

Since we construct a complete ranking, for each pair of alternatives (a_i,a_k), r_{ik} or r_{ki} has to be instantiated with one (see constraint $[R1']$), thus, excluding incomparability. Again, we require that a weak preference relation is transitive (see constraint [T]). Finally, in the objective function we minimize the overall distance between relations observed in the individual DMs' rankings and the one (P^+,P^-, or I) adopted for each pair of alternatives in the final ranking:

$$\min \sum_{i,k:i>k} \sum_{d=1}^{D} \left[r_{ik}\delta\left(S^d_{ik}, P^+_{ik}\right) + r_{ki}\delta\left(S^d_{ik}, P^-_{ik}\right) + z_{ik}\left[\delta(S^d_{ik}, I_{ik}) - \delta(S^d_{ik}, P^+_{ik}) - \delta(S^d_{ik}, P^-_{ik})\right]\right]$$

$$\left.\begin{array}{c} [R'] \text{ for all } i,k = 1,2,\ldots,n: i \neq k \\ [R1']\ r_{ik} + r_{ki} \geq 1, \\ [R2']\ z_{ik} = r_{ik} + r_{ki} - 1, \\ [R3']\ r_{ik}, z_{ik} \in \{0,1\}, \\ [T] \text{ for all } i,k,p = 1,2,\ldots,n: i \neq k \neq p \\ r_{ik} \geq r_{ip} + r_{pk} - 1.5. \end{array}\right\} E^{utilitarian}_{complete}$$

where for $i > k$, S^d_{ik} represents a particular relation (P^{+d}_{ik}, P^{-d}_{ik}, or I^d_{ik}) observed for the comparison between a_i and a_k for d-th DM, and $\delta(\cdot,\cdot)$ are constants representing distances between pairs of relations (see Table 3). To support understanding of the formulation of an objective function, let us consider the following two examples:

- assuming that a strict preference has been adopted for a_i, $a_k \in A$, $i > k$ (i.e., $r_{ik} = 1$, $r_{ki} = 0$ and $z_{ik} = 0$), then this relation contributes with the following distance to a value of the objective function:

$$\sum_{d=1}^{D} \left[\delta\left(S^d_{ik}, P^+_{ik}\right) + 0\delta\left(S^d_{ik}, P^-_{ik}\right) + 0\left[\delta(S^d_{ik}, I_{ik}) - \delta(S^d_{ik}, P^+_{ik}) - \delta(S^d_{ik}, P^-_{ik})\right]\right] = \sum_{d=1}^{D} \delta\left(S^d_{ik}, P^+_{ik}\right);$$

- in case of indifference i.e., $r_{ik} = 1$, $r_{ki} = 1$ and $z_{ik} = 1$), the respective distance is modelled as follows:

$$\sum_{d=1}^{D}\left[\delta\left(S_{ik}^{d}, P_{ik}^{+}\right) + \delta\left(S_{ik}^{d}, P_{ik}^{-}\right) + \left[\delta(S_{ik}^{d}, I_{ik}) - \delta(S_{ik}^{d}, P_{ik}^{+}) - \delta(S_{ik}^{d}, P_{ik}^{-})\right]\right] = \sum_{d=1}^{D}\delta\left(S_{ik}^{d}, I_{ik}\right).$$

The egalitarian complete ranking can be constructed analogously by considering the following objective function:

$$\min\alpha,$$

and incorporating the following set of constraints into $E_{complete}^{utilitarian}$, for $d = 1, \ldots, D$:

$$\alpha \geq \sum_{i,k:i>k}\left[r_{ik}\cdot\delta(S_{ik}^{d}, P_{ik}^{+}) + r_{ki}\cdot\delta\left(S_{ik}^{d}, P_{ik}^{-}\right) + z_{ik}\left[\delta(S_{ik}^{d}, I_{ik}) - \delta(S_{ik}^{d}, P_{ik}^{+}) - \delta(S_{ik}^{d}, P_{ik}^{-})\right]\right].$$

3.4. Robustness analysis

In this section, we discuss how to conduct robustness analysis (Roy, 2010) for the constructed preference relations in view of the imprecision in the specification of criteria weights. Thus, instead of assuming that the revised Simos procedure delivers precise criteria weights for each DM, we will refer to the ordinal information on the importance of criteria and to the ratio *z* between the most and the least important criteria. In our implementation, robustness analysis verifies the consequences of all combinations of weights compatible with the order provided by the DM on the final ranking. In this regard, we differ in understanding of robustness analysis, e.g., from Munda, 2006, who postulated taking into account only some clear ethical positions rather than all possible scenarios.

The set of constraints *E*(*w*) defining the space of weights and underlying outranking flows compatible with the specified preference information can be formulated as follows:

$$\left.\begin{array}{c}
\text{for all } a_i, a_k \epsilon A: \\
\Phi(a_i) = \Phi^{+}(a_i) - \Phi^{-}(a_i), \\
\Phi^{+}(a_i) = \dfrac{1}{n-1}\sum_{a_k\in A}\pi(a_i, a_k), \\
\Phi^{-}(a_i) = \dfrac{1}{n-1}\sum_{a_k\in A}\pi(a_k, a_i), \\
\pi(a_i, a_k) = \sum_{j=1}^{m} w_j\pi_j(a_i, a_k), \\
\pi_j(a_i, a_k) = 1, \quad if\, g_j(a_i) > g_j(a_k), \\
\pi_j(a_i, a_k) = 0, \quad if\, g_j(a_i) \leq g_j(a_k), \\
\text{for } l = 1, \ldots, v: \\
w_i \geq w_j + \varepsilon \;\; if \;\; g_i \in L_l \;\; and \;\; g_j \in L_{l-1}, \\
w_i = w_j \;\; if \;\; g_i, g_j \in L_l \\
\mathrm{w_i} = \mathrm{zw_j}, \quad \text{if } \mathrm{g_i} \in \mathrm{L_v} \text{ and } \mathrm{g_j} \in \mathrm{L_1} \\
\sum_{j=1}^{m} w_j = 1,
\end{array}\right\} E(w)$$

where ε is a variable whose value will be subsequently maximized.

To materialize the outcomes of robustness analysis, we will refer to the concept of the necessary preference relation P^N, which holds for an ordered pair of alternatives (a_i, a_k) if the preference of a_i over a_k is confirmed by all compatible sets of preference model parameters (i.e., all admitted weight vectors) (Kadziński et al, 2012, Corrente et al., 2014b). To check whether $a_i P^N a_k$, we assume that this relation does not hold for at least one compatible weight vectors by adding the following constraints to $E(w)$:

for PROMETHEE II:

$$\left.\Phi(a_i) + \varepsilon \leq \Phi(a_k),\right\} E^N_{PII}(a_i, a_k)$$

for PROMETHEE I:

$$\left.\begin{array}{c} \Phi^+(a_i) + \varepsilon \leq \Phi^+(a_k) + 2y_1, \\ \Phi^-(a_i) \geq \Phi^-(a_k) + \varepsilon - 2y_2, \\ y_1 + y_2 \leq 1, \\ y_1, y_2 \in \{0,1\}. \end{array}\right\} E^N_{PI}(a_i, a_k)$$

Thus, for PROMETHEE II, we assume that the net outranking flow of a_i is worse than that of a_k, i.e.,. $\Phi(a_i) < \Phi(a_k)$. For PROMETHEE I, the hypothesis relates to the positive or negative outranking flow of a_i being worse than the respective flow of a_k. This can be modeled using binary variables $y_1$and y_2. If $y_1 = 0$, then $\Phi^+(a_i) < \Phi^+(a_k)$, while if $y_2 = 0$, then $\Phi^-(a_i) > \Phi^-(a_k)$. If $y_t = 1$, t = 1,2, then the respective constraint is always verified, being eliminated. Since it is enough if one of these conditions holds, y_1 and y_2 cannot be instantiated with 1 at the same time ($y_1 + y_2 \leq 1$).

Let us denote the set of constraints obtained in this way by $E^N(a_i, a_k)$ (i.e., $E^N(a_i, a_k) = E(w) \cup E^N_{PII}(a_i, a_k)$ or $E^N(a,b) = E(w) \cup E^N_{PI}(a_i, a_k)$). If $E^N(a_i, a_k)$ is infeasible or $\varepsilon^* \leq 0$, such that $\varepsilon^* = max\ \varepsilon$, subject to $E^N(a_i, a_k)$, the conditions for preference of a_i over a_k are never violated within the space of feasible weights, which, in turn, means that for all compatible weight vectors a_i is preferred to a_k, and, thus, $a_i P^N a_k$. Let us note that, in general, the necessary relation for PROMETHEE II can be richer, but never poorer, than the necessary relation for PROMETHEE I.

The necessary preference relations P^N_d obtained for each DM, d=1,...D, can be used to derive the group preference relations defined as follows (Greco et al., 2012):

- $a_i P^{N,N} a_k$ (a_i is necessarily-necessarily preferred to a_k) if $a_i P^N_d a_k$ for all $d \in \{1,...,D\}$;
- $a_i P^{N,P} a_k$ ($a_i$is necessarily-possibly preferred to a_k) if $a_i P^N_d a_k$ for at least one $d \in \{1,...,D\}$.

Thus defined, $P^{N,N}$ indicates the most certain part of recommendations confirmed by all DMs. Further, the truth of $P^{N,P}$ indicates that at least one DM strongly confirms the underlying preference, while its falsity indicates that none of the DMs opts for such preference with certainty.

4. Case study

The Indian food processing industry is the largest and one of the fast growing sectors in the current market. It covers 32% of the country's total food market (IBEF, 2013). This sector constructs a dynamic bridge between agriculture and industrial sectors for economic growth. A reduction in agricultural raw material waste, an improvement in shelf-life and nutritional values of food products, the offer of remunerative prices to farmers, as well as affordable prices to consumers are all actions that will strengthen the relationship of this sector (MOFPI, 2013). Currently, many international food processors expect that future growth in an Indian food market and are showing interest in partnering with domestic food processing industries (IBEF, 2013).

In view of the recent growth of the food processing sector, it is necessary for food processing industries to implement greener and eco-friendly atmosphere in their operations to survive in the global competition (F&B News, 2011). These industries also need to introduce environmentally friendly technologies in their operations such as pre-production, post-production, maintenance, and service activity. Moreover, food processing industries have to implement and follow the HACCP management system to ensure the food safety and quality, which helps to earn the purchasing confidence from customers and to ensure industry growth (Losito et al., 2011). Hence, they need to maintain monitoring and controlling measures on each stage over the inflow and outflow of the goods to sustain food quality and to ensure food safety. In order to attain green goals in the food supply chain, the food industry firms are expected to develop excellent controls and measures in their processes as well as effective green strategic partnerships with food suppliers.

This study deals with the green supplier selection model in food processing industry situated in India. The case company is a large, well-known food processing company that sells food all over India. It manufactures a few hundred varieties of products and plans to manufacture a new beverage product to compete in the global market. The management board wishes to select a raw material supplier to purchase the base materials for new products in order to optimize its purchase process management and to have a powerful presence for sale to compete successfully with other rivals in national and international markets. Thus, the purchase process plays a vital role in its success.

Five suppliers who had capability to fulfill the companies purchasing requirement are nominated for selection. They are named as A1, A2, A3, A4, and A5. The decision criteria have been identified through literature review and discussion with experts who have vast knowledge and experience in food supply chain and environmental management systems. Finally, five main criteria and 15 sub-criteria organized in the hierarchy have been selected for evaluation of the suppliers (see Table 4). Note that C_{11}, C_{12}, C_{22}, C_{41}, C_{42} and C_{43} are the cost-type (minimizing) criteria, while the remaining ones are gain-type (maximizing) criteria.

Table 4: The green supplier selection criteria definition.

Main Criteria	Sub-criteria		Definition / Aim
Cost (C_1)	Product price	C_{11}	Lower product price without compromising the quality; includes warranty cost, processing cost
	Logistic cost	C_{12}	Fixed transportation cost for the supply of the product
Quality (C_2)	Quality assurance	C_{21}	Ensure high quality control on the products and provide the quality related certificates like ISO9000,QS9000, etc.
	Reject rate	C_{22}	The percentage of supplied materials is rejected by the quality control
Delivery (C_3)	Delivery capabilities	C_{31}	Ability to meet delivery schedules or promises, and ability to react quickly to customer orders
	Order fulfillment rate	C_{32}	Compliance with the predetermined order quantities
Environmental impacts (C_4)	Energy consumption	C_{41}	Control of energy consumption
	Solid waste generation	C_{42}	Quantity control and treatment of solid waste
	Air emission	C_{43}	Quantity control and treatment of hazardous emission, such as SO2, NH3, CO, and HC1
	Waste water treatment	C_{44}	Quantity control and treatment of waste water
	Food safety	C_{45}	Implementation of HACCP system to identify, assess and control hazards in the food production process
	Environmental management system	C_{46}	Whether the supplier has environment-related certificates, such as ISO14000
	Corporate social responsibility	C_{47}	Labor relations, human rights and interests of employees, comply with local regulations and policies
Technology capability (C_5)	R&D capability	C_{51}	Having infrastructure for research and development work
	Capability of design	C_{52}	Capability of developing new designs and speed of development

The team for supplier selection is composed of three managerial level experts from the purchase department (DM_1), production department (DM_2), and food safety department (DM_3). The evaluation of criteria is done through a survey by sending the questionnaire to the food processing industry experts and asking them to use the 10-point scale for evaluating supplier performance on each criterion. Obviously, for the gain-type criteria 10 means the best performance, while for the cost-type criteria, 1 is the best evaluation. The collected performances of five suppliers are provided in Table 5.

Table 5: The evaluations of five suppliers provided by the three DMs.

		min	min	max	min	max	max	min	min	min	max	max	max	max	max	max
		C_{11}	C_{12}	C_{21}	C_{22}	C_{31}	C_{32}	C_{41}	C_{42}	C_{43}	C_{44}	C_{45}	C_{46}	C_{47}	C_{51}	C_{52}
A1	DM_1	9	7	10	2	8	7	7	3	2	7	10	9	9	7	9
	DM_2	7	5	10	3	8	9	9	5	3	9	9	8	8	7	9
	DM_3	9	7	9	2	9	9	9	5	2	9	9	9	9	9	9
A2	DM_1	7	9	9	1	9	9	7	3	3	9	9	8	9	5	7
	DM_2	9	7	9	2	8	9	7	3	3	9	9	6	8	7	7
	DM_3	7	7	10	2	9	9	7	3	2	9	7	8	9	7	7
A3	DM_1	9	5	9	2	9	7	5	3	5	7	9	6	9	7	7
	DM_2	9	5	9	2	10	5	7	2	3	9	9	8	9	9	9

	DM_3	7	7	9	2	9	7	7	3	3	7	9	8	10	9	7
A4	DM_1	5	5	6	7	6	10	7	5	5	5	7	6	8	3	5
	DM_2	7	7	4	7	8	9	7	5	5	7	7	6	9	2	3
	DM_3	5	5	4	9	6	10	7	3	5	5	7	6	9	3	3
A5	DM_1	7	7	8	3	8	7	7	3	3	7	7	9	8	5	7
	DM_2	9	7	9	5	9	7	5	2	3	7	9	8	8	5	7
	DM_3	9	7	8	5	9	9	5	2	3	7	9	9	9	7	5

In this way, each DM contributed to the group's common decision from his/her own perspective on the suppliers. Even though some MCDM methods assume that all DMs need to share the same description of the decision problem (including the performance matrix), this assumption is relaxed in other approaches asking the DMs to evaluate alternatives using their individual model or value systems (Keeney, 2015). This is particularly practiced when a collective recommendation is built by combining the recommendations obtained individually for each DM instead of constructing a joint preference model used to evaluate the alternatives.

4.1. Deriving criteria weights with the revised Simos procedure

To derive the weights of criteria for each DM, we used the revised Simos procedure. The rankings of criteria provided by all three DMs are presented in Table 6. Note that all DMs have taken advantage of inserting the white cards to control the intensity of preference for different pairs of criteria. Moreover, the greater the position of a criterion in Table 6, the more significant it is.

Table 6: The order of cards with criteria names, white cards (w.c.) and the ratio (z) between the most and the least important criteria provided by the three DMs in the revised Simos procedure (the greater the position of criterion, the more important it is).

DM_1 (z=6)			DM_2 (z=9)			DM_3 (z=8)		
Group	No. of cards	Positions	Group	No. of cards	Positions	Group	No. of cards	Positions
C_{51}, C_{52}	2	1, 2	C_{51}, C_{52}	2	1, 2	C_{32}	1	1
2 w.c.	2	3, 4	1 w.c.	2	3	3 w.c.	3	2, 3, 4
C_{31}	1	5	C_{31}, C_{32}	2	4, 5	C_{31}	1	5
2 w.c.	2	6, 7	1 w.c.	1	6	2 w.c.	2	6,7
C_{32}	1	8	C_{11}, C_{12}	2	7,8	C_{52}	1	8
1 w.c.	1	9	2 w.c.	2	9, 10	3 w.c.	3	9, 10, 11
C_{12}	1	10	C_{41}, C_{42}	2	11, 12	C_{51}	1	12
3 w.c.	3	11, 12, 13	4 w.c.	4	13, 14, 15, 16	1 w.c.	1	13
C_{11}	1	14	C_{47}, C_{43}, C_{44}	3	17, 18, 19	C_{12}	1	14
C_{41}	1	15	1 w.c.	1	20	4 w.c.	4	15, 16, 17, 18
2 w.c.	2	16, 17	C_{46}	1	21	C_{11}	1	19

C_{42}, C_{43}, C_{44}	3	18, 19, 20	1 w.c.	1	22	1 w.c.	1	20
2 w.c.	2	21, 22	C_{45}	1	23	C_{41}, C_{42}, C_{47}, C_{43}, C_{44}	5	21, 22, 23, 24, 25
C_{46}	1	23	1 w.c.	1	24	1 w.c.	1	26
1 w.c.	1	24	C_{21}, C_{22}	2	25, 26	C_{46}	1	27
C_{45},C_{47}	2	25, 26				3 w.c.	3	28, 29, 30
1 w.c.	1	27				C_{45}	1	31
C_{22}	1	28				C_{22}	1	32
2 w.c.	2	29, 30				2 w.c.	2	33, 34
C_{21}	1	31				C_{21}	1	35

All three DMs indicate that the criteria related to quality (C_{21} and C_{22}) are the most important. Further, the criteria related to delivery (C_{31} and C_{32}) and technology capability (C_{51} and C_{52}) are among the least important. Nevertheless, the ranking provided by each DM is unique so as the ratio between the weights of the most and least important criteria. It has been set to 6 (DM_1), 9 (DM_2), or 8 (DM_3). The weights obtained with the revised Simos procedure for each DM are given in Table 7.

Table 7: The weights (in %) derived with the revised Simos procedure for the three DMs.

	C_{11}	C_{12}	C_{21}	C_{22}	C_{31}	C_{32}	C_{41}	C_{42}	C_{43}	C_{44}	C_{45}	C_{46}	C_{47}	C_{51}	C_{52}
DM_1	6.2	4.8	11.2	10.2	3.0	4.0	6.5	7.6	7.6	7.6	9.4	8.7	9.4	1.9	1.9
DM_2	3.9	3.9	12.5	12.5	2.6	2.6	5.7	5.7	8.8	8.8	11.3	10.1	8.8	1.4	1.4
DM_3	6.9	5.4	10.7	9.7	2.6	1.3	7.52	7.52	7.52	7.52	9.4	8.2	7.52	4.7	3.5

4.2. Ranking the suppliers with PROMETHEE

To use PROMETHEE for ranking the suppliers, each DM agreed to employ the preference function depicted in Figure 2 for all criteria. This function indicates that one alternative is strongly preferred to another if its performance is strictly better (i.e., $\pi_j(a_i,a_k)=1$ if $g_j(a_i) > g_j(a_k)$ for the gain-type criteria or $g_j(a_i) < g_j(a_k)$ for the cost-type criteria). The resulting marginal preference indices are aggregated into the comprehensive strength and weakness of each alternative, i.e., respectively, its positive $\Phi^{+}(a_i)$ and negative $\Phi^{-}(a_i)$ flows. These flows can be aggregated into the comprehensive net flows $\Phi(a_i)$. The results for the three DMs are presented in Table 8.

Table 8: The positive, negative, and comprehensive flows obtained with PROMETHEE for the three DMs.

	DM_1			DM_2			DM_3		
Supplier	$\Phi^+(a_i)$	$\Phi^-(a_i)$	$\Phi(a_i)$	$\Phi^+(a_i)$	$\Phi^-(a_i)$	$\Phi(a_i)$	$\Phi^+(a_i)$	$\Phi^-(a_i)$	$\Phi(a_i)$
A1	0.214	0.066	0.148	0.169	0.072	0.097	0.150	0.071	0.079
A2	0.208	0.087	0.121	0.109	0.103	0.006	0.145	0.100	0.045
A3	0.153	0.116	0.037	0.183	0.036	0.147	0.162	0.067	0.095
A4	0.055	0.285	-0.230	0.049	0.284	-0.235	0.062	0.268	-0.206
A5	0.102	0.178	-0.076	0.113	0.127	-0.014	0.136	0.149	-0.013

The positive and negative flows can be used to construct the ranking with PROMETHEE I, whereas the net outranking flows order the suppliers from the most to the least preferred as defined in PROMETHEE II. The rankings obtained with these methods for all DMs are depicted in Figure 3. The three DMs agree that A1 is among the top two suppliers, A2 and A5 are intermediate suppliers, whereas A4 is ranked at the very bottom. The major difference among the DMs concerns the comparison of A1 with A2 and A3.

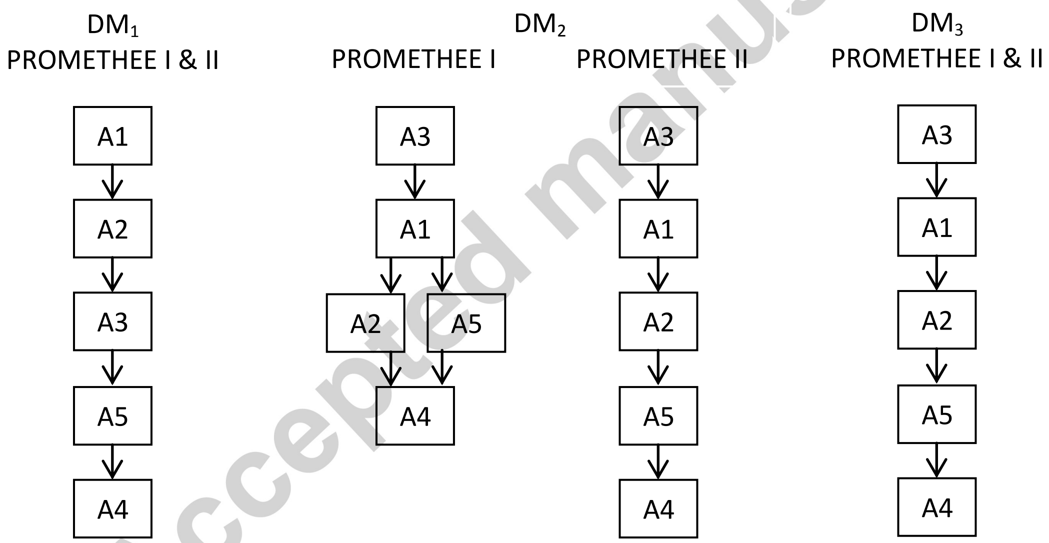

Figure 3: The rankings of suppliers obtained for the three DMs with PROMEHEE I and PROMETHEE II.

4.3. Construction of the compromise ranking

The individual rankings are used to construct a compromise ranking for the whole group. In this regard, let us first discuss the distances between individual rankings (see Table 9). They indicate that the rankings of experts from the production department (DM_2) and food safety department (DM_3) are similar to a large extent, while differing vastly from the ranking delivered for the expert from the purchase department (DM_1). The analysis of these distances can be used to indicate the groups of DMs whose interests are closer to the others and possibly constructing a dendrogram of coalitions reflecting the level of conflict among stakeholders in the spirit of the NAIADE method (Munda, 2006). Indeed, a lower distance implies a major likelihood of forming a coalition.

Table 9: The distances between the rankings obtained with PROMETHEE I and II for the three DMs.

	PROMETHEE I				PROMETHEE II		
	DM_1	DM_2	DM_3		DM_1	DM_2	DM_3
DM_1	0	11	8	DM_1	0	8	8
DM_2	11	0	3	DM_2	8	0	0
DM_3	8	3	0	DM_3	8	0	0

In Figure 4, we present the compromise rankings obtained with PROMETHEE I and II. Although for the case study we have adopted the egalitarian approach, for illustrative purposes we depict also the utilitarian rankings. The egalitarian rankings obtained with PROMETHEE I and II differ in that both A1 and A3 are ranked at the very top (for PROMETHEE I) or only A1 is ranked first (for PROMETHEE II). They both confirm, however, that A2, A5, and A4 are ranked at positions between third and fifth.

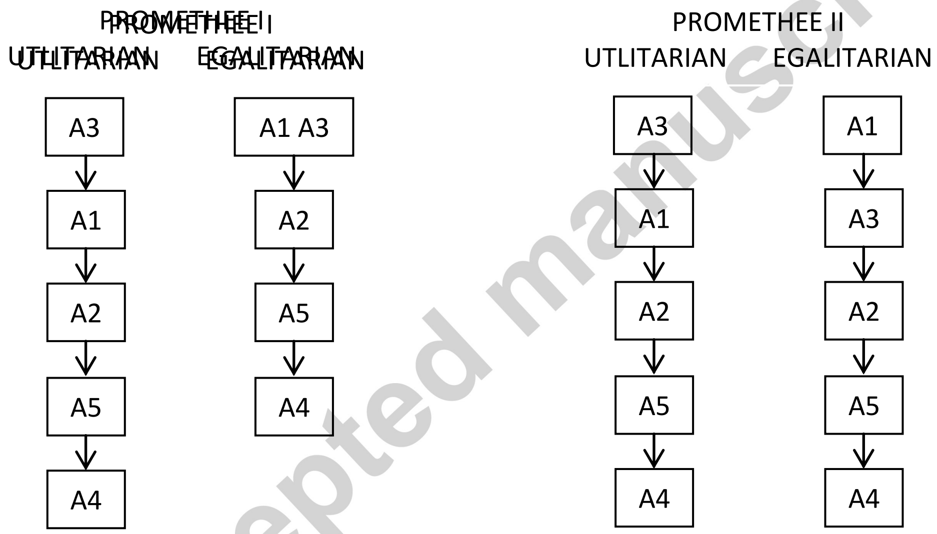

Figure 4: The compromise rankings of suppliers for PROMEHEE I and PROMETHEE II obtained with utilitarian and egalitarian approaches.

For PROMETHEE I, the comprehensive egalitarian distance of the individual rankings from the compromise one is equal to 6 (6 for DM_1, 5 for DM_2, and 2 for DM_3). Precisely, DM_1 needs to transform two preference relations into inverse preference (for A3 and A1) or indifference (for A1 and A3); DM_2 has to accept the change of incomparability between A2 and A5 into the preference of A2 over A5 as well as transformation of the preference of A3 to A1 into indifference; DM_3 needs to change just the latter relation. For PROMETHEE II, the comprehensive egalitarian distance is equal to 4. Each DM needs to accept the transformation of a preference relation into inverse preference just for a single pair of alternatives. In any case, A1 should be considered as the most preferred green supplier, A3 can be indicated as its desired replacement, while A4 is judged as the worst option.

The utilitarian rankings differ slightly from the egalitarian ones. For PROMETHEE I, to reduce the adaptations required for the entire group of DMs, it is beneficial to rank A3 better than A1. Then, the distances of individual rankings from the compromise one are as follows: 8 for DM_1, 3 for DM_2, and 0 for DM_3, and the comprehensive utilitarian distance is equal to 11 (=8+3+0). Thus, the greatest changes are again required for DM_1, but they are even more demanding than in the egalitarian case. This, however, allows us to reduce the adaptations imposed for DM_2 and DM_3. Analogously, for PROMETHEE II, it pays off to rank A3 rather than A1 at the very top. In this way, only DM_1 needs to accept the transformation of a preference relation into inverse preferences for A3 and A1 as well as for A3 and A2, while the rankings of DM_2 and DM_3 agree with the compromise one. Thus, the utilitarian distance of all individual rankings from the compromise one is equal to 8 (=8+0+0).

4.4. Robustness analysis

In this section, we indicate the most certain part of the provided recommendations. First, we refer to the necessary preference relation obtained from the robustness analysis conducted individually for each DM. In Figures 5 and 6, we present the graphs of these relations obtained with PROMETHEE I and II, respectively. Let us remind that if two suppliers are connected with an arc (either directly or when considering transitivity of the necessary relation), one of them is at least as good as the other for all weight vectors compatible with the order of criteria and ratio *z* provided in the revised Simos procedure.

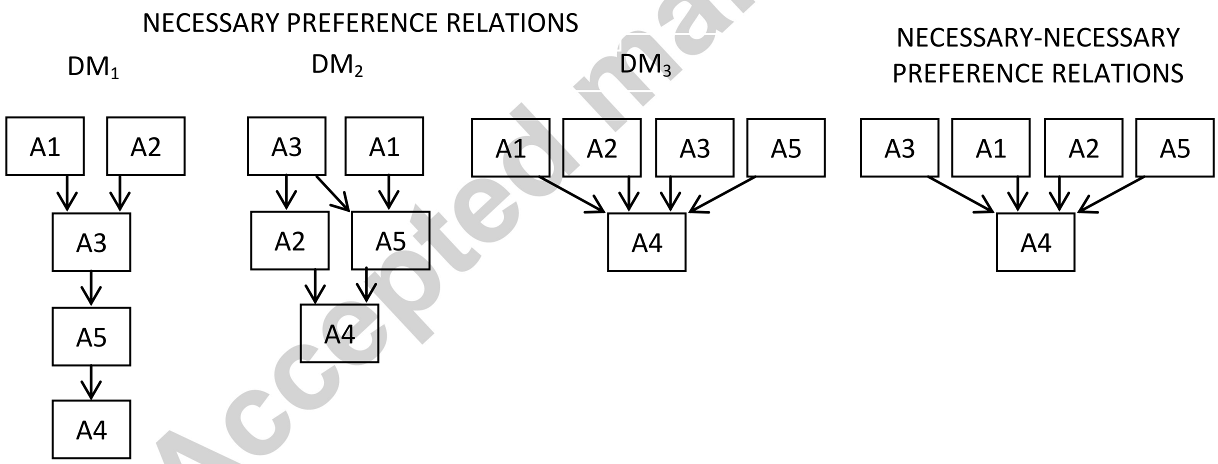

Figure 5: The necessary preference relations obtained with PROMETHEE I.

For both methods, the most certain recommendation can be observed for DM_1. In this case, all compatible rankings provide the same order of alternatives with the proviso that for some of them, A1 is ranked better than A2, while for some other rankings the order of these two suppliers is inverse. In this regard, DM_1 may be asked to reflect on the direct comparison of A1 and A2.

On the contrary, the recommendation obtained for DM_3 is the least certain. When using PROMETHEE I, all compatible weight vectors confirm that A4 is the worst supplier. They leave, however, all remaining alternatives incomparable in terms of the necessary relation. In PROMETHEE

II, A1, A2, and A3 are additionally preferred to A5. Such great variation observed in the possible rankings of DM_3 should encourage him/her to reflect on the order of criteria and the value of z provided in the revised Simos procedure.

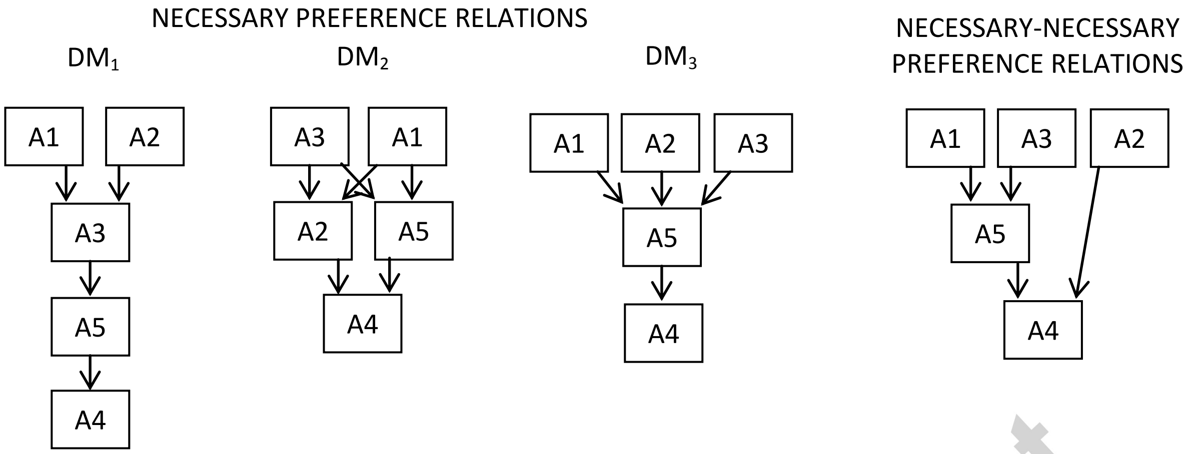

Figure 6: The necessary preference relations obtained with PROMETHEE II.

The necessary-necessary preference relation (see Figures 5 and 6) indicates the parts of the final recommendation on which all DMs agree with certainty (e.g., that A4 is the worst option, while A5 is considered worse than A1 and A3). Again, they are more conclusive for PROMETHEE II. Let us emphasize that this relation is contained in the compromise rankings that we discussed in the previous section. It is also interesting to analyze the necessary-possible preference relation. For example, A1 is the only supplier which is not necessarily preferred by any other alternative for each DM. It confirms the validity of the recommendation obtained with the egalitarian approach in Section 4.3, i.e., selecting A1 as the most preferred green supplier and treating A3 as its desired replacement. This observation confirms the usefulness of robustness analysis in enriching conclusions derived from using non-robust MCDM methods in case some uncertainties arise with respect to selection of the most preferred alternative.

To further address the robustness concern, in Appendix A we report the results obtained for our study when using one of the robust rules proposed by Siskos and Tsotsolas, 2015, for selection of the precise weights consistent with the DMs' rankings of criteria. Overall, the obtained results confirm selection of A1 as the most preferred supplier and A3 as an optional choice.

5. Managerial implications

From the managerial perspective, our paper yields the following implications:

- The proposed method helps the company's management involved in the purchasing activities to implement an integrated framework for green supplier selection involving a set of qualitative and quantitative economic and environmental criteria. In particular, the constructed family of criteria involving viewpoints related to cost, quality, delivery, environmental impacts, and technology capability can be adopted in other case studies concerning supplier selection. Furthermore, the introduced hybrid approach can be rigorously followed to indicate the most preferred supplied while taking into account multiple conflicting points of view and different stakeholders.

- As the food industry is mainly focused on the quality and environmental criteria, the suppliers being more advantageous in these two aspects are favoured. In particular, we found that the decision makers valued most highly the suppliers' quality materialized with the quality assurance and reject rate. On the contrary, the criteria related to the delivery and technology capability were among the least important. Since our model performs a ranking of the suppliers, it provides a means to suggest benchmarks for guiding the lower-ranked suppliers to improve their performance against the most relevant factors. These levels may be derived from the higher-rated suppliers.
- Leading publications in business management argue that it is necessary for the managerial decisions to be consistent with the corporate strategy for effective operations management. In this perspective, the group decision making procedure introduced in this paper can be used to construct a consensus ranking of the suppliers while taking into account viewpoints of different stakeholders within a company. For each decision maker, the proposed technique provides a gap between one's individual ranking and the suggested consensus. This approach can be effectively used by the managers. On one hand, they have a better idea on the acceptance of the decision by different stakeholders. Such analysis can be strengthened with the validation of results through robustness analysis. Indeed, it helps to reduce the risk and uncertainty in choosing the green supplier. On the other hand, the derived distances can be employed as a part of negotiation tool to reveal the levels of agreement within a decision making team and to provide adequate insight on the role of team members.

6. Conclusions

Supplier selection problem is a challenging and critical decision making issue for most organizations seeking to obtain competitive advantages in purchasing. The traditional supplier selection process followed in many companies involves only economic-oriented criteria. However, the recent trend of environmental awareness drives organizations to implement environmental requirements along with economic ones to select suitable suppliers for the green purchasing activities and to seek effective supplier selection models and methods.

This paper deals with the green supplier selection for a food processing industry in India. According to the literature, only a few papers discussed the supplier selection problem in the food industry. In this study, an integrated PROMETHEE-based multiple criteria ranking approach for group decision making has been proposed for evaluation and selection of the most preferred green supplier. As an initial step, the suitable green criteria were defined for supplier evaluation process with the help of experts' opinions and a literature survey. The five potential suppliers were evaluated on each criterion using a 10-point scale by the three DMs representing different managerial points of view. Then, the criteria weights were derived individually for each DM using the revised Simos procedure. Next, the PROMETHEE method was applied to construct for each DM his/her individual ranking of suppliers. Subsequently, the compromise ranking was constructed to minimize the distance of the individual's rankings from the solution adopted by the whole group. Finally, the results were validated against the outcomes of robustness analysis. The proposed integrated approach has proved to effectively support decision making regarding supplier evaluation and selection in the food industry. Let us emphasize, however, that the presented method is flexible enough to be applied in various decision problems faced by the management in other industries.

From the application point of view, in future research the data related to the evaluation of suppliers within a case study can be collected from more respondents to validate the research results. One can also incorporate more green criteria to develop even more effective method for green supplier selection. Moreover, a comparison with other MCDM approaches can be established. In particular, it may be useful to compare against AHP or ANP which have been so far most widely employed in the supplier selection problems.

From the methodological viewpoint, the proposed approach can be extended to use a variant of the Simos procedure that explicitly accounts for the hierarchical structure of criteria and admits imprecision in judgments provided by the decision makers (Corrente et al., 2016a). Furthermore, the proposed algorithms for constructing group consensus ranking can be adapted to deal with valued preference relations rather than only crisp ones. This would allow applying the introduced procedures, e.g., to the stochastic results derived with the SMAA-based methods (see, e.g., Angilella et al., 2016, Corrente et al., 2014b, Durbach and Calder, 2016, Kadziński and Tervonen, 2013). Finally, we envisage implementation of a dedicated decision support system within the *diviz* platform (Meyer and Bigaret, 2012).

Acknowledgments

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Appendix A. Ranking the suppliers while using criteria weights derived with the Max-Min average rule

In this section, we report the results of our study while further addressing the robustness concern. Since there exists an infinite number of weights that are consistent with the DMs' rankings, a selection of a single weight vector for each DM can be conducted in different ways. For this purpose, Siskos and Tsotsolas, 2015, proposed a set of robustness rules. We implement one of them (so called Max-Min average) which computes the variation range of the weight of each separate criterion by solving $2m$ linear programs, and then computes the average weighting vector (barycenter) of all $2m$ different vectors (Siskos and Tsotsolas, 2015). In all computations, we incorporate in the analysis the ratio z provided by each DM.

The weighting vectors obtained for the three DMs are presented in Table 10. Obviously, the ranges between the extreme weights obtained in the analysis were relatively great. For example, for DM_1 the range for C_{11} was [1.2, 9.4] and for C_{21} - [7.1, 30.0]. When comparing these weights with the ones derived with the revised Simos procedure, relatively greater values are assigned to the most important criteria (C_{21}, C_{22} and C_{45}), while the worst rated criteria (C_{12}, C_{11},C_{51} and C_{52}) have become, in general, even less advantageous.

Table 10: The weights (in %) derived with the Max-Min average rule for the three DMs.

	C_{11}	C_{12}	C_{21}	C_{22}	C_{31}	C_{32}	C_{41}	C_{42}	C_{43}	C_{44}	C_{45}	C_{46}	C_{47}	C_{51}	C_{52}
DM_1	4.2	3.7	15.1	13.5	2.7	3.2	4.8	6.2	6.2	6.2	10.8	8.7	10.8	1.9	1.9
DM_2	3.4	3.4	17.1	17.1	2.0	2.0	4.4	4.4	6.9	6.9	12.3	10.3	6.9	1.3	1.3
DM_3	3.9	3.4	16.6	14.9	1.9	1.5	5.9	5.9	5.9	5.9	12.6	10.7	5.9	2.8	2.3

Obviously, these variations imply slight differences in the values of positive, negative, and comprehensive flows (see Table 11). These changes are the most advantageous for A1 for which the positive flows for all DMs are significantly greater, and the least favorable for A4 whose performance decreased vastly in terms of both positive and negative flows.

Table 11: The positive, negative, and comprehensive flows obtained with PROMETHEE for the three DMs while using weights derived from the Max-Min average rule.

	DM_1			DM_2			DM_3		
Supplier	$\Phi^+(a_i)$	$\Phi^-(a_i)$	$\Phi(a_i)$	$\Phi^+(a_i)$	$\Phi^-(a_i)$	$\Phi(a_i)$	$\Phi^+(a_i)$	$\Phi^-(a_i)$	$\Phi(a_i)$
A1	0.235	0.056	0.179	0.187	0.071	0.116	0.169	0.059	0.110
A2	0.218	0.082	0.135	0.118	0.096	0.021	0.161	0.098	0.063
A3	0.158	0.111	0.047	0.183	0.036	0.147	0.165	0.069	0.096
A4	0.040	0.304	-0.264	0.039	0.304	-0.265	0.040	0.299	-0.259
A5	0.098	0.196	-0.098	0.111	0.131	-0.020	0.144	0.155	-0.011

The rankings obtained for these flows with PROMETHEE I and II are depicted in Figure 7. These have not changed for DM_1 or for DM_2 using PROMETHEE II. For DM_3 the order of A1 and A3 has been inverted, whereas for DM_2 using PROMETHEE I A1 and A3 are now incomparable and A2 is preferred to A5.

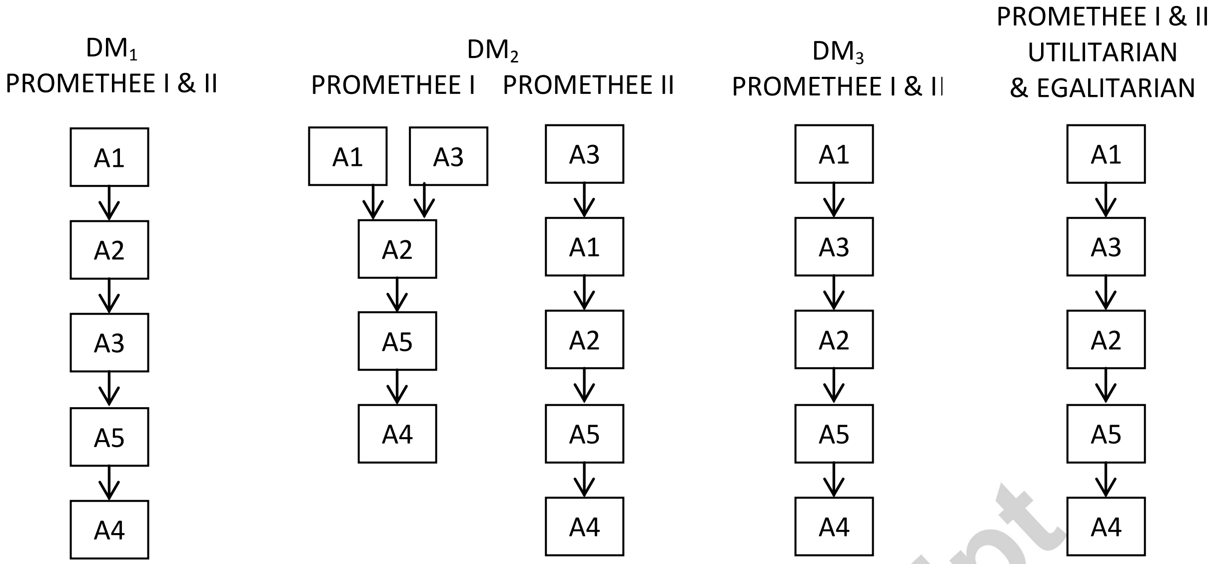

Figure 7: The rankings of suppliers obtained for the three DMs with PROMEHEE I and PROMETHEE II for the weights selected with the Max-Min average rule, and the compromise ranking of suppliers.

When using the individual rankings to construct a compromise recommendation for the whole group, the same ranking is obtained for PROMETHEE I and II implementing the utilitarian and egalitarian paradigms. It corresponds to the ranking obtained for DM_3. As a result, DM_1 needs to accept that A3 is preferred to A2, while DM_2 has to accept that A1 is preferred A3. For PROMETHEE I and II, the comprehensive egalitarian distance of the individual rankings from the compromise one is equal to 4, while the utilitarian distance is equal to 8 or 7 for, respectively, PROMETHEE I and II. Overall, these results confirm the selection of A1 as the most preferred supplier and A3 as an optional choice, while indicating A4 and A5 as the least advantageous alternatives.

Appendix

Application of a novel PROMETHEE-based method for construction of a group compromise ranking to prioritization of green suppliers in food supply chain

In this section, we present the mathematical programming models that had to be solved to construct a group-compromise ranking for the case study presented in the main paper. The binary linear program to be solved to construct a compromise utilitarian partial ranking is formulated in the following way:

$$
\begin{aligned}
min\ & P^{+}_{12}(0+0+0)+P^{-}_{12}(4+4+4)+I_{12}(2+2+2)+R_{12}(3+3+3)\\
&+P^{+}_{13}(0+4+4)+P^{-}_{13}(4+0+0)+I_{13}(2+2+2)+R_{13}(3+3+3)\\
&+P^{+}_{14}(0+0+0)+P^{-}_{14}(4+4+4)+I_{14}(2+2+2)+R_{14}(3+3+3)\\
&+P^{+}_{15}(0+0+0)+P^{-}_{15}(4+4+4)+I_{15}(2+2+2)+R_{15}(3+3+3)\\
&+P^{+}_{23}(0+4+4)+P^{-}_{23}(4+0+0)+I_{23}(2+2+2)+R_{23}(3+3+3)\\
&+P^{+}_{24}(0+0+0)+P^{-}_{24}(4+4+4)+I_{24}(2+2+2)+R_{24}(3+3+3)\\
&+P^{+}_{25}(0+3+0)+P^{-}_{25}(4+3+4)+I_{25}(2+2+2)+R_{25}(3+0+3)\\
&+P^{+}_{34}(0+0+0)+P^{-}_{34}(4+4+4)+I_{34}(2+2+2)+R_{34}(3+3+3)\\
&+P^{+}_{35}(0+0+0)+P^{-}_{35}(4+4+4)+I_{35}(2+2+2)+R_{35}(3+3+3)\\
&+P^{+}_{45}(4+4+4)+P^{-}_{45}(0+0+0)+I_{45}(2+2+2)+R_{45}(3+3+3)
\end{aligned}
$$

subject to:

$$
\left.
\begin{array}{c}
[\mathrm{R}]\text{ for all } i,k = 1,2,3,4,5:\ i\neq k:\\
[R1]\ r_{ik}-r_{ki}\leq P^{+}_{ik},\\
[R2]\ r_{ki}-r_{ik}\leq P^{-}_{ik},\\
[R3] r_{ij}+r_{ji}-1\leq I_{ik},\\
[R4] 1-r_{ik}-r_{ki}\leq R_{ik},\\
[R5]\ P^{+}_{ik}+P^{-}_{ik}+I_{ik}+R_{ik}=1\\
[R6]\ r_{ik,}P^{+}_{ik},P^{-}_{ik},I_{ik},R_{ik}\in\{0,1\}\\
[\mathrm{T}]\text{ for all } i,k,p = 1,2,3,4,5:\ i\neq k\neq p:\\
r_{ik}\geq r_{ip}+r_{pk}-1.5.
\end{array}
\right\} E^{utilitarian}_{partial}
$$

To better explain the formulation of the objective function, let us consider A2 and A5. In the individual rankings of DM_1 and DM_3. A2 is preferred to A5 (P^{+}_{25}), whereas for DM_2 these alternatives are incomparable (R_{25}). Thus, if P^{+}_{25} would be instantiated in the compromise ranking, this would involve no regret (distance) from DM_1 and DM_3, and a distance of 3 from DM_2 (overall, 0 + 3 + 0 = 3). If some other relation would be adopted, this would involve the following distances: 11 (=4 + 3 + 4) for P^{-}_{25}, 6 (=2 + 2 + 2) for I_{25}, or 6 (=3 + 0 + 3) for R_{25}. Since only one of these four relations can be instantiated ($P^{+}_{25}+P^{-}_{25}+I_{25}+R_{25}=1$), the overall distance of the compromise ranking from the individual ones concerning only A2 and A5 can be expressed as follows:

$$P_{25}^{+}(0+3+0) + P_{25}^{-}(4+3+4) + I_{25}(2+2+2) + R_{25}(3+0+3).$$

As far as the constraint set [R] is concerned, let us explicitly show how it is instantiated for $i = 2$ and $k = 5$:

$$\left.\begin{array}{c} r_{25} - r_{52} \leq P_{25}^{+}, \\ r_{25} - r_{52} \leq P_{25}^{-}, \\ r_{25} + r_{52} - 1 \leq I_{25}, \\ 1 - r_{25} - r_{52} \leq R_{25}, \\ P_{25}^{+} + P_{25}^{-} + I_{25} + R_{25} = 1, \\ r_{25}, r_{52},\ P_{25}^{+}, P_{25}^{-}, I_{25}, R_{25} \in \{0,1\}. \end{array}\right\}$$

In the optimal solution, the following relations have been instantiated: P_{12}^{+}, P_{13}^{-}, P_{14}^{+}, P_{15}^{+}, P_{23}^{-}, P_{24}^{+}, P_{25}^{+}, P_{34}^{+}, P_{35}^{+}, and P_{45}^{-}, which resulted in the following utilitarian distance:

$$(0+0+0) + (4+0+0) + (0+0+0) + (0+0+0) + (4+0+0) + (0+0+0) + (0+3+0) + (0+0+0) + (0+0+0) + (0+0+0) = 11.$$

The binary linear program that has to be solved to construct a compromise egalitarian partial ranking in our study is formulated in the following way:

$$min\ \alpha$$

subject to: $E_{partial}^{utlitarian}$

DM$_1$: $\alpha \geq 0P_{12}^{+} + 4P_{12}^{-} + 2I_{12} + 3R_{12} + 0P_{13}^{+} + 4P_{13}^{-} + 2I_{13} + 3R_{13} + 0P_{14}^{+} + 4P_{14}^{-} + 2I_{14} + 3R_{14} + 0P_{15}^{+} + 4P_{15}^{-} + 2I_{15} + 3R_{15} + 0P_{23}^{+} + 4P_{23}^{-} + 2I_{23} + 3R_{23} + 0P_{24}^{+} + 4P_{24}^{-} + 2I_{24} + 3R_{24} + 0P_{25}^{+} + 4P_{25}^{-} + 2I_{25} + 3R_{25} + 0P_{34}^{+} + 4P_{34}^{-} + 2I_{34} + 3R_{34} + 0P_{35}^{+} + 4P_{35}^{-} + 2I_{35} + 3R_{35} + 4P_{45}^{+} + 0P_{45}^{-} + 2I_{45} + 3R_{45}$

DM$_2$: $\alpha \geq 0P_{12}^{+} + 4P_{12}^{-} + 2I_{12} + 3R_{12} + 4P_{13}^{+} + 0P_{13}^{-} + 2I_{13} + 3R_{13} + 0P_{14}^{+} + 4P_{14}^{-} + 2I_{14} + 3R_{14} + 0P_{15}^{+} + 4P_{15}^{-} + 2I_{15} + 3R_{15} + 4P_{23}^{+} + 0P_{23}^{-} + 2I_{23} + 3R_{23} + 0P_{24}^{+} + 4P_{24}^{-} + 2I_{24} + 3R_{24} + 3P_{25}^{+} + 3P_{25}^{-} + 2I_{25} + 0R_{25} + 0P_{34}^{+} + 4P_{34}^{-} + 2I_{34} + 3R_{34} + 0P_{35}^{+} + 4P_{35}^{-} + 2I_{35} + 3R_{35} + 4P_{45}^{+} + 0P_{45}^{-} + 2I_{45} + 3R_{45}$

DM$_3$: $\alpha \geq 0P_{12}^{+} + 4P_{12}^{-} + 2I_{12} + 3R_{12} + 4P_{13}^{+} + 0P_{13}^{-} + 2I_{13} + 3R_{13} + 0P_{14}^{+} + 4P_{14}^{-} + 2I_{14} + 3R_{14} + 0P_{15}^{+} + 4P_{15}^{-} + 2I_{15} + 3R_{15} + 4P_{23}^{+} + 0P_{23}^{-} + 2I_{23} + 3R_{23} + 0P_{24}^{+} + 4P_{24}^{-} + 2I_{24} + 3R_{24} + 0P_{25}^{+} + 4P_{25}^{-} + 2I_{25} + 3R_{25} + 0P_{34}^{+} + 4P_{34}^{-} + 2I_{34} + 3R_{34} + 0P_{35}^{+} + 4P_{35}^{-} + 2I_{35} + 3R_{35} + 4P_{45}^{+} + 0P_{45}^{-} + 2I_{45} + 3R_{45}$

In the optimal solution, the following relations have been instantiated: P_{12}^{+}, I_{13}, P_{14}^{+}, P_{15}^{+}, P_{23}^{-}, P_{24}^{+}, P_{25}^{+}, P_{34}^{+}, P_{35}^{+}, and P_{45}^{-}, which resulted in the egalitarian distance equal to 6, i.e.:

$min\ \alpha$ such that for DM$_1$: $\alpha \geq 2 + 4 = 6$; DM$_2$: $\alpha \geq 2 + 3 = 5$; DM$_3$: $\alpha \geq 2 \rightarrow \alpha = 6$.

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Highlights

- We propose a hybrid approach to prioritization of green suppliers in food supply chain
- PROMETHEE is applied to rank the suppliers according to each Decision Maker's preferences
- We introduce the original methods for constructing a group compromise ranking
- The proposed approach is endorsed with a case study in an Indian food industry
- The results are validated against the outcomes of robustness analysis