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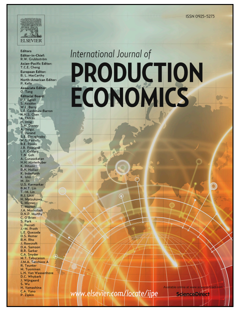

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[1] This paper is an extended version of a conference paper accepted for INCOM 2015

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Abstract:

Politico-economic deregulation, new communication technologies, and cheap transport have pushed companies to increasingly outsource business activities to geographically distant countries. Such outsourcing has often resulted in complex supply chain configurations. Because social and environmental regulations in those countries are often weak or poorly enforced, stakeholders impose responsibility on focal companies to ensure socially and environmentally sustainable production standards throughout their supply chains. In this paper, we present an integrated fuzzy AHP-VIKOR approach-based framework for sustainable global supplier selection that takes sustainability risks from sub-suppliers (i.e., *(1+n)*th-tier suppliers) into account. Sustainability criteria (including risk concerns) were identified from the existing literature and were further narrowed with the assistance of field experts and case decision makers to remove any literature bias. Then, based on the finalized sustainability criteria, suppliers and sub-suppliers were evaluated altogether. In previous studies, this approach was limited. The problem is addressed in two stages as follows. In the first stage, fuzzy AHP is used to generate criteria weights for sustainable global supplier selection, and in the second stage, fuzzy VIKOR is used to rate supplier performances against the evaluation criteria. Among five sustainability criteria (economic, quality, environment, social, and global risk), economic criteria demonstrated the greatest weight and global risk displayed the least weight. This result clearly shows that global risks are still not considered a major criterion for supplier selection. Further, the proposed framework may serve as a starting point for developing managerial decision-making tools to help companies more effectively address sustainability risks occurring further upstream in their supply chains. These vital tools are particularly important if focal companies are under intense scrutiny by their stakeholders.

Keywords:

Global supply chain management, multi-tier suppliers, sustainable supplier selection, multi-criteria decision making, fuzzy AHP, fuzzy VIKOR, risk mitigation

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1. Introduction

Globalization has pushed companies in the industrialized world to increasingly outsource their work and to shift offshore production to low cost economies. These steps help to leverage the cost advantages of sourced materials and products they are able to secure and to enhance their competitiveness (Steven et al., 2014). Gains are generated through economies of scale implied by specialization on certain production steps and on local production factor endowments such as cheap labour and natural resources (Den Butter, 2012). While benefits certainly exist, there are challenges to continuous outsourcing as well. Outsourcing to developing and emerging countries may have unintended side-effects, such as adding complexity to work processes and potentially fragmenting elements of the supply chains, which will result in quality problems (Steven et al., 2014), and risks from unsustainable production in the upstream chain (Fahimnia et al., 2015). Consequently, increasing coordination and transaction costs necessitate supply-base reduction, tighter integration, and stronger collaboration with strategic suppliers (Chen and Paulraj, 2004). Global supplier selection represents a strategic and complex managerial decision-making problem (Chan et al., 2008). Because supplier selection is intimately connected to corporate performance and competitive positioning, the decision is usually made by firms holding a leading supply chain position and brand ownership (cf. Andersen and Skjoett-Larsen, 2009). Any valid comparison of potential suppliers embraces several dimensions and represents a multi-attribute managerial decision-problem, so supplier selection on a global scale extends these evaluation dimensions. Additional risk factors, such as geographical location, political and economic framework conditions, and threats by terrorism must be considered (Chan and Kumar, 2007).

In 1987, the concept of sustainable development entered the global political agenda through the Brundtland Report (WCED, 1987). This concept was quickly embraced by pressure groups (such as NGOs, trade unions, student groups, etc.) to investigate business practices in general and internationally operating corporations in particular (Lund-Thomsen and Lindgreen, 2014). Sustainability as a core business principle has been pro-actively adopted by some pioneering companies. The label of corporate social responsibility (Goodpaster, 1983) generally refers to the specific contributions of a particular business to overall global sustainable development. The key role of business in ensuring development derives from its significant impacts on both social and environmental matrices. The workplace obviously creates social issues that set powerful lifestyle demands and influences, and environmental issues, concerning soil, water, air, biodiversity, and renewable and non-renewable resources are cornerstones of business management. The new objective of sustainability on the business agenda requires extending collaboration with suppliers towards environmental, social, and human issues (Vachon and Klassen, 2006), with the ideal objective of making those issues "corporate core issues themselves, on an equal footing with conventional economic considerations" (Gold et al., 2010). Neglecting public calls for contributing to sustainable development or not doing "net harm to natural or social systems" (Pagell and Wu, 2009, p.38) can turn out to be costly for focal companies. Companies with a leading supply chain position, brand ownership, and visibility to the consumers are under extreme pressure to address ecological issues such as looming climate change (MacKay and Munro, 2012) or social issues such as labour conditions in supply chains (Bair and Palpacuer, 2012). As a fundamental gatekeeper decision, the selection of global suppliers plays an extraordinary role for alleviating adverse impacts of business on societies and eco-systems. To this end, economic and environmental criteria are to be complemented by social sustainability criteria, such as the abolition of child labour, ensuring employee health and safety, and offering decent wages and social equity (Govindan et al., 2013, Wieland and Handfield, 2013). Some research sheds light on how an extended set of sustainability criteria can be integrated into the supplier selection process (see Handfield et al., 2002; Bai and Sarkis, 2010; Dai and Blackhurst, 2013), but some important research questions remain. For example:

RQ1: What is the best approach to evaluate supplier sustainability?

RQ2: Which sustainability criteria need to be considered for evaluating sustainable suppliers?

Most existing approaches largely neglect the fact that focal companies are held accountable for adverse impacts or grievances of their entire supply chain. In fact, current supplier selection models do not reach beyond the focal company's direct (first-tier) suppliers. The neglect of suppliers further upstream in the supply chain selection models does not address the fact that companies are held accountable for social and environmental impacts along the full chain, including the initial stage of raw material extraction. Non-compliance with societal expectations puts focal companies at risk of losing brand reputation, legitimacy, and may subject them to unfavourable governmental actions. Recent examples suggest how (multinational) corporations may be blamed for sub-suppliers' business practices that are considered unsustainable or unethical. One illustrative case concerns European and Northern American supermarkets (Wal-Mart, Carrefour, Tesco) that were accused of selling prawns produced under inhumane working conditions. Prawns were supplied by Charoen Pokphand Foods (CPF), a Thai corporation and the largest prawn farming company worldwide. CPF was charged with allegedly buying fishmeal for feeding their prawn farms from fishing boats that employ slave labour (Hodal et al., 2014). Campaigns initiated by NGOs and propelled by media tainted the brand image of the targeted supermarkets (with corresponding repercussions on their financial bottom line) and forced them to remove the respective prawn products from their supermarket shelves (Gold et al., 2015). This example shows that it was indeed the misconduct of second—and $(1+n)$th-tier (with $n \in \mathbb{N}_{>0}$)—suppliers, respectively, that triggered significant reputational threats. Following the first-tier suppliers, $(1+n)$th-tier suppliers belong to the “extended” and “ultimate” supply chain in the sense of Mentzer et al. (2001); they are largely beyond the control of focal firms although they might be visible to them (Carter et al., 2015). Nonetheless, sustainability performance achieved by the focal company itself may be entirely devalued by the poor sustainability performance of members—even far upstream ones—within its supply chain (Gimenez and Tachizawa, 2012 referring to Faruk et al., 2002). Hence, it is vital for companies that are exposed to public scrutiny to pay attention to their entire supply chain’s business behaviour. Companies should not only consider operational, financial, and sustainability criteria of their first-tier suppliers but also to be cognizant of the wider sustainability risks relating to their first-tier suppliers’ own extended suppliers. With these discussions, the following research questions emerge:

RQ3: How should the sub-suppliers (first-tier supplier’s suppliers) sustainability in global supply chain be evaluated?

RQ4: What are the major global risks involved in supply chain and how can they be used to select the sub-suppliers?

RQ5: What is the best way to assess the sustainability of suppliers and their sub-suppliers simultaneously?

In this paper, we address the problem of global sustainable supplier selection considering risks that arise from a focal company’s sub-suppliers. Most of the existing studies consider sustainability based on three pillars (economy, environment, and social) in general. Including global risks in sustainable supplier selection activities will make the selection process more efficient. Due to the lack of relevant literature and background settings, five research questions were made and detailed in earlier sections. These research questions can be classified as assessments of both sustainability and risk, which are further unified with an examination of both suppliers and sub-suppliers together to achieve the aim of the study. Hence, common sustainability criteria including risk concerns were collected from the literature and were further evaluated with the help of case industrial managers and field experts. The sustainability and risk criteria were used at two stages of supplier evaluation. The first stage of evaluation considers first-tier suppliers, and the second stage focuses on the sub-suppliers of the first-tier suppliers. Both evaluations were done by the focal firm, which wishes to maintain its brand reputation throughout the supply chain. In particular, our focus is on investigating how the global sustainable supplier selection model can be extended to integrate sustainability risks from *(1+n)*th-tier suppliers. A model framework is proposed and validated with a case study. AHP and VIKOR techniques are used to evaluate the supplier and sub-suppliers based on the sustainability criteria. Fuzzy set theory is used to address uncertainties arising due to lack of quantitative evaluations. A detailed description of the method and their applications is discussed in the upcoming sections.

The rest of the paper is structured as follows. In section 2, we present the related literature and research gaps. Section 3 contains the proposed methodology of global sustainable supplier selection based on fuzzy AHP and fuzzy VIKOR that also embraces sustainability risks from *(1+n)*th-tier suppliers. Subsequently, a numerical application is demonstrated in section 4. The paper ends with managerial implications and conclusions in sections 5 and 6.

2. Literature Review

Purchasing reached strategic relevance in the 1990s (Kraljic, 1983) due to its crucial impact on corporate core performance objectives, fostered by a strategic orientation towards core competencies (Hafeez et al., 2002). These core competencies boost the level of outsourced non-core activities, and these developments have resulted in purchasing costs representing the major part of product costs in many sectors (Ghodsypour and O'Brien, 1998). The strategic relevance of purchasing assigns high importance to the selection of suppliers. The aim of the selection process is to identify suitable suppliers that are able to fulfil the requirements of the buying company consistently and cost-efficiently (Kahraman et al., 2003). Supplier selection largely determines subsequent endeavours of establishing buyer-supplier partnerships and of increasing supplier capabilities by supplier development programmes (Yawar and Seuring, 2017).

De Boer et al. (2001) categorize supplier selection process into four phases (1) problem definition, (2) formulation of selection criteria, (3) preselection of candidates, and (4) final choice. Phases 2-4 of the selection process will profit most from quantitative managerial decision-support tools (De Boer et al., 2001). Most of the tools discussed in the current literature refer to phase 4, the final supplier choice, and integrate multiple supplier attributes rather than only the factor of costs (Ho et al., 2010). Typical quantitative techniques for supplier selection embrace mathematical programming models such as linear, goal, and multi-objective programming, analytic hierarchy and network process (AHP/ANP), fuzzy-set theory, simple multi-attribute rating technique (SMART), artificial neural networks, and various integrated solutions combining those approaches (see De Boer et al., 2001; Ho et al., 2010; Agarwal et al., 2011).

2.1 Sustainable supplier selection

Following the mainstreaming of sustainability into business strategies and operations, there are some approaches that attempt to integrate sustainability-related information into the supplier selection decision-making process (see Handfield et al., 2002 for an early attempt). Shaw et al. (2013) extend traditional supplier selection problems by including the criteria of carbon footprint induced by the outsourcing decision. Grimm et al. (2016) classify first-tier supplier management practices to ensure their compliance with CSS along two dimensions: supplier assessment and supplier collaboration. The supplier assessment methods involve requesting certifications from suppliers (e.g., ISO 14000), supplier evaluation and selection in accordance with selected sustainability criteria, and supplier monitoring and auditing programmes (Gimenez and Tachizawa, 2012). Supplier collaboration practices include supplier development programmes with training, workshops, transfer of employees, and investments. Bai and Sarkis (2010) propose a novel modelling technique based on a grey system and rough set theory for integrating sustainability criteria comprehensively into the selection process. Dai and Blackhurst (2013) propose an approach of integrating triple-bottom-line considerations into supplier selection by combining AHP with Quality Function Deployment (QFD) in order to make explicit the sustainability requirements of company stakeholders. These techniques—within their specific limits—represent powerful tools for selecting suppliers and have been refined by previous research. Nonetheless, the literature usually applies them to the situation of choosing domestic suppliers, having largely neglected global sourcing (i.e., supplier selection across country and continental borders) so far (Chan and Kumar, 2007).

2.2 Global sustainable supplier selection

Min (1994) offered one early approach of international supplier selection, using multiple attribute utility theory (MAUT), which underlined the multitude of (possibly conflicting) criteria to be taken into account for global supplier selection. This approach also comprehends risk factors that need to be made explicit and factored into the supplier selection decision, such as “risks of political instability, contract disputes or legal claims, currency inconvertibility, unstable foreign exchange rates, labour disputes, local price control, and so forth” (Min, 1994, p. 27). According to Chan and Kumar (2007), specific risks of global purchasing are linked to the geographical location (e.g., physical location of plant, mother country of supplier, probability of natural calamities), political stability (stability of governments and of legal and policy system), economy (local prices, currency exchange rate), and terrorism (supplier's policies for preventing and managing disruptions by terroristic acts).

While models of global supplier selection extend models of domestic supplier selection through the integration of additional risk factors (cf. Chan and Kumar, 2007; Chan et al., 2008; Kumar P. et al., 2011), risk is primarily included as direct cost or supply disruption risks (see Chan and Kumar, 2007; Schoenherr et al., 2008 for respective AHP approaches).

2.3 Global sustainable supplier selection considering sub-supplier(s) sustainability

There is a modest amount of research investigating sustainability relationships between focal firms and their sub-suppliers. Many firms simply rely on their first-tier suppliers to manage sub-suppliers in the upstream supply chain (Gonzalez et al., 2008, Lee and Klassen 2008, Spence and Bourlakis, 2009). In cases where first-tier suppliers do not take the responsibility for passing sustainability requirements to sub-suppliers, focal firms might establish direct relationships with higher-tier upstream suppliers or request their first-tier suppliers to select sub-suppliers from approved vendor lists. HP and Migros use site visits, on-site assessments, audit reports and sub-suppliers' self-assessments for sub-supplier CSS assessment. The collaboration practices include training workshops, exchange of experience workshops, awareness raising workshops, and corrective action plans. Supply chain mapping can help firms acquire data on each partner in the supply chain, from which audits can be completed to assess sustainability performance. Voluntary sustainability initiatives and strong partnerships form with stakeholders from multiple supply chain tiers.

While Kahraman et al. (2003, p. 383) generally suggest in the case of global supplier selection that the buying firm needs to scrutinize the "industrial infrastructure that supports the supplier," there are not yet any models that do this under the additional consideration of sustainability-related risks. Indeed, the vulnerability of focal firms towards stakeholders denouncing sustainability-related non-compliance, no matter where they appear throughout their supply chains, suggests the necessity of revealing these lurking risks through adapted supplier selection models. This is the research gap we address in this paper.

3 Proposed framework

The proposed solution approach for global sustainable supplier selection considering *(1+n)*th-tier supplier sustainability risks is comprised of the following main steps.

1. Development of a conceptual global supplier selection model embracing *(1+n)*th-tier supplier sustainability risks
2. Identification of criteria (and sub-criteria) for measuring supplier sustainability risks across *n*-tiers
3. Gathering information about *(1+n)*th supplier sustainability risks
4. Development of a methodology for ranking supplier performances across *n*-tiers

3.1 The iceberg model conceptualizing sub-supplier sustainability risks

To envision the rather abstract concept of sustainable development, the integration of different sustainability dimensions (economic, ecological, and social) into a "triple-bottom line" has been proposed (Dyllick and Hockerts, 2002). For the purpose of our study, we take these three pillars of sustainability and integrate them as assessment categories into our global sustainable supplier selection model. We complement them by the category of additional global risks linked to off-shoring decisions; this category had been repeatedly incorporated as specific elements of global supplier selection models (e.g., Ku et al. 2010; Kumar, S. et al., 2011; Shaw et al., 2013). Furthermore, we consider the category of relationship quality as an additional important category for choosing suppliers; hence, we follow other studies such as Bai and Sarkis (2010), Lee (2009), and Büyüközkan (2012). The various parts of the global sustainability supplier selection model are illustrated in Figure 1.

<Insert Figure 1>

This comprehensive model incorporates risks and opportunities from global sourcing and expands to the three sustainability dimensions as well as the dimension of relationship quality as a measure for predicted inter-organizational compatibility and collaboration. This model, however, is largely blind towards sustainability risks stemming from contraventions of sustainability standards by suppliers' suppliers upstream in the supply chain. Hence, these risks are further incorporated by two additional categories of supplier selection criteria: namely, environmental risks from *(1+n)*th-tier suppliers and social risks from *(1+n)*th-tier suppliers. In fact, the sustainability risks from *(1+n)*th-tier suppliers are basically hidden risks, which may only occasionally flare up when exploited by NGOs and other civil society organizations for campaigns, holding focal firms to account for their entire supply chains. This situation is illustrated in Figure 2, showing *(1+n)*th-tier suppliers' sustainability risk as the underwater part of the iceberg usually invisible from stakeholders' (and focal company's) scrutiny. Nonetheless, the underwater part of the iceberg represents substantial danger, as is common knowledge since the Titanic disaster; this metaphorical harm may range from drastic decreases in sales figures to more abstract reputational damage that may, in turn, have severe repercussions on the company-government (or other stakeholders) relationships or on the conditions of refinancing on the capital markets.

<Insert Figure 2>

3.2 Deriving supplier selection criteria for each assessment category

The procedure of deriving criteria for selecting suppliers is inherently guided by the opposing issues of completeness and practicability. While most material (and most relevant) aspects should definitely be covered, the number of assessment criteria has to remain restricted so that the assessment remains feasible in terms of both data collection and data analysis (Hubbard, 2009). The specific contingencies of application—such as the industry sector, the type of sourced material or pre-product, or the predominant geographical region of sourcing, etc.—may require some adaptations to the framework of selection criteria used. In the following, we present supplier selection criteria according to the relevant categories identified in Figure 1 and Figure 2 that are then used in the application case (see Table 1). The criteria have been collected from the existing literature on (sustainable global) supplier assessment for the categories of economic issues, quality of relationship, and global risks as well as from the Global Reporting Initiative G4 sustainability reporting guidelines (GRI, 2013) for the categories of environmental and social issues.

<Insert Table 1>

3.2.1 Economic issues

Economic issues are naturally at the heart of the supplier selection problem; it is understandable why a majority of papers present a supplier selection model that addresses some of these issues. While the criteria to be included and the exact wording of their definitions vary, there is relative consensus that cost, quality, speed, and flexibility are key decision criteria (cf. Dou and Sarkis, 2010). We complemented these four criteria by dependability in the sense of on-time delivery reliability level (e.g., Kuo and Lin, 2012; Genovese et al., 2013; Azadnia et al., 2014) and innovativeness (e.g., Bai and Sarkis, 2010; Kumar, S. et al., 2011; Lin et al., 2012) in the sense of a supplier's capability to implement product and process innovations.

3.2.2 Quality of relationship

Economic criteria are sometimes complemented by criteria assessing the quality of the buyer-supplier relationship, forecasting the effectiveness of future communication and collaboration between buyer and supplier. Screening previous approaches to supplier selection, we operationalize relationship quality by trust (e.g., Bai and Sarkis, 2010; Lin et al., 2012; Genovese et al., 2013), effectiveness of communication (e.g., Dou and Sarkis, 2010; Ku et al., 2010; Scott et al., 2013), and Electronic Data Interchange (EDI) between supplier and buyer (e.g., Ku et al., 2010; Ravindran et al., 2010; Büyüközkan, 2012).

3.2.3 Environmental issues

When sustainability thinking emerged from an international political debate (WCED, 1987), it was rather quickly absorbed by business management, although remaining rather tightly coupled only to the environmental dimension for a long time. Due to this long-standing "green" predominance, many of global sustainable supplier selection models have been integrating the environmental dimension in some form. This integration of environmental issues ranges from focused approaches relying on a few assessment categories to detailed assessment frameworks. Following the rough approach, Kuo and Lin (2012), for example, refer to the broad categories of environmental administration system, environmental system, environmental planning, and green purchasing; Kumar et al. (2014) consider the carbon footprint of suppliers (CO_2 equivalent emissions) as only environmental criteria. In contrast, other authors employ highly fine-grained assessment frameworks: for example, Awasthi et al. (2010), who exclusively focus on environmental evaluation of suppliers. For the purpose of this paper, we follow the environmental indicators as proposed by the GRI G4 sustainability reporting guidelines (GRI, 2013); they comprise materials, energy, water, biodiversity, emissions, effluents and waste, and supplier environmental selection procedure. Some studies address various environmental issues of the supply chain, including emissions (Zakeri et al., 2015; Fahimnia et al., 2013; Fahimnia et al., 2014a; 2014b; Bai et al., 2016), regulations

(Bojarski et al., 2009), location (Diabat et al., 2013), network design (Pishvaee and Razmi, 2012; Pinto-Varela et al., 2011; Nagurney and Nagurney, 2010; Hugo and Pistikopoulos, 2005; Chaabane et al., 2011; 2012), supplier selection (Banaeian et al., 2016), resilience (Fahimnia and Jabbarzadeh, 2016), reviews (Fahimnia et al., 2015; Seuring., 2013), and development models (Brandenburg et al., 2014).

3.2.4 Social issues

The social dimension of sustainability has long been neglected in management and business research (Barkemeyer et al., 2014), but in recent years the social dimension has gained greater attention and has been increasingly included into supplier selection models (e.g., Büyüközkan and Çifçi, 2011; Shaw et al., 2013; Azadnia et al., 2014). Following the approach by Varsei et al. (2014), we assess social performance of suppliers by four criteria suggested by GRI (2013): namely, labour practices and decent work conditions, human rights, society, and product responsibility. Analogous to the criterion of supplier environmental selection procedure (Kuo and Lin, 2012), we add as fifth category "supplier social selection procedure" since we deem the selection procedure regarding environmental and social issues as equally important.

3.2.5 Global risks

Global supplier selection needs to acknowledge additional risk factors linked to global sourcing. Such complementary risk factors have been successively incorporated into supplier selection models following the early papers by Chan and Kumar (2007), Chan et al. (2008), and Levary (2008). Investigating previous global supplier selection models, the main risks of sourcing from geographically and culturally distanced suppliers are currency (convertibility) risks (e.g., Levary, 2008; Ku et al., 2010; Kumar et al., 2011), disruption risks through political instability (e.g., Chan et al., 2008; Ku et al, 2010; Shaw et al., 2013), disruption risks through terrorism (e.g., Chan and Kumar, 2007; Chan et al., 2008; Shaw et al., 2013), and cultural (in-)compatibility issues (e.g., Ku et al., 2008; Kumar et al., 2011; Lee et al., 2011).

3.2.6 (1+n)th-tier supplier sustainability risks

While there have been a few articles that hint towards including business activities beyond the first-tier of suppliers into the analysis, these approaches have only concerned single issues so far. Genovese et al. (2013) incorporate communication speed on environmental issues to sub-suppliers into the category of environmental criteria. Similarly, Kannan et al. (2014) extend the evaluation of environmental performance to second-tier suppliers. Kuo and Lin (2012) address green purchasing policies, and Levary (2008) integrates the reliability of supplier's suppliers into his global supplier selection model. Finally, Tse and Tan (2011) embrace information sharing about *(1+n)*th-tier suppliers with the aim to make product quality risks visible.

Seeking to fill the blank in current global supplier selection assessment approaches, we comprehensively integrate sustainability risks spreading from *(1+n)*th-tier suppliers into our model. For this end, we take the social and environmental assessment criteria outlined above and transfer them to *(1+n)*th-tier suppliers to cover the focal company's risk from non-compliance of suppliers further up the supply chain (see Table 1).

3.3 Gathering and evaluating information about *(1+n)*th-tier suppliers

While corporate transparency may be conceived as one of today's management mantras, it is uncertain how far companies are actually willing to create knowledge about themselves and to reveal it both internally and externally to stakeholders. In this respect, Christensen (2002) emphasizes that corporate transparency goals may end up as polished advertisements of company activities and a useless accumulation of information that does not provide better insights into corporate conduct.

The challenge of corporate transparency is even more valid for international supply chains where the collection of comprehensive information about business behaviours and production conditions among *(1+n)*th-tier suppliers (defined as those beyond the direct reach of focal companies because no direct contractual relationships exist) represents an extraordinary managerial and information-technical challenge (Grimm et al., 2014). Sustainability performance can, in large part, only be evaluated at the site of production itself (e.g., working conditions, wages, pollution), whereas traditional performance objectives (e.g., product availability, price, material product features) can also be assessed ex-post by the focal company (Grimm et al., 2014). This poses additional challenges on ensuring compliance to standards of sustainable business operations along the supply chain. For assessing *(1+n)*th-tier suppliers, the focal company relies in large parts on information provided by the first-tier supplier who may be unwilling to reveal even the names of their suppliers and their sub-suppliers. There may be good reasons for such a secretive attitude of (potential) first-tier suppliers; for example, a risk exists of becoming redundant if focal companies unfairly deal directly with suppliers' suppliers after such information disclosure. Solutions such as approved sub-supplier lists imposed on first-tier suppliers (Choi and Linton, 2011) imply immense managerial complexity for focal firms and may be opportunistically circumvented by first-tier suppliers when opportunities for cost savings arise in the course of the business relationship.

Next to the issue of availability of information about *(1+n)*th-tier suppliers, there is usually substantial uncertainty about the credibility of the information made available to focal firms. Uncertainty may be reduced by various forms of third-party certification such as SA 8000 or ISO 14000 (Darnall et al., 2008; Ciliberti et al., 2012) without making the need for a focal firm's final judgement redundant, as audit results may be flawed or misleading. For instance, the textile company Ali Enterprises in Karachi (Pakistan) received the prestigious SA 8000 certification (approving *inter alia* satisfactory on-site workers' health and safety conditions) only weeks before a fire killed almost 300 workers trapped within the factory building (Walsh and Greenhouse, 2012).

Bearing these challenges of data availability and credibility in mind, a committee of experts may be seen as well suited for assessing *(1+n)*th-tier suppliers by the focal company; those committees can leverage their vast experience and may thus cope with high levels of missing or uncertain information. Qualitative (linguistic) assessments can be used to evaluate the criteria and alternatives, which are converted into fuzzy triangular numbers (Table 2) in this paper for numerical processing to generate final alternative rankings. Due to the costs (in terms of corporate resources) of gathering information and deploying expert committees, *(1+n)*th-tier suppliers assessment may only be conducted in a second step for a small number of preselected first-tier suppliers that have been filtered beforehand, as, for example, through a threshold value.

<Insert Table 2>

3.4 Evaluating the sustainability performance of global suppliers

The sustainability performance evaluation of global suppliers extended towards *(1+n)*th-tier suppliers comprises two stages. Stage I involves a sustainability evaluation of main suppliers, and stage II involves a sustainability risk evaluation of *(1+n)*th-tier suppliers of the top ranked suppliers (selected using a threshold) retained from stage I. The overall ranking of the supplier is obtained using weighted scoring of the results obtained from both stages, and the top-ranked supplier is finally chosen (in case of single sourcing). The criteria used for evaluation are obtained using Table 1. Fuzzy AHP is applied to rate the criteria while Fuzzy VIKOR is used to rank the suppliers. The fuzzy AHP approach performs within fuzzy environments to address uncertain, imprecise judgements of experts through the use of linguistic variables or fuzzy numbers (Saaty, 1988), whereas the fuzzy VIKOR (in Serbian: VlseKriterijumska Optimizacija I Kompromisno Resenje) technique involves fuzzy assessments of criteria and alternatives in VIKOR (Opricovic, 1998). The strength of fuzzy AHP is the ability to handle uncertainty and perform pairwise comparisons to ensure consistent rankings from the decision makers (Wei et al., 2005, Chan and Kumar, 2007, Govindan et al., 2013); fuzzy VIKOR is able to handle large number of alternatives and generates alternative rankings based on proximity to ideal solution.

3.4.1 Fuzzy AHP

The first step in fuzzy AHP involves decomposing the problem into a hierarchical structure comprising of goal, criteria, sub-criteria, and alternatives to construct the model. Then, the elements are compared pairwise with respect to the importance to the goal, importance to the criterion, and importance to the sub-criterion. The relative importance values are defined using triangular fuzzy numbers (TFNs) on a scale of $\tilde{1}$ and $\tilde{9}$ to take the imprecision of human qualitative assessments into consideration. Five TFNs $\tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9}$ are used in our study where $\tilde{1}$ denotes equal importance and $\tilde{9}$ denotes extreme relative importance. More details on the TFNs, their corresponding membership functions, and the linguistic variables associated with them can be found in Table 3. A reciprocal value is assigned to the inverse comparison, i.e., $a_{ji} = \frac{1}{a_{ij}}$ where a_{ij} denotes the importance of the i^{th} element compared to the j^{th} element. The resulting fuzzy comparison matrix $\tilde{A}$ is given by:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & . & \tilde{a}_{1n} \\ \tilde{a}_{21} & . & . & . \\ . & . & . & . \\ \tilde{a}_{n1} & \tilde{a}_{n2} & . & 1 \end{bmatrix}$$

where $\tilde{a}_{ij} = 1$, if *i* equals *j* and $\tilde{a}_{ij} = \tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9}$ or $\tilde{a}_{ij} = \tilde{1}^{-1},\tilde{3}^{-1},\tilde{5}^{-1},\tilde{7}^{-1},\tilde{9}^{-1}$ if *i* does not equal *j*.

<Insert Table 3>

Once all the pairwise comparisons are made at the individual level, group priority vectors are generated by aggregating the individual judgements in the third step. Two approaches can be used: aggregating individual judgements (AIJ) and aggregating individual priorities (AIP). The former is appropriate for group members that act together as a unit while the latter is appropriate for separate individuals (Forman and Peniwati, 1998). We are using the AIJ method for aggregating the evaluations (pairwise comparison matrices) in this paper since this method treats expert judgements at earlier stages, thereby avoiding any expert re-evaluations required due to inconsistencies arising in alternative rankings at later stages. Let us denote that the fuzzy TFN ranking provided by expert *i* on element *j* as $\tilde{w}_{ij} = (a_{ij}, b_{ij}, c_{ij}), i = 1,2,..,n; j = 1,2,..,m$. The aggregate judgement $\tilde{w}_j = (a_j, b_j, c_j), j = 1,2,..,m$ of the group is given by $a_j = \underset{i}{Min}\{a_{ij}\}, b_j = \frac{1}{n}\sum_{i=1}^{n} b_{ij}, c_j = \underset{i}{Max}\{c_{ij}\}$. The crisp value w_j for fuzzy number $\tilde{w}_j = (a_j, b_j, c_j), j = 1,2,..,m$ is obtained using $w_j = \frac{a_j + (4 * b_j) + c_j}{6}$.

Having obtained the aggregate judgement matrix of all the pairwise comparisons, the consistency is determined by using the eigenvalue λ_{max} to calculate the consistency index CI in step 4 where CI = $(\lambda_{max} - n)/(n - 1)$ and n is the matrix size. Judgement consistency can be checked by seeing the value of consistency ratio CR = CI/RI where RI is the random consistency index whose value can be obtained from Table 4. If CR ≤ 0.1, the judgement matrix is acceptable; otherwise, it is considered inconsistent. To obtain a consistent matrix, judgements should be reviewed and improved.

A variety of methods have been reported in the literature for priority vector derivation in AHP including the eigenvector method (EV), weighted least squares method (WLS), additive normalization method (AN), logarithmic least squares method (LLS), cosine maximization method, and so forth (Kou and Lin, 2014). Our study relies on the eigenvector method. The eigenvalue of a matrix is calculated using det(A-λI) = 0. The eigenvector provides the priority vector (or local weights) associated with the elements $j = 1,2,..,m$.

<Insert Table 4>

Finally, in step 5, the final priorities of alternatives are obtained by multiplying the group priority vectors of criteria, sub-criteria, and alternatives.

3.4.2 Fuzzy VIKOR

Let us consider a set of *m* alternatives (urban mobility projects) called $A = \{A_1, A_2,.., A_m\}$ that are to be evaluated against a set of *n* criteria, $C = \{C_1, C_2,.., C_n\}$. The criteria weights are denoted by $w_j (j=1,2,..,n)$. The performance ratings of decision makers $D_k (k = 1,2,.., K)$ for each alternative $A_i (i=1,2,..,m)$ with respect to criteria $C_j (j = 1, 2,.., n)$ are denoted by $\tilde{R}_k = \tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}), i = 1,..,m; j = 1,2,..,n; k = 1,2,..K$ with membership function $\mu_{\tilde{R}_k}(x)$.

If the fuzzy ratings of *k* decision makers are described by triangular fuzzy number $\tilde{R}_k = (a_k, b_k, c_k), k = 1,2,.., K,$ then the aggregated fuzzy rating is given by $\tilde{R} = (a,b,c), k = 1,2,.., K$, where

$$a = \min_k\{a_k\}, b = \frac{1}{K}\sum_{k=1}^{K} b_k, c = \max_k\{c_k\} \tag{1}$$

If the fuzzy rating of the k^{th} decision maker for alternative A_i and criteria C_j are given by $\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk})$ and the importance weight by $\tilde{w}_{jk} = (a_{jk}, b_{jk}, c_{jk}), i = 1,2,,,m, j = 1,2,..n$ respectively, then the aggregated fuzzy ratings ($\tilde{x}_{ij}$) of alternatives with respect to each criteria based on Eqn. (1) are given by $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ where

$$a_{ij} = \min_k\{a_{ijk}\}, b_{ij} = \frac{1}{K}\sum_{k=1}^{K} b_{ijk}, c_{ij} = \max_k\{c_{ijk}\} \tag{2}$$

The aggregated fuzzy weights ($\tilde{w}_j$) of each criterion are calculated as $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$ where

$$w_{j1} = \min_k\{w_{jk1}\}, w_{j2} = \frac{1}{K}\sum_{k=1}^{K} w_{jk2}, w_{j3} = \max_k\{c_{jk3}\} \tag{3}$$

The fuzzy decision matrix for the alternatives ($\tilde{D}$) and the criteria ($\tilde{W}$) is constructed as follows:

$$\tilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ . \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \end{array} \quad ,i=1,2,\dots,m;\ j=1,2,..,n \tag{4}$$

$$\tilde{W} = (\tilde{w}_1, \tilde{w}_2, .., \tilde{w}_n) \tag{5}$$

Once these matrices are obtained, overall criteria scores for evaluating the alternatives are generated using the following steps.

Step 1: Defuzzify the elements of fuzzy decision matrix for the criteria weights and the alternatives into crisp values. A fuzzy number $\tilde{a} = (a_1, a_2, a_3)$ can be transformed into a crisp number a by employing the below equation:

$$a = \frac{a_1 + 4a_2 + a_3}{6} \tag{6}$$

Step 2: Determine the best f_j^* and the worst values f_j^- of all criteria ratings j=1,2,...,n

$$f_j^* = \max_i\{x_{ij}\} \qquad \text{and} \qquad f_j^- = \min_i\{x_{ij}\} \tag{7}$$

Step 3: Compute the values S_i and R_i using the following equations

$$S_i = \sum_{j=1}^{n} w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \qquad \text{and} \qquad R_i = \max_j w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \tag{8}$$

Step 4: Compute the values Q_i as following

$$Q_i = v\frac{S_i - S^*}{S^- - S^*} + (1-v)\frac{R_i - R^*}{R^- - R^*} \tag{9}$$

where:

$$\begin{aligned} S^* &= \min_i S_i; \\ S^- &= \max_i S_i; \\ R^* &= \min_i R_i; \\ R^- &= \max_i R_i; \end{aligned} \tag{10}$$

Additionally, v is the weight for the strategy of maximum group utility, and 1-v is the weight of the individual regret.

Step 5: Rank the alternatives, sorting by the values S,R and Q in ascending order.

Step 6: Propose as a compromise solution the alternative ($A^{(1)}$) that is the best ranked by the measure Q (minimum) if the following two conditions are satisfied:

C1: Acceptable advantage

$$Q(A^{(2)}) - Q(A^{(1)}) \geq DQ \tag{11}$$

Where $A^{(2)}$ is the alternative with second position in the ranking list by Q and J is the number of alternatives.

$$DQ = 1/J\text{-}1 \tag{12}$$

C2: Acceptable stability in decision making

The alternative $A^{(1)}$ must also be the best ranked by S or/and R. The compromise solution is stable within a decision-making process, which could be the strategy of maximum group utility (when ν >0.5 is needed), or "by consensus $\nu \approx 0.5$", or "with veto" (ν<0.5). Please note that ν is the weight of the decision-making strategy of maximum group utility.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of

- Alternatives $A^{(1)}$ and $A^{(2)}$ if only the condition C2 is not satisfied, or
- Alternatives $A^{(1)}, A^{(2)}, ..., A^{(M)}$ if the condition C1 is not satisfied.

Alternatives $A^{(M)}$ are determined by the relation $Q(A^{(M)}) - Q(A^{(1)}) < DQ$ for maximum M (the position of these alternatives in closeness).

4. Numerical Application

In this section, we demonstrate the numerical application of the proposed approach for an electronic goods manufacturing company (denoted as ABC), which is interested in evaluating its global suppliers from a comprehensive sustainability perspective. ABC procures materials from suppliers all over the world. Due to the increasing pressure from customers and heightened awareness from government and environmental organizations on development of eco-friendly products, ABC is involved in several sustainability initiatives at organizational levels, particularly in procurement, manufacturing, and transportation of goods. One such initiative at ABC is green supplier development, which involves training and collaborating with suppliers for purchasing and production of goods that meet eco-friendly requirements. Another initiative is providing pre-approved vendor (sub-supplier) lists to its main suppliers to minimize sustainability risks arising from lower-tier suppliers. To identify suppliers (and sub-suppliers) that perform poorly on sustainability requirements of ABC and, hence, require improvement, the proposed framework (section 3) is used. With the assistance of the existing literature, the criteria for evaluating the suppliers were collected and circulated to the case company decision makers. A committee of three decision makers, comprising department heads from Production, Logistics, and Purchasing, was formed, and the collected criteria were adjusted to meet real life situations. Once several rounds of discussions occur, the evaluation criteria for supplier selection are finalized as shown in Table 1 (section 3.2). These decision makers are directly involved with the firm's supplier selection processes, so a questionnaire identifying the pertinent criteria was given to the decision makers. Based on their preferences on suppliers and based on the evaluating criteria, they employ the scale of linguistic preferences mentioned earlier. Generally, these decision makers' choices are based on the performance of the considered suppliers in past years. To tackle unethical documentation, decision makers come with a solid report on suppliers based on their life data. It includes direct inspection and is further coordinated with investigations of reporting (including social reporting, environmental reporting, and so on). Based on the pilot report on supplier performance on the considered criteria, they rated the suppliers and subbing suppliers. This evaluation is performed in two stages. In the first stage, the sustainability performance of global suppliers is evaluated by the focal company using stage I criteria (economic, quality of relationship, environmental, social, and global risks). In the second stage, the *(1+n)*th-tier suppliers of the top suppliers retained from stage I are evaluated using stage II criteria (environmental and social).

4.1 Generating criteria weights

The decision-making committee performs pairwise evaluations of criteria to generate their priorities. Using the AIJ method (section 4.2), aggregate pairwise scores for the various criteria and sub-criteria (Table 4) are generated. Table 5 presents the aggregated pairwise comparison matrix of the decision committee members for stage I criteria. It can be seen that the C.R. = C.I./R.I. =0.1028/1.12 = 0.0917 < 0.1; hence, the evaluations can be called consistent. The last column shows the eigenvector matrix (priorities or the local weights) for the stage I criteria.

<Insert Table 5>

Likewise, the priorities of sub-criteria associated with stage I are demonstrated after performing pairwise comparison matrices and checking consistencies. Table 6 presents the local weights and global weights of the various sub-criteria associated with stage I. The global weights are obtained by multiplying the local weights with the respective criteria weight. For example, for sub-criteria Ec1, the local weight is 0.367, and for criteria Ec, the local weight is 0.6; therefore, the global weight of Ec1 = 0.367*0.6 = 0.221.

<Insert Table 6>

Likewise, the criteria and sub-criteria weights for stage II are computed. Table 7 presents the pairwise comparison matrix for the (stage II criteria) and the resulting weights.

<Insert Table 7>

Table 8 presents the local and global weights for the stage II criteria and sub-criteria.

<Insert Table 8>

4.2 Sustainable supplier and sub-supplier(s) selection

Fuzzy VIKOR is used to select the sustainable supplier and sub-supplier(s) against the weighted criteria obtained from fuzzy AHP (stage I and II). A committee of three decision makers (D1, D2, and D3) is formed to evaluate the alternatives (suppliers S1, S2, and S3 and sub-suppliers SS1, SS2, and SS3) against the selected criteria using qualitative (linguistic) ratings (Table 2). The ratings obtained are presented in Table 9.

<Insert Table 9>

The aggregated fuzzy weights (w_{ij}) for the alternatives are obtained using Eqn. (2). For example, for criteria C1 (Qualitative Rating = (L,L,VH)), the aggregated fuzzy weight is given by $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$ where:

$$w_{j1} = \min_k(1,1,7), w_{j2} = \frac{1}{3}(3+3+9), w_{j3} = \max_k(5,5,9)$$
$$\tilde{w}_j = (1,5,9)$$

The aggregated fuzzy weights $\tilde{w}_j$ are transformed into crisp number w_j using Eqn. (6). For example, for criteria C1, $\tilde{w}_j = (1,5,9)$, we have $\tilde{w}_j = \frac{1+(4*5)+9}{6} = 5$. Likewise, we compute the aggregate weights of the three alternatives for all the remaining criteria. Based on these values and Eqn. (7), the best f_j^* and the worst values f_j^- of the alternatives for the 25 criteria are computed. Table 10 shows the aggregate fuzzy decision matrix for alternatives (main suppliers), and the f_j^* and f_j^- values.

<Insert Table 10>

Then, the S_i, R_i and Q_i values for the three alternatives are computed using Eqns. (8-9). The values of S^*= 0.365, S^- = 0.689, R^*= 0.116, R^- =0.221 are obtained using Eqn. (10). Note that

$\nu = 0.5$. Table 11 ranks the three alternatives, sorting by the values of Q_i, R_i and S_i, in ascending order.

<Insert Table 11>

It can be seen from the results of Table 11 that alternative S3 is the best ranked by the measure Q_i (minimum). We now check it for the following two conditions (section 3.3.1).

1). C1: Acceptable advantage (Eqn. (11)).

Using Eqn. (11), DQ = 1/3-1 = 1/2 = 0.5. Applying Eqn. (10), we find Q(S1)-Q(S3) = 0.493 - 0= 0.493 < 0.5; hence, the condition $Q(A^{(2)}) - Q(A^{(1)}) \geq DQ$ is not satisfied.

2). C2: Acceptable stability in decision making (Eqn. (12))

Since alternative A3 is also best ranked by S_i and R_i (considering the "by consensus rule $\nu \approx$ 0.5"), this condition is therefore satisfied.

Since only condition C2 is satisfied, the alternatives rank is given by S3 ~S1 > S2, and both A3 and A1 are finally chosen and ranked the best supplier (stage I).

Table 12 presents the stage II evaluations provided by the decision-making committee for sub-suppliers. Fuzzy VIKOR will be applied in a similar manner to generate final rankings for sub-suppliers.

<Insert Table 12>

Table 13 ranks the three sub-suppliers sorting by the values of S_i, R_i and Q_i in ascending order. It can be seen that SS3 is best ranked based on least value of Q_i

<Insert Table 13>

Since it also satisfies the other two conditions (section 3.3.1), it is finally chosen as the best sub-supplier (stage II).

Therefore, based on the results of stage I and II, supplier, the focal (buyer) organization can select S1 and S3 as main suppliers and recommend SS3 as sub-supplier to them for procurement.

5. Research implications

The proposed work has several implications for managers, society, and academicians. Current managerial decision-making tools for supplier selection do not take sustainability risks from the wider supply chain into account. This is a relevant absence since these risks, indeed, could result in material losses for focal firms in Europe, Japan, Northern America, and elsewhere, if contraventions of international social and environmental conventions in their supply chains are taken up by civil society campaigns and propelled by (conventional and/or social) media. The present paper proposes an approach for managers to select suppliers based on a comprehensive framework of selection criteria, including social and environmental sustainability risks from *(1+n)*th-tier suppliers. The proposed managerial tool responds in particular to the risks that multi-national corporations (MNCs) face if they source their pre-products globally (including from low-income countries) and particularly if they are under public scrutiny, which generally holds the focal firms accountable for their entire supply chains. It also helps managers decide supplier (and sub-supplier) development approaches for high-risk or poorly performing suppliers (and sub-suppliers) on corporate sustainability standards.

From the academic's point of view, the proposed work proposes an integrated approach based on fuzzy AHP-VIKOR for global sustainable supplier selection under limited or no quantitative information. Expert committees and fuzzy theory are particularly suitable to address the challenge of assessing sustainability risks from *(1+n)*th-tier suppliers, which feature high degrees of missing and uncertain data. Due to high costs of extending the assessment towards sub-supplier levels up to *(1+n)*th-tier suppliers, we recommend managers follow a hierarchical two-step-approach. The sustainability risks of sub-suppliers are in a second step; they are only assessed for a limited number of top-ranked first-tier suppliers that were selected by a certain cut-off value. AHP is able to provide consistent criteria ratings whereas VIKOR generates alternative (suppliers and sub-suppliers) rankings based on proximity to the ideal solution.

From societal perspective, applying a comprehensive supplier selection model (as proposed in this paper based on fuzzy AHP-VIKOR) makes the supply chain more transparent for internal and external stakeholders and, therefore, helps focal firms gain more accountability and decrease their vulnerability towards adverse campaigns from civil society. The proposed approach also aids in minimization of environmental and economic risks to society arising from poorly performing suppliers (and sub-suppliers) on corporate sustainability standards.

6. Conclusions and future works

Politico-economic deregulation, new communication technologies, and cheap transport have pushed companies to increasingly outsource business activities to geographically distant countries; these choices have often resulted in complex supply chain configurations involving many stages from raw material extraction to the final customer. In particular, cheap labour and the disposability of natural resources have spurred supply chains to reach out to low-income countries. Since social and environmental regulations in those countries are often weak or weakly enforced, focal companies are assigned responsibility from the civil society to enforce at least minimum sustainability-related production standards. The increased awareness of NGOs, student groups, trade unions, citizens and other civil society actors and their power of adversely affecting financial and economic objectives of focal companies has not been sufficiently reflected in supplier selection models so far. This article contributes to filling this gap by proposing a comprehensive model of global sustainable supplier selection extended towards sustainability risks from *(1+n)*th-tier suppliers, using fuzzy AHP-VIKOR based approach. Fuzzy AHP is used to generate criteria weights whereas fuzzy VIKOR is used to rank the alternatives against the selected criteria.

The main limitation of our work is the lack of quantitative data and the presence of a limited number of respondents in the study.

Based on the proposed work, several extensions are possible. First, the proposed model could be tested using real data. Second, comparison of the model results with other MCDM techniques could be performed. Third, comparison of the model results with other uncertainty modelling techniques could be done. Finally, the robustness of proposed model could be tested by including sensitivity analysis, scenario analysis, and uncertainty analysis.

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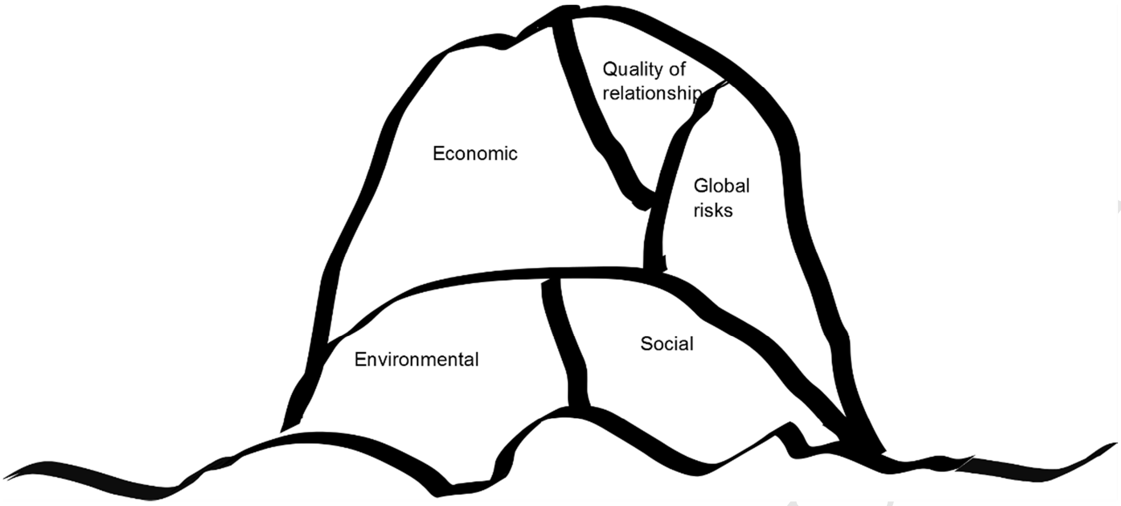

Figure 1. Supplier selection: Embracing sustainability and global sourcing

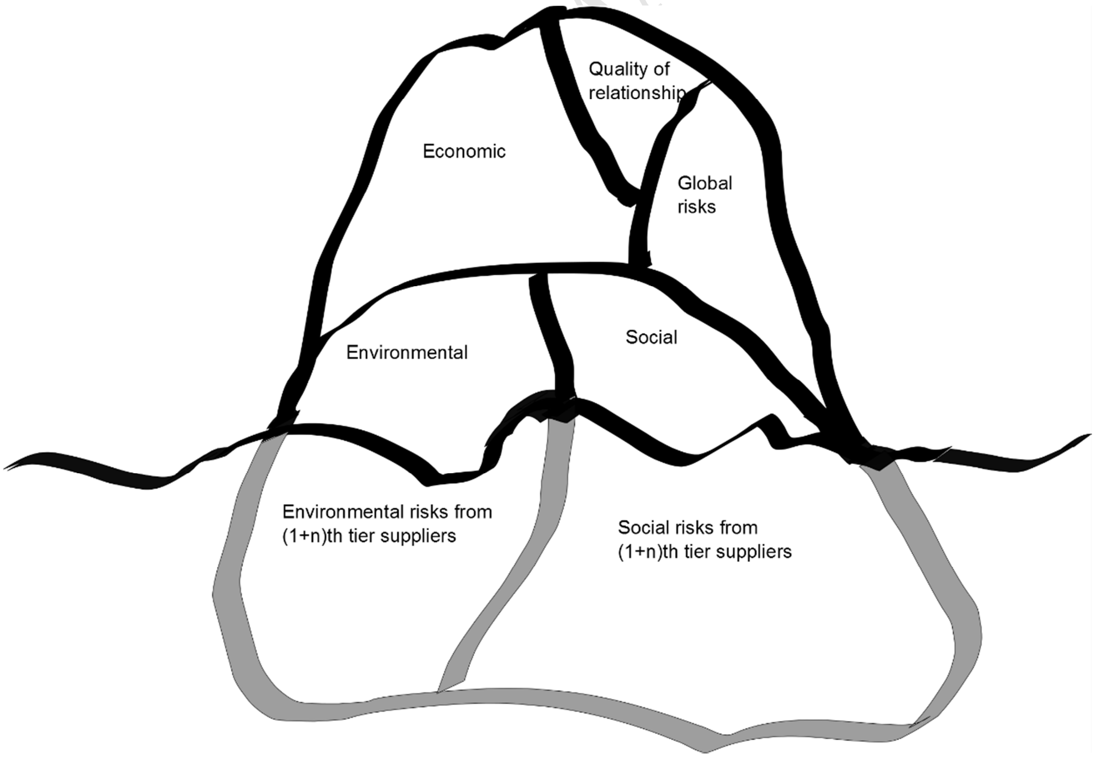

Figure 2. Supplier-selection: Extended towards *(1+n)*th-tier supplier sustainability risks

List of Tables

	Category/Criteria	*Sub-Criteria*
Supplier selection criteria embracing sustainability and global sourcing (Stage I)	Economic (Ec1)	Cost (Ec1.1) Quality (Ec1.2) Flexibility (Ec1.3) Speed (Ec1.4) Dependability (Ec1.5) Innovativeness (Ec1.6)
	Quality of relationship (Qr1)	Trust (Qr1.1) Effectiveness of communication (Qr1.2) EDI (Qr1.3)
	Environmental* (Env1)	Materials (Env1.1) Energy (Env1.2) Water (Env1.3) Biodiversity (Env1.4) Emissions (Env1.5) Effluents and waste (Env1.6) Supplier environmental selection procedure (Env1.7)
	Social** (Soc1)	Labour practices and decent work (Soc1.1) Human rights (Soc1.2) Society (Soc1.3) Product responsibility (Soc1.4) Supplier social selection procedure (Soc1.5)
	Global risks (Gr1)	Currency risks (Gr1.1) Disruption risks through political instability (Gr1.2) Disruption risks through terrorism (Gr1.3) Cultural compatibility (Gr1.4)
Supplier-selection criteria: Extended towards *(1+n)*th-tier supplier sustainability risks (Stage II)	Environmental* (Env2) (***Environmental risks from (1+n)th-tier suppliers***)	Same as in stage I (1+n)th-tier suppliers' materials (Env2.1) (1+n)th-tier suppliers' energy (Env2.2) (1+n)th-tier suppliers' water (Env2.3) (1+n)th-tier suppliers' biodiversity (Env2.4) (1+n)th-tier suppliers' emissions (Env2.5) (1+n)th-tier suppliers' effluents and waste (Env2.6) (1+n)th-tier suppliers' supplier environmental selection procedure (Env2.7)
	Social** (Soc2) ***Social risks from (1+n)th-tier suppliers***	Same as in stage I (1+n)th-tier suppliers' labour practices and decent work (Soc2.1) (1+n)th-tier suppliers' human rights (Soc2.2) (1+n)th-tier suppliers' society (Soc2.3) (1+n)th-tier suppliers' supplier social selection procedure (Soc2.4)

Table 1. Global sustainable supplier evaluation criteria (*Source*: Chan and Kumar (2007), Chan et al. (2008), Levary (2008), Ku et al. (2010), Dou and Sarkis (2010), Ravindran et al. (2010), Bai and Sarkis (2010), Kumar et al. (2011), Lin et al. (2012), Büyüközkan (2012), Lin et al. (2012), Kuo and Lin (2012), Genovese et al. (2013), GRI (2013), Scott et al. (2013), Azadnia et al. (2014))

Linguistic Term (criteria)	*Linguistic Term (alternative)*	*Fuzzy Triangular Number*
Very Low	Very poor (VP)	(1,1,3)
Low	Poor (P)	(1,3,5)
Medium	Fair (F)	(3,5,7)
High	Good (G)	(5,7,9)
Very High	Very Good (VG)	(7,9,9)

Table 2. Linguistic ratings and fuzzy numbers

Intensity of importance	**Fuzzy number**	**Linguistic variables**	**Membership function**
1	$\tilde{1}$	Equally important/preferred	(1, 1, 3)
3	$\tilde{3}$	Weakly important/preferred	(1, 3, 5)
5	$\tilde{5}$	Strongly more important/preferred	(3, 5, 7)
7	$\tilde{7}$	Very strongly important/preferred	(5, 7, 9)
9	$\tilde{9}$	Extremely more important/preferred	(7, 9,9)

Table 3. Scale of relative importance used in the pairwise comparison matrix

Size (*n*)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Table 4. The random consistency index (RI) (Saaty, 1990)

	Ec	**Qr**	**Env**	**Soc**	**Gr**	**Weights (Eigen Vector)**

Ec	1	7.85	4.14	6.17	7.85	0.600
Qr	0.127	1	2.38	4.14	6.17	0.191
Env	0.241	0.420	1	1.96	2.38	0.102
Soc	0.162	0.241	0.510	1	2.38	0.066
Gr	0.127	0.162	0.420	0.420	1	0.040

Maximum Eigen Value =5.411, C.I.=0.102

Table 5. Pairwise comparison matrix and weights for the stage I criteria

Criteria	*Sub-Criteria*	*Local weights*	*Global weights*
Ec1 (0.6)	**Ec1.1**	0.368	0.221
	Ec1.2	0.245	0.147
	Ec1.3	0.144	0.087
	Ec1.4	0.097	0.058
	Ec1.5	0.096	0.057
	Ec1.6	0.050	0.030
Qr1 (0.191)	**Qr1.1**	0.609	0.116
	Qr1.2	0.283	0.054
	Qr1.3	0.108	0.021
Env1 (0.102)	**Env1.1**	0.343	0.035
	Env1.2	0.231	0.024
	Env1.3	0.131	0.013
	Env1.4	0.138	0.014
	Env1.5	0.057	0.006
	Env1.6	0.059	0.006
	Env1.7	0.041	0.004
Soc1 (0.066)	**Soc1.1**	0.650	0.043
	Soc1.2	0.133	0.009
	Soc1.3	0.093	0.006
	Soc1.4	0.073	0.005
	Soc1.5	0.051	0.003
Gr1 (0.04)	**Gr1.1**	0.633	0.026
	Gr1.2	0.165	0.007
	Gr1.3	0.115	0.005
	Gr1.4	0.087	0.003

Table 6. Local and global weights for the 25 sub-criteria

	Env2	Soc2	Weights (Eigen Vector)
Env2	1	1.96	0.662
Soc2	0.510	1	0.337

Maximum Eigen Value =2, C.I.=0

Table 7. Pairwise comparison matrix for the *(1+n)*th-tier suppliers (stage II criteria)

Criteria	*Sub-criteria*	*Local weight*	*Global Weight*
Env2 (0.662)	**Env2.1**	0.343	0.2272
	Env2.2	0.231	0.1530
	Env2.3	0.131	0.0868
	Env2.4	0.138	0.0914
	Env2.5	0.057	0.0377
	Env2.6	0.059	0.0390
	Env2.7	0.041	0.0271
Soc2 (0.337)	**Soc2.1**	0.65	0.2192
	Soc2.2	0.133	0.0448
	Soc2.3	0.093	0.0313
	Soc2.4	0.073	0.0246
	Soc2.5	0.051	0.0172

Table 8. Local and global weights for the 12 sub-criteria

	S1			S2			S3		
Criteria	**D1**	**D2**	**D3**	**D1**	**D2**	**D3**	**D1**	**D2**	**D3**
Ec1.1	L	L	VH	VL	VH	VL	H	H	L
Ec1.2	VL	L	VL	VL	VL	M	H	L	VL
Ec1.3	H	VH	VL	VH	VH	M	VH	H	VL
Ec1.4	L	VL	VH	VL	VL	M	H	H	VL
Ec1.5	M	H	L	H	M	M	H	VL	VL
Ec1.6	VH	L	VH	M	M	M	L	VH	L
Qr1.1	VL	M	M	H	L	H	M	M	M
Qr1.2	M	VH	VH	M	M	VL	M	VL	VH
Qr1.3	VL	H	H	H	VL	VL	M	VH	L
Env1.1	H	M	M	H	L	VH	H	M	L
Env1.2	H	VL	VH	VH	H	L	L	VH	VL
Env1.3	VL	M	VH	VL	VL	VL	H	VL	M
Env1.4	L	H	M	VH	VH	M	L	VH	VH
Env1.5	VL	L	L	VL	VL	M	M	VH	M
Env1.6	VH	L	H	VL	H	M	L	H	VH
Env1.7	H	H	H	L	M	M	M	VL	M
Soc1.1	L	L	VH	VL	VH	VL	H	H	L
Soc1.2	VL	L	VL	VL	VL	M	H	L	VL
Soc1.3	H	VH	VL	VH	VH	M	VH	H	VL
Soc1.4	L	VL	VH	VL	VL	M	H	H	VL
Soc1.5	M	H	L	H	M	M	H	VL	VL
Gr1.1	VH	L	VH	M	M	M	L	VH	L
Gr1.2	VL	M	M	H	L	H	M	M	M
Gr1.3	M	VH	VH	M	M	VL	M	VL	VH
Gr1.4	VL	H	H	H	VL	VL	M	VH	L

Table 9. Linguistic Assessment for the three alternatives (stage I)

Criteria	Fuzzy decision matrix			Crisp ratings			f_j^* (best)	f_j^- (worst)
	S1	**S2**	**S3**	**S1**	**S2**	**S3**		
Ec1.1	(1,5,9)	(1,3.67,9)	(1,5.67,9)	5	4.11	5.44	4.11	5.44
Ec1.2	(1,1.67,5)	(1,2.33,7)	(1,3.67,9)	2.11	2.89	4.11	2.11	4.11
Ec1.3	(1,5.67,9)	(3,7.67,9)	(1,5.67,9)	5.44	7.11	5.44	5.44	7.11
Ec1.4	(1,4.33,9)	(1,2.33,7)	(1,5,9)	4.56	2.89	5	2.89	5
Ec1.5	(1,5,9)	(3,5.67,9)	(1,3,9)	5	5.78	3.67	3.67	5.78
Ec1.6	(1,7,9)	(3,5,7)	(1,5,9)	6.33	5	5	5	6.33
Qr1.1	(1,3.67,7)	(1,5.67,9)	(3,5,7)	3.78	5.44	5	3.78	5.44
Qr1.2	(3,7.67,9)	(1,3.67,7)	(1,5,9)	7.11	3.78	5	3.78	7.11
Qr1.3	(1,5,9)	(1,3,9)	(1,5.67,9)	5	3.67	5.44	3.67	5.44
Env1.1	(3,5.67,9)	(1,6.33,9)	(1,5,9)	5.78	5.89	5	5.89	5
Env1.2	(1,5.67,9)	(1,6.33,9)	(1,4.33,9)	5.44	5.89	4.56	5.89	4.56
Env1.3	(1,5,9)	(1,1,3)	(1,4.33,9)	5	1.33	4.56	5	1.33
Env1.4	(1,5,9)	(3,7.67,9)	(1,7,9)	5	7.11	6.33	7.11	5
Env1.5	(1,2.33,5)	(1,2.33,7)	(3,6.33,9)	2.556	2.89	6.22	6.22	2.56
Env1.6	(1,6.33,9)	(1,4.33,9)	(1,6.33,9)	5.89	4.56	5.89	5.89	4.56
Env1.7	(5,7,9)	(1,4.33,7)	(1,3.67,7)	7	4.22	3.78	7	3.78
Soc1.1	(1,5,9)	(1,3.67,9)	(1,5.67,9)	5.00	4.11	5.44	4.11	5.44
Soc1.2	(1,1.67,5)	(1,2.33,7)	(1,3.67,9)	2.11	2.89	4.11	2.11	4.11
Soc1.3	(1,5.67,9)	(3,7.67,9)	(1,5.67,9)	5.44	7.11	5.44	5.44	7.11
Soc1.4	(1,4.34,9)	(1,2.33,7)	(1,5,9)	4.56	2.89	5.00	2.89	5.00
Soc1.5	(1,5,9)	(3,5.67,9)	(1,3,9)	5.00	5.78	3.67	3.67	5.78
Gr1.1	(1,7,9)	(3,5,7)	(1,5,9)	6.33	5.00	5.00	5.00	6.33
Gr1.2	(1,3.67,7)	(1,5.67,9)	(3,5,7)	3.78	5.44	5.00	3.78	5.44
Gr1.3	(3,7.67,9)	(1,3.67,7)	(1,5,9)	7.11	3.78	5.00	3.78	7.11
Gr1.4	(1,5,9)	(1,3,9)	(1,5.67,9)	5.00	3.67	5.44	3.67	5.44

Table 10. Aggregate fuzzy decision matrix for the alternatives (stage I)

	S1	**S2**	**S3**	Alternative rankings (ascending order)
$\boldsymbol{Q_i}$	0.4939	1	0	S3>S1>S2
$\boldsymbol{S_i}$	0.5066	0.6034	0.3456	S3>S1>S2
$\boldsymbol{R_i}$	0.0693	0.0876	0.0589	S3>S1>S2

Table 11. Fuzzy VIKOR results (S_i, R_i and Q_i values and alternative rankings)

	SS1			SS2			SS3		
Criteria	**D1**	**D2**	**D3**	**D1**	**D2**	**D3**	**D1**	**D2**	**D3**
Env2.1	M	H	L	H	M	M	H	VL	VL
Env2.2	VH	L	VH	M	M	M	L	VH	L
Env2.3	VL	M	M	H	L	H	M	M	M
Env2.4	M	VH	VH	M	M	VL	M	VL	VH
Env2.5	VL	H	H	H	VL	VL	M	VH	L
Env2.6	H	M	M	H	L	VH	H	M	L
Env2.7	H	VL	VH	VH	H	L	L	VH	VL
Soc2.1	VL	M	VH	VL	VL	VL	H	VL	M
Soc2.2	L	H	M	VH	VH	M	L	VH	VH
Soc2.3	VL	L	L	VL	VL	M	M	VH	M
Soc2.4	VH	L	H	VL	H	M	L	H	VH
Soc2.5	H	H	H	L	M	M	M	VL	M

Table 12. Linguistic Assessment for the three alternatives (stage II)

	SS1	**SS2**	**SS3**	Alternative rankings (ascending order)
$\boldsymbol{Q_i}$	0.634	1	0	**SS**3>SS1>SS2
$\boldsymbol{S_i}$	0.507	0.601	0.262	**SS**3>SS1>SS2
$\boldsymbol{R_i}$	0.153	0.227	0.063	**SS**3> **SS**1>SS2

Table 13. Fuzzy VIKOR results (S_i, R_i and Q_i values and alternative rankings)