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Abstract: Partner selection is crucial to green supply chain management as the focal firm is responsible for the environmental performance of the whole supply chain. The construction of appropriate selection criteria is an essential, but often neglected pre-requisite in the partner selection process. This paper proposes a three-stage model that combines Dempster-Shafer belief acceptability theory and particle swarm optimization technique for the first time in this application. This enables optimization of both effectiveness, in its consideration of the inter-dependence of a broad range of quantitative and qualitative selection criteria, and efficiency in its use of scarce resources during the criteria construction process to be achieved simultaneously. This also enables both operational and strategic attributes can be selected at different levels of hierarchy criteria in different decision-making environments. The practical efficacy of the model is demonstrated by an application in Company ABC, a large Chinese electronic equipment and instrument manufacturer.

Keywords: Green supply chain; Partner selection criteria; Dempster-Shafer theory; Particle swarm optimization

1. Introduction

The growing acceptance of the concept of the Triple Bottom Line, and the need to comply with a series of regulatory and legislative requirements for environment protection (e.g. the WEEE and the RoHS Directives) has seen an increased concern that organizations should strive for environmental sustainability (Tsai 2012). The behaviour of consumers has also begun to change as they start to evaluate the environmental impact of the products and services they buy (Montoya-Torres et al. 2015). The focus of environmental management and operations has moved from local optimization of environmental factors to consideration of the entire supply chain (Jayaraman et al. 2007, Tseng et al. 2014). For the focal firm in a supply chain, this concern must also extend to the environmental practices and performance of its partners throughout its supply chain, as it is likely to be held responsible for any of their adverse environmental impacts as well as its own (Rao and Holt 2005). The need to construct and operate green supply chains (GSCs) was highlighted some time ago by Noci (1997). He summarised the four key reasons why focal firms need to evaluate their supply chain partners' environmental performance as: (1) to avoid negative managerial implications for the customer's value chain by reducing the quantity of supplied components with low environmental performance, (2) to control the cost of their green products effectively, (3) to favour frequent modification of the key product environmental performance by reducing the company's response time to the market, and (4) to avoid problems associated with the company's green image which depends on a supplier's environmental efficiency. Since then, the environmental performance of supply chain partners has become an even more important issue, and hence, partner selection has become a crucial issue in green supply chain management (Awasthi et al. 2010, Bhattacharya et al. 2014).

Green supply chain management (GSCM) encompasses the plans and activities of a focal firm, which integrate environmental issues into supply chain management in order to improve the environmental performance of all its supply chain partners (Bowen et al. 2001, Large and Thomsen 2011). GSCM has becoming one of the main issues in supply chain management due to both dramatic increasing of air emissions and progressive scarcity of nature resources (Savino et al. 2015). The key purpose of GSCM is to control and reduce the environmental impact of all its supply chain activities, both upstream and downstream, including the purchase of raw materials, the production and delivery of products and services, and the recycling of waste products (Kuo et al. 2010a). GSCM not only enables a company to comply with different regulatory requirements, but can also cultivate green business opportunities (Tsai 2012, Mohanty and Prakash 2014). A commitment to environment sustainability in the supply chain can be a source of competitive advantage and sustainable development (George et al. 2006, Large and Thomsen 2011).

The construction of a GSC requires that only the most environmentally appropriate partners be incorporated within it. However, any process used to select supply partners needs a comprehensive set of appropriate criteria. However, this is far from straightforward as the criteria may vary across different product categories and situations (Kannan and Haq 2007). Without appropriate criteria, decision-makers cannot collect and evaluate adequate and appropriate information on potential partners (Wu and Barnes 2016). Furthermore, those criteria need to reflect the relative importance of different environmental regulations under which the focal firm and its partners operate. Without appropriate criteria, even the most advanced models/methods cannot perform well thereby reducing the effectiveness of the partner selection process (De Boer et al. 2001). Without appropriate criteria, valuable evaluation resources (e.g. time and money) will be wasted, reducing the efficiency of the partner selection process (Wu and Barnes 2010). In short, the effectiveness and efficacy of GSC construction process will be seriously adversely affected if there is not a systematic method to construct a set of feasible and practicable criteria. The aim of the research is to analyse and to assess how the most appropriate criteria for partner selection in GSCs can be identified and organized under different decision-making situations considering the managerial resource constraints.

The remainder of this paper is organized as follows. Section 2 presents a literature review of criteria selection and construction in GSCs. Section 3 describes the methodology of this research. Section 4 sets out a three-stage model for partner selection criteria construction in GSCs based on the use of Dempster-Shafer belief acceptability theory and particle swarm optimization technique. Section 5 tests the efficacy of the model by presenting an empirical illustration of its application in the Chinese Electronic Equipment & Instruments industry. Section 6 summaries a managerial application process for the proposed model. The paper closes with some concluding remarks in Section 7.

2. Literature Review

Noci (1997) was the first to propose that a supplier's environmental performance should be incorporated within a comprehensive vendor rating system. Within a pro-active green strategy, his model identified four key measures for vendor rating and selection, namely the potential vendors' green competencies, their green image, their current environmental efficiency and the net life cycle cost. Three or four sub-measures are then included in each of the key measures. These measures can not only be used in vendor rating systems but can also be used by firms to drive continuous improvements in their environmental performance. Based on the empirical evidence from 119 manufacturing firms, Lee et al. (2015) argue that green suppliers do have positive and significant effects on environmental performance and competitive advantage. Therefore, green supplier selection becomes an important decision in efforts to improve and enhance the environmental performance and competitive advantage of GSCs.

Noci's work has provided the foundation on which much of the subsequent research on hierarchy criteria in this field has been built. In particular, Klassen and Vachon (2003), Zhu and Sarkis (2004), Bai and Sarkis (2010a, 2010b), Erol et al. (2011), Buyukozkan and Cifci (2012), and Kannan et al. (2015) join Noci in including green competencies as a partner selection criterion for GSCs. Potential partners could demonstrate their green competencies by, for example, their efficiency at managing green supply chain management issues, having a reverse logistics system, and transferring employees with environmental expertise to suppliers. Melnyk et al. (2003), Matos and Hall (2007), Kuo et al. (2010a) and Hashemi et al. (2015) also follow Noci in including green image. Examples of meeting this criterion might include having ISO 14000 certification, the extent to which the partner is seen to follow green policies, and the extent to which its market share relates to green customers. Noci's environmental efficiency criterion has been extended by beyond emissions and energy consumption to encompass broader as aspects of environmental performance including product recycling rates and responses to environmental product requests (Sarkis 2003, Kassinis and Soteriou 2003, Kleindorfer et al. 2005, Corbiere-Nicollier et al. 2011, Dey and Cheffi 2013). Similarly, Noci's net life cycle cost criterion has been extended to encompass other pollution control initiatives, including Waste Electrical and Electronic Equipment (WEEE) directive (Sroufe 2003, Linton et al. 2007, Awasthi et al. 2010, Tsai 2012). Other researchers have put forward alternative sets of criteria to Noci (1997). Yeh and Chuang (2011) identify four main criteria for green partner selection, whilst other researchers have suggested as many as twelve (Awasthi et al. 2010), or in the case of Tseng and Chiu (2013), eighteen qualitative and quantitative criteria.

As can be inferred from the above discussion, each of the potential criteria for partner selection in green supply chains tends to consist of multiple dimensions that can be arranged in a hierarchy. Thus, any method used in determining appropriate criteria must also include a consideration of what sub-criteria to include within each of the chosen top-level criteria (Wu and Barnes 2011, 2012). Based on a literature survey and the approval of experts, Hashemi et al. (2015) identified their green supplier evaluation criteria under economic and environment categories. As there are only three sub-criteria, grouped under each of the top-level criteria, theirs is a fairly simple grouping process. In addition, Sarkis and Dhavale (2015) proposed a set of criteria for supplier selection for sustainable operations. They supplemented economic and environmental criteria with a social criteria category in accordance with the theory of triple bottom line (Elkington 1998). Similarly, three sub-criteria were identified and included in each of the top-level criteria categories based on a literature survey. It is both efficient and practical to identify and cluster criteria in this way, if their number is limited. However, if the decision-making situation calls for a more compressive evaluation, then, many more criteria need to be identified and clustered; this requires a more reliable and systematic approach.

Kannan et al. (2015) proposed a multi-criteria decision-making approach to select the best green supplier for a Singapore-based plastic manufacturing company. At their criteria construction stage, they used an affinity diagram to gather large amounts of language data and organized them into groupings based on their natural relationships. In this way, they narrowed the green supplier selection criteria from the 26 traditional criteria and 72 environmental criteria under 13 main criteria in the beginning to 21 traditional criteria and 39 environmental criteria under 11 main criteria in the end. This represents significant progress in both the efficiency of green supplier selection and in that the potential criteria can be easily identified, grouped, and filtered. Yet, this criteria construction process is mostly qualitative and misses out on quantitative analysis and evaluation of factors such as financial cost and management resources. Govindan et al. (2015) reviewed thirty three papers which focused on multi criteria decision making approaches for green supplier evaluation and selection in recent years. They pointed out that additional research is required on identifying, defining, grouping, and filtering the criteria of green supplier evaluation and selection. "*These areas are important and necessary directions*" as they concluded.

Additionally, one of the most distinctive features of GSCM is the increased number of performance objectives involved than would be the case for more traditional supply chains (Seuring and Muller 2008). Thus, the challenge of developing a method to solve this problem must take into account not only the hierarchical relationships between criteria but also be able to optimize between multiple, and potentially conflicting objectives. This makes for a much more complex problem not only than would be the case with a single objective but also when the objectives are mainly economic in nature. Thus, any proposed techniques must enable the problem to be solved both efficiently and effectively having regard to resource constraints and the decision-making environment.

A variety of methods have been applied tackle the green partner selection problem. These have included Analytic Hierarchy Process (AHP)/Analytic Network Process (ANP) (Sarkis 2003), ANP (Yang et al. 2010), Artificial Neural Network (ANN) (Kuo et al. 2010a), Interpretive Structural Modelling (Kannan and Haq 2007), grey system and rough sets (Bai and Sarkis 2010a, 2010b), DEA (Kumar et al. 2014) and multi-objective mixed-integer programming (Abdallah et al. 2012). Whilst fuzzy logic has been applied by Erol et al. (2011) - fuzzy entropy, Lee et al. (2009) - fuzzy AHP, and Tseng and Chiu (2013) - fuzzy set theory. One of the common limitations of such works has been a tendency for researchers to initiate their partner selection criteria without a systematic way to identify, group and filter the potential criteria (Govindan et al. 2015). Additionally, the emphasis of most current works has been placed on the partner selection methods and approaches (Genovese et al. 2014), rather than first addressing the more fundamental problem of constructing a set of appropriate partner selection criteria reasonably and systematically. To date, only limited attention has been given to partner selection criteria construction which is an essential pre-requisite in any selection process (Wu and Barnes, 2011). Lin and Chen (2004) applied Dempster-Shafer theory when constructing a partner selection criteria hierarchy within their strategic alliance selection model. However, their main focus is on the strategic alliance selection approach rather than the partner selection criteria construction, which makes their model hard to apply by supply chain managers in practice. Wu and Barnes (2010) tried to simplify Lin and Chen’s framework in order to make it more accessible to practicing managers. However, their approach to constructing partner selection criteria is limited to the use of only a single objective viewpoint and method, namely belief acceptability, when a multi-objective approach would be more beneficial for the quality of decision-making and closer to realistic decision-making environments.

In summary, the construction of a set of selection criteria is a necessary pre-requisite in any partner selection process. Yet, current approaches to partner selection in green supply chains do not consider how to construct an appropriate set of appropriate partner selection criteria systematically. Current literature places the emphasis on the partner selection method, with little or no consideration being given to the prior construction of selection criteria. Approaches that have tackled this issue (e.g. Lin and Chen, 2004; Wu and Barnes, 2010) can be shown to have shortcomings. This is a significant gap in the literature. There is a need to develop a method that can systematically construct an appropriate set of criteria for partner selection in green supply chains. Such a method should be able to identify, group and filter all the potential criteria. This paper proposes such a method. It is based on multiple objective programming rather than a single objective. This enables it to be comprehensive enough to consider a broad range of possible criteria, both qualitative and quantitative, whilst being efficient in its use of scarce management resources during the criteria construction process.

3. Methodology

The methodology for this research involved the use of a three step process as shown Figure 1.

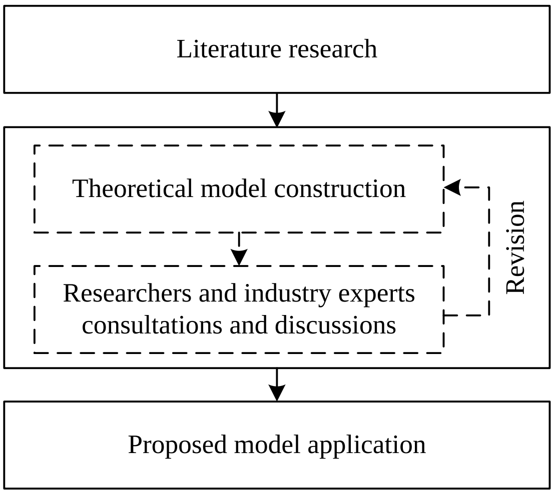

Figure 1: Research process of the proposed model

1) Literature review: Recent literature on partner selection criteria construction in GSCs was reviewed in order to identify research gaps and opportunities for further

development. Keywords, such as partner selection, criteria construction and formulation, and green supply chain, were used to search papers published in the leading operations management journals from 1990s onwards in the database of ISI Web of Knowledge. 67 papers in high ranked journals were selected for inclusion in the review.

2) Model construction: From the literature research, a three-stage model for partner selection criteria construction in GSCs was proposed based on the use of the Dempster-Shafer belief acceptability theory and particle swarm optimisation technique (see below). An expert panel of researchers and industry experts were consulted about the proposed model. During several rounds of discussion and revision, they provided a number of helpful comments and suggestions for improvement, which were incorporated into the finalised proposed model.

3) Application: The efficacy and effectiveness of the proposed model was then tested through an empirical illustration of its application in the Chinese Electronic Equipment & Instruments industry.

This research is based on the use of the Dempster-Shafer theory and the particle swarm optimization technique. These are now briefly explained in the following two sub-sections.

3.1 Dempster-Shafer theory

The Dempster-Shafer theory (DST) of evidence was originated by Dempster’s concept of lower and upper probabilities (Dempster 1967), and extended by Shafer as a theory (Shafer 1976). The basic idea of DST is that numerical measures of uncertainty may be assigned to overlapping sets and subsets of hypotheses or events (Beynon et al. 2000). As it can include situations of uncertainty and ignorance in the same formulation, DST can build a unifying framework for describing uncertainty and ignorance in the decision-making environment (Yager 1987). Compared to probability theory, such as the conventional Bayesian technique, DST can capture and represent more information to support decision-making, by representing uncertain and ignorance evidence (Wu 2009). In more detail, rather than being represented by exactly specified probability distributions as conventional Bayesian technique, DST proposes a mechanism to derive solutions from various vague sets of evidence (Beynon et al. 2000). Furthermore, DST can combine unexpected empirical evidence in decision-maker’s mind, and then formulate a coherent picture of reality.

There are three main advantages of applying DST during the partner selection criteria construction process. First of all, DST is a valuable tool for the evaluation of risk and uncertainty when knowledge is obtained from experts (Sentz and Ferson, 2002). DST can build a unifying framework for describing uncertainty and ignorance. Secondly, the uncertainty we have to take into consideration during decision-making on partner selection criteria construction is epistemic uncertainty. Thus, traditional probability theory is not the most appropriate theory to apply. Compared to more traditional Bayesian technique, DST can capture and represent more information to support decision-making on partner selection criteria construction. Last but not least, criterion dependency, which is a common phenomenon in multi-attribute decision-making problems, can be considered simultaneously by applying DST. For a target criterion in a specific layer, decision-makers can form any meaningful combination out of the criteria in the lower layer and generate the subordinate criteria sets with their different belief acceptabilities. More importantly, the combination of evidence can be obtained from multiple sources (say a panel of decision-makers) in DST while the potential conflicts among them can be well modeled. Therefore, in this research, DST is applied for representing the uncertainty and ignorance during the prior processes of partner selection criteria construction in GSCs.

3.2 Particle swarm optimization

Particle Swarm Optimization (PSO) is a metaheuristic algorithm based on the social behaviour of a flock of birds or shoal of fish; it is similar to evolutionary computation techniques, for instance, genetic algorithm. First proposed by Kennedy and Eberhart (1995), PSO is initialized with a population of random solutions, which it then searches for optima by updating generations. Then, unlike genetic algorithm, which is based on the survival of fitness, the potential solutions will move through the problem space by following the current optimum particles (Kuo et al. 2010b). In more detail, each particle's movement is guided toward its local best known position. At the same time, this movement is also influenced by the best known positions in the whole search space.

These basic characteristics are in favour of the swarm moving toward its best solution. In addition, PSO can search very large spaces of possible solutions and so can be used for complex optimization problems (Zhao et al. 2008, Huang et al. 2011, Che 2012).

There are two main advantages of applying PSO during the partner selection criteria construction process. On the one hand, PSO has been proved to be a simple, sound, and effective metaheuristic algorithm (Che 2012). Zhao et al. (2008) and Huang et al. (2011) pointed out that PSO is an effective and efficient method to solve a complex optimization problem. PSO offers easy programming and can be used on optimization problems that are partially irregular, noisy and changes over time. In use, PSO provides high efficiency as a result of its fast computation ability. PSO can search a very large space of possible solutions, which makes it very suitable for criteria construction problems in GSCs. In other words, compared to other multi-objective optimization algorithms, such as genetic algorithm, PSO algorithm is a helpful metaheuristic approach which can clearly obtain acceptable solutions (Kuo et al. 2010b). On the other hand, the PSO technique is flexible enough to solve the multiple-objective optimization problem, which makes it very suitable for decision-making in partner selection criteria construction. As the proposed multiple-objective programming model is flexible enough to incorporate an increased number of objectives and/or constraints, the PSO technique can adapt and solve it efficiently. As such, it seems to offer an appropriate approach to solving the partner selection criteria construction sub-problem. Therefore, in this research, a PSO based methodology is proposed for solving the multi-objective optimization sub-problem within the partner selection criteria construction in GSCs.

4. The three-stage DS-PSO model for partner selection criteria construction in GSCs

This research therefore proposes a model that offers a new systematic approach to systematically solving this complex and important problem. Its innovativeness lies in its three-stage structure and its combination use of both Dempster-Shafer belief acceptability theory and particle swarm optimization technique.

The proposed three stages are as follows:

(1) GSC partner selection General Hierarchy Criteria (GSC-GHC) construction;

(2) GSC partner selection Specific Hierarchy Criteria (GSC-SHC) construction;

(3) GSC partner selection Optimization Hierarchy Criteria (GSC-OHC) construction.

In each stage the hierarchy criteria are constructed and operated in accordance with different decision-making environments and requirements. The internal logic of the three-stage model is shown in Figure 2.

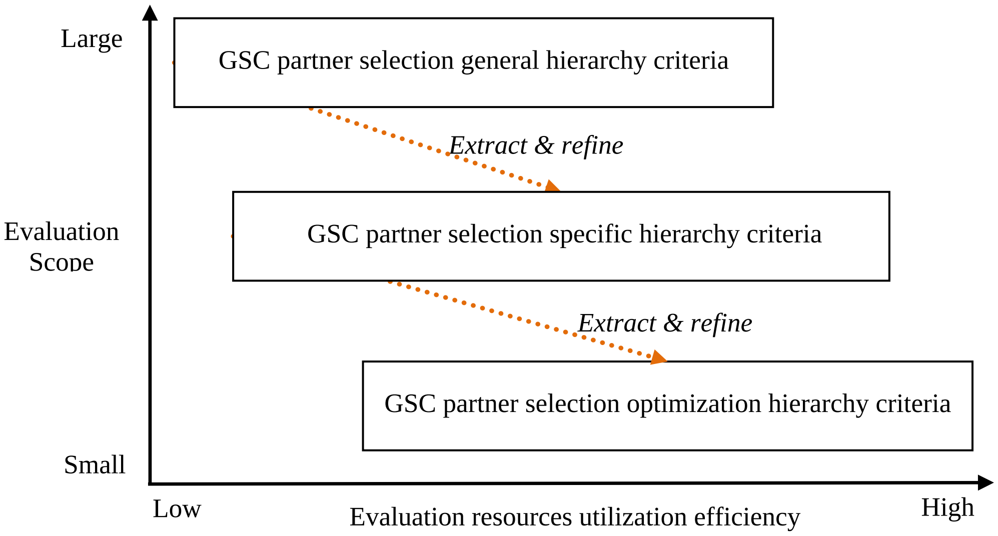

Figure 2: The three-stage model for GSC partner selection criteria construction

The vertical and horizontal axes in Figure 2 are evaluation scope and evaluation resources utilization efficiency, respectively. As Figure 2 illustrates, as the construction process advances from stage 1 to stage 3, the scope of the evaluation reduces, whilst evaluation resource utilization efficiency increases. This is because that, at the GSC partner selection general hierarchy criteria construction stage, the numbers of criteria are larger than the later stages. Therefore, the scope of evaluation is relatively larger than the later stages. However, because of the large numbers of criteria, more resources for evaluation are required. Thus, the evaluation resources utilization efficiency is relatively lower than the later stages. In contrast, at the GSC partner selection optimization hierarchy criteria construction stage, the numbers of criteria have been reduced systematically and effectively. Therefore, less resources for evaluation are required. In return, the efficiency of evaluation resources utilization can be improved while the scope of evaluation being smaller than the former stages. The model enables decision-makers to find an optimization hierarchy of criteria that optimises evaluation scope for partner selection in GSCs whilst simultaneously optimising evaluation resource efficiency.

The advantage of a three stage structure is that it offers a well-balanced trade-off between effectiveness and efficiency within the hierarchy criteria construction process. On the one hand, if only one or two stages are used to construct the hierarchy criteria, some requirements and demands of decision-making cannot be adequately fulfilled. In particular, it would limit the development of criteria that can be tailored to specific decision-making contexts. Therefore, the effectiveness of hierarchy criteria construction would be affected. On the other hand, if there are more than three stages (perhaps four or five stages), the efficiency of the hierarchy criteria construction would be adversely affected as each additional stage requires the consumption of more valuable resource and decision-making time. In adopting a three stage model, we follow an approach used in previous proposals for the design and formulation of hierarchy criteria for partner selection (e.g. Lin and Chen 2004, Wu and Barnes 2010, Kuo et al. 2010a). A three stage process has also been used in other comparable decision-making models. For example, De Snoo et al. (2012) when developing a categorization of scheduling performance criteria in an extended planning and scheduling theory, and Mexas et al. (2012) when constructing criteria for the selection of ERP systems.

The use of Dempster-Shafer theory provides an effective way of giving decision-makers confidence in the information used and thereby the value of the evaluation criteria developed. PSO technique provides sufficient flexibility to enable the model to be adapted for use with differing numbers of optimization objectives and/or constraints. The use of Dempster-Shafer and PSO technique in combination provides a systematic and comprehensive way of solving the problem efficiently and effectively, thereby opening the way for the use of the proposed model in real business situations.

The following three sub-sections describe each of the sub-stages in the three-stage model for GSC partner selection criteria construction in more details.

4.1 GSC partner selection General Hierarchy Criteria construction

Like Lin and Chen (2004) and Wu and Barnes (2010), the start point of this research an initial generic hierarchy of selection criteria derived from a review of the most relevant extant literature. Thus, in the GSC-GHC construction stage, a comprehensive partner selection hierarchy criteria for GSCs is built. This comprises the three-level hierarchy criteria, shown in Table 1.

Table 1: GSC partner selection General Hierarchy Criteria

Hierarchy levels	Selected criteria	
High level	Partner performance in green supply chains	
Middle level	Green competencies	(Klassen and Vachon 2003, Zhu and Sarkis 2004, Bai and Sarkis 2010a, b, Erol et al. 2011)
	Environmental performance	(Sarkis 2003, Kassinis and Soteriou 2003, Kleindorfer et al. 2005, Corbiere-Nicollier et al. 2011, Dey and Cheffi 2013)
	Partner's green image	(Noci 1997, Melnyk et al. 2003, Matos and Hall 2007, Kuo et al. 2010a)
	Pollution control	(Sroufe 2003, Linton et al. 2007, Awasthi et al. 2010, Tsai 2012)
	Operations and financial capability	(Sha and Che 2006, Luo et al. 2009, Burke et al. 2009, Yang et al. 2010)
	Partnership and technology management	(Amaral and Tsay 2009, Sosic 2011, Cui et al. 2012)
Low level	See Table 2 to Table 7 for more details.	

Descending the hierarchy criteria from High level to Middle level and to Low level requires an increasing amount of detailed information. The High level only includes a single criterion, namely supply partner's green performance. At the Middle level, six criteria are proposed, about which information on different potential partners needs to be collected and evaluated. The first four of these are derived directly from Noci's (1997) four criteria as discussed in Section 2 above, namely:

1) Green competencies: The same as Noci's criterion of the same name.
2) Environmental performance: An extension of Noci's environmental efficiency criterion.
3) Green image: The same as Noci's criterion of the same name.

4) Pollution control: An extension of Noci's net life cycle cost criterion

To these four green-related criteria, we propose two additional, economic criteria:

5) Operations and financial capability
6) Partnership and technology management

The two additional factors (5 and 6 above) ensure that economic as well as environmental objectives are incorporated into the criteria chosen for GSC construction as firm's will wish to optimize economic as well as environmental performance (Sha and Che 2006, Luo et al. 2009, Sosic 2011, Cui et al. 2012, Wu and Barnes 2014).

Collecting and evaluating information directly on these six aspects of performance is likely to be neither feasible nor effective in practice. A better and more acceptable approach method is to break down each dimension into a set of more detailed Low level criteria, for which comprehensive and objective performance measures are available. These are identified from the literature relevant for each of the respective six Middle level criteria as outlined below and shown in Tables 2 through 7. There are no consensus rules for classification of the criteria at the lowest level of hierarchy either within academia or practice. In this research, the classification of those criteria is based on an analysis of their objective and relevance to each of the six aspects of performance. Accordingly, the clustering process was discussed by the expert panel of academic researchers and industry experts (as noted in Section 3 Methodology).

1) **Green competencies** can be broken down into eighteen sub-criteria (see Table 2). A supplier's ability to *design recyclable products, design renewable product* and possess *a reverse logistics system* are identified as green competencies by Klassen and Vachon (2003). Similarly, Bai and Sarkis (2010a) list the abilities to s*olve supplier environmental technical problems, transfer employees with environmental expertise to suppliers,* and *reduce supplier's environmental costs* as green competencies. Whilst operating appropriate technology, such as the *availability of clean technologies* and *use of environment friendly technology* are also green competencies (Noci 1997, Tsai 2012). Likewise, appropriate planning & control and regulatory policies are also sources of green competencies. For instance, *green process planning, internal control process, establishment of environmental commitment and policy,* and *continuous*

monitoring and regulatory compliance (Klassen and Vachon 2003, Zhu and Sarkis 2004, Bai and Sarkis 2010b, Corbiere-Nicollier et al. 2011). Finally, the ability to cooperate with green partners is also a source of green competencies. Thus identified are *joint and team problem solving on environmental issues*, *information sharing on environmental topics*, *partnership with green organizations*, *green supply chain management efficiency* and *green market share* (Linton et al. 2007, Awasthi et al. 2010, Erol et al. 2011).

2) **Environmental performance** has nineteen sub-criteria (see Table 3). *Product recycling rate, product remanufacturing rate* and *product reuse rate* all reflect the potential partners' environmental performance in aspects of recycling, remanufacturing and re-use (Sarkis 2003, Kleindorfer et al. 2005). In addition, *air emissions, solid wastes* and *waste water* represent another side of the recycling, remanufacturing and re-use environmental performance (Noci 1997, Matos and Hall 2007, Corbiere-Nicollier et al. 2011). Energy use as reflected *energy consumption*, and *energy efficiency* (Bauer et al. 2010, Erol et al. 2011) are also part of potential partners' environmental performance. Similarly, with the ability to co-operate with suppliers influences environmental performance. Therefore, *having environmental protection plans of suppliers*, *having environmental protection policies of suppliers*, *supplier rewards and incentives for environmental performance*, *amount of environmentally safe alternatives* and *green knowledge transfer and communication* (potential partner's incentive for green knowledge transferring within the GSCs) are all identified as criteria (Klassen and Vachon 2003, Bai and Sarkis 2010a). Finally, *ratio of green customers to total customers, response to environmental product requests, identification of environmental aspects, green packaging,* and *adherence to environmental policies* are all measures that directly show the environmental performance of potential partners (Kassinis and Soteriou 2003, Kleindorfer et al. 2005, Awasthi et al. 2010, Bai and Sarkis 2010b).

3) **Green image** has eighteen sub-criteria (see Table 4). The partner's green image reflects the ways in which they cooperate with their suppliers. Thus, *building top management commitment/support for supplier organization for green supply practices*, *building top management commitment/support within buyer*

organization for green supply practices, *introducing a cross-functional supply chain team with environmental presence, the participation level of suppliers in the eco-design stage*, and/or *in the process of procurement and production* are identified as criteria (Zhu and Sarkis 2004, Bai and Sarkis 2010a). A partner's green image is enhanced and recognised by their having some *environmental related certificates* (e.g. ISO 14000) and then them having *respect for the policy* (the attitudes toward the environmental protection policy) (Melnyk et al. 2003, Kassinis and Soteriou 2003, Kuo et al. 2010a). A partner's green image is also reflected in their relationships with their customers, employees and stakeholders. Thus, *market share related to green customers*, *customers' purchase retention* (it's cheaper to get current customer to purchase from you again, therefore if you have a good green image from your current customers who care about your environmental impact, you may have higher customer purchase retention rate), *the interests and rights of employee*, and the *type of relationships with stakeholders* are also recognised as criteria (Noci 1997, Matos and Hall 2007, Kuo et al. 2010a). Additionally, *information disclosure* is identified as an important aspect of a potential partner's green image (Kuo et al. 2010a). Finally, investment and planning in relation to environmental issues contribute to green image. Thus, *green R&D investment*, *depreciation for investments aimed at improving the partner's environment performance*, *planning of environmental objectives*, *checking and evaluation of environmental activities*, and *assignment of environmental responsibility* are appropriate criteria (Zhu and Sarkis 2004, Bai and Sarkis 2010b, Corbiere-Nicollier et al. 2011).

4) **Pollution control** has seventeen sub-criteria (see Table 5). Firstly, environmental regulations provide both restrictions and motivations for pollution control. Thus, *ISO14001 certificate, Waste Electrical and Electronic Equipment* (WEEE), and *Restriction of the use of certain hazardous substances in electrical and electronic equipment* (e.g. RoHS) can be used as criteria (Melnyk et al. 2003, Tsai 2012). Secondly, the costs for pollution treatment also influence the scale and scope of pollution control, such indicated by as *air pollution treatment costs, chemical wastes treatment costs, cost for component disposal, energy consumption costs, solid wastes treatment costs,* and *water*

pollution treatment costs can be criteria (Noci 1997, Sroufe 2003, Matos and Hall 2007, Erol et al. 2011). Thirdly, the methods of pollution control affect the result of pollution control. So, *end-of-pipe control* (pollution control capability), *pollution control initiatives*, *design for environment*, and *production of polluting agents* are also criteria (Linton et al. 2007, Awasthi et al. 2010, Bai and Sarkis 2010b). Lastly, the materials used also reflect the pollution control performance. So *type of materials used in the supplied component* (environmental friendly or not), *use of environment friendly materials*, *use of harmful materials*, and *production of toxic products* are also suitable criteria (Noci 1997, Bai and Sarkis 2010b, Corbiere-Nicollier et al. 2011, Tsai 2012).

5) **Operations and financial capability** can be broken down into two separate sub-categories of criteria, operations and financial- related respectively (see Table 6). For the first sub-category, producing and delivering the required products and services are the key functions of GSCM. To achieve their main objective, GSCs need *capabilities to provide quality product/service* (Zhu and Sarkis 2004). This also calls for the ability to meet a high level of *production volume flexibility*, *delivery reliability and capacity* and *variation in types of products or services* (Sha and Che 2006, Yang et al. 2010, Cui et al. 2012). In addition, *order lead time* and *order fulfilment rate* are also very important attributes when evaluating the flexibility of potential partners (Chung et al. 2005, Burke et al. 2009). As quality of products has been one of the top concerns in literature for some time, an appropriate *quality assurance* system and *warranty periods* are considered to be relevant criteria (Zhu and Sarkis 2004, Xia and Wu 2007), as is good *quality philosophy* (Pil and Rothenberg 2003). As product and service delivery is a key attribute of any potential partner, there is a need to consider their *geographical location* (Bauer et al. 2009). Other partner attributes identified in this category include the *condition of physical facilities*, *consistent conformance to specifications* and *design capability* (Choi and Hartley 1996, Sroufe 2003, Chung et al. 2005). Last, but not least, cost factors are likely to influence partner selection decision-making. So, *cost-reduction capability* remains vital to a GSCs' performance (Sha and Che 2006). For the second sub-category, prudent financial capability is the foundation of any business operation. Accordingly, various financial accounting ratios can be used

as appropriate criteria. Firstly, a firm’s ability to pay its debts as they fall due can be assessed from the *asset/liability ratio,* and the *debt/equity ratio* (Luo et al. 2009). Secondly, a firm’s ability to grow and develop can be assessed from the *assets rates of increment,* the *net profits growth rates* and *total revenue* (Lin and Chen 2004). Thirdly, the ability of a firm to make profits, which is fundamental to its future health, can be assessed from the *gross profit margin* and the *net operating margin* (Burke et al. 2009). Finally, a firm’s operation ability, which is its ability to operate smoothly on a day-to-day basis can be assessed from the *receivable turnover* and the *inventory turnover ratios* (Luo et al. 2009).

6) **Partnership and technology** has twenty sub-criteria (see Table 7). The ability of a potential partner to manage technology and knowledge is one of the key attributes in a GSC partner. Thus *technical capability*, *technical advice*, *technology innovation* and *knowledge of local business practices* are used as indicators of a potential supplier’s performance (Hajidimitriou and Georgiou 2002, Yang et al. 2010, Cui et al. 2012). In regard to technology management, a *partner’s equipment status*, their *product familiarity*, and *repair turnaround time* are basic criteria against which potential partners should be evaluated (Xia and Wu 2007, Amaral and Tsay 2009, Cui et al. 2012). As technology has to be updated continuously, the purchaser should also evaluate the *cost of alternatives* before selecting a particular partner (Burke et al. 2009). As a GSC needs to be a dynamic alliance of member companies in order to respond to fast-changing markets, so decision-making about the formation of a new GSC is an important consideration. Thus, *relationship building flexibility* and *company’s reputation to integrity* should be considered as criteria, alongside the *cost of integration* and the *time needed to integrate* (Lin and Chen 2004, Sosic 2011). Similarly, *compatible management styles* and *compatible organization cultures* will also influence decision making in this regard (Hajidimitriou and Georgiou 2002). Also, likely to be included in this evaluation category are *special skills that you can learn from partners*, *closeness of past relationship* and *ease of communication* (Choi and Hartley 1996, Amaral and Tsay 2009, Yang et al. 2010). The ability to share knowledge is another key aspect of partnership management. Thus, an *ability to obtain partner’s local knowledge* (Amaral and

Tsay 2009) and *partner's ability to acquire your firm' special skills* (Xia and Wu 2007) are also included as criteria. Finally, it is also important to assess the *risk of failure of cooperation* when choosing a supply partner in GSCs (Amaral and Tsay 2009).

Table 2: Sub-criteria on green competencies

Index	Criteria details
$y_{a,1}$	Availability of clean technologies (Noci 1997)
$y_{a,2}$	Capacity to respond in time (Zhu and Sarkis 2004)
$y_{a,3}$	Continuous monitoring and regulatory compliance (Klassen and Vachon 2003)
$y_{a,4}$	Establishment of environmental commitment and policy (Bai and Sarkis 2010b)
$y_{a,5}$	Green Market share (Awasthi et al. 2010)
$y_{a,6}$	Green process planning (Corbiere-Nicollier et al. 2011)
$y_{a,7}$	Green supply chain management efficiency (Erol et al. 2011)
$y_{a,8}$	Having recycling product design of suppliers (Klassen and Vachon 2003)
$y_{a,9}$	Having renewable product design of suppliers (Klassen and Vachon 2003)
$y_{a,10}$	Having reverse logistics system of suppliers (Klassen and Vachon 2003)
$y_{a,11}$	Information sharing on environmental topics (Erol et al. 2011)
$y_{a,12}$	Internal control process (Zhu and Sarkis 2004)
$y_{a,13}$	Joint and team problem solving on environmental issues (Linton et al. 2007)
$y_{a,14}$	Partnership with green organizations (Erol et al. 2011)
$y_{a,15}$	Reduce suppliers environmental costs (Bai and Sarkis 2010a)
$y_{a,16}$	Solve supplier environmental technical problems (Bai and Sarkis 2010a)
$y_{a,17}$	Transferring employees with environmental expertise to suppliers (Bai and Sarkis 2010a)
$y_{a,18}$	Use of environment friendly technology (Tsai 2012)

Table 3: Sub-criteria on environmental performance

Index	Criteria details
$y_{b,1}$	Adherence to environmental policies (Awasthi et al. 2010)
$y_{b,2}$	Air emissions (Matos and Hall 2007)
$y_{b,3}$	Amount of environmentally safe alternatives (Klassen and Vachon 2003)
$y_{b,4}$	Energy consumption (Erol et al. 2011)
$y_{b,5}$	Energy efficiency (Bauer et al. 2010)
$y_{b,6}$	Green knowledge transfer and communication (Bai and Sarkis 2010a)
$y_{b,7}$	Green packaging (Kleindorfer et al. 2005)
$y_{b,8}$	Having environmental protection plans of suppliers (Klassen and Vachon 2003)
$y_{b,9}$	Having environmental protection policies of suppliers (Klassen and Vachon 2003)
$y_{b,10}$	Identification of environmental aspects (Bai and Sarkis 2010b)
$y_{b,11}$	Product recycling rate (Kleindorfer et al. 2005)
$y_{b,12}$	Product remanufacturing rate (Sarkis 2003)
$y_{b,13}$	Product reuse rate (Sarkis 2003)
$y_{b,14}$	Ratio of green customers to total customers (Kassinis and Soteriou 2003)
$y_{b,15}$	Reduce rate (Sarkis 2003)
$y_{b,16}$	Response to environmental product requests (Kassinis and Soteriou 2003)
$y_{b,17}$	Solid wastes (Noci 1997)

$y_{b,18}$	Supplier rewards and incentives for environmental performance (Bai and Sarkis 2010a)
$y_{b,19}$	Waste water (Corbiere-Nicollier et al. 2011)

Table 4: Sub-criteria on partner's green image

Index	Criteria details
$y_{c,1}$	Assignment of environmental responsibility (Bai and Sarkis 2010b)
$y_{c,2}$	Building top management commitment/support for supplier organization for green supply practices (Bai and Sarkis 2010a)
$y_{c,3}$	Building top management commitment/support within buyer organization for green supply practices (Bai and Sarkis 2010a)
$y_{c,4}$	Checking and evaluation of environmental activities (Bai and Sarkis 2010b)
$y_{c,5}$	Customers' purchase retention (Noci 1997)
$y_{c,6}$	Depreciation for investments aimed at improving the partner's environment performance (Corbiere-Nicollier et al. 2011)
$y_{c,7}$	Environmental related certificates (Kassinis and Soteriou 2003)
$y_{c,8}$	Green R&D investment (Zhu and Sarkis 2004)
$y_{c,9}$	Having ISO 14000 verification of suppliers (Melnyk et al. 2003)
$y_{c,10}$	Information disclosure (Kuo et al. 2010a)
$y_{c,11}$	Introducing a cross-functional supply chain team with environmental presence (Bai and Sarkis 2010a)
$y_{c,12}$	Market share related to green customers (Noci 1997)
$y_{c,13}$	Planning of environmental objectives (Bai and Sarkis 2010b)
$y_{c,14}$	Respect for the policy (Kuo et al. 2010a)
$y_{c,15}$	The interests and rights of employee (Kuo et al. 2010a)
$y_{c,16}$	The participation level of suppliers in the eco-design stage (Zhu and Sarkis 2004)
$y_{c,17}$	The participation level of suppliers in the process of procurement and production (Bai and Sarkis 2010a)
$y_{c,18}$	Type of relationships with stakeholders (Matos and Hall 2007)

Table 5: Sub-criteria on pollution control

Index	Criteria details
$y_{d,1}$	Air pollution treatment costs (Matos and Hall 2007)
$y_{d,2}$	Chemical wastes treatment costs (Sroufe 2003)
$y_{d,3}$	Cost for component disposal (Noci 1997)
$y_{d,4}$	Design for environment (Linton et al. 2007)
$y_{d,5}$	End-of-pipe control (Bai and Sarkis 2010b)
$y_{d,6}$	Energy consumption costs (Sroufe 2003)
$y_{d,7}$	ISO14001 certificate (Melnyk et al. 2003)
$y_{d,8}$	Pollution control initiatives (Awasthi et al. 2010)
$y_{d,9}$	Production of polluting agents (Bai and Sarkis 2010b)
$y_{d,10}$	Production of toxic products (Bai and Sarkis 2010b)
$y_{d,11}$	Solid wastes treatment costs (Sroufe 2003)
$y_{d,12}$	The Restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) (Tsai 2012)
$y_{d,13}$	Type of materials used in the supplied component (Noci 1997)
$y_{d,14}$	Use of environment friendly materials (Tsai 2012)
$y_{d,15}$	Use of harmful materials (Corbiere-Nicollier et al. 2011)
$y_{d,16}$	Waste Electrical and Electronic Equipment (WEEE) (Tsai 2012)

$y_{d,17}$	Water pollution treatment costs (Erol et al. 2011)

Table 6: Sub-criteria on operations and financial capability

Index	Criteria details
$y_{e,1}$	Asset/Liability ratio (Luo et al. 2009)
$y_{e,2}$	Assets rates of increment (Luo et al. 2009)
$y_{e,3}$	Capabilities to provide quality product/service (Zhu and Sarkis 2004)
$y_{e,4}$	Condition of physical facilities (Chung et al. 2005)
$y_{e,5}$	Consistent conformance to specifications (Choi and Hartley 1996)
$y_{e,6}$	Cost-reduction capability (Sha and Che 2006)
$y_{e,7}$	Debt/equity ratio (Luo et al. 2009)
$y_{e,8}$	Delivery reliability and capacity (Sha and Che 2006)
$y_{e,9}$	Design capability (Sroufe 2003)
$y_{e,10}$	Inventory turnover ratios (Luo et al. 2009)
$y_{e,11}$	Geographical location (Bauer et al. 2009)
$y_{e,12}$	Gross Profit Margin (Burke et al. 2009)
$y_{e,13}$	Net Operating Margin (Burke et al. 2009)
$y_{e,14}$	Net profits growth rates (Lin and Chen 2004)
$y_{e,15}$	Order fulfilment rate (Burke et al. 2009)
$y_{e,16}$	Order lead time (Chung et al. 2005)
$y_{e,17}$	Production volume flexibility (Cui et al. 2012)
$y_{e,18}$	Quality assurance (Zhu and Sarkis 2004)
$y_{e,19}$	Quality philosophy (Pil and Rothenberg 2003)
$y_{e,20}$	Receivable turnover (Luo et al. 2009)
$y_{e,21}$	Total Revenue (Chung et al. 2005)
$y_{e,22}$	Variation in types of products or services (Yang et al. 2010)
$y_{e,23}$	Warranty period (Xia and Wu 2007)

Table 7: Sub-criteria on partnership and technology management

Index	Criteria details
$y_{f,1}$	Closeness of past relationship (Choi and Hartley 1996)
$y_{f,2}$	Company’s reputation to integrity (Sosic 2011)
$y_{f,3}$	Compatible management styles (Hajidimitriou and Georgiou 2002)
$y_{f,4}$	Compatible organization cultures (Hajidimitriou and Georgiou 2002)
$y_{f,5}$	Cost of alternatives (Burke et al. 2009)
$y_{f,6}$	Cost to integration (Sosic 2011)
$y_{f,7}$	Easy communication (Yang et al. 2010)
$y_{f,8}$	Equipment status of the partners (Cui et al. 2012)
$y_{f,9}$	Knowledge of local business practices (Hajidimitriou and Georgiou 2002)
$y_{f,10}$	Obtain partner’s local knowledge (Amaral and Tsay 2009)
$y_{f,11}$	Partner’s ability to acquire your firm’ special skills (Xia and Wu 2007)
$y_{f,12}$	Product Familiarity (Amaral and Tsay 2009)
$y_{f,13}$	Relationship building flexibility (Lin and Chen 2004)
$y_{f,14}$	Repair turnaround time (Xia and Wu 2007)
$y_{f,15}$	Risk of failure of cooperation (Amaral and Tsay 2009)

$y_{f,16}$	Special skills that you can learn from partners (Amaral and Tsay 2009)
$y_{f,17}$	Technical advice (Cui et al. 2012)
$y_{f,18}$	Technical capability (Cui et al. 2012)
$y_{f,19}$	Technology innovation (Yang et al. 2010)
$y_{f,20}$	Time needed to integration (Sosic 2011)

There are two main advantages of using the GSC-GHC, namely flexibility and adaptability. On the one hand, given the different features of every specific GSC, the GSC-GHC can be adapted to meet individual needs within partner selection resource constraints. On the other hand, given that the information on different criteria may not be completely certain, Dempster-Shafer theory can be used to assign a belief acceptability to represent the bias of decision-makers (Shafer 1976). This is discussed below.

Additionally, our proposal pays particular attention to a common phenomenon in multi-attribute decision-making problems, namely attribute dependency. In this case, for any target dimension criterion in the high and/or middle layer, decision-makers can generate different meaningful combinations out of the criteria in the low layer and build the subordinate criteria sets for the GSC-SHC and GSC-OHC. This is also discussed below.

4.2 GSC partner selection Specific Hierarchy Criteria construction

In the second stage, the output from the GSC-GHC construction is used to formulate the GSC-SHC. Every GSC requires its own specific hierarchy criteria because every GSC has distinctive characteristics, which arise from its industry and the stage of its development. It is very hard to collect the required information on supplier's performance by simply using the same set of attributes across different industries. There is not a one size "criteria set" fit for all industries (Genovese et al. 2015). During the GSC-SHC construction sub-stage, decision-makers have the opportunities to build their own partner selection hierarchy criteria in accordance with their specific requirements. This requires the construction of a belief acceptability using the Dempster-Shafer theory. To do this, we follow the approach of Wu and Barnes (2010).

Firstly, let us note the terminology inherent within the Dempster-Shafer theory, which is somewhat different from that used in probability theory. (The notations used are set out in Figure 3.)

l	layer index of configuration hierarchy, $l = 1,2, \ldots, L$
y_{li}	the evaluation attribute *i* in layer *l*
y_{Li}	the evaluation attribute *i* which always located in the bottom layer of the attribute configuration hierarchy
y_{11}	the final aggregate evaluations attribute
V_{lk}	the k^{th} set of selected attributes *s* in layer *l*
Γ	a general notation to represent the subordinate attributes set
Γ_{11j}	the j^{th} subordinate attributes set of the final aggregate evaluation attribute
Γ_{lij}	the j^{th} subordinate attributes set of its master attribute y_{li}
$m(\cdot)$	the basic probability assignment function of a given proposition
$m(\Gamma_{lij})$	the belief acceptability for Γ_{lij} of the master attribute y_{li}
π	a general notation to represent the acceptability of an evaluation attribute
π_{li}	the belief acceptability of the subordinate evaluation attribute y_{li}
V_i	the binary attribute selection variable that if the evaluation attributes is selected, then V_i = 1; otherwise V_i = 0
j	the number of subsets on the different criteria groups of 3rd level hierarchy configuration

Figure 3: Notations used in the Dempster-Shafer theory (adopt from Wu and Barnes 2010: 292)

Let $\varphi = \{\mathrm{x}_1, \mathrm{x}_2, \ldots, \mathrm{x}_\mathrm{n}\}$ be a finite set of hypotheses (the frame of discernment). A basic probability assignment (*bpa*) is a function m: $2^\varphi \rightarrow [0,1]$ such that:

$$m(\phi) = 0 \text{, and } \sum_{x \in 2^\varphi} m(x) = 1 .$$

We use the notation 2^φ because we have to consider the number of elements in the power set. All of the assigned probabilities sum to unity and there is no belief in the empty set. Any subset *x* of the frame of discernment φ for which m(*x*) is non-zero is called a focal element. A focal element represents the exact belief in the proposition depicted by *x*. Possible propositions of interest are “the true value of *z* lies in *Z*”, where $\mathrm{Z} \subseteq \varphi$. Thus, propositions are subsets. The value m(*Z*) represents the confidence that “the true value of *z* lies in *Z*, and not in any proper subset of *Z* ”.

Other measures of confidence can be defined based on the *bpa*. A belief measure is a function $Bel : 2^\varphi \rightarrow [0,1]$. It is drawn from the sum of probabilities that are subsets of the probabilities in question, defined by

$$Bel(A) = \sum_{B \subseteq A} m(B)\text{, for all } A \subseteq \varphi.$$

This represents the confidence that the value of z lies in A or any subset of A. A plausibility measure is a function $Pls: 2^{\varphi} \to [0,1]$, defined by

$$Pls(A) = \sum_{B \cap A \neq \phi} m(B)\text{, for all } A \subseteq \varphi$$

$Pls(A)$ represents the extent to which we fail to disbelieve A. These measures are clearly related to one another, for example,

$$Bel(A) = 1 - Pls(\overline{A}) \text{ and } Pls(A) = 1 - Bel(\overline{A}),$$

where $\overline{A}$ refers to 'not A', also $Bel(\overline{A})$ is often called the doubt in A. Another notable relationship includes;

$$Bel(A) + Bel(\overline{A}) \leq 1,\ Pls(A) + Pls(\overline{A}) \geq 1.$$

These two inequalities represent a major difference from the traditional simple probability function used in the Bayesian approach. However, when each of the focal elements are singletons, we can revert to traditional Bayesian analysis incorporating normal probability theory, because in this case $Bel(A) = Pls(A)$.

For any given green supply chain, taking into account its individual characteristics and the judgment bias due to incomplete and inaccurate information used by the decision-makers, a GSC-SHC can be extracted from the GSC-GHC with assigned belief acceptabilities. An illustrative example of the GSC-SHC, where $V_{lk} = \cup_k \Gamma_{lik} = \{y_{li} | y_{li} \in \Gamma_{lij}, \forall j\}$ represents the subordinate attributes set in the lower layer of the master evaluation criterion, y_{li} is shown in Figure 4.

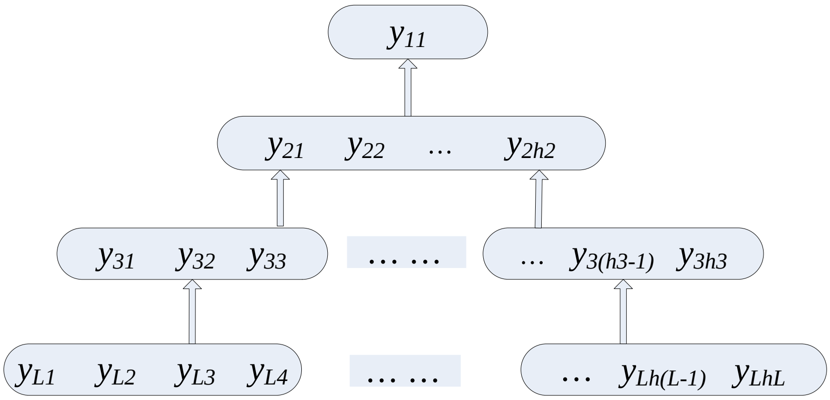

Figure 4: An example of GSC-SHC construction

Uncertainty and ignorance are the two important characteristics of the evaluation criteria for the GSC partner selection problem. Uncertainty comes from the available information for decision-making which is unreliable, imprecise, or incomplete. Ignorance exists when there is a lack of information during decision-making (Beynon et al. 2000). For example, if the decision-makers are either not completely certain about the performance of potential partners, or if it is too costly to obtain the exact information required, then a belief acceptability is assigned to represent the confidence of the decision-makers in the information and value of these evaluation criteria.

The belief acceptability of an attribute equates to the lower bound of the belief interval (Guan and Bell 1991) in this study. The value of the belief acceptability of an attribute is calculated from the summation of the basic acceptabilities of all its subordinate attributes sets, as follows:

$$\pi_{li} = \sum_{\Gamma_{lij} \subset V_{lk}} m(\Gamma_{lij}) \text{ and } \sum_{j=1}^{V_{lk}} \mathrm{m}(\Gamma_{\mathrm{lij}}) = 1 \tag{1}$$

The procedures to calculate the resultant belief acceptability of the GSC-SHC can be summarized as follows:

- Step 1. Let $l = L$, where L is the total number of layers of the GSC-SHC. $\forall i$, calculate the belief acceptability π_{Li}, of y_{Li}.
- Step 2. Let $l = L - 1$. $\forall i$, compute π_{li} of y_{li} based on Equation (1).

- Step 3. $\forall i$, repeat step 2 and calculate π_{li} for $y_{(L-3)i}$, $y_{(L-4)i}$,. . ., y_{1i}, and y_{11}, respectively, y_{11} is the resultant favourability attribute of the GSC-SHC.

4.3 GSC partner selection Optimization Hierarchy Criteria construction

The final stage of the process is the construction of the GSC-OHC based on the output of previous sub-process - the GSC-SHC. During this stage, as the evaluation scope has been reduced further, the usage of evaluation resources needs to be strictly controlled. This is because, in practice, any organization has only limited resources available. If no reasonable trade-off between evaluation scope and evaluation resources were made, the partner selection hierarchy criteria construction task is potentially inefficient and unfeasible (Tsai 2012). Thus, obtaining the GSC-OHC requires balancing the scope of evaluation, the belief acceptability and the usage of evaluation resources simultaneously. In this research, we propose to do this by developing a PSO based multiple objective programming model.

The proposed multiple-objective programming model contains two main objectives, namely, maximizing the total belief acceptability of the GSC-OHC and minimizing the human resource usage (including management and administration work) during the criteria construction process. The constraints of the programming model include the total financial costs related to each selected criterion. The optimization multiple-objective model and constraints for the evaluation criteria are introduced as follows:

$$\textbf{Max. } \left(\sum_{l}\sum_{i}\pi_{li}\times V_i\right) \tag{2}$$

$$\textbf{Min. } \left(\sum_{l}\sum_{i}h_{li}\times V_i\right) \tag{3}$$

s.t.:

$$\sum_{i} f_{ik}\times V_i \le f_k \qquad \forall k \tag{4}$$

$$V_i = 0 \text{ or } 1 \qquad \forall i \tag{5}$$

$$\sum_{i=1}^{j} V_i \le 1 \qquad \forall j \tag{6}$$

In more detail, objective (2) seeks to maximize the total belief acceptability of the final GSC-OHC, whilst objective (3) seeks to minimize the required human resource usage to construct it. At the same time, inequality (4) constrains the total financial costs of the final GSC-OHC to equal or less than the available amount of financial resources (f_k). Equation (5) constrains the criteria selection variables to a binary value. Last but not least, inequality (6) constrains each criterion to appear only once in the final GSC-OHC.

In the PSO algorithm, particles are represented as $X_a = (x_{a1}, x_{a2}, \ldots , x_{aM})$. This expression represents a potential solution to a problem in M-dimensional space. The velocity of this particle can be represented as $V_a = (v_{a1}, v_{a2}, \ldots , v_{aM})$. In addition, the best previous position of each particle is defined as *pbest*. The global best position of the whole swarm found so far is defined as *gbest*. The updating rule is:

$$v_{am}^{n+1} = wv_{am}^{n} + c_1 \times rand_1() \times (pbest - x_{am}^{n}) + c_2 \times rand_2() \times (gbest - x_{am}^{n}) \quad (7)$$

$$x_{am}^{n+1} = x_{am}^{n} + v_{am}^{n+1} \quad (8)$$

in which, a is the particle index,
m is the dimension index,
n is the number of iterations,
w is the inertia weight,
c_1 and c_2 are acceleration constants,
$rand_1()$ and $rand_2()$ are independent random variables within [0, 1].

Equation (7) is applied to calculate the particle’s new velocity in accordance with its previous velocity and the distances of its current position from the group’s best position and its own best position (Huang et al. 2011). Rand numbers in the Equation (7) are independent variables which can serve as the weights of speed moving towards gbest and pbest for updating positions. Through varying the above random numbers, particle *a* will attempt to move towards the best particle and provides coverage of solution space of the potentially good solutions (Zhao et al. 2008). Equation (8), then, is used to calculate the particle flies toward a new position. The pseudo code of the PSO algorithm and the procedure of the PSO algorithm are shown in Appendices A and B.

5. Empirical illustration

In this section, the proposed three-stage DS-PSO model for partner selection criteria construction in GSCs is applied to a real company, as a case study to illustrate its practical operability. The company (we use the pseudonym, Company ABC) is a large company operating within the Chinese Electronic Equipment & Instruments industry. China is currently a particularly important country for GSCM. As a rapidly industrialising country, it is in the process of evaluating and attempting to draft appropriate environmental standards (Zhu et al. 2012). Company ABC manufactures products ranging from high-voltage power transmission to industrial motors and drives.

In the first stage, according to the proposed three-stage DS-PSO model for partner selection criteria construction in GSCs, the GSC-GHC is applied without any modification, as this is entirely appropriate for the green supply chain partner selection decision-making environment.

The second stage is to construct the GSC-SHC. During this stage, it is necessary to organize numbers of experts to select criteria from GSC partner selection general hierarchy criteria to construct the GSC partner selection specific hierarchy criteria based on their own experience and industry knowledge. It is also necessary to ask them to assign the belief acceptability to different alternatives (criteria combinations, such as the first column of Table 9 shown) in accordance with the chosen GSC's business characteristics and the judgement bias caused by inaccuracy and incomplete information. The group of experts comprised two Chinese academics, one British academic, and four purchasing managers within the Chinese Electronic Equipment & Instruments industry (three of the four come from the Company ABC). Each of them was asked open questions about the different alternatives. A Delphi method was used during this stage. The Delphi method is suitable for semi-structured decision making within a variable decision-making environment (Hassan et al. 2015). As such, there is no standard structured questionnaire (Okoli and Pawlowski 2004). Rather, experts are independently asked open questions about their views on the partner selection criteria within the framework. If there was still disagreement amongst the experts after two or three rounds of Delphi questioning, the Dempster-Shafer evidence combination theory (Beynon et al. 2000) was then used to obtain the combined evidence. The GSC-SHC and its belief acceptabilities are obtained and calculated in accordance with the Dempster-Shafer methodology discussed in Section 4.2 during this stage. The results are shown in Figure 5, Table 8 and Table 9 (Figure 5 is a more visual way to show Table 8).

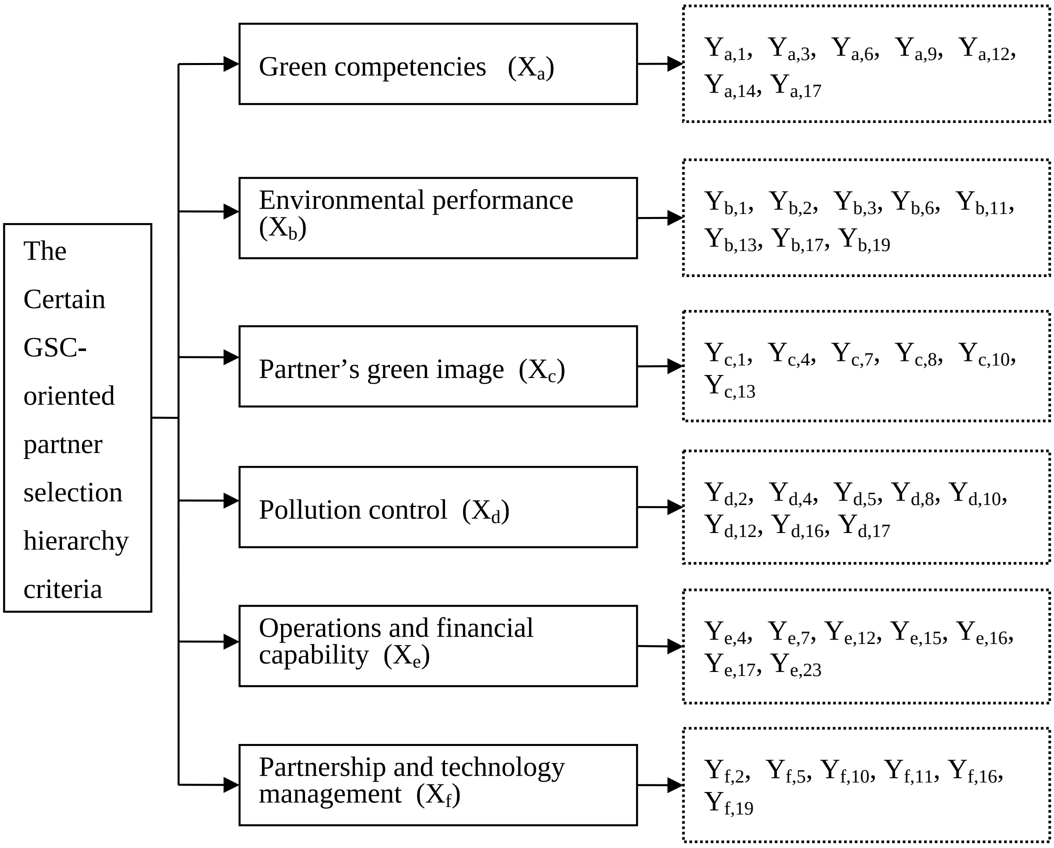

Figure 5: The *GSC-SHC* for Chinese Electronic Equipment & Instruments industry

Table 8: The GSC-SHC for Chinese Electronic Equipment & Instruments industry

Hierarchy level	Selected criteria
High level	Partner performance in green supply chain
Middle level	Green competencies
	Environmental performance
	Partner’s green image
	Pollution control
	Operations and financial capability
	Partnership and technology management
Low level	
$y_{a,1}$	Availability of clean technologies
$y_{a,3}$	Continuous monitoring and regulatory compliance
$y_{a,6}$	Green process planning
$y_{a,9}$	Having renewable product design of suppliers
$y_{a,12}$	Internal control process
$y_{a,14}$	Partnership with green organizations
$y_{a,17}$	Transferring employees with environmental expertise to suppliers
$y_{b,1}$	Adherence to environmental policies
$y_{b,2}$	Air emissions
$y_{b,3}$	Amount of environmentally safe alternatives
$y_{b,6}$	Green knowledge transfer and communication
$y_{b,11}$	Product recycling rate
$y_{b,13}$	Product reuse rate
$y_{b,17}$	Solid wastes
$y_{b,19}$	Waste water
$y_{c,1}$	Assignment of environmental responsibility
$y_{c,4}$	Checking and evaluation of environmental activities
$y_{c,7}$	Environmental related certificates
$y_{c,8}$	Green R&D investment
$y_{c,10}$	Information disclosure
$y_{c,13}$	Planning of environmental objectives
$y_{d,2}$	Chemical wastes treatment costs
$y_{d,4}$	Design for environment
$y_{d,5}$	End-of-pipe control
$y_{d,8}$	Pollution control initiatives
$y_{d,10}$	Production of toxic products
$y_{d,12}$	The Restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)
$y_{d,16}$	Waste Electrical and Electronic Equipment (WEEE)
$y_{d,17}$	Water pollution treatment costs
$y_{e,4}$	Condition of physical facilities
$y_{e,7}$	Debt/equity ratio
$y_{e,12}$	Gross Profit Margin
$y_{e,15}$	Order fulfilment rate
$y_{e,16}$	Order lead time
$y_{e,17}$	Production volume flexibility
$y_{e,23}$	Warranty period
$y_{f,2}$	Company’s reputation to integrity
$y_{f,5}$	Cost of alternatives
$y_{f,10}$	Obtain partner’s local knowledge
$y_{f,11}$	Partner’s ability to acquire your firm’ special skills
$y_{f,16}$	Special skills that you can learn from partners
$y_{f,19}$	Technology innovation

Table 9: The combined evidence, human resource requirements and financial costs of the GSC-SHC for Chinese Electronic Equipment & Instruments industry

Potential Combinations	Combined evidence	Human resource requirements *(hours)*	External financial costs *($)*	Internal financial costs *($)*
$(y_{a,1}; y_{a,9}; y_{a,12}; y_{a,17})$	0.112	12	201	30
$(y_{a,3}; y_{a,12}; y_{a,14}; y_{a,17})$	0.152	15	220	32
$(y_{a,6}; y_{a,9}; y_{a,12}; y_{a,14})$	0.162	16	210	29
$(y_{a,1}; y_{a,6}; y_{a,14}; y_{a,17})$	0.133	13	230	31
$(y_{b,1}; y_{b,3}; y_{b,11}; y_{b,17})$	0.163	23	327	35
$(y_{b,1}; y_{b,6}; y_{b,13}; y_{b,19;})$	0.175	24	354	34
$(y_{b,2}; y_{b,6}; y_{b,11}; y_{b,19})$	0.161	25	368	36
$(y_{b,3}; y_{b,6}; y_{b,11}; y_{b,13;})$	0.169	22	345	29
$(y_{c,1}; y_{c,4}; y_{c,13})$	0.133	20	178	23
$(y_{c,1}; y_{c,10}; y_{c,13})$	0.149	19	185	25
$(y_{c,7}; y_{c,8}; y_{c,10})$	0.154	17	194	24
$(y_{c,7}; y_{c,8}; y_{c,13})$	0.150	18	169	22
$(y_{d,5}; y_{d,8}; y_{d,16}; y_{d,17})$	0.170	27	402	51
$(y_{d,2}; y_{d,5}; y_{d,12}; y_{d,16})$	0.158	29	409	56
$(y_{d,4}; y_{d,8}; y_{d,10}; y_{d,17})$	0.160	28	415	58
$(y_{d,2}; y_{d,4}; y_{d,10}; y_{d,12})$	0.172	25	420	59
$(y_{e,4}; y_{e,12}; y_{e,16})$	0.136	12	265	38
$(y_{e,7}; y_{e,15}; y_{e,16})$	0.119	16	256	39
$(y_{e,12}; y_{e,17}; y_{e,23})$	0.142	14	248	33
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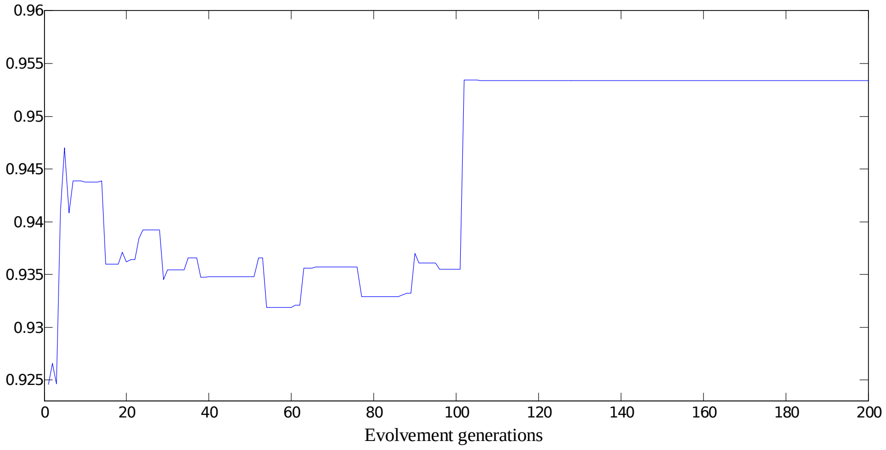
$(y_{f,11}; y_{f,16}; y_{f,19})$	0.174	24	333	47

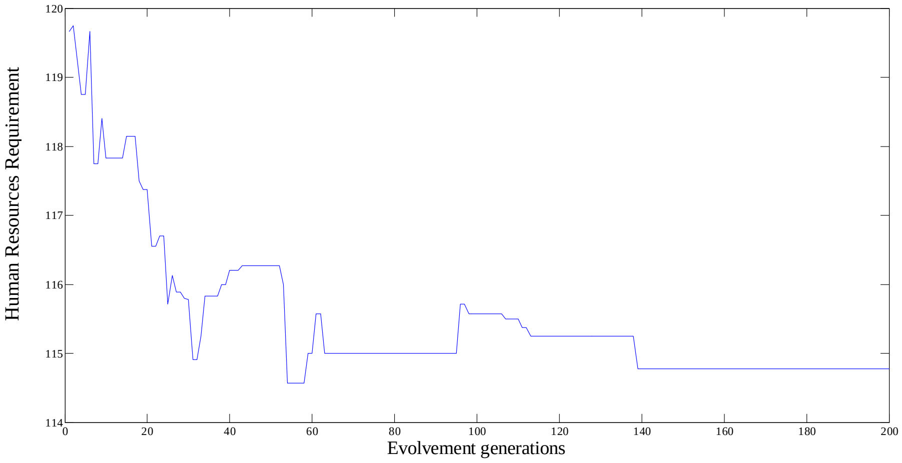
Combining evidence in this way offers a meaningfully way to summarize and simplify different assessments from a panel of decision-makers. It is done by using the combinational rule which is an aggregation method for data obtained from multiple sources. In this case, the group of experts are the multiple sources, who each provide different assessments in accordance with their own knowledge and judgements. To capture and summarize their assessments into one meaningfully “number” is a very useful preparation for the application of the PSO sub-model. For instance, in Table 9, the first row, the combined evidence of the potential choices - $(y_{a,1}; y_{a,9}; y_{a,12}; y_{a,17})$ is 0.112. It represents the level of belief that the group of experts on the combination of criteria ($y_{a,1}; y_{a,9}; y_{a,12}; y_{a,17}$) under Green Competencies sub-criteria. (Appendix C shows an example of the combined evidence calculation). From Table 9 we can see that different criteria combinations have different combined evidence. These "numbers" (the combined evidence) represent the different levels of belief the decision-makers have on different possible criteria combinations. The higher the "number", the higher level of belief the decision-makers have. In addition, each possible criteria combination corresponds to different managerial resource requirements. Therefore, it becomes an optimization problem which will be solved in the following step by PSO sub-model shown in Section 4.3.

The third stage, after constructing the GSC-SHC, is to construct the GSC-OHC by applying the PSO sub-model. Under the condition of objectives of combined evidence and human resource requirements (shown in Table 9), and the constraint of total financial resources of $2,000, the non-inferior solution set is obtained by a number of algorithm iterations. The search processes of the PSO sub-model are shown in Figure 6. From Figure 6(a) and 6(b), we can see that, after completing 120 to 140 algorithm iterations, the two basic objectives of the multi-objective model for constructing the GSC-OHC are reaching their non-inferior solutions progressively. In other words, 140 times of iteration are good enough. More iterations cannot improve the effectiveness of the PSO sub-model. To achieve the best effectiveness and save the calculation time, the number of iterations would be set around 140 to 150.

These processes demonstrate both the applicability of PSO technique and its high level of performance in this decision-making situation. It also indicates that the non-inferior solutions of the construction of GSC-OHC can be obtained using the multi-objective mathematical model (2) – (6), and that the PSO technique can successfully undertake the search for non-inferior solutions. (In this research, the mathematic optimization model was programmed and run by applying the toolbox in Matlab®.) Therefore, the proposed model and method are effective in solving the problem.



(a)



(b)

Figure 6: Search process of the PSO technique

The non-inferior solution set for the construction of the GSC-OHC is shown in Tables 10 and 11. The results are also shown in Figures 7 through 9 in a more intuitive way.

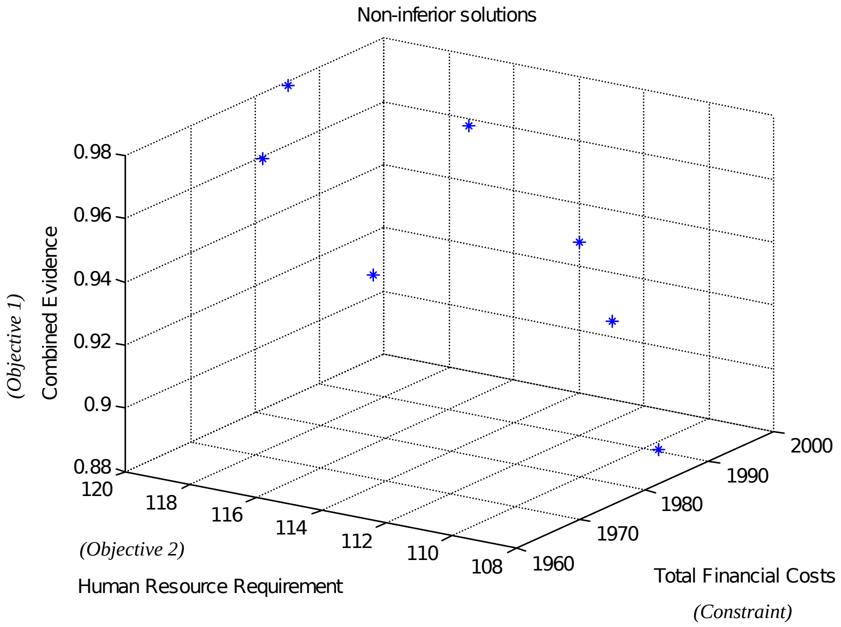


Figure 7: The non-inferior solution set found by PSO algorithm

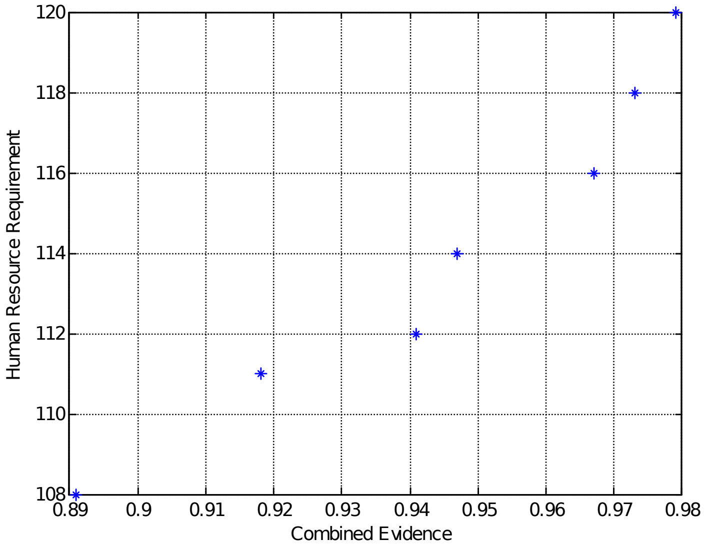


Figure 8: The non-inferior solution set with respect to combined evidence and human resource requirement

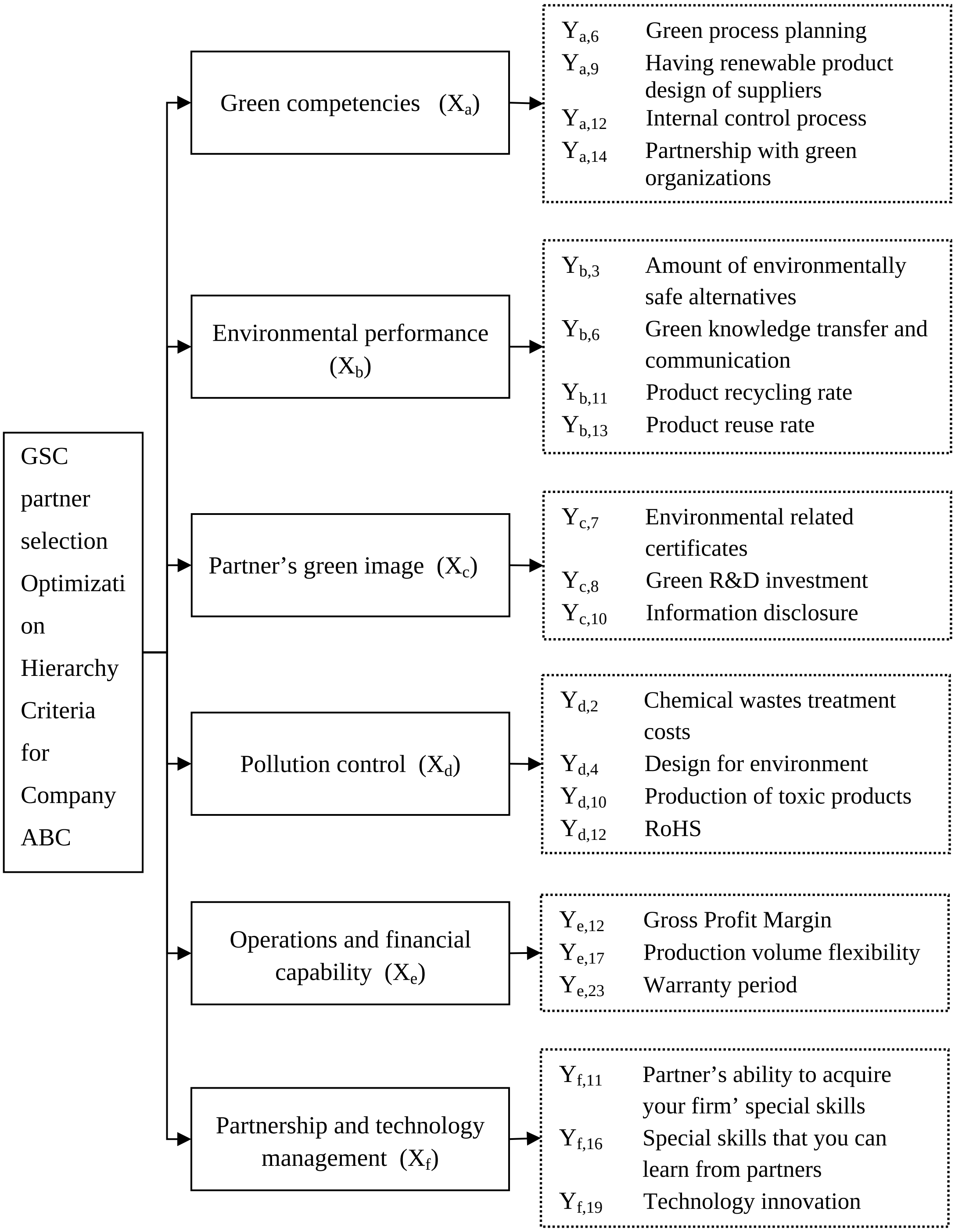


Figure 9: The *GSC-OHC* for Company ABC*

Note*: An example of the seven non-inferior solutions

Table 8: The GSC-SHC for Chinese Electronic Equipment & Instruments industry

Hierarchy level	Selected criteria
High level	Partner performance in green supply chain
Middle level	Green competencies Environmental performance Partner's green image Pollution control Operations and financial capability Partnership and technology management
Low level	
$y_{a,1}$	Availability of clean technologies
$y_{a,3}$	Continuous monitoring and regulatory compliance
$y_{a,6}$	Green process planning
$y_{a,9}$	Having renewable product design of suppliers
$y_{a,12}$	Internal control process
$y_{a,14}$	Partnership with green organizations
$y_{a,17}$	Transferring employees with environmental expertise to suppliers
$y_{b,1}$	Adherence to environmental policies
$y_{b,2}$	Air emissions
$y_{b,3}$	Amount of environmentally safe alternatives
$y_{b,6}$	Green knowledge transfer and communication
$y_{b,11}$	Product recycling rate
$y_{b,13}$	Product reuse rate
$y_{b,17}$	Solid wastes
$y_{b,19}$	Waste water
$y_{c,1}$	Assignment of environmental responsibility
$y_{c,4}$	Checking and evaluation of environmental activities
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$y_{c,10}$	Information disclosure
$y_{c,13}$	Planning of environmental objectives
$y_{d,2}$	Chemical wastes treatment costs
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$y_{d,5}$	End-of-pipe control
$y_{d,8}$	Pollution control initiatives
$y_{d,10}$	Production of toxic products
$y_{d,12}$	The Restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)
$y_{d,16}$	Waste Electrical and Electronic Equipment (WEEE)
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$y_{e,7}$	Debt/equity ratio
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$y_{e,23}$	Warranty period
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$y_{f,5}$	Cost of alternatives
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($y_{f,5}; y_{f,10}; y_{f,19}$)	0.157	25	328	42
($y_{f,2}; y_{f,5}; y_{f,11}$)	0.160	28	319	41
($y_{f,11}; y_{f,16}; y_{f,19}$)	0.174	24	333	47

Table 10: The non-inferior solutions found by PSO technique

Non-inferior solution	Combined evidence	Human resources requirement *(hours)*	Total financial costs *($)*
1	0.973	118	1971
2	0.918	111	1990
3	0.979	120	1985
4	0.947	114	1968
5	0.967	116	1993
6	0.941	112	1990
7	0.891	108	1982

Table 11: The non-inferior solutions of the GSC-OHC

Non-inferior solution	Green competencies (X_a)	Environmental performance (X_b)	Partner's green image (X_c)	Pollution control (X_d)	Operations and financial capability (X_e)	Partnership and technology management (X_f)
1	$(y_{a,6}; y_{a,9}; y_{a,12}; y_{a,14})$	$(y_{b,3}; y_{b,6}; y_{b,11}; y_{b,13};)$	$(y_{c,7}; y_{c,8}; y_{c,10})$	$(y_{d,2}; y_{d,4}; y_{d,10}; y_{d,12})$	$(y_{e,12}; y_{e,17}; y_{e,23})$	$(y_{f,11}; y_{f,16}; y_{f,19})$
2	$(y_{a,1}; y_{a,6}; y_{a,14}; y_{a,17})$	$(y_{b,3}; y_{b,6}; y_{b,11}; y_{b,13};)$	$(y_{c,7}; y_{c,8}; y_{c,10})$	$(y_{d,2}; y_{d,4}; y_{d,10}; y_{d,12})$	$(y_{e,12}; y_{e,17}; y_{e,23})$	$(y_{f,2}; y_{f,10}; y_{f,16})$
3	$(y_{a,6}; y_{a,9}; y_{a,12}; y_{a,14})$	$(y_{b,1}; y_{b,6}; y_{b,13}; y_{b,19};)$	$(y_{c,7}; y_{c,8}; y_{c,10})$	$(y_{d,2}; y_{d,4}; y_{d,10}; y_{d,12})$	$(y_{e,12}; y_{e,17}; y_{e,23})$	$(y_{f,11}; y_{f,16}; y_{f,19})$
4	$(y_{a,6}; y_{a,9}; y_{a,12}; y_{a,14})$	$(y_{b,3}; y_{b,6}; y_{b,11}; y_{b,13};)$	$(y_{c,7}; y_{c,8}; y_{c,10})$	$(y_{d,2}; y_{d,4}; y_{d,10}; y_{d,12})$	$(y_{e,12}; y_{e,17}; y_{e,23})$	$(y_{f,2}; y_{f,10}; y_{f,16})$
5	$(y_{a,6}; y_{a,9}; y_{a,12}; y_{a,14})$	$(y_{b,3}; y_{b,6}; y_{b,11}; y_{b,13};)$	$(y_{c,7}; y_{c,8}; y_{c,10})$	$(y_{d,2}; y_{d,4}; y_{d,10}; y_{d,12})$	$(y_{e,4}; y_{e,12}; y_{e,16})$	$(y_{f,11}; y_{f,16}; y_{f,19})$
6	$(y_{a,6}; y_{a,9}; y_{a,12}; y_{a,14})$	$(y_{b,3}; y_{b,6}; y_{b,11}; y_{b,13};)$	$(y_{c,7}; y_{c,8}; y_{c,10})$	$(y_{d,2}; y_{d,4}; y_{d,10}; y_{d,12})$	$(y_{e,4}; y_{e,12}; y_{e,16})$	$(y_{f,2}; y_{f,10}; y_{f,16})$
7	$(y_{a,1}; y_{a,9}; y_{a,12}; y_{a,17})$	$(y_{b,3}; y_{b,6}; y_{b,11}; y_{b,13};)$	$(y_{c,7}; y_{c,8}; y_{c,10})$	$(y_{d,2}; y_{d,4}; y_{d,10}; y_{d,12})$	$(y_{e,4}; y_{e,12}; y_{e,16})$	$(y_{f,2}; y_{f,10}; y_{f,16})$

From Tables 10 and 11, we can see that seven non-inferior solutions have been found (each row of Table 11 indicates one of the non-inferior solutions). Figure 9 shows the first row of the seven non-inferior solutions in Table 11 in a more visual way as an example. A non-inferior solution is one in which an improvement in one objective requires a degradation of another (also called Pareto optimality). In most of multi objective-decision-making problems, satisfactory solutions often need to be searched for in a non-inferior solution set. This characteristic gives the decision-makers more flexibility than identifying a single solution only. Having several non-inferior choices gives the different decision-makers, who have different personalities, more scope and freedom to make the final decision under different decision-making conditions. Then, the final decision will be the one which is based not only on concrete quantitative calculations but also on comprehensive qualitative analysis as well.

In this practical example, decision-makers need to make the final decision on trade-offs between the seven non-inferior solutions (shown in Figures 7 and 8). Figure 7 includes information on the total financial costs (constraint) with other two objectives. This is because the different solutions in the non-inferior set correspond to different levels of total financial costs. Figure 7 aims to provide a full picture for decision-makers about the non-inferior solutions. Therefore, the final decision on trade-off could be made depending upon the preferred combination of human resources and/or total financial costs. For instance, if a green supply chain has very limited financial resources during the decision-making process but has sufficient human resources, it could choose the non-inferior solution which requires fewer financial resources but a little higher human resources (say non-inferior solution 1 or non-inferior solution 4).

Considering the metaheuristic algorithm attribute, the optimization results searched by PSO technique could be the local optimization solutions only rather than the global optimization ones. Therefore, in-depth and comprehensive analysis and comparison on the key parameters are necessary and helpful to find the most suitable ones. Table 12 shows detailed comparisons of the key parameters (acceleration constants c_1 and c_2) in the PSO sub-model. From this we can see that the mean and standard deviations of the combined evidence varies slightly from 0.936 to 0.961 and from 0.017 to 0.034, respectively. Also, the mean and standard deviations of the human resource requirement varies slightly from 113.6 to 116.0 and from 3.162 to 4.536, respectively. In more detail, Figures 10 and 11 indicate the variation tendency of the means of combined evidence and human resource requirement in the non-inferior solution set. From Figure 10, it is easy to see that the middle area and top right corner area (in purple) have higher combined evidence than other areas. In Figure 11, as the objective is the lower the better, so the bottom left, bottom right, and top right areas (in red) have top priority. Combining the results of the analysis based on Figures 10 and 11, we should try our best to choose the overlapping areas from the above identified areas to ensure the most suitable parameters are chosen. In this case, $c_1 = 0.7$ and $c_2 = 0.9$ (top right areas in the figures) is the best choice for applying PSO sub-model to solve the GSC-OHC construction problem in the Chinese Electronic Equipment & Instruments industry and a case company within it. With the same analysis procedures and methods, we can also undertake more analysis and comparisons between standard deviations in the non-inferior set.

Table 12: Result of multiple comparisons of the parameter of acceleration constants

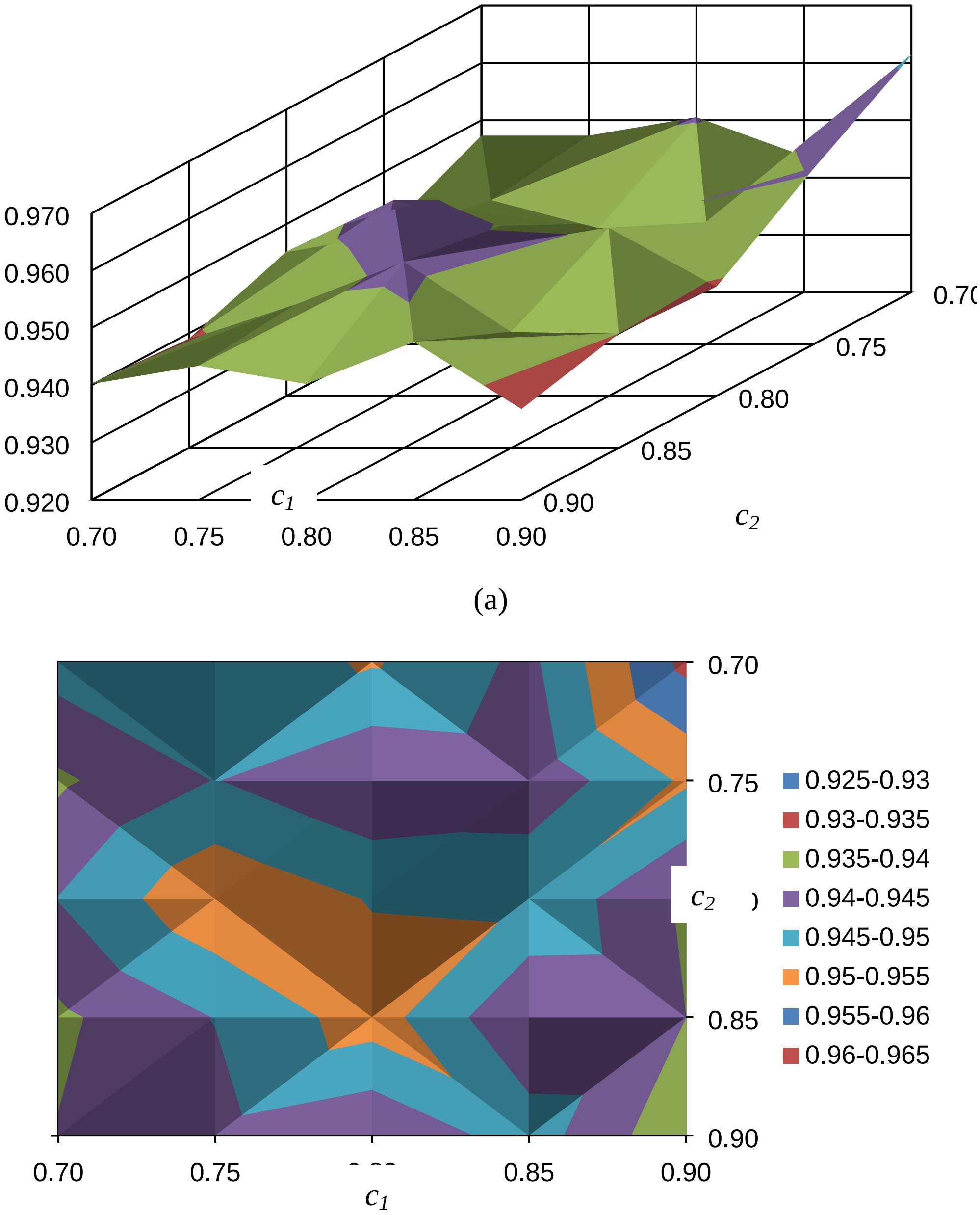
	□	c_1									
		0.70		0.75		0.80		0.85		0.90	
c_2	0.70	0.947*	0.028**	0.947	0.028	0.951	0.027	0.944	0.033	0.961	0.017
		114.429***	3.735****	114.429	3.735	115.500	4.536	114.000	4.320	116.000	3.162
	0.75	0.939	0.034	0.945	0.032	0.940	0.033	0.941	0.032	0.951	0.027
		113.625	4.138	114.143	4.180	113.625	4.138	114.111	4.106	115.500	4.536
	0.80	0.945	0.032	0.954	0.023	0.950	0.032	0.949	0.030	0.939	0.034
		114.143	4.180	115.167	3.488	114.667	4.320	115.500	4.536	113.625	4.138
	0.85	0.939	0.028	0.945	0.032	0.953	0.026	0.940	0.033	0.940	0.033
		113.909	3.477	114.143	4.180	115.000	3.742	113.625	4.138	113.750	3.955
	0.90	0.940	0.033	0.943	0.034	0.940	0.033	0.948	0.027	0.936	0.033
		113.625	4.138	114.000	4.320	113.625	4.138	114.429	3.735	113.600	4.006

* The mean of combined evidence in the non-inferior solution set

** The standard deviation of combined evidence in the non-inferior solution set

*** The mean of human resource requirement in the non-inferior solution set

**** The standard deviation of human resource requirement in the non-inferior solution set

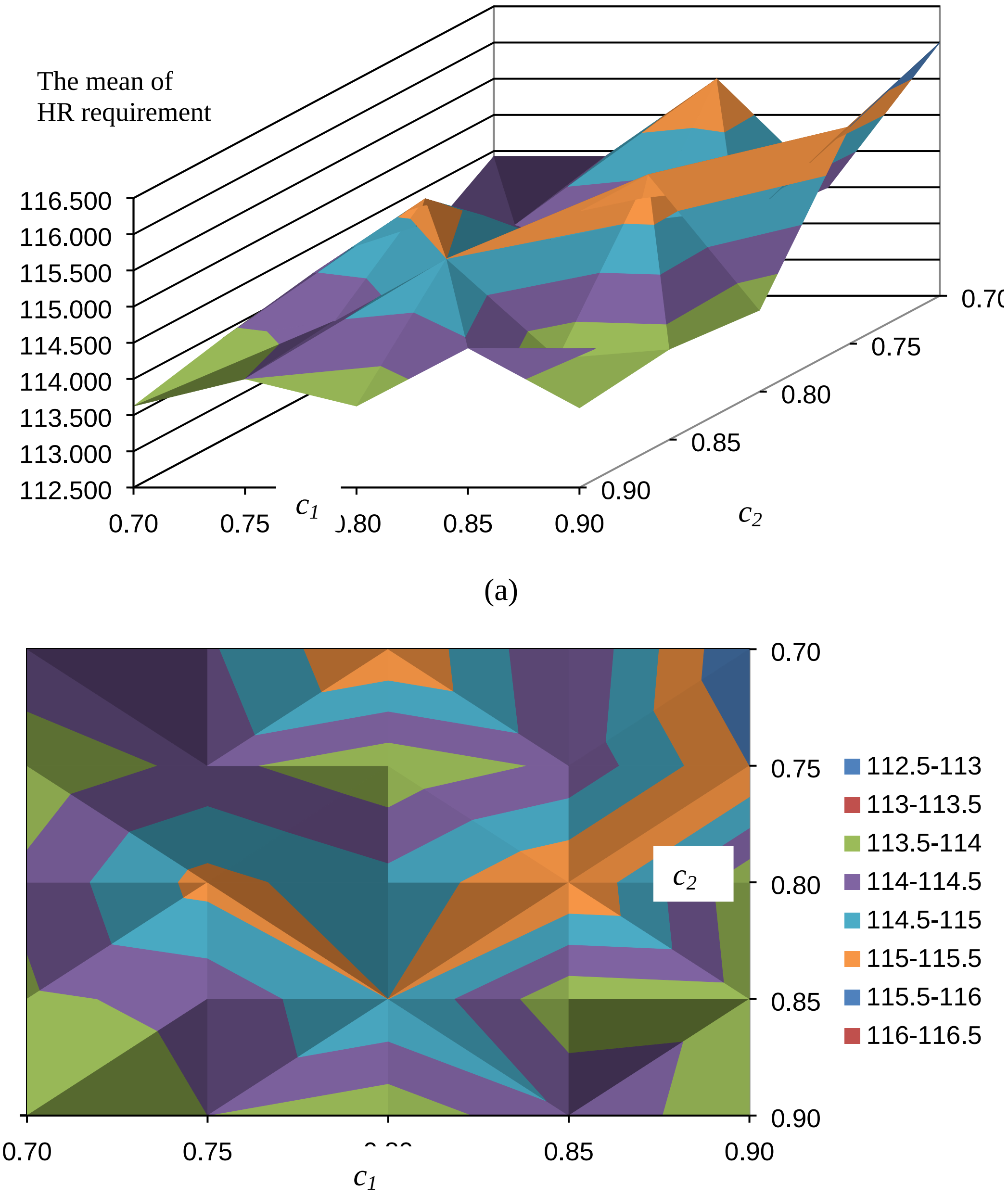


(a)

(b)

Figure 10: The mean of combined evidence in non-inferior solution set with different acceleration constants

Note: c_1 and c_2 are acceleration constants in the PSO sub-model



(a)

(b)

Figure 11: The mean of human resource requirement in non-inferior solution set with different acceleration constants

Note: c_1 and c_2 are acceleration constants in the PSO sub-model

6. Managerial application process

In this section, we present a six step application process for use by managers wishing to apply the proposed method in their own an organization. This process (as shown in Figure 12) aims to enable managers to construct their own customized optimization hierarchy criteria for partner selection in GSCs (GSC-OHC).

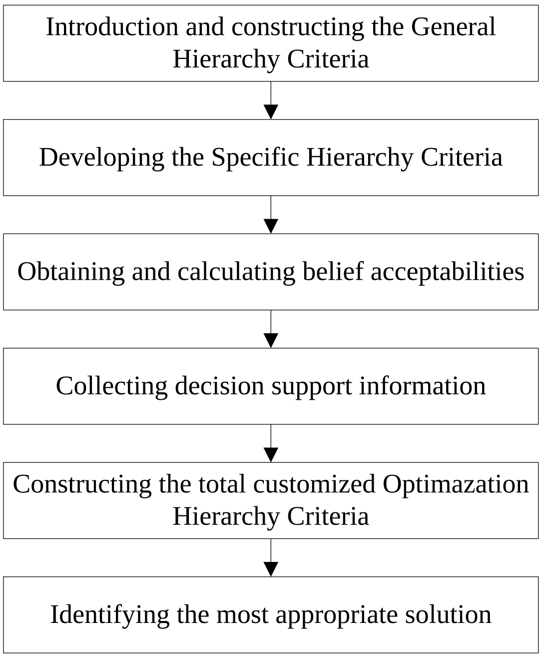


Figure 12: The managerial application process of the proposed model

1) *Introduction & constructing the General Hierarchy Criteria*

   First of all, managers should get to know the whole picture of the proposed methodology shown as Figure 2. At this stage, the managers can apply the GSC-GHC without any modification as it is appropriate for GSC partner selection decision-making environment (shown as Tables 1 to 7).

2) *Developing the Specific Hierarchy Criteria*

   As different industries have different characteristics, the managers could organize a decision-making team to construct a specific hierarchy criteria (GSC-SHC) customized in accordance with the unique characteristics of their industry. The team should ideally consist of industry experts, academics whose research expertise fall in the specific industry, and purchasing managers who have rich knowledge and experience of their suppliers/partners in their specific industry. Then, the team can discuss and construct their own GSC-SHC shown as Figure 5 and Table 8 based on their specialist knowledge and experience of their industry and the GSC-GHC.

3) *Obtaining and calculating belief acceptabilities*

Based on the structure of the GSC-SHC, its belief acceptabilities can be obtained by experts and then calculated by applying the Dempster-Shafer theory. This can be done by asking open questions about the different alternatives/combinations (such as the first column of Table 9 shown) to the decision-making team members. The Delphi method and the Dempster-Shafer theory (shown in Section 4.2) can be used during this step to get a consensus view (such as the second column of Table 9 shown). The participants who will take part in the Delphi method can be chosen in accordance with the requirement and nature of the decision-making. If the decisions are strategic, the numbers and level of participants should be relatively more and higher. In addition, it is also helpful to include participants from outside of the organization (e.g. academics, industry experts and purchasing managers from partner organizations).

4) *Collecting decision support information*

Managers then need to prepare and collect the decision support information, such as the human resources requirements, external and internal financial costs, for each alternatives/combinations (such as the third to fifth columns of Table 9 shown) required for the subsequent optimization step.

5) *Constructing the total customized Optimization Hierarchy Criteria*

By applying both the optimization objectives and resource constraints previously collected, the managers can apply the PSO sub-model (shown in Section 4.3) to construct their own total customized optimization hierarchy criteria for partner selection in GSCs based on the GSC-SHC and its belief acceptabilities for different alternatives/combinations. The managers will thus get the outputs found by the PSO sub-model (such as shown in Tables 10 and 11), which are the non-inferior solutions. Accordingly, the combined evidence, the human resource requirements, and the total financial costs of the GSC-SHC are the two objectives and main constraint of the PSO sub-model, respectively. The PSO sub-model aims to find an optimization solution(s) which has the highest combined evidence and lowest human resource requirements while fulfilling the total financial costs constraint. The potential combinations and their different characteristics for this multi-objective optimization are collected and analysed during steps 3) and 4) discussed above (such as shown in Table 9). During this step, the managers could also compare the different outputs by varying the parameters of the PSO sub-model to find the most appropriate parameters (such as the acceleration constraints c_1 and c_2 shown in Table 12 and Figures 10 and 11).

6) *Identifying the most appropriate solution*

   Lastly, the managers can analysis these non-inferior solutions and make final trade-offs to identify the most suitable solution in accordance with the different preferences and the specific decision-making environment identified in the prior steps. The final output of the above processes is the total customized optimization hierarchy criteria for partner selection in GSCs (GSC-OHC) (such as shown in Figure 9). Managers could then apply the GSC-OHC for potential partners' evaluation and selection by integrating it with other decision-making methods/models, such as AHP/ANP, DEA, and mathematic programming, etc.

7. Conclusion

With changes in public policy making, environmental performance is increasingly important for manufacturers, who are now exploring how best to improve the sustainability of their operations across the whole supply chain (Linton et al. 2007). Accordingly, partner selection has become a crucial issue in GSCM. However, various studies in partner selection in GSCs conclude that there is a gap between partner selection criteria construction theory and practice (e.g. Jayaraman et al. 2007, Singhal and Singhal 2012). This has highlighted the need for a new method for identifying the most appropriate selection criteria to evaluate and select partner selection criteria in the GSC. Such a method needs to be comprehensive through its consideration of a broad range of possible evaluation criteria but also efficient in its use of scarce resources during the criteria selection process (Guide and Van Wassenhove 2006). It must also be flexible in order to cope with different product categories and different decision-making situations. Accordingly, this paper has proposed a three-stage model for the construction of partner selection criteria in GSCs by combining Dempster-Shafer belief acceptability theory and PSO technique. The efficacy of the model is demonstrated by way of an illustrative application in Company ABC, a manufacturer in the Chinese Electronic Equipment & Instruments industry.

The paper makes a number of contributions. Firstly, it offers an advance to current methods used for partner selection in green supply chains by providing a systematic method of constructing appropriate partner selection criteria. This is an essential but often neglected pre-requisite in any partner selection process.

Secondly, the proposed model combines, for the first time, Dempster-Shafer theory and PSO technique within a three-stage model for the construction of GSC partner selection criteria. This model has a number of advantages:

- It enables the inter-dependence between criteria to be considered by applying Dempster-Shafer theory, and enables optimization levels of both effectiveness and efficiency in criteria construction to be achieved simultaneously through the use of PSO technique.
- It enables both operational and strategic attributes to be selected at different levels of hierarchy criteria in different specific decision-making situations and environments.
- It is comprehensive enough to consider a broad range of possible criteria, both qualitative and quantitative, whilst being efficient in its use of scarce resources during the criteria construction process. In other words, it is feasible and practicable in the GSC decision-making environment.
- It is an advance on previous single objective seeking solutions as it provides a multiple objectives seeking solution. This enables the trade-offs between different objectives to be achieved more effectively and practically.

Thirdly, the model incorporates a comprehensive General Hierarchy Criteria list for partner selection in GSCs, based on in-depth analysis of the existing literatures and expert opinion. This offers a sound basis for both future academic research and practical applications.

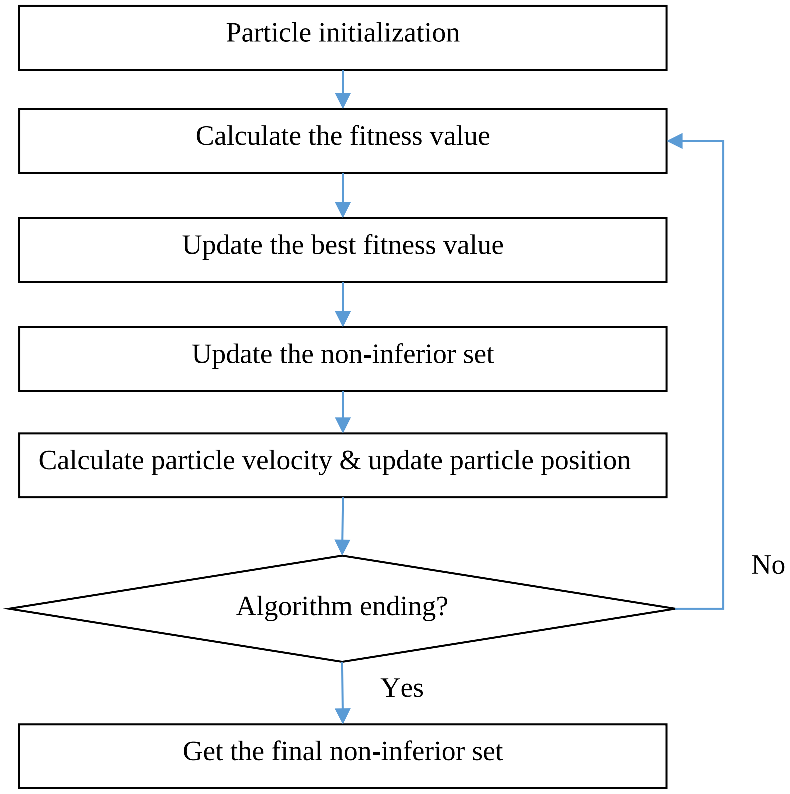
Finally, the paper demonstrates the potential of this approach to be applied in practice, through its application in a real company, Company ABC, a manufacturer in the Chinese Electronic Equipment & Instruments industry.

There are three main disadvantages with the model. Firstly, there are no general standards for coding in PSO technique. So, the coding process may be inaccurate. However, this characteristic also gives enough flexibility to decision-makers to design their own coding in order to accommodate their own specific requirements. Secondly, as a metaheuristic technique, PSO does not guarantee that an optimization solution is ever found within the non-inferior solution set. Therefore, the choice of the most appropriate key parameters becomes more important. The cross analysis of key parameters proposed in the Empirical illustration is one of the good solutions in this respect. Thirdly, in the second stage of framework, the construction of GSC-SHC depends heavily on the subjective judgements of decision-makers when assigning belief acceptabilities to different attributes.

Further work is required to overcome the limitations of the model discussed above. In particular, research could be undertaken to investigate if other methods/models (e.g. DEA, fuzzy set theory, AHP/ANP, etc.) could be beneficially introduced into the stages of the partner selection process for GSCs that follow the three-stage DS-PSO model for the construction of selection criteria. The choices of the most appropriate combinational rules of Dempster-Shafer theory in accordance with specific decision-making contexts is also an important direction for future research. Further research is also required to investigate how to group lower level criteria in order to ensure that PSO technique programming can be undertaken more efficiently.

Appendices

Appendix A: The procedure of the PSO algorithm



Appendix B: The pseudo code of the PSO algorithm

```
For each particle
    Particle initialization
End
Do
    For each particle
        Calculate the fitness value
        If  (The fitness value is better than the best fitness value in the history)
        Then  Set current value as the new pBest
    End
    Choose the particle with the best fitness value of all the particles as the gBest
    For each particle
        Calculate the particle velocity according Equation (7)
        Update the particle position according Equation (8)
    End
Until (the maximum iteration number is not reached or the minimum error condition is not satisfied)
```

Appendix C: An example of combined evidence calculation by applying Dempster’s Rule

Given $M_1\{\{y_{a,1}\},\{y_{a,9}\},\{y_{a,12}\},\{y_{a,17}\},\{y_{a,1}, y_{a,9}, y_{a,12}, y_{a,17}\}\}$

$= (0.15, 0.17, 0.20, 0.13, 0.35)$

$M_2\{\{y_{a,1}\},\{y_{a,9}\},\{y_{a,12}\},\{y_{a,17}\},\{y_{a,1}, y_{a,9}, y_{a,12}, y_{a,17}\}\}$

$= (0.17, 0.19, 0.18, 0.20, 0.26)$

Following the Dempster’s combinational rule, we can get the normalization constant (K) firstly:

$$\mathrm{K} = 1 - \sum_{\mathrm{B} \cap \mathrm{C} \neq \emptyset} \mathrm{M}_1(\mathrm{B}) \times \mathrm{M}_2(\mathrm{C})$$

$$K = 1 - [\mathrm{M}_1(y_{a,1})\times\mathrm{M}_2(y_{a,9}) + \mathrm{M}_1(y_{a,1})\times\mathrm{M}_2(y_{a,12}) + \mathrm{M}_1(y_{a,1})\times\mathrm{M}_2(y_{a,17}) + \mathrm{M}_1(y_{a,9})\times\mathrm{M}_2(y_{a,12}) + \mathrm{M}_1(y_{a,9})\times\mathrm{M}_2(y_{a,17}) + \mathrm{M}_1(y_{a,12})\times\mathrm{M}_2(y_{a,17})]$$

$$= 0.8099$$

By applying the normalization constant (K), then, we can calculate the combined evidence of the candidate criteria $\{y_{a,1}, y_{a,9}, y_{a,12}, y_{a,17}\}$:

$$\mathrm{M}(\mathrm{y}_{a,1}, \mathrm{y}_{a,9}, \mathrm{y}_{a,12}, \mathrm{y}_{a,17}) = \frac{1}{\mathrm{K}} \sum_{\substack{\mathrm{B} \cap \mathrm{C} = \\ \{\mathrm{y}_{a,1}, \mathrm{y}_{a,9}, \mathrm{y}_{a,12}, \mathrm{y}_{a,17}\}}} \mathrm{M}_1(\mathrm{B}) \times \mathrm{M}_2(\mathrm{C})$$

$= 0.112$

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