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Chong Wu
David Barnes

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Chong Wu

School of Management, Xiamen University, Xiamen, 361005 P.R. China

Tel: +86 (0) 592 2180776

Fax: +86 (0) 592 2187289

Email: Chong.Wu@xmu.edu.cn

David Barnes

Westminster Business School, University of Westminster, London, NW1 5LS, U.K.

Tel: +44 (0) 20 7911 5000 Extension: 66531

Fax: +44 (0) 20 7911 5703

Email: D.Barnes@westminster.ac.uk

Corresponding author's contact details:

David Barnes

Email: D.Barnes@westminster.ac.uk

Postal address: Westminster Business School, University of Westminster, London, NW1 5LS, U.K.

Tel: +44 (0) 20 7911 5000 Extension: 66531

Fax: +44 (0) 20 7911 5703

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Abstract: Stricter governmental regulations and rising public awareness of environmental issues are pressurising firms to make their supply chains greener. Partner selection is a critical activity in constructing a green supply chain because the environmental performance of the whole supply chain is significantly affected by all its constituents. The paper presents a model for green partner selection and supply chain construction by combining analytic network process (ANP) and multi-objective programming (MOP) methodologies. The model offers a new way of solving the green partner selection and supply chain construction problem both effectively and efficiently as it enables decision-makers to simultaneously minimize the negative environmental impact of the supply chain whilst maximizing its business performance. The paper also develops an additional decision-making tool in the form of the *environmental difference*, the *business difference* and the *eco-efficiency ratio* which quantify the trade-offs between environmental and business performance. The applicability and practicability of the model is demonstrated in an illustration of its use in the Chinese electrical appliance and equipment manufacturing industry.

Keywords: Partner selection; Green supply chain; ANP; Multi-objective programming

1. Introduction

Prompted by the concept of the triple bottom line (Elkington, 1998), the integration of environmental, economic and social performances to achieve sustainable development has become a major business challenge (Srivastava, 2007; Verghese and Lewis, 2007). In response to stricter governmental regulations and rising public awareness of environmental protection, many firms are now undertaking major initiatives to make their supply chains greener (Zhu et al., 2013; Mirhedayatian et al., 2014).

Partner selection in a green supply chain (GSC) is a critical activity because the environmental performance of the whole supply chain is significantly affected by its constituent partners (Kuo et al., 2010). In order to reap the greatest benefits from environmental management, firms must integrate the performance of all the members of a supply chain if it is to be truly green (van Hoek, 1999). In so doing, they face a trade-off between sustainability and cost when selecting new partners (Reuter et al., 2012).

As environmental awareness increases, firms today seek to purchase products and services from suppliers who can provide them with high quality, low cost, short lead time and high flexibility, whilst at the same time displaying high environmental responsibility (Lee et al., 2009). A green partner is expected not only to achieve environmental compliance but also to undertake green product design and life cycle analysis. Thus, in a GSC, companies need to have rigorous partner selection and performance evaluation processes (Kainuma and Tawara, 2006).

The growing worldwide environmental awareness has seen increasing amounts of research on green partner selection (Sarkis, 2003; Seuring and Muller, 2008; Ng, 2008; Bai and Sarkis, 2010a, Bai and Sarkis, 2010b; Yeh and Chuang, 2011; Govindan et al., 2013a; Kannan et al., 2013). However, existing research generally considers environmental aspects in isolation (Lee et al., 2009). For a company to select the most appropriate partners when constructing a GSC, it has to consider both contemporary environmental issues and traditional economic factors. On the one hand, as companies feel greater pressures to have a greener supply chain they will wish to place emphasis on, and devote resources to green partner selection and development programmes (Bai and Sarkis, 2010a). On the other hand, companies do not want to see their supply chains becoming greener at the expense of poorer business performance. Therefore, they will not wish these green partner selection and development programmes to adversely affect the business performance of the supply chain in terms of cost, quality, customer service and so on.

Furthermore, stricter regulations and directives, such as WEEE (Waste Electrical and Electronic Equipment), RoHS (Restriction of Hazardous Substances), ErP (Energy related Products) and REACH (Registration, Evaluation, Authorisation and

Restriction of Chemicals), require companies and their products to become more eco-friendly, especially in the electronics industries (Hsu and Hu, 2008; Kuo and Chu, 2013). On the one hand, there is increased pressure on such companies to adopt more green practices within their supply chains, including souring, manufacturing and logistics (Chien and Shih, 2007). This includes pressure to ensure that only green partners are selected when constructing their supply chains. On the other hand, there are advantages for companies that are capable of meeting global green production standards, as they will be able to participate in global green supply chains. For example, there are significant opportunities for some high-technology electronic companies in mainland China who wish to sell their products overseas within global supply chains (Zhu and Sarkis, 2006).

In this paper, we propose a comprehensive model for green partner selection and supply chain construction, which combines analytic network process (ANP) and multi-objective programming (MOP) methodologies. The term *partner selection* refers to the process of deciding which firms are to be the constituent members of a supply chain, whereas the term *supply chain construction* refers to the process of organizing the activities of the constituent members of the whole supply chain in order to match supply and demand in any given situation. Its aim is to minimize the environmental negative influence of the supply chain while simultaneously maximizing its business performance.

The rest of the paper is organized as follows. Section 2 reviews the extant research on green supply chain management, green partner selection models and criteria for green partner evaluation and selection. Section 3 introduces the proposed model for green partner selection. Section 4 presents an illustrative application of the model with a sensitivity analysis. In Section 5 some of the issues and implications raised by the use of the proposed model are discussed in more detail. Section 6 closes the paper with some concluding remarks assessing its contribution and limitations, and suggesting future research.

2. Literature review

2.1 Green supply chain management

Research into green supply chain management (GSCM) remains in its infancy, and until recently there has been relatively little published in the leading academic journals (Srivastava, 2007). However, interest in the topic has been growing apace resulting in increased research output (Schoenherr et al., 2012; Govindan et al., 2013b).

2.1.1 Motivations and drivers of GSCM

Testa and Iraldo (2010) summarized three different strategic approaches which are able to favour the adoption of GSCM practices. By using data from over 4000 manufacturing facilities in seven countries, they found that the “reputation-led” and “innovation-led” approaches seem to be the most effective ones for the adoption of GSCM practices, whereas an “efficiency-led” approach is not. One of limitations is that the study only focused on supplier assessment and supplier requirement practices. By using fuzzy DEMATEL methodology, Lin (2013) identified that regulation is the most important cause criterion which influences GSCM. As the cause group criteria have influences on the effect group criteria, managers in GSC need to pay more attention to these cause group criteria. Yet, one of the main limitations of the research is the shortage of respondents when compared with Testa and Iraldo (2010)’s study.

Diabat and Govindan (2011) firstly developed an Interpretive Structural Modelling (ISM) model of drivers of the implementation of GSCM in Indian aluminium industries. The interaction relationships among the 11 types of drivers had been analysed by using the ISM model and MICMAC analysis. Thereafter, Diabat et al. (2014) summarized and analysed the 13 enablers for implementing sustainable supply chain management in Indian textile industries further. By applying similar ISM approach, they found that the adoption of green purchasing enabler occupies the top level. These research findings will be very helpful for easy implementation of effective GSCM if the leading enabler can be identified scientifically in practice.

Based on empirical data from high-tech industry in Taiwan, Lo (2014) analysed the effect of a firm's position in the GSCs on its attitude toward green. The empirical analysis results showed that the further downstream a firm is in the supply chain, the more proactive its attitude toward going green. The further upstream in the supply chain, the more reactive and conservative is its attitude toward going green. These findings indicate that upstream green partner selection will be more important and sensitive compared with downstream partner selection. Furthermore, Mirhedayatian et al. (2014) proposed a novel network data envelopment analysis (DEA) model to evaluate GSC management in the presence of undesirable outputs and fuzzy data. Their findings emphasise that economic and environmental performance in a supply chain are inextricably linked. GSCM should not and cannot improve the environmental performance at the expense of its economic performance.

2.1.2 Performance measures and implementation barriers of GSCM

Based on five case studies from Portuguese automotive industries, Azevedo et al. (2011) found that the most extensively used performance measures are "customer satisfaction", "quality" and "cost". Yet, the enablers and drivers regarding the reasons managers of supply chain do or do not implement GSCM practices were not explored at the beginning of the research. Moreover, applying the empirical results from 249 enterprise respondents in Korea, Kim and Rhee (2012) pointed out that "planning and implementation", "collaboration with partners" and "integration of infrastructure" were dominant antecedent factor in the causal relation between GSCM critical success factors and the balanced scorecard performance. Effective partner selection and collaboration play an important role and result in high GSCM performance.

Dey and Cheffi (2013) proposed a new GSC performance measurement framework by combining supply chain processes with organisational decision levels. Based on the three case studies in manufacturing industries in UK, their research pointed out that internal operations and suppliers activities are the most important factors in environmental performance. In addition, using an intra-organisational collaborative decision-making approach, Bhattacharya et al. (2014) proposed a new GSC performance measurement framework. Based on the empirical investigation into the UK-based carpet manufacturing industries, their research pointed out that internal operations play a key role in assessing the environmental performance of GSCs. More importantly, internal operations were dependent on supplier's activities. Therefore, effective supplier selection is a prerequisite for high environmental performance in GSCs.

In recent research on the implementation barriers of GSCM, Walker and Jones (2012) divided the barriers and enablers of sustainable SCM implementation into external and internal ones. Thereby they proposed a 2 X 2 four quadrant typology of organisational responses to sustainable SCM. This typology is useful for showing how organisations vary in their perceptions of internal and external barriers and enablers. Furthermore, Muduli et al. (2013) pointed out that capacity constraints have a more adverse impact on GSCM practices than other barriers in Indian small scale mining industries. However, their proposed model was based only on four variables which may not adequately represent all barriers to GSCM practices.

Zaabi et al. (2013) analysed the relationship between the barriers of implementing GSCM in the two fastener manufacturing industries in India. Their research classified the 13 barriers they analysed into three categories. This classification will be helpful for managers who wish to evaluate the impacts of different barriers on GSCM implementation in practice. Moreover, based on literature research and industrial expert consultations, Mathiyazhagan et al. (2013) summarized 26 barriers to implementing GSCM in Indian auto component manufacturing industries. Then, they analysed mutual influences amongst the barriers using the ISM approach. The quantitatively analysis results showed that the "supplier barrier" was dominant for the implementation of GSCM. This finding shows that supplier/partner evaluation and selection is one of the most critical factors in the implementation of GSCM.

Through literature research, industrial expert discussions and a survey from various industrial sectors, Govindan et al. (2014) identified 47 barriers under five main categories. By applying AHP approach, their research ranked the 26 essential barriers. As it is not easy to remove all barriers when starting GSCM implementation, ranking the main barriers enables managers in GSCs to give different priorities and appropriate resources to remove and/or relieve the most influential barriers.

In short, from the above literature review we can conclude that supplier/partner selection is both one of the most essential enablers and one of the most essential barriers for the implementation of effective GSCM. Thus, this research will propose a new comprehensive method for green partner selection. The following subsection 2.2 will review the existing literatures on the models/methods for the green partner selection. Subsection 2.3 will then review the criteria used for the green partner evaluation and selection.

2.2 Green partner selection models

Whilst there is a large quantity of literature on supplier evaluation and selection, there is very little that specifically considers supplier evaluation from an environmental perspective (Govindan et al., 2013b). This section now compares the different methods and models that have been applied to green partner selection in recent research. These are summarised in Table 1.

[Insert Table 1 about here.]

Bruno et al. (2012) implemented a model for partner evaluation based on Analytic Hierarchy Process (AHP). They analysed the AHP implementation process which can identify the strengths and weaknesses of using formalized partner selection models. Their research highlighted the potential barriers which prevent firms from adopting partner evaluation methods/models. Kuo et al. (2010) integrated artificial neural network (ANN) and two multi-attribute decision analysis methods (namely ANP and DEA), to evaluate the green performance of suppliers. Lee et al. (2009) proposed a fuzzy AHP model for green partner selection, building their hierarchy criteria by combining six main attributes and twenty three sub-attributes. Their hierarchy criteria are easier for decision-makers to apply, as fewer attributes are included in each of the main attributes, whilst more attributes are located in higher levels. However, their hierarchy is hard to change when adapting to a new decision-making environment. Awasthi et al. (2010) presented a fuzzy multi-criteria approach for evaluating the environmental performance of suppliers. As the decision-making process is relatively insensitive to the criteria weights, the approach has the ability to perform environmental performance assessment of suppliers under partial or insufficient quantitative information. However, because the number of participants involved and their expertise with the subject will influence the decision-making process, their selection needs to be carried out carefully when using this approach.

Bai and Sarkis (2010b) applied grey system and rough set theory to the process of partner selection in GSCs. They proposed an expanded methodology which introduced an additional level of analysis and the explicit consideration of sustainability attributes. The strength of grey system theory integration is that it is capable of combining intangible and subjective decision-making and attributes valuations into the decision process. However, the shortcoming of this model is that the number of attributes used may cause greater difficulty in narrowing sets and possibly result in greater sensitivity over time as decisions become updated. Wu and Barnes (2012) proposed a dynamic feedback model for partner selection in agile supply chains. They divided the whole partner selection process into four interrelated steps. However, the adaption and application of their method for partner selection in green supply chains has not yet been tested. By reviewing the research published from 1997 to 2011, Govindan et al. (2013b) found that the fuzzy based single model approaches are the most commonly applied technique. Whilst the existence of an "environmental management system" is the most commonly applied criterion for green supplier selection. By combining fuzzy multi attribute utility theory and multi-objective programming technologies, Kannan et al. (2013) proposed an integrated approach to rate and select the best green suppliers. Whilst this model can allocate the optimum order quantities among the best green suppliers, the maxi-min method they applied may not result a Pareto-efficient solution. Using rough set theory, Bai and Sarkis (2010a) introduced a formal model to investigate the relationships between organizational attributes, green supplier development programme involvement attributes, and the performance outcomes which focus on environmental and business dimensions. Yet, the sensitivity of the results may arise from the levels selected when discrediting the data.

Each of these approaches has its own particular strengths. However, they are all inadequate in some way when solving the green partner selection problem effectively and efficiently at the same time. Mathematic programming permits managers to model the partner selection problem by using mathematical functions (Wu and Barnes, 2011), given a proper decision environment. However, generally, mathematic programming models only consider quantitative criteria. This may cause a significant decision-making problem if all qualitative factors are ignored. AHP cannot consider uncertainty and risk in estimating a partner's performance effectively (Wu and Barnes, 2009). Furthermore, it also does not take into account the interactions among the various factors (Saaty, 1996). ANP can overcome some of the shortcomings of AHP, but it cannot solve the lot-sizing problem (Wu and Barnes, 2014). Finally, the complexity of both rough set and fuzzy set theories makes it difficult for users to understand the foundations of their outputs (Luo et al., 2009). Therefore, a new method is required if the green partner selection problem is to be solved effectively as well as efficiently.

2.3 Criteria for green partner evaluation and selection

As increasing environmental awareness has favoured the emergence of the GSC, green criteria have been incorporated in the partner selection process. This section reviews and analyses the criteria used in existing literature for green partner selection and supply chain construction. These are summarised in Table 2.

[Insert Table 2 about here.]

Noci (1997) initiated the inclusion of green criteria in supplier evaluation and rating. He constructed hierarchy structural criteria focused on green competencies, current environmental efficiency, supplier's green image and net life cycle cost as its main green concerns. These have become the foundation on which much of the subsequent research has built. Sarkis (2003) advanced Noci (1997)'s work through the application of AHP/ANP methodology. By setting "Improve green supply chain practices" as the goal of his GSC evaluation framework, he identified four primary clusters of supplier selection criteria, namely Product life cycle stage, Operational life cycle, Environmental influential organizational practices and Organizational performance. The importance of this work lies in its expansion of the organizational and operational factors incorporated into the criteria for partner evaluation and selection in the GSC in comparison with previous research. Subsequent to the launch of the EU's Restriction of Hazardous Substances (RoHS) directives of 2003 and 2011, Hsu and Hu (2009) and Kuo and Chu (2013) include the need to ensure hazardous free substances as a supplier selection criterion in the electronics sector. Awasthi et al. (2010) proposed flat criteria for evaluating environmental performance of suppliers. The use of flat structure makes it easier for sensitivity analysis. Bai and Sarkis (2010b) categorized the environmental metrics of supplier selection into environmental practices as well as environmental performance. At the same time, they divided the social metrics in supplier selection into internal and external criteria. By integrating the above four categories, decision-makers could conveniently evaluate potential partners from several angles: internal and/or external, practices and/or performance.

Wu and Barnes (2010) introduced a Dempster-Shafer belief acceptability optimization approach for partner selection criteria formulation. Unlike most of the existing models in this field, it focused on the criteria formulation methodology only by applying the systematic optimization theory. But, its application to GSC has not as yet been demonstrated. Yeh and Chuang (2011) introduced hierarchy criteria for green supplier selection by combining quantitative and qualitative criteria. Yet, these hierarchy criteria could not be used as a whole in evaluating potential suppliers. Only part of them would be selected as the objective criteria while searching the Pareto-optimal solutions under specific conditions. Chen et al. (2012) summarized four types of GSC strategy, and then proposed an ANP approach for selecting them. Based on the internal environment viewpoint, their approach simultaneously considers design, purchasing, manufacturing, and marketing and service of the GSCs. It can be extended to supplier selection decision-making by adding more clusters in the network. Yet, it still cannot solve the lot-sizing problem at plant level. Govindan et al. (2013a) extended the criteria for supplier's evaluation in sustainable supply chains to social, environment and economic criteria based on the triple bottom line approach. In each category, four sub-criteria were selected to evaluate the potential suppliers. For this kind of hierarchy criteria, it is very suitable for pair-wise comparisons when applying the AHP or ANP methodology as the criteria weights assignment method.

In their literature review, Govindan et al. (2013b) reviewed the research on supplier evaluation and selection in GSCs from 1997 to 2011. They report that only one article (i.e. 2.77% of their data set) proposed mathematical programming for the green supplier selection process (e.g. Yeh and Chuang, 2011), which indicates an interesting research gap for further research. More specifically, Yeh and Chuang (2011) proposed an optimum mathematical planning model for green partner selection, which involved four main objectives such as ‘cost’, ‘time’, ‘product quality’, and ‘green appraisal score’. Each of these main objectives also contains their own sub-objectives. Therefore, although this method may appear to have only four objectives in the multi-objective functions, it also seeks to encompass more information and detail in each category.

Based on the above review and the summary in Table 2, it is possible to draw two conclusions with regard to the evaluation criteria used in partner evaluation and selection in GSCs. Firstly, the two main green environmental performance criteria are pollution control (air emission, water waste, hazardous substances, etc.) and resource consumption (energy and non-renewable resources, etc.). Most other criteria can be considered to be sub-criteria of these two fields. Secondly, the two most frequently used business performance evaluation criteria are cost and quality (Noci, 1997; Wu and Barnes, 2011). Consequently, in this study, we will apply these four main criteria as the programming objectives to achieve the optimal solution for both environmental as well as business performance.

In summary, the above literature review has highlighted that the penetration of green issues into the partner selection problem is still quite limited. This is confirmed by the relatively small number of papers published that incorporate green criteria, compared with the huge body of literature covering the topic of partner selection in supply chains more generally (Genovese et al., 2011). Secondly, few of those papers that do investigate green partner selection consider environment factors and business factors simultaneously. Neither do they consider how to balance the pursuit of both environmental and business objectives. Finally, published research tends to focus on either identifying the most appropriate suppliers or on supply chain construction. Rarely does research consider how to tackle these two decisions simultaneously. By doing this, on the one hand, the efficiency of the partner selection and supply chain construction can be improved (Wu and Barnes 2009, 2012). On the other hand, if the two decisions could be made at the same time, the results of both decisions could be mutually corroborated simultaneously. This would avoid the risk of an unsuitable, or even wrong decision, from one decision-making phase being carried forward to the subsequent phase. This would improve decision-making effectiveness. It would also avoid the need to iterate between these two decision-making phases, further improving decision-making efficiency.

The research presented in this paper seeks to address this gap by proposing a new method to solve the green partner selection and supply chain construction problems simultaneously, effectively and efficiently.

3. The ANP-MOP green partner selection and supply chain construction model

The analytic network process–multi-objective programming (ANP-MOP) model proposed in this paper is based on that developed by Wu et al. (2009) and Wu and Barnes (2012) for use in agile supply chains. This method has great flexibility and so can, with suitable adaption, be applied to partner selection in the GSC decision-making context.

The motivations to combine ANP and MOP methodologies to solve the green partner selection problem are two-fold. On the one hand, as argued in section 2, neither of these two methods alone can solve the green partner selection problem effectively and efficiently at the same time. For example, the ANP methodology can express and consider the internal and external relationships between and/or within different evaluation factors very efficiently (Kuo et al., 2010), but it cannot solve the lot-sizing problem. On the other hand, whilst the strong point of the MOP methodology is that it can resolve the lot-sizing problem very effectively (Nepal et al., 2009; Mendoza and Ventura, 2010), but it tends to ignore qualitative factors. However, these two methods are mutually reinforcing, in that the shortcomings of one method can be compensated by the strong points of the other (Wu et al., 2009). Specifically, ANP can consider the complex relationships between and/or within different evaluation factors at different levels, which MOP cannot do (Wu and Barnes, 2011). Yet, MOP has the ability to make an optimal solution for lot-sizing, which ANP cannot do. Therefore, combining them could increase the chances of solving the partner selection and GSC construction problem effectively and efficiently at the same time.

Noci (1997) identified two corporate green strategies. One in which the environmental dimension is considered to be a significant competitive priority and one in which it is considered to be a constraint. In this paper, primarily due to considerations of length, we focus on the first of these strategies in developing our model for partner selection in the GSC.

Our proposed method for partner selection in GSCs effectively and efficiently divides the process into four steps as follows:

3.1 Identification of the ANP network structure and relationships

The first step is to formulate the structure of the analytic network process to express the internal and external relationships between and/or within different evaluation factors. Therefore, the goal is "Construct green supply chain". To fulfil this goal, as per the discussion and summary in Section 2.3, this study applies "pollution control" and "resource consumption" as the environmental evaluation clusters, whilst using "cost" and "quality" as the business evaluation clusters. Accordingly, the structure of the analytic network as depicted in Figure 1 is proposed to express the internal and external relationships.

[Insert Figure 1 about here.]

In the structure of the ANP network, there are four clusters: Cost, Pollution control, Resource consumption and Quality. The definition of each cluster is as follows:

a) Cost cluster (CC). Minimizing cost is always an important issue in any supply chain including a GSC. This study defines the cost cluster as all of the related expenses occurring during product manufacture. More specifically, the three factors within the cost cluster are taken to be production costs, the costs of component disposal and chemical waste treatment costs.

b) Pollution control cluster (PC). The operation of a GSC and the provision of products and services require that pollution control be undertaken. The proposed model seeks to minimize these costs, which arise from the control of air emissions, waste water and solid waste including the hazardous substance management (HSM).

c) Quality cluster (QC). Like any other supply chain, a GSC needs to satisfy customer demands for the highest possible levels of quality in its products and services, whilst operating in an environmentally friendly way. Thus, both production quality and service level have been included as factors in the quality cluster.

d) Resource consumption cluster (RC). The production and transportation of products and services will involve the consumption of many resources. The drive for improved environmental performance requires that resource consumption is minimized. This model considers energy consumption as well as non-renewable resources consumption in the resource consumption cluster.

The construction of the ANP network has at least two advantages. On the one hand, its four clusters contain both economic criteria and business criteria. This structure can effectively avoid the potential biases of only focusing on economic performance while neglecting business performance, or vice versa. On the other hand, the proposed method is not intended to be prescriptive with regard to the evaluation criteria incorporated within it. The ANP network structure is flexible enough to be adjusted to meet the requirements of each specific decision-making environment for any given company. The evaluation criteria could be varied to suit other particular applications in different decision-making situations, thereby extending the choices and freedom of the decision-makers involved.

3.2 Building a supermatrix and finding priorities for different criteria

After confirming the structure and internal relationships of the analytic network process, the next step in the model is to generate the priorities of the different criteria.

This step involves three stages:

i. generating the unweighted supermatrix for green partner selection based on the structure and internal relationships of analytic network process,
ii. calculating the weighted supermatrix in terms of the unweighted supermatrix,
iii. computing the limiting supermatrix in accordance with the weighted supermatrix.

The different criteria can then be obtained from the limiting supermatrix. The generalised form of the unweighted supermatrix based on Figure 1 is shown in Figure 2.

[Insert Figure 2 about here.]

In Figure 2, W represents the individual relationships between different clusters. Zero means there is no interaction between clusters. For instance, $W_{PC,K}^{QC}$ indicates that cluster PC depends on cluster QC. Because there is usually interdependence among clusters in a network, the columns of the unweighted supermatrix usually sum to more than one (Saaty, 1996; Wu et al., 2009). Therefore, the unweighted supermatrix needs to be transformed to make each column of the unweighted supermatrix sum to unity by determining the relative importance of the clusters (Meade and Sarkis, 1999). This transformation process can be done by pairwise comparison (PWC) of the matrix of the row components with respect to the column components. For each column cluster, the entry of each respective eigenvector is multiplied by all the elements in each cluster of that column. At the end of this process, the weighted supermatrix in which the clusters in each column of the supermatrix are weighted is produced. Saaty (1996) proposes a classic method for PWC. In this, the values assigned to the comparisons of the factors are made in the range 1/9 to 9. At one extreme, ‘nine’ denotes one factor is extremely more important than the other. Whereas at the other extreme, ‘one ninth’ denotes one factor is extremely less important than the other. In the middle of ‘nine’ and ‘one ninth’, ‘one’ denotes an equal importance of the two comparison factors. During the PWC, the consistency of each comparison also needs to be checked. In the last of the three stages, the weighted supermatrix will be raised to the power of $2n+1$ to achieve a convergence on the comparatively important weights (n is an arbitrarily large number). In this way, the limiting supermatrix is produced (Saaty, 1996). The final priorities of all criteria can be obtained by normalizing each block of the limiting supermatrix.

3.3 Construction of optimization objectives of the MOP

Figure 3 shows a general structure of a GSC comprising the constituents of suppliers, producers, distribution centres (DCs), and customer zones. For simplicity the model presented in this paper follows this structure.

[Insert Figure 3 about here.]

The notations used in the MOP are shown below.

Notations:

- i is the index for a supplier, $i = 1,2, \dots , I$
- j is the index for a producer, $j = 1,2, \dots , J$
- k is the index for a distribution centre, $k = 1,2, \dots , K$
- m is the index for a customer zone, $m = 1,2, \dots , M$
- r is the index for a raw material, $r = 1,2, \dots , R$
- s is the index for a product, $s = 1,2, \dots , S$

Decision Variables:

- SPQ_{rij} total units of raw material r purchased from supplier i and transport to producer j
- PDQ_{sjk} total units of product s is manufactured and shipped from producer j to DC k
- DCQ_{skm} total units of product s transported from DC k to customer zone m
- SL_{sm} service satisfaction level in customer zone m for product s

Model Parameters:

- PC_{sj} unit production cost of product s manufactured by producer j
- DC_{sj} unit cost of component disposal when product s is manufactured by producer j
- CC_{sj} unit chemical waste treatment cost when product s is manufactured by producer j
- WW_{sj} unit waste water when product s is manufactured by producer j
- SW_{sj} unit solid waste when product s is manufactured by producer j

AEX_{sjk}	unit air emission when product *s* shipped from producer *j* to DC *k*
AEY_{skm}	unit air emission when product *s* shipped from DC *k* to customer zone *m*
EC_{rij}	unit energy consumption when raw material *r* shipped from supplier *i* to producer *j*
NC_{sj}	unit non-renewable resource consumption when product *s* is manufactured by producer *j*
TD_{sm}	total customer demand for product *s* in customer zone *m*
DR	defective rate threshold level of the whole supply chain
DR_{sj}	defective rate of product *s* from producer *j*
MR_{rs}	material requirement rate for one unit product *s* needs the units of material *r*
SCL_{ri}	supplier i^{th} capacity limit to supply material *r*
PCL_{sj}	production capacity limit of producer *j* for product *s*
DCL_{sk}	distribution limit of DC *k* to distribute product *s*
w_p	the different weights of p^{th} main criterion (get from ANP sub-model shown in the section 3.1 and 3.2)

We assume that the objective of the model is to seek optimal solutions for the whole GSC for the following factors:

a) Cost cluster. There are three sub-objectives within the cost cluster. The model seeks to minimize the production cost, component disposal cost and chemical waste treatment cost of GSC. The mathematic expressions are formulated as follows:

i. Production cost. The GSC seeks to minimize the production cost when product *s* is produced by producer *j*.

$$obj_1 = w_1 \times \sum_{s=1}^{S}\sum_{j=1}^{J}[(\sum_{k=1}^{K} PDQ_{sjk}) \times PC_{sj}] \quad (1)$$

ii. Cost of component disposal. The GSC also seeks to minimize the component disposal cost during manufacturing process.

$$obj_2 = w_2 \times \sum_{s=1}^{S}\sum_{j=1}^{J}[(\sum_{k=1}^{K} PDQ_{sjk}) \times DC_{sj}] \quad (2)$$

iii. Chemical waste treatment cost. At the same time, the GSC hopes to minimize the chemical waste treatment cost during manufacturing process.

$$obj_3 = w_3 \times \sum_{s=1}^{S}\sum_{j=1}^{J}[(\sum_{k=1}^{K} PDQ_{sjk}) \times CC_{sj}] \quad (3)$$

b) Pollution control cluster. There are also three sub-objectives within the pollution control cluster. The model seeks to minimize the waste water, the solid waste and the air emission of GSC. The mathematic expressions are formulated as follows:

i. Waste water. The GSC hopes to minimize the waste water when products are produced by producers.

$$obj_4 = w_4 \times \sum_{s=1}^{S}\sum_{j=1}^{J}[(\sum_{k=1}^{K} PDQ_{sjk}) \times WW_{sj}] \quad (4)$$

ii. Solid waste. The GSC seeks to minimize the solid waste including the hazardous substance when products are produced by producers.

$$obj_5 = w_5 \times \sum_{s=1}^{S}\sum_{j=1}^{J}[(\sum_{k=1}^{K} PDQ_{sjk}) \times SW_{sj}] \quad (5)$$

iii. Air emission. The GSC aims to minimize the air emission during the transportation process from producers to distributors, and from distributors to customer zones.

$$obj_6 = w_6 \times [\sum_{s=1}^{S}\sum_{j=1}^{J}\sum_{k=1}^{K}(\mathrm{AEX}_{sjk} \times PDQ_{sjk}) + \sum_{s=1}^{S}\sum_{k=1}^{K}\sum_{m=1}^{M}(AEY_{skm} \times DCQ_{skm})] \quad (6)$$

c) Quality cluster. There are two sub-objectives within the quality cluster. The model seeks to maximize the products quality level and the customer service level of GSC. The mathematic expressions are formulated as follows:

i. Quality level. The GSC wants to maximize the product quality level while minimizing the defective rate for every kind of product and rewards the producers with higher quality performance levels.

$$obj_7 = w_7 \times \sum_{s=1}^{S}\sum_{j=1}^{J}(\frac{\sum_{k=1}^{K} PDQ_{sjk}}{\sum_{j=1}^{J}\sum_{k=1}^{K} PDQ_{sjk}} \times DR_{sj}) \quad (7)$$

ii. Service level. For the any given level of customer demand, this expression maximizes the total service level of the customer zone and rewards the customer zone with higher satisfaction levels.

$$obj_8 = w_8 \times \sum_{s=1}^{S}\sum_{m=1}^{M}(\frac{\sum_{k=1}^{K} DCQ_{skm}}{TD_{sm}}) \quad (8)$$

d) Resource consumption cluster. There are two sub-objectives within the resource consumption cluster. The model seeks to minimize the energy consumption and the non-renewable resources consumption of GSC. The mathematic expressions are formulated as follows:

i. Energy consumption. The GSC seeks to minimise the energy consumption when raw material *r* shipped from supplier *i* to producer *j*.

$$obj_9 = w_9 \times \sum_{r=1}^{R} \sum_{i=1}^{I} \sum_{j=1}^{J} (EC_{rij} \times SPQ_{rij}) \quad (9)$$

ii. Non-renewable resources consumption. The GSC seeks to minimise the Non-renewable resources consumption when products are manufactured.

$$obj_{10} = w_{10} \times \sum_{s=1}^{S} \sum_{j=1}^{J} [(\sum_{k=1}^{K} PDQ_{sjk}) \times NC_{sj}] \quad (10)$$

3.4 Formulation of constraints of the MOP

There are several constraints which need to be taken into account. First of all, as indicated in a Bill of Material (BOM), raw materials have constraints arising from the different demands of different product structures. Secondly, in supplying different raw materials, different suppliers have different capacity limits for different types of raw materials. Thirdly, the producers of finished goods also have capacity limits for the manufacture of different finished goods. Fourthly, because of warehouse and transportation limitations, distribution centres have different throughput limits. Fifthly, if it is assumed that a GSC operates on demand-pull principles, no extra finish goods beyond those required to meet actual customer demand will be produced. Consequently, the total supply within the GSC will be equal to or less than the total demand of customers. Sixthly, it can be assumed that a quality constraint in a GSC will be the requirement for a maximum product defect rate to be an order-qualifying criterion. Seventhly, in order to achieve the highest levels of efficiency and effectiveness in distribution centres, the input quantities of different finished goods should be equal to the outputs quantities of different finished goods. Finally, the decision variables should be all natural numbers in order to avoid any half finished goods.

The constraints can be expressed as follows:

(1) Material balance. If one unit of product s needs MR_{rs} units of raw material r, these constraints can be expressed as:

$$MR_{rs} \times \sum_{k=1}^{K} PDQ_{sjk} = \sum_{i=1}^{I} SPQ_{rij} \qquad \forall \ s, r, j \qquad (11)$$

(2) Supplier's capacity limit. As supplier i can provide up to SCL_{ri} units of raw material r and its order quantities SPQ_{rij} should be equal or less than its capacity, these constraints are:

$$\sum_{j=1}^{J} SPQ_{rij} \le SCL_{ri} \qquad \forall \ r, i \qquad (12)$$

(3) Production capacity limit. As producer j can produce up to PCL_{ij} units of product s and its order quantities PDQ_{sjk} should be equal or less than its capacity, these constraints are:

$$\sum_{k=1}^{K} PDQ_{sjk} \le PCL_{sj} \qquad \forall \ s, j \qquad (13)$$

(4) Distribution centre throughput limit. As DCk can distribute up to DCL_{sk} units of product s and its distribution quantity DCQ_{skm} should be equal or less than its capacity limit, these constraints are:

$$\sum_{m=1}^{M} DCQ_{skm} \le DCL_{sk} \qquad \forall s, k \qquad (14)$$

(5) Total supply and total demand limit. As sum of the assigned order quantities from a DC should meet the customer zone's demand, it can be stated as:

$$\sum_{k=1}^{K} \sum_{m=1}^{M} DCQ_{skm} \le \sum_{m=1}^{M} TD_{sm} \qquad \forall \ s \qquad (15)$$

(6) Defective rate constraints. Since DR is the GSC's maximum acceptable defective rate of all products and DR_{sj} is the defective rate of products s produced in producer j, the quality constraints can be shown as:

$$\sum_{j=1}^{J} \left(\frac{\sum_{k=1}^{K} PDQ_{sjk}}{\sum_{j=1}^{J} \sum_{k=1}^{K} PDQ_{sjk}} \times DR_{sj} \right) \le DR \qquad \forall \ s \qquad (16)$$

(7) Distribution centres constraints. Product input quantity should be equal to product output quantity in a single period.

$$\sum_{j=1}^{J} PDQ_{sjk} = \sum_{m=1}^{M} DCQ_{skm} \qquad \forall \; s, k \qquad (17)$$

(8) Variable constraints.

$$SPQ_{rij} \geq 0 \qquad \forall \; r, i, j \qquad (18)$$

$$PDQ_{sjk} \geq 0 \qquad \forall \; s, j, k \qquad (19)$$

$$DCQ_{skm} \geq 0 \qquad \forall \; s, k, m \qquad (20)$$

The foregoing objectives and constraints are offered by way of example. The model could easily be amended to incorporate more, less or different objectives and/or constraints to cater for different decision-making situations within different GSCs. Therefore, the decision-makers involved get the freedom to set their own objectives and criteria, which makes the application of this model highly flexible in practice.

4. An empirical illustrative application

This section provides an empirical illustrative application of a GSC in the Chinese electrical appliance and equipment manufacturing industries and a case company (Company A) within it. Since many Chinese manufacturers in this sector are OEMs (Original Equipment Manufacturers) and ODMs (own design manufacturers), in order to export more products overseas, the businesses not only need to comply with the environmental policies of the target market, but also need to have their own corporate environmental policies (Lee et al., 2009). Furthermore, the WEEE and RoHS regulations, first published by the European Union in 2003, have impacted on the industries associated with electric and electronic equipment, since incompatible products are barred from the markets of the EU countries. As supply chains in the electrical and electronic industry are consequently under significant pressure to be green, this makes it a most suitable industry for research into GSC management (Kuo and Chu, 2013). Zhu and Sarkis (2006), Chien and Shih (2007), Zhu et al. (2007), Hsu and Hu 2008 and Hsu et al. (2013) have all researched GSC in the electrical and electronic industry, offering a basis for this empirical illustrative application.

Company A designs and manufactures power and distribution transformers, electrical drives and motors on the southeast coast of China. According to its policies, it believes sustainability is a competitive advantage. It seeks to minimize the environmental impact of its products. During its daily operations and supply chain management, it tries to ensure that its manufacturing processes are environmentally friendly and energy-efficient. At the same time, it endeavours to transfer this expertise to its suppliers as well as customers across the supply chains. Furthermore, Company A strives to reduce the use of energy and hazardous materials, optimize the means of transportation, and design recyclable products. All of manufacturing facilities along its supply chain need to comply with ISO 14001 international standards on the management of environmental.

In the first half of the empirical application, based on the decision-making environment faced by Company A, the authors invited senior purchasing managers from Company A to apply the proposed ANP sub-model to a specific decision-making situation. (In other applications, different firms could well have different decision-making processes, involving different numbers and types of managers, representing different units within the firm, such as product quality, environmental engineering/management, supply chain management and so on. Therefore, the numbers and types of managers involved in this phase of the decision-making will be specific to the firm involved.) Next, by using the output from the ANP sub-model, the managers then applied the proposed MOP sub-model to green partner selection and supply chain construction within the same decision-making situation. During the MOP sub-model application, because of the difficulties of defining and measuring all of the environmental parameters (e.g. chemical waste, waste water, air pollution) throughout the whole supply chain, these were considered to be out of the scope of this research. Therefore, this research limits itself in the use of data to illustrate the proposed model (see Tables A1 to A15). Thus, in the application of the MOP sub-model, the research relies on illustrative rather than real-life data. In this illustrative application, we follow the approach of previous researchers in this field, such as Awasthi et al. (2010), Bai and Sarkis (2010a, 2010b), Yeh and Chuang (2011) and Govindan et al. (2013a).

To illustrate the application of the proposed model, this paper adopts a generic GSC structure comprising four stages in total: suppliers, producers, distribution centres and customer zones. It is assumed that each stage of the supply chain has several potential partners (I = 4, J = 3, K = 2, M = 4). It is further assumed that to fulfil the demands of the customer zones, the GSC needs to purchase four different raw materials (R = 4) to manufacture two types of products (S = 2), whilst achieving both environmental and business objectives. The structure of GSC before the proposed model is applied is shown in Figure 4.

[Insert Figure 4 about here.]

In this research, we utilised *Super Decision*® (Version 2.0.8) as well as *LINGO*® (Version 11.0) as the decision-making software. The illustrative parameters are shown in the Appendix. Tables A1, A2 and A3 represent the unit production cost, component disposal cost, and unit chemical waste treatment cost respectively for different types of products manufactured by different producers. Similarly, the unit waste water and unit solid waste when different types of products manufactured by different producers are shown in Tables A4 and Table A5. Tables A6 and A7 describe the unit of air emission when finished goods are shipped from producers to DCs, and from DCs to customer zones respectively. The unit energy consumption during the supply of different kinds of raw materials from different suppliers to different producers is shown in Table A8. Table A9 shows the unit non-renewable resource consumption for different types of products manufactured by different producers. Total customer demand for the different products in different customer zones is shown in Table A10. Table A11 describes the defect rates for different types of products manufactured by different producers. The BOM table is shown in Table A12. The capabilities limit for suppliers, producers and DCs are shown in Tables A13-A15 respectively.

4.1 Calculating criteria priorities

The first phase to solve the whole problem is to obtain the priorities of different criteria. This research invited a total of five experts to use their professional experience on partner selection in GSCs. Three of them are senior purchasing managers from the case company. The other two are senior academic researchers in operations management from universities in the UK and China. Following the three sub-steps proposed in sections 3.1 and 3.2, these experts were asked to do PWC of the factors with the relationships shown in Figure 1. By using *Super Decision*, the consistency of each comparison is also checked automatically during this stage. The resultant unweighted supermatrix is shown in Table 3. In the next stage, the unweighted supermatrix is multiplied by the priority weights which are calculated for the cluster by using the experts' opinions. Finally, by powering the weighted supermatrix to $(2n+1)^{th}$, the limiting supermatrix which has the limiting priorities is obtained as shown in Table 4. From Table 4, the priorities of the criteria are: w_p = (0.10003, 0.01950, 0.03163, 0.03707, 0.06621, 0.21978, 0.25959, 0.20744, 0.04809, 0.01066). The result of the calculation of criteria priorities in this empirical illustrative application shows that during its partner selection decision-making process, Company A sets 'Quality level' as its first priority in business performance while setting 'Air emission' as its first priority in environmental performance. As a high-end electrical products provider, Company A puts product quality as its highest priority. Thus, 'Quality level' is its first priority in the business performance category. Similarly, 'Air emission' is its first priority in the environmental performance category due to its main customer market (EU countries) governments' strict regulations on air emission (e.g. European Union Emission Trading System, European Union Aviation Emission Scheme, etc.). In the next phase, these criteria priorities will be used as the input for green supply chain construction and lot-sizing.

[Insert Tables 3 to 5 about here.]

4.2 Green supply chain construction and lot-sizing

During the GSC construction and lot-sizing phase, the structure of the GSC and lot-sizing problem can be solved with the priorities of the criteria obtained in section 4.1. This sub-problem can be solved efficiently by applying the MOP model proposed in sections 3.4 and 3.5. This study programs the programming objectives (Equation 1 - 10) and constraints (Equation 11- 20) within the *LINGO*. After running the programme, the results are shown in Table 5 and 6.

[Insert Tables 5 and 6 about here.]

In Figure 5, depicts diagrammatically depicts the detailed lot-sizing information after the application of the MOP model.

[Insert Figures 5 about here.]

As per the results shown in the respective Tables and in Figure 5, the structure of GSC is now determined. The lot-sizing problem is also solved whilst simultaneously minimizing the environmental impact and maximizing business performance.

4.3 Sensitivity analysis

The purpose of a sensitivity analysis is to examine the effect of specified parameters on the final results (Chen et al., 2012). This research increases and decreases the customer demand of product s_1 and s_2 by 5% – 15%, respectively. The results of the MOP sub-model optimization are shown in Table 7 and 8.

[Insert Tables 7 and 8 about here.]

a) From Table 7 and 8 we can see that the MOP sub-model proposed in this research is insensitive to customer demand, achieving the optimal results irrespective of different levels of customer demand for different products. Figure 6 to Figure 8 show the figures in Table 7 and 8 in a more institutive way.

[Insert Figure 6 to 8 about here.]

b) Figure 6 shows the total numbers of product s_1 and s_2 produced, with total customer demand of product s_1 and s_2 varying, respectively. There is a supply gap after the customer demand exceeds the normal customer demand level. This is because there are several constraints on raw materials supply capability of suppliers, production capability of producers, and shipment capability of DCs. This also shows that the supply capability of the supply chain matches customer demand well currently. To meet this supply and capability gap, the supply chain needs to improve its raw materials supply capability, production capability and shipment capability, if the customer demand level is to exceed the normal demand level.

c) The cost structure is different with different customer demand levels. As the demand for product s_1 increases, the environmental related objectives decreases, whilst the business related objectives increase, until the point when raw material resources supply capability and manufacturing capability reach their maximum utilization (see Figure 7).

d) As the demand for product s_2 increases, the environmental related objectives increases, whilst the business related objectives decrease, until the raw material resources supply capability and manufacturing capability reach their maximum utilization (see Figure 7).

e) The reasons for these results can be deduced as follows. Firstly, different material requirement rate of each unit product (shown in Table A12). This is because different material requirement rates result in different energy consumption during the supply of raw materials from suppliers to producers. Secondly, there are different unit non-renewable resources consumption rates during different kinds of product manufacturing in different producers. Finally, there are different air emission levels for different kinds of products during their shipment from DCs to customer zones.

f) As customer demand and the supply chain's supply increase, the quality level of product improves whilst the defect rate decreases. This improvement is thanks to the benefits of economies of scale as the volumes of both demand and supply increases. Learning curves also demonstrates the same effect (shown in the Figure 8).

g) Since the subjective evaluation of the decision-makers in the ANP sub-model will affect the optimal solution, Table 9 shows the sensitivity analysis on the different weighting methods. There are three optimal solutions achieved by using different weighting methods. The first column is the optimal solution obtained by using the ANP sub-model this paper proposed. The second column is the optimal solution obtained by treating all criteria equally. The last column is the optimal solution obtained by using the weighting information from a senior purchasing manager in

Company A. This manager did not apply any systematic method but rather depended entirely on their working experience. The w_p' = (0.3, 0.05, 0.05, 0.08, 0.12, 0.07, 0.13, 0.1, 0.04, 0.06).

[Insert Table 9 about here.]

i) From Table 9 we can see that, first of all, the MOP sub-model this paper proposed has high robustness. It can reach optimal solutions under different decision-making contexts. Secondly, in comparison with the last two optimal solutions, the proposed ANP-MOP model solution (column one) takes advantage of the PC, QC and RC clusters. In other words, the ANP-MOP model is more capable of balancing the economic and environment objectives during the decision-making process. Last but not least, by comparing the last two columns, we can see that the third column optimal solution is better than the second column optimal solution. This result shows that it is necessary to treat different criteria/objectives differently in accordance with specific decision-making contexts to achieve a better solution.

j) If the assumption on *I*, *J*, *K*, *M* changes, it means that the decision-making circumstance is changed. The following sensitivity analysis plans to see if the proposed model can handle these changes for different decision-making circumstances. In this part, the research makes a new assumption on J = 2, while keeping *I*, *K*, *M* unchanged. This means that the number of qualified producers is reduced to two only (for instance, j_3 is removed from the decision-making circumstance and the production capacity of j_3 transferred to j_1 and j_2 equally). The optimal results under the new assumption of decision-making circumstance are shown in Table 10 and Figure 9. From Table 10 and Figure 9 we can see that the proposed model can handle the new decision-making circumstance with different combinations well and give the optimal results for decision-makers. In more detail, on the one hand, as the number of producers decreases from three to two, the effects of economies of scale on manufacturing and shipment take effect. The total cost of production and the total energy consumption of shipment are all decreased under the new decision-making circumstance. On the other hand, as the removed producer j_3 has better quality control performance (see Table A11), the quality level of the two products is lower under the new decision-making circumstance. In this way, decision-makers could compare different optimal results under different decision-making circumstances. This also gives the decision-makers enough rooms and opportunities to compare different solutions with respect to each possible combination.

[Insert Table 10 and Figure 9 about here.]

In short, from Tables 7 to 10, Figures 6 to 9, and the above analyses a) to j), we can conclude that the proposed model is insensitive to the change of decision-making circumstance, for instance the different customer demand and the different combinations of potential partners in GSC. In addition, by applying a sensitivity analysis, decision-makers can also make such a comparison and hence find the optimal GSC structure as well as the optimal operations capabilities to match the changing customer demand.

5. Discussion

5.1 The environmental differences, business differences and eco-efficiency ratio

From the empirical illustrative example presented in Section 4, it is clear that the model enables both environmental and business objectives to be considered at the same time. Such a trade-off is essential when constructing a GSC in today's competitive business environments. A GSC must focus on both business objectives, such as production costs, quality, service levels etc., and also on environmental objectives, such as air emissions, water waste, energy consumption etc. However, the latter should not be achieved at the expense of the former. Therefore, this section will explore the relationship of these two objectives in the proposed model in more detail.

To do this, we simulate three different decision-making scenarios by way of illustration. These scenarios are (1) only environmental objectives are considered, (2) both environmental and business objectives are considered, and (3) only business objectives are considered. In more detail, scenario (1) only tries to optimise the environmental objectives/criteria when searching for the optimal solution. On the other hand, scenario (3) only tries to optimise the business objectives/criteria when searching for the optimal solution. However, scenario (2) tries to balance the environmental and business objectives/criteria simultaneously as the proposed ANP-MOP model did. As the business goal changes, so the results of whole environmental objectives under these three scenarios will vary. In general, the results of whole environmental objectives of scenario (1) will be greater than those in scenario (2), and those in scenario (2) will be greater than those in scenario (3).

The optimal objectives under the three different decision-making scenarios are shown in Table 11. From this, we can see that if we consider only environmental objectives (*scenario 1*), the results of whole environmental objectives sum up to 8,828,140. If both environmental and business objectives are considered, as in Section 4 (*scenario 2*), the results of whole environmental objectives sum to 8,826,640. Finally, If only business objectives are considered (*scenario 3*), the results of whole environmental objectives sum up to 11,072,670. These are illustrated graphically in Figure 10.

[Insert Table 11 and Figure 10 about here.]

In practice, any number of different scenarios could be considered, each based on different business goals and competitive pressures (for example tighter legal environmental requirements). In each case there will be different optimal solutions. The model enables the outcomes of the different scenarios to be compared. For instance, in the illustration above, the difference between the optimal results of scenarios 1 and 2 is 1,500. This figure represents the loss in environmental performance that would result if the decision-makers considered only business objectives. This might be termed the "*environmental difference*". In contrast, the difference between the optimal results of scenarios 3 and 2 in the above illustration is 2,246,030. This figure represents the level of effort needed if the decision-makers want to optimize environmental outcomes as well as business performance. This might be termed the "*business difference*". The ratio of the *environmental difference* to the *business difference* can be defined as *eco-efficiency ratio*

$$Eco\text{-}efficiency\ ratio = \frac{Environmental\ difference}{Business\ difference} \tag{21}$$

The bigger the *eco-efficiency ratio*, the more efficient the GSC is in achieving environmental performance improvements. If the *eco-efficiency ratio* is greater than one, every one unit of economic expense on environmental improvement generates more than one unit of environmental performance improvement in return. However, if the *eco-efficiency ratio* is smaller than one, much more resource will need to be expended in order to achieve environmental performance improvements. In the above illustration, the GSC has an *eco-efficiency ratio* of 0.00067; much smaller than one. Under the assumptions made in this case, there seems to be little internal incentive within the supply chain to seek improvements in environmental performance. In this situation, which is one currently faced by most developing countries, stricter government laws are likely to be necessary to promote improved environmental performance and change the current trends of sacrificing the environment for short-sighted economic development.

Eco-efficiency first emerged from the 1990s as a measure of the efficiency with which ecological resources are used to meet human requirements (Mickwitz et al., 2006). Huppes and Ishikawa (2005) defined eco-efficiency by the idea of ‘frontier’. Their research proposed a methodology to assess the ‘frontier’ and the trade-offs between costs and a single environmental impact factor. This pioneering research was one of the first approaches to quantitatively assess the trade-offs between business and environment, and to explore the idea of an efficient ‘frontier’. Using the extended DEA approach, Hua et al. (2007) also proposed an ecological efficiency indicator/method which considers undesirable output, biochemical oxygen demand in their research, and a non-discretionary input, emission quota in their research, simultaneously. Furthermore, Neto et al. (2009) developed a methodology to explore Pareto-optimal solutions for business and the environment. They also proposed a concept of eco-topology to assess the trade-offs between profitability and environmental impacts. One shortcoming of the model is that it focuses only on a single organization or firm. Thus, it is not suitable for assessing the green supply chain as a whole.

In short, most of the current approaches to defining eco-efficiency are based on ratios of some kind of business criteria, such as transportation cost, and some environmental impacts, such as energy use or waste, individually. To the best of our knowledge, no other method proposes the use of eco-efficiency, the ratio of business and environmental performance, as a measure of environmental impact for the whole supply chain. The *eco-efficiency ratio*, as defined in this research, assesses the environmental performance of the whole supply chain. It thus has the advantage of enabling a holistic optimal solution rather than several local optimal solutions.

Furthermore, any change to the *eco-efficiency ratio* would create a new decision-making situation. Such a change could result from actions taken both inside and outside of the supply chain. Internally, for example, technological advances might provide opportunities to increase energy efficiency or to reduce the cost of chemical waste treatment. Externally, for instance, stricter government legislation could increase the costs to creators of air emission, waste water and solid wastes. In summary, the proposed model and particularly its use of the concepts of the *environmental difference*, the *business difference* and the *eco-efficiency ratio*, offer decision-makers within a GSC the means of examining the trade-offs between economic and environmental performance in the context of their specific competitive environment.

5.2 The ANP-MOP green partner selection and supply chain construction model

The ANP-MOP green partner selection and supply chain construction model proposed in this research has the following characteristics:

1) It is designed specifically for green partner selection and supply chain construction, enabling an in-depth analysis to be conducted within the green decision-making environment. Supply chain managers can apply it directly without further adjustment to fit the GSC decision-making environment. As such it is an advance on other existing partner selection models/methodologies which are designed only for more general decision-making situations (for example, Humphrey et al., 2007; and Ng, 2008). Whilst the proposed model designs for green partner selection and supply chain construction, but it does not focus only on green related criteria. Rather it considers both green and business criteria at the same time. This is an advance on other existing models/methodologies for green

partner selection and supply chain construction, such as the models/methodologies proposed by Noci (1996) and Awasthi et al. (2010). This characteristic overcomes the limitations of models which only pay attention to green related objectives whilst neglecting traditional business attributes. For instance, in the fuzzy multi-criteria model presented by Awasthi et al. (2010) for evaluating suppliers, there are only twelve environmental criteria in total. However, in the ANP-MOP green partner selection and supply chain construction model proposed in this research, four clusters which contain both green and business criteria were constructed. This not only represents an advances in research on green partner selection and supply chain construction but also a means of improving efficiency and effectiveness in GSC business practice.

2) The proposed model's use of ANP methodology enables a good balance between both green and business criteria to be achieved when selecting potential green partners. Based on the inputs of professional experts, the proposed ANP sub-model enables differential consideration to be given to the different clusters of criteria (Saaty, 1996; Kuo et al., 2010). This is an advance on existing models such as the optimum mathematical planning model for partner selection in GSCs proposed by Yeh and Chuang (2011), in which four main objectives are treated equally. In contrast, the proposed ANP sub-model can balance the different green criteria and business criteria more reasonably and efficiently.

3) The proposed model introduces new and potentially very important performance indicators in the form of the *environmental difference*, the *business difference* and the *eco-efficiency ratio.* These can help decision-makers in GSCs to quantify the trade-offs between environmental and business performance. They also have the potential for use by national and local policy makers and legislators to help formulate and adjust environmental regulations for businesses as well as providing guidance to specific industrial development (Walton et al., 1998). For instance, in the electrical industry, as highlighted by the results of the empirical illustrative application in this paper, the *eco-efficiency ratio* is relatively low. Therefore, the internal incentive within the industry to achieve a more green supply chain is limited. This would offer explain, at least in part, why environmental regulations

and restrictions for this industry have been made stricter (e.g. with the introduction of WEEE and RoHS).

4) Compared to existing research such as Lee et al. (2009)'s fuzzy AHP partner selection model and Chen et al. (2012)'s GSC strategy-selection model, the proposed ANP-MOP green partner selection and supply chain construction model can achieve the goal of partner selection and supply chain construction simultaneously. Thereby, the efficiency of decision-making of partner selection in GSCs can be improved significantly. For example, by applying Lee et al. (2009)'s fuzzy AHP partner selection model, managers in GSCs would only be able to identify the best potential partners. To complete the supply chain construction and lot-sizing problem, the managers would also have to apply other managerial tools and/or models. However, the ANP-MOP green partner selection and supply chain construction model proposed in this research can accomplish the above two tasks simultaneously. Thus, the proposed model can enable decision-makers in real practice to identify the most suitable potential partners and construct the optimal GSC structure at the same time.

5) The proposed model is effective and efficient for green partner selection and supply chain construction. On the one hand, as the illustrative application and the sensitivity analysis show, the proposed model is designed to solve the green partner selection and supply chain construction simultaneously, thereby improving the efficiency of partner selection and supply chain construction (Wu and Barnes 2009, 2012). On the other hand, the results of the two decisions can be mutually corroborated if they are made at the same phase. If we separated these decisions into different phase, if inappropriate or even wrong decisions on the previous phase were made, it would transfer to the following decision-making phase, which is bound to reduce the effectiveness of the whole decision-making process. Furthermore, finding problems in the second decision-making phase would prompt the need to return to the previous phase, thereby affecting the efficiency of decision-making overall.

6) The numbers of objectives/criteria and constraints in the proposed model are flexible. Firms wishing to adopt the proposed model could select their own

objectives/criteria and constraints to suit their own decision-making circumstances and demands. The choices of how many and which objectives/criteria and constraints to use rely both on firms' preferences and judgement on their competitiveness and the decision-making data/information availability. Thus, they can decide to remove or add objectives/criteria and constraints as they deem appropriate. According to the conceptual model proposed by Wu and Barnes (2012), building a set of customized criteria is a prerequisite step in partner selection and lot-sizing decision-making. Managers in GSCs could apply systematic methods (e.g. Lin and Chen, 2004; Wu and Barnes, 2010) to construct their own optimal customized criteria before final selection decision-making.

6. Conclusions

In presenting a model for green partner selection and supply chain construction, this paper makes the following contributions: Firstly, the proposed model can enable organisational decision-makers to simultaneously meet the highly desirable objectives of both minimizing the negative environmental impact of the supply chain whilst maximizing business performance. This is an advance on existing methods, which do not offer this capability. Secondly, the proposed model can achieve the goal of partner selection and supply chain construction (i.e. the lot-sizing problem) simultaneously. Thereby, managers of GSCs can identify the most suitable potential partners and construct the optimal GSC structure at the same time. The results of these two decisions can be mutually corroborated if they are made during the same phase of decision-making. Thirdly, the proposed model combines two established techniques, namely analytic network process (ANP) and multi-objective programming (MOP) methodologies, to a new context, namely that of meeting environmental goals in business. Whilst the use of a model based on a combination of ANP and MOP for supply chain partner selection is not new (Wu *et al.,* 2009), this is the first time that such a model has been applied to the green partner selection and supply chain construction problem. As such, this represents an advance on existing approaches, as it offers a new way of solving the green partner selection and supply chain construction problem effectively and efficiently. Fourthly, through the extension of the proposed model to develop the concepts of the *environmental difference*, the *business difference* and the e*co-efficiency ratio*, the paper provides an additional tool for decision-makers to quantify the trade-offs between environmental and business performance. Furthermore, the *eco-efficiency ratio* could also be used by government and other regulatory bodies to help them to adjust the intensity of their environmental regulations in order to improve the environmental performance of specific industries. Last but not least, the paper makes an additional contribution through the use of the ANP sub-model, which can balance the different green criteria and business criteria more reasonably and efficiently. This is an advance on existing models, such as the optimum mathematical planning model for partner selection in GSCs, in which main objectives are treated equally.

It is possible to identify some shortcomings in the proposed model. Firstly, it does not consider the uncertainty both of costs and customer demand. This could lead to lower sensitivity in decision-making in its application in high uncertainty environments. Secondly, the complexity and number of PWCs required increases markedly as the numbers of factors and clusters increases. Therefore, formulating and selecting the most suitable number of factors and clusters becomes a problem that needs to be tackled in the first instance (Wu and Barnes, 2010). Thirdly, using the weights to combine the different objectives is one of the features of this multi-objective decision-making problem. Comparing with other non-weights combination methods, such as AHP, ANP, and ANN, the MOP sub-model is a single objective problem in nature. This is also one of the reasons why this research includes ANP at the first stage to minimize this limitation. Fourthly, because the measurement and quantification of environmental influence along the supply chain it is out of the scope of this paper, only illustrative data rather than real data were used in the MOP sub-model illustration. Furthermore, due to space limitations, this research does not provide a more complex illustration application example. Doing so, could be one of the directions for future research. Finally, applying ANP methodology requires a significant input of resources and the participation of relevant experts, especially when there is a large number of PWCs to undertake. This makes the proposed model more suitable for strategic decisions. However, as MOP methodology has enough flexibility, more frequent lot-sizing decision-making can be easily undertaken by the proposed model.

Most research in this field, including that presented in this paper, evaluates suppliers only from the buyer's perspective (Li et al., 2009; Ho et al., 2010). Further research is required to provide the flexibility to incorporate the perspective of the supplier in the application of the model. This would provide additional insights to help identify the attributes that suppliers need to focus on in order to become preferred suppliers (Bai and Sarkis, 2010b). Additionally, more research could be undertaken in order to incorporate a consideration of the environment in which decision-making takes place. Finally, the research on the *eco-efficiency ratio* as presented in this paper is just in its infancy. Further development and application of the *eco-efficiency ratio* is a key direction for future research.

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Tables

Table 1: Models/methods for green partner selection in selected papers

Model types	Authors/Years	Structures of criteria	Types of criteria	Criteria aggregation	Assignment of weights
Analytic hierarchical process	Bruno et al. (2012)	Hierarchy	Qualitative and Quantitative	Linear aggregation	Pair-wise comparison
ANN & ANP/DEA	Kuo et al. (2010)	Hierarchy	Quantitative	Neural network generation	Analytic network process
Delphi & fuzzy set theory	Lee et al. (2009)	Hierarchy	Qualitative	Fuzzy set algorithm	Fuzzy comparison
Fuzzy set theory	Awasthi et al. (2010)	Flat	Qualitative	Fuzzy set algorithm	Fuzzy favourability
Grey system & rough set theory	Bai and Sarkis (2010b)	Hierarchy	Qualitative	Rough set algorithm	Fuzzy comparison
Mathematic programming	Kannan et al. (2013)	Hierarchy	Qualitative and Quantitative	Maxi-min method	Pair-wise comparison
Rough set theory	Bai and Sarkis (2010a)	Flat	Qualitative and Quantitative	Rough set algorithm	No weights consideration
ANP-MOP	Proposed approach	Hierarchy	Qualitative and Quantitative	Multi-objective programming	Pair-wise comparison

Table 2: Criteria for green partner selection in selected papers

Authors/ Years	Green Criteria	Sub criteria
Noci (1997)	Green competencies Current environmental efficiency Supplier's green image Net life cycle cost	1) Availability of clean technologies; 2) Type of materials used in the supplied component; 3) Capacity to respond in time; 4) Air emissions; 5) Solid wastes; 6) Waste water; 7) Energy consumption; 8) Customers' purchase retention; 9) Market share related to green customers; 10) cost of the supplied component; 11) Cost for component disposal; 12) Investments aimed at improving the supplier's environment performance
Sarkis (2003)	Operational life cycle Organizational performance criteria Environment influential organization practices Product life cycle stages	1) Procurement; 2) Production; 3) Distribution; 4) Reverse logistics; 5) Packaging; 6) Time; 7) Quality; 8) Cost; 9) Flexibility; 10) Reduce; 11) Recycle; 12) Remanufacture; 13) Reuse; 14) Disposal; 15) Introduction; 16) Growth; 17) Maturity; 18) Decline
Hsu and Hu (2009)	Procurement management R&D management Process management Incoming quality control Management system	1) Requirement of green purchasing 2) Green materials coding and recording 3) Inventory of substitute material 4) Supplier management 5) Capability of green design 6) Inventory of hazardous substances 7) Legal-compliance competency 8) Management for hazardous substances 9) Prevention of mixed material 10) Process auditing 11) Pre-shipment inspection 12) Warehouse management 13) Standard for incoming quality control 14) Test equipment 15) Record of incoming quality control 16) Quality management system 17) Environmental management system 18) Hazardous substance management system 19) Information systems
Awasthi et al. (2010)	Flat criteria structure	1) Use of environment friendly technology 2) Use of environment friendly materials 3) Green market share 4) Partnership with green organizations 5) Management commitment 6) Adherence to environmental policies 7) Green R & D projects 8) Staff Training 9) Lean process planning 10) Design for environment 11) Environmental certification 12) Pollution control initiatives
Bai and Sarkis (2010b)	Env. practices Env. performance Internal social criteria External social criteria	1) Pollution controls 2) Pollution prevention 3) Environmental management system 4) Resource consumption 5) Pollution production 6) Employment practices 7) Health and safety 8) Local communities influence 9) Contractual stakeholders influence 10) Other stakeholders influence
Chen et al. (2012)	Green design Green manufacturing Green purchasing Green marketing and service	1) Abstaining from utilizing toxic substances 2) Complying with DfDRR principles 3) Increasing innovation capabilities 4) Saving energy 5) Green image 6) Green competencies 7) Green management abilities 8) The amount of energy and/or resource utilization 9) Green degree of energy 10) The amount of hazardous waste 11) The number of reuses of hazardous waste 12) Make good use of ICT tools 13) Disclose environmental information of products and services 14) Apply EPR 15) Risk-based strategy 16) Efficiency-based strategy 17) Innovation-based strategy 18) Closed-loop strategy
Govindan et al. (2013a)	Economic criteria Environmental criteria Social criteria	1) Cost 2) Delivery reliability 3) Quality 4) Technology capability 5) Pollution production 6) Resource consumption 7) Eco-design 8) Environment management system 9) Employment practices 10) Health and safety 11) Local communities influence 12) Contractual stakeholders influence

Table 3: Unweighted supermatrix of ANP

	CGSC	Production cost	Component disposal cost	Chemical waste treatment cost	Waste water	Solid waste	Air emission	Quality level	Service level	Energy consumption	Non-renewable resources consumption
CGSC	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Production cost	0.56954	0.63010	0.63698	0.63010	0.68334	0.55842	0.72858	0.63010	0.70886	0.61441	0.68698
Component disposal cost	0.09739	0.15146	0.10473	0.15146	0.11685	0.12195	0.10884	0.15146	0.11252	0.11722	0.12654
Chemical waste treatment cost	0.33307	0.21844	0.25829	0.21844	0.19981	0.31963	0.16258	0.21844	0.17862	0.26837	0.18648
Waste water	0.08807	0.00000	0.00000	0.00000	0.09140	0.13650	0.07824	0.13650	0.10203	0.00000	0.00000
Solid waste	0.19469	0.00000	0.00000	0.00000	0.21765	0.23849	0.17135	0.23849	0.17212	0.00000	0.00000
Air emission	0.71723	0.00000	0.00000	0.00000	0.69096	0.62501	0.75040	0.62501	0.72585	0.00000	0.00000
Quality level	0.66667	0.66667	0.24998	0.33333	0.66667	0.33333	0.66667	0.33333	0.66667	0.66667	0.33333
Service level	0.33333	0.33333	0.75002	0.66667	0.33333	0.66667	0.33333	0.66667	0.33333	0.33333	0.66667
Energy consumption	0.80000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.80000	0.83333	0.83333	0.80000
Non-renewable resources consumption	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.20000	0.16667	0.16667	0.20000

Table 4: Limiting supermatrix of ANP

	CGSC	Production cost	Component disposal cost	Chemical waste treatment cost	Waste water	Solid waste	Air emission	Quality level	Service level	Energy consumption	Non-renewable resources consumption
CGSC	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Production cost	0.10003	0.10003	0.10003	0.10003	0.10003	0.10003	0.10003	0.10003	0.10003	0.10003	0.10003
Component disposal cost	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950
Chemical waste treatment cost	0.03163	0.03163	0.03163	0.03163	0.03163	0.03163	0.03163	0.03163	0.03163	0.03163	0.03163
Waste water	0.03707	0.03707	0.03707	0.03707	0.03707	0.03707	0.03707	0.03707	0.03707	0.03707	0.03707
Solid waste	0.06621	0.06621	0.06621	0.06621	0.06621	0.06621	0.06621	0.06621	0.06621	0.06621	0.06621
Air emission	0.21978	0.21978	0.21978	0.21978	0.21978	0.21978	0.21978	0.21978	0.21978	0.21978	0.21978
Quality level	0.25959	0.25959	0.25959	0.25959	0.25959	0.25959	0.25959	0.25959	0.25959	0.25959	0.25959
Service level	0.20744	0.20744	0.20744	0.20744	0.20744	0.20744	0.20744	0.20744	0.20744	0.20744	0.20744
Energy consumption	0.04809	0.04809	0.04809	0.04809	0.04809	0.04809	0.04809	0.04809	0.04809	0.04809	0.04809
Non-renewable resources consumption	0.01066	0.01066	0.01066	0.01066	0.01066	0.01066	0.01066	0.01066	0.01066	0.01066	0.01066

Table 5: The optimal objectives achieved in GSC construction

Sub-objectives	Detail description	Performance
Obj_1	Total production cost	1,824,600
Obj_2	Total cost of component disposal	508,850
Obj_3	Total chemical treatment cost	1,269,950
Obj_4	Total waste water	88,610
Obj_5	Total solid waste	263,450
Obj_6	Total air emission	847,530
Obj_{71}	Quality level of product s_1 (Defect rate)	1.147%
Obj_{72}	Quality level of product s_2 (Defect rate)	1.308%
Obj_{81}	Service level of product s_1	98.00%
Obj_{82}	Service level of product s_2	98.00%
Obj_9	Total engergy consumption	7,182,800
Obj_{10}	Total non-renewable resources consumption	444,250

Table 6: The optimal lot-sizing in GSC construction

SPQ_{rij}		PDQ_{sjk}		DCQ_{skm}	
(r1, i1, j1)	1,650	*(s1, j1, k2)*	1,150	*(s1, k1, m3)*	680
(r1, i2, j1)	450	*(s1, j2, k1)*	380	*(s1, k1, m4)*	900
(r1, i2, j2)	1,600	*(s1, j2, k2)*	700	*(s1, k2, m1)*	1,050
(r1, i3, j3)	2,180	*(s1, j3, k1)*	1,200	*(s1, k2, m2)*	800
(r2, i2, j1)	3,450	*(s2, j1, k2)*	1,050	*(s2, k1, m1)*	610
(r2, i2, j2)	3,240	*(s2, j2, k1)*	270	*(s2, k1, m4)*	750
(r2, i3, j3)	3,600	*(s2, j2, k2)*	530	*(s2, k2, m2)*	680
(r3, i1, j1)	1,150	*(s2, j3, k1)*	1,090	*(s2, k2, m3)*	790
(r3, i2, j2)	1,080			*(s2, k2, m4)*	110
(r3, i2, j3)	1,020				
(r3, i4, j3)	180				
(r4, i1, j3)	2,400				
(r4, i3, j1)	2,300				
(r4, i4, j2)	2,160				

Table 7: The optimal objectives achieved with respect of each customer demand of s_1

Sub-objectives	Demand reduced 15%	Demand reduced 10%	Demand reduced 5%	Normal demand	Demand increased 5%	Demand increased 10%	Demand increased 15%
Obj_1	1,636,750	1,699,700	1,761,750	1,824,600	1,820,280	1,823,520	1,821,720
Obj_2	476,270	486,525	497,464	508,850	508,034	508,646	508,306
Obj_3	1,153,225	1,189,395	1,230,196	1,269,950	1,267,250	1,269,275	1,268,150
Obj_4	80,790	83,530	86,422	88,610	88,466	88,574	88,514
Obj_5	239,345	247,326	255,270	263,450	262,862	263,303	263,058
Obj_6	776,514	799,165	822,781	847,530	844,420	844,670	842,680
Obj_{71}	1.15%	1.14%	1.16%	1.15%	1.15%	1.15%	1.15%
Obj_{72}	1.36%	1.36%	1.33%	1.31%	1.31%	1.31%	1.31%
Obj_{81}	98.02%	98.00%	98.01%	98.00%	93.01%	89.01%	85.02%
Obj_{82}	98.00%	98.00%	98.00%	98.00%	98.00%	98.00%	98.00%
Obj_9	6,384,850	6,645,920	6,912,280	7,182,800	7,163,840	7,178,060	7,170,160
Obj_{10}	410,530	421,873	433,496	444,250	443,530	444,070	443,770

Table 8: The optimal objectives achieved with respect of each customer demand of s_2

Sub-objectives	Demand reduced 15%	Demand reduced 10%	Demand reduced 5%	Normal demand	Demand increased 5%	Demand increased 10%	Demand increased 15%
Obj_1	1,729,785	1,761,390	1,792,995	1,824,600	1,822,235	1,823,955	1,822,880
Obj_2	466,955	480,920	494,885	508,850	507,805	508,565	508,090
Obj_3	1,188,365	1,215,560	1,242,755	1,269,950	1,267,915	1,269,395	1,268,470
Obj_4	82,436	84,494	86,552	88,610	88,456	88,568	88,498
Obj_5	248,456	253,454	258,452	263,450	263,076	263,348	263,178
Obj_6	787,033	806,635	827,075	847,530	845,097	845,437	843,952
Obj_{71}	1.15%	1.15%	1.15%	1.15%	1.15%	1.15%	1.15%
Obj_{72}	1.45%	1.40%	1.35%	1.31%	1.31%	1.31%	1.31%
Obj_{81}	98.00%	98.00%	98.00%	98.00%	98.00%	98.00%	98.00%
Obj_{82}	98.04%	98.00%	98.03%	98.00%	93.01%	89.00%	85.01%
Obj_9	6,900,560	6,994,640	7,088,720	7,182,800	7,175,760	7,180,880	7,177,680
Obj_{10}	410,293	421,612	432,931	444,250	443,403	444,019	443,634

Table 9: The optimal objectives achieved with respect of different weighting methods

Sub-objectives	Weights were assigned by using ANP sub-model	Without weighting, all criteria have the same importance	Weights were assigned without using systematic method
Obj_1	1,824,600	1,822,350	1,822,350
Obj_2	508,850	509,600	509,600
Obj_3	1,269,950	1,267,400	1,267,400
Obj_4	88,610	88,310	88,310
Obj_5	263,450	264,050	264,050
Obj_6	847,530	848,430	848,430
Obj_{71}	1.15%	1.15%	1.15%
Obj_{72}	1.31%	1.36%	1.36%
Obj_{81}	98.00%	98.00%	98.00%
Obj_{82}	98.00%	98.00%	98.00%
Obj_9	7,182,800	7,185,800	7,182,800
Obj_{10}	444,250	443,200	444,250
CC Cluster	0%	+0.11%	+0.11%
PC Cluster	0%	-0.10%	-0.10%
QC Cluster	0%	-3.90%	-3.90%
RC Cluster	0%	-0.03%	0%

Table 10: The optimal objectives achieved with respect of different combinations

Sub-objectives	$I = 4, J = 2^*, K = 2, M = 3$	$I = 4, J = 3, K = 2, M = 3$
Obj_1	1,798,750	1,824,600
Obj_2	507,825	508,850
Obj_3	1,245,045	1,269,950
Obj_4	91,780	88,610
Obj_5	261,060	263,450
Obj_6	824,235	847,530
Obj_{71}	1.23%	1.147%
Obj_{72}	1.78%	1.308%
Obj_{81}	98.00%	98.00%
Obj_{82}	98.00%	98.00%
Obj_9	7,223,000	7,182,800
Obj_{10}	450,620	444,250

Note: *The production capacity of j_3 transferred to j_1 and j_2 equally.

Table 11: The optimal objectives under different decision-making scenarios

Sub-objectives	Scenarios (1) Only environmental objectives considered	Scenarios (2) Both sides are considered	Scenarios (3) Only business objectives considered
Obj_1	1,827,600	1,824,600	1822350
Obj_2	508,100	508,850	509600
Obj_3	1,268,600	1,269,950	1267400
Obj_4	88,910	88,610	88310
Obj_5	264,350	263,450	264050
Obj_6	850,530	847,530	872160
Obj_{71}	1.147%	1.147%	1.147%
Obj_{72}	1.282%	1.308%	1.359%
Obj_{81}	98.00%	98.00%	98.00%
Obj_{82}	98.00%	98.00%	98.00%
Obj_9	7,181,300	7,182,800	9,404,950
Obj_{10}	443,050	444,250	443,200
Environmental Related Objectives	8,828,140	8,826,640	11,072,670

Figures

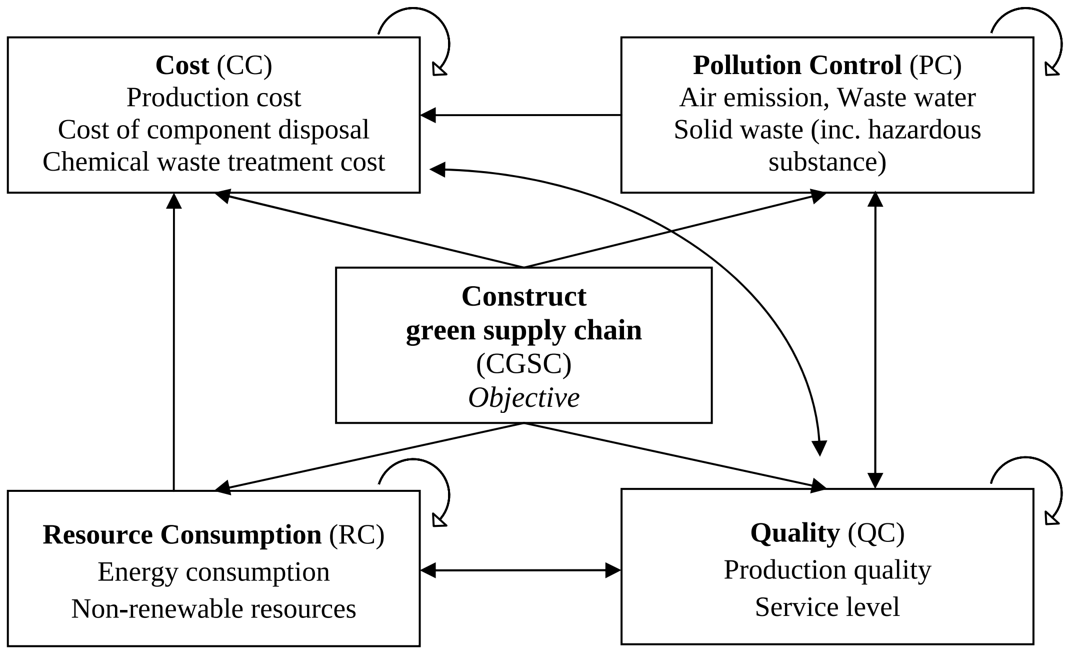


Figure 1: The structure and relationships of the network for partner selection in green supply chains

	CGSC	CC	PC	QC	RC
CGSC	0	0	0	0	0
CC	$W_{CC,K}^{CGSC}$	$W_{CC,K}^{CC}$	$W_{CC,K}^{PC}$	$W_{CC,K}^{QC}$	$W_{CC,K}^{RC}$
PC	$W_{PC,K}^{CGSC}$	0	$W_{PC,K}^{PC}$	$W_{PC,K}^{QC}$	0
QC	$W_{QC,K}^{CGSC}$	$W_{QC,K}^{CC}$	$W_{QC,K}^{PC}$	$W_{QC,K}^{QC}$	$W_{QC,K}^{RC}$
RC	$W_{RC,K}^{CGSC}$	0	0	$W_{RC,K}^{QC}$	$W_{RC,K}^{RC}$

Figure 2: The original format of the matrix for partner selection in green supply chains

(NB: based on the structure and relationships shown in Figure 1)

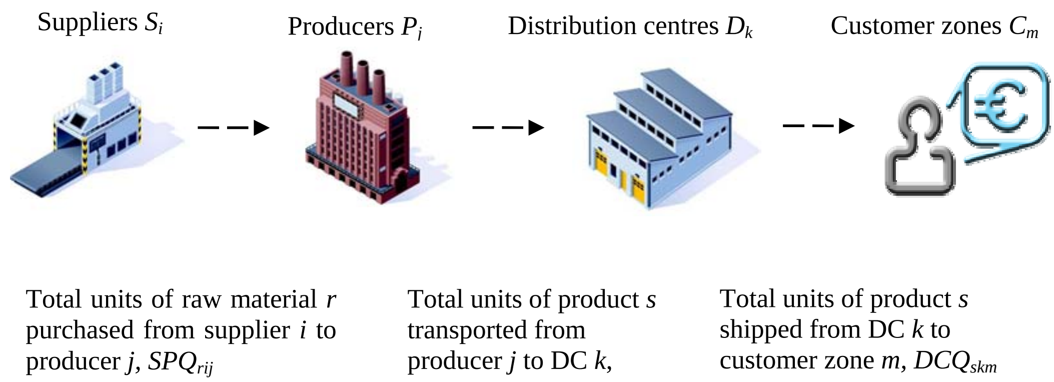


Figure 3: The positions of different partners and notations

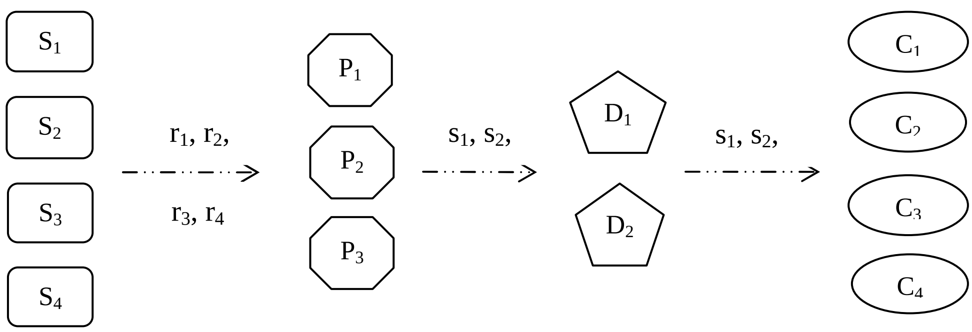


Figure 4: The structure of the green supply chain before applying the ANP-MOP model

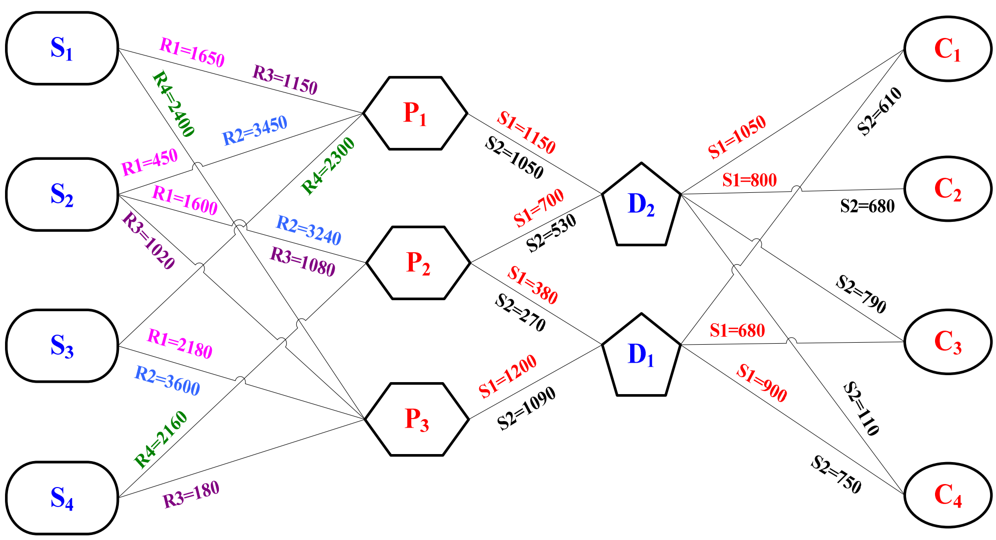
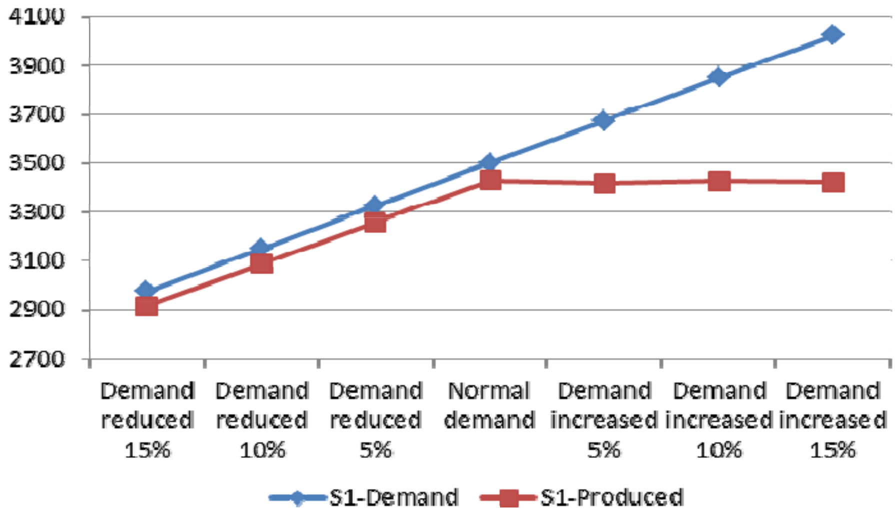
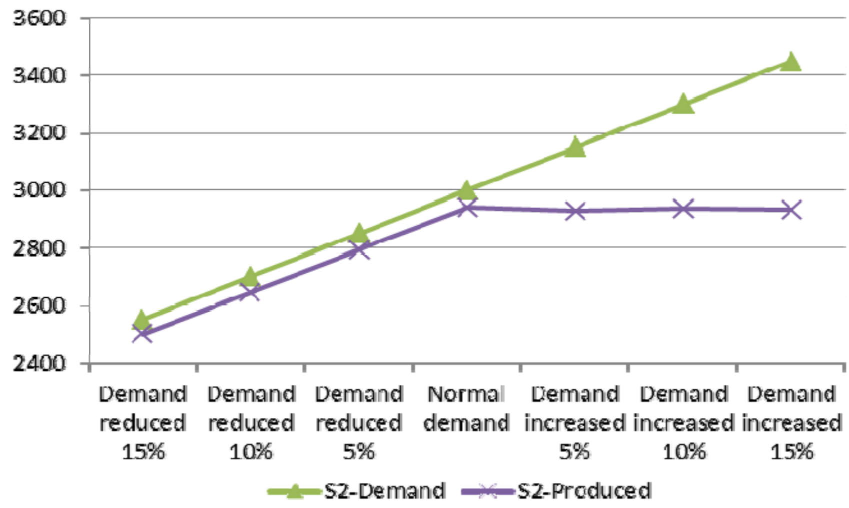


Figure 5: The optimal structure and lot-sizing of the green supply chain



(a)

Figure 6: The comparation of the number of customer demand and the optimal produced products



(b)

Figure 6: The comparation of the number of customer demand and the optimal produced products

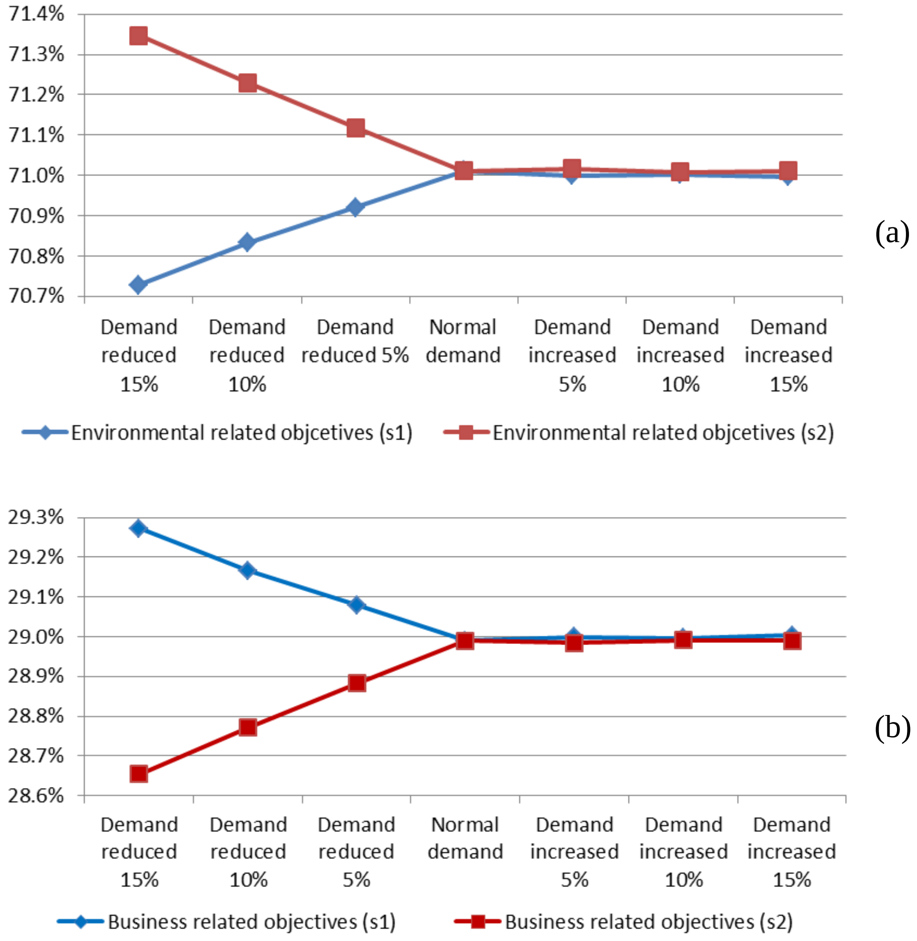


Figure 7: Performance of green supply chain with respect to the change of customer demand

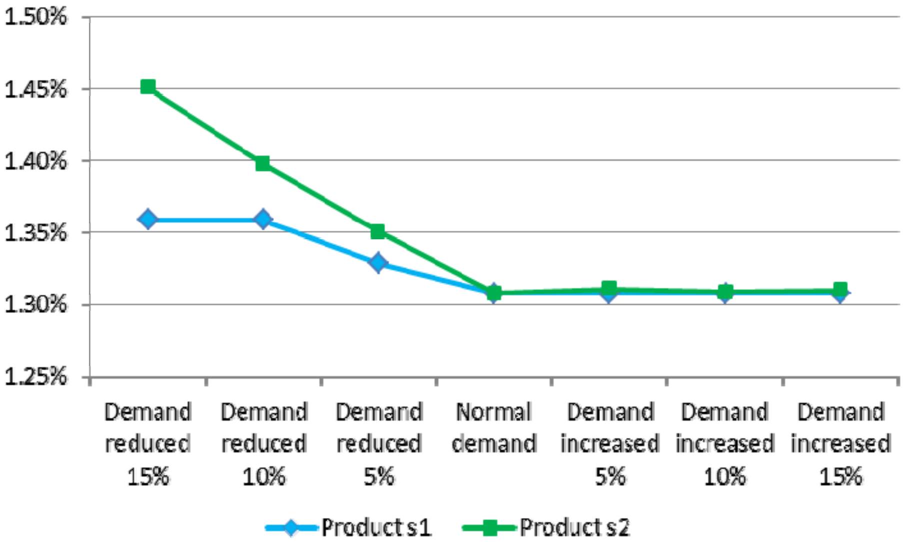


Figure 8: Quality level with respect to the change of customer demand

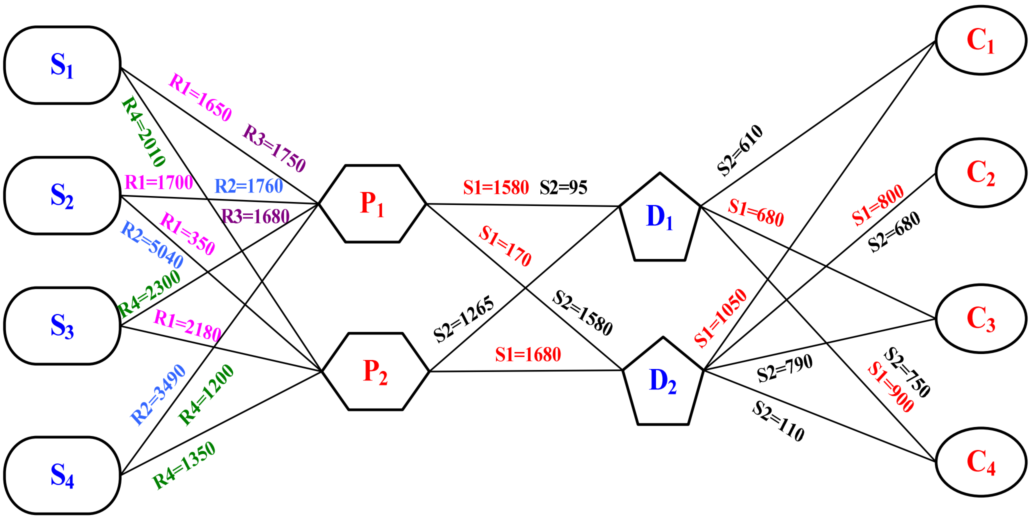


Figure 9: The optimal structure and lot-sizing of GSC with respect of different combinations

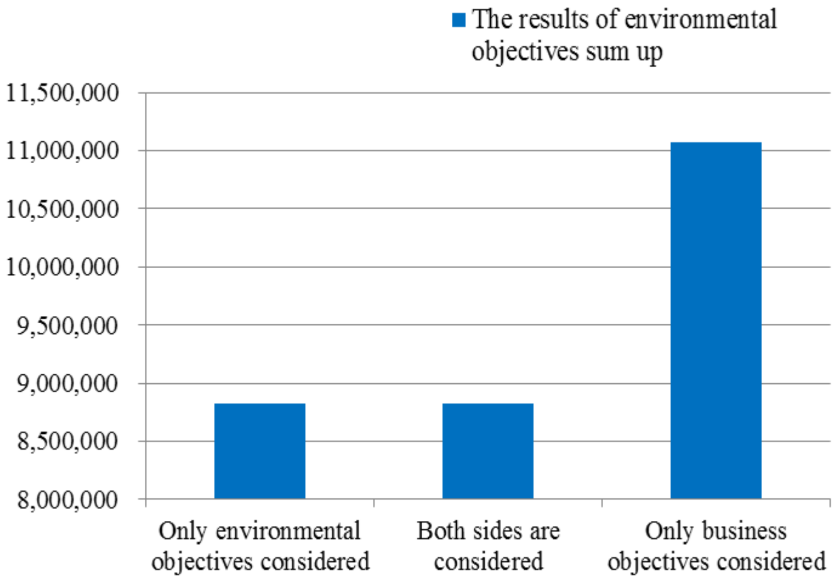


Figure 10: The optimal environmental objectives results under different decision-making scenarios

Appendix

Tables for the illustrative analysis

Table A1. Assumptions of unit production cost of product *s* in producer *j*

PC_{sj}	j_1	j_2	j_3
s_1	375	350	360
s_2	180	200	215

Table A2. Assumptions of unit cost of component disposal when product *s* is manufactured by producer *j*

DC_{sj}	j_1	j_2	j_3
s_1	55	65	68
s_2	105	100	95

Table A3. Assumptions of unit chemical waste treatment cost when product *s* is manufactured by producer *j*

CC_{sj}	j_1	j_2	j_3
s_1	195	235	225
s_2	177	168	185

Table A4. Assumptions of unit waste water when product *s* is manufactured by producer *j*

WW_{sj}	j_1	j_2	j_3
s_1	15	20	12
s_2	10	12	14

Table A5. Assumptions of unit solid waste when product *s* is manufactured by producer *j*

SW_{sj}	j_1	j_2	j_3
s_1	45	48	49
s_2	32	38	34

Table A6. Assumptions of unit of air emission when product *s* is shipped from producer *j* to DC *k*

AEX_{sjk}		k_1	k_2		k_1	k_2
	j_1	70	50		68	55
$s=1$	j_2	80	60	$s=2$	81	75
	j_3	90	70		75	95

Table A7. Assumptions of unit of air emission when product *s* is shipped from DC *k* to Customer Zone *m*

AEY_{skm}		m_1	m_2	m_3	m_4		m_1	m_2	m_3	m_4
$s=1$	k_1	95	65	55	70	$s=2$	50	75	91	56
	k_2	77	60	85	90		90	75	60	76

Table A8. Assumptions of unit energy consumption when raw material *r* shipped from supplier *i* to producer *j*

ECrij		j_1	j_2	j_3		j_1	j_2	j_3		j_1	j_2	j_3		j_1	j_2	j_3
$r=1$	i_1	300	320	330	$r=2$	180	205	185	$r=3$	240	260	270	$r=4$	400	375	365
	i_2	315	310	325		195	190	215		255	250	245		385	390	375
	i_3	340	330	320		200	220	200		280	250	260		360	395	380
	i_4	325	330	310		195	210	205		260	270	250		385	370	400

Table A9. Assumptions of unit non-renewable resource consumption when product *s* is manufactured by producer *j*

NC_{sj}	j_1	j_2	j_3
s_1	66	69	60
s_2	78	70	77

Table A10. Assumptions of total customer demand for product *s* in customer zone *m*

TD_{sm}	m_1	m_2	m_3	m_4
s_1	1050	800	680	970
s_2	610	680	790	920

Table A11. Assumptions of defective rate of product *s* from producer *j*

DR_{sj}	j_1	j_2	j_3
s_1	0.005	0.020	0.010
s_2	0.020	0.015	0.005

Table A12. Assumptions of material requirement rate for one unit product *s* needs the units of material *r*

MR_{rs}	s_1	s_2
r_1	0	2
r_2	3	2
r_3	1	1
r_4	2	0

Table A13. Assumptions of supplier i^{th} capacity limit to supply material r

SCL_{ri}	i_1	i_2	i_3	i_4
r_1	1650	2050	2200	0
r_2	0	6800	5800	4200
r_3	2150	2100	0	2250
r_4	2450	0	2300	2550

Table A14. Assumptions of production capacity limit of producer j for product s

PCL_{sj}	j_1	j_2	j_3
s_1	1150	1080	1200
s_2	1050	950	1250

Table A15. Assumptions of distribution limit of DC k to distribute product s

DCL_{sk}	k_1	k_2
s_1	1980	1850
s_2	1360	1650