Chapter 66
Research on Network Optimization of Green Supply Chain: A Low-Carbon Economy Perspective

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Abstract Based on the theory of low-carbon economy, this paper evaluates the influence of carbon emissions on supply chains' overall value using carbon footprint. It is showed that three objects, namely, profitability, service level and environmental protection should be coordinated, and to balance cost, response time and carbon footprint, the penalty function coefficient is introduced, which coverts a multi-objective optimization problem to a single objective one. Also, a network optimization model is formulated to offer a supplementary solution for optimization design of green supply chain network.

Keywords Low-carbon economy · Carbon footprint · Green supply Chain · Network optimization

66.1 Introduction

Since the beginning of twenty-one century, climate change has become a challenge mankind has to meet in the economic and social development. Carbon emission is one of the main causes of global warming. China, one of the top countries in terms of carbon dioxide (CO_2) emission, faces great pressure to reduce carbon emission.

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As an important part of the Third Industry, green supply chain is an ecological industry system characterized by low carbon emissions, and so it is the government's possible policy choice to develop low-carbon economy. Green supply chain optimization drives at a balance between environmental protection and profitability, achieving systematic coordination in order to improve both environmental quality and competitive edge in a dynamic way and for a win–win effect. To use carbon footprint to measure carbon emissions as an environment index is a reliable way in dealing with environmental pollution, caused mainly by carbon emissions. Carbon emission has great bearing on the design of supply chain network, so to take the factor of carbon emissions into account is inevitably a tendency in the network design of supply chain (Fang and Xu 2012). Therefore, in the context of low carbon economy, to introduce the notion of carbon footprint to measure the influence of carbon emissions on the overall cost of supply chain is of great theoretical and pragmatic meaning to developing low carbon logistics, undertaking green supply chain management, and facilitating sustainable development strategy.

66.2 Literature Review

Green supply chain has been one of the hottest topics in recent years' supply chain management research (Zhang and Xu 2009), and many people pay their attentions to the green supply chain network optimization and design. Wang et al. (2011), analyzing environmental issues, build a related multi-objective model, and solve the model with heuristic algorithm. Sundarakani et al. (2010) formulates a model of carbon footprint across supply-chain under both static and dynamic situations, and checks it numerically, demonstrating the importance of carbon footprint in supply chain design. Chaabane et al. (2011) analyzes the green supply chain network design problem in carbon exchange market, and try to help decision makers find the efficient solution that balances the increase of supply chain cost and emission reduction. In China, thorough analysis of green supply chain network optimization is far from enough. Fang and Xu (2012), drawing on research findings in network designs of the green supply chain and sustainable supply chain, elaborates some important relevant issues in supply chain network design with carbon emission taken into consideration. However, up to now there has been no in depth, detailed design model for establishing a green supply chain network, overall there is no quantitative research in this respect, either.

Based on low-carbon economy theory, this paper evaluates the influence of carbon emissions on supply chains' overall value using carbon footprint, and seeks to balance the three targets,namely, supply chain profitability, service level and environmental protection, so as to achieve a green, low-carbon supply chain. Penalty function coefficient is introduced to balance cost, response time and carbon footprint, converting the multi-objective optimization problem to a single-objective one. An optimization model is developed to offer supplementary decision solutions for the optimization and design of the green supply chain network, aiming at pushing effective implementation of green supply chain management and realizing low-carbon development.

66.3 Thought and Assumptions of Network Optimization

66.3.1 Basic Idea of Green Supply Chain Network Optimization

The difference between general supply chain network design and the green supply chain lies in that the green supply chain not only needs to optimize cost and service level at the same time and reach the network structure solution at Pareto curve (He and Meng 2009), but also needs to consider the influence of carbon emission on the overall value of the supply chain and sustainable development. Therefore, the research on the green supply chain network optimization based on low-carbon economy's perspective should first clarify the internal mechanism of carbon emissions' influence on the overall cost of the supply chain network, measure the emission accurately on the supply chain level (Sundarakani et al. 2010) and analyze the cost influence. Then considering the effect of carbon emissions on strategic and tactical factors of the green supply chain network design, it should apply carbon emissions' limit to the selection of network nodes strategically, and network channels tactically, thus effectively building a green supply chain network.

66.3.2 Model Assumptions

In the paper, we use carbon footprint to measure the carbon emissions at all the nodes and channels of the supply chain, and the penalty function is applied to realize the balance of cost, response time and carbon footprint. Two coefficients of the penalty function are introduced: one is penalty coefficient of late delivery, which is defined as the unit increase in objective function because of late response to customer needs in the supply chain system; the other is penalty coefficient of carbon emission, which is the unit increase in objective function when the carbon emission exceeds the system's limit. Thus, the penalty coefficients can be set differently according to different regions, products, and phases to balance supply chains' cost, response time, and carbon footprint. Now the assumptions are as follows:

(i) All facilities to be built are only built at places that are given, and all these places can be scientifically simulated in systems' daily operation and satisfy needs of the green supply chains' management very well;

(ii) The capacity of all nodes, the building and operation cost, and carbon footprint can be tracked and acquired in real time via the supply chains' sharing system of information;
(iii) The unit transport cost, time, and carbon footprint between any source node and any destination node can be learned from system simulations and they have linear relations with transport quantity in the mean time.

66.4 Network Optimization Decision Model

66.4.1 Model Notations

For convenience, here we give some notations which are used in the sequel. P, D, R denote the set of nodes for manufacturing facilities, the set of nodes for distribution centers and the set of demand nodes, respectively. DC_e denotes the distribution center e and R_j denotes the demand quantity for demand node j. P_i, $C_i^{\mathrm{P}}, T_i^P, CF_i^P$ denote the manufacturing capacity, the construction and operation cost, the unit production time and the carbon footprint of unit production activity of plant i, respectively. $D_e, C_e^D, T_e^D, CF_e^D$ denote the capacity, the construction and operation cost, the unit processing time, the carbon footprint of unit processing activity of DC_e, respectively. $T_{GSN}, CF_{\mathrm{GS}N}$ denote the target response time, the limit carbon footprint of the network, respectively. Let $C_{ie}^D, T_{ie}^D, CF_{ie}^D$ denote respectively the unit transport cost, the unit transport time and the unit transport carbon footprint from plant i to DC_e, and let $C_{ej}^R, T_{ej}^R, CF_{ej}^R$ denote respectively the unit transport cost, the unit transport time and the unit carbon footprint from DC_e to demand node j. $CT_{\mathrm{GS}N}$ denotes the penalty function coefficient for late delivery and $CCF_{\mathrm{GS}N}$ denotes the penalty function coefficient for carbon footprint.

In addition, let x_{ie} be the transport quantity from plant i to DC_e and y_{ej} be the transport quantity from DC_e to demand node j. Let u_i be the binary variable with 1 representing building plant i and 0 otherwise; let v_e be the binary variable with 1 representing building DC_e and 0 otherwise.

66.4.2 Math Model

$$
\begin{aligned}
&\textit{Minimize } TC \\
&= \sum_{i \in P}\sum_{e \in D} C_{ie}^D x_{ie} + \sum_{e \in D}\sum_{j \in R} C_{ej}^R y_{ej} + \sum_{i \in P} C_i^P u_i + \sum_{e \in D} C_e^D v_e \\
&\quad + CT_{GSN} \times \Big(\sum_{i \in P}\sum_{e \in D} T_{ie}^D x_{ie} + \sum_{e \in D}\sum_{j \in R} T_{ej}^R y_{ej} + \sum_{i \in P} T_i^P u_i \sum_{e \in D} x_{ie} + \sum_{e \in D} T_e^D v_e \sum_{j \in R} y_{ej} - T_{GSN}\Big) \\
&\quad + CCR_{GSN} \times \Big(\sum_{i \in P}\sum_{e \in D} CF_{ie}^D x_{ie} + \sum_{e \in D}\sum_{j \in R} CF_{ej}^R y_{ej} + \sum_{i \in P} CF_i^P u_i \sum_{e \in D} x_{ie} + \sum_{e \in D} CF_e^D v_e \sum_{j \in R} y_{ej} - CF_{GSN}\Big)
\end{aligned}
$$

Subject to

$$\sum_{e \in D} x_{ie} \leq P_i u_i, \quad i \in P \tag{66.1}$$

$$\sum_{j \in R} y_{ej} \leq D_e v_e, \quad e \in D \tag{66.2}$$

$$\sum_{e \in D} y_{ej} \geq \mathrm{R}_j, \quad j \in R \tag{66.3}$$

$$\sum_{i \in P} x_{ie} = \sum_{j \in R} y_{ej}, \quad e \in D \tag{66.4}$$

$$u_i \in \{0, \quad 1\}, \quad i \in P; \quad v_e \in \{0, \quad 1\}, \quad e \in D \tag{66.5}$$

$$x_{ie} \geq 0\,, y_{ej} \geq 0, \quad i \in P, \quad e \in D, \quad j \in R \tag{66.6}$$

where the first part of the objective function is construction and transport cost, the second part is the penalty cost indicating the failure in responding to customer needs, and the third part is the penalty cost caused by carbon footprint which exceeds the system limit. Constraints (66.1) and (66.2) are the capacity limits; (66.3) is the limit of demand quantity; (66.4) is the limit of balancing node capacities; (66.5) and (66.6) limit the range of variables.

66.5 Analysis of Example

A multinational company TC needs to optimize supply chain network. Currently two high value-added innovative products have been developed to be launched in three markets. The response time to product orders is set to be 1 week. The whole supply chain's carbon footprint is 8,500 ton. There are three candidate plants and three distribution centers for these products. The detailed data is shown in Tables 66.1, 66.2, and 66.3.

Usually, innovative high value-added products need very agile and adaptable supply chains, and in the investment period, a higher response ability and service level for customers are required. So by combining market investigation with empirical analysis, and applying LINGO 11.0 to test the model repeatedly, we find that the penalty function coefficient CT_{GSN} should be set as the greater number 999, while CCF_{GSN} can be set as 650 by reference to the carbon taxes in different regions. After coding and solving the problem, the optimized solutions can be obtained: strategically, nodes selected are plants 1 and 3, DC 1 and 2; operationally, detailed distribution path can be optimized real time by using this model. This can guarantee the feasibility and effectiveness of the model.

Table 66.1 Unit transport cost, unit time, and unit carbon footprint between nodes

From	To	C ($)	T(h)	CF(t)	From	To	C ($)	T(h)	CF(t)
P1	DC1	2000	1	780	DC1	C1	4000	2	983
P1	DC2	4000	2	890	DC1	C2	1000	3	786
P1	DC3	3000	1	560	DC1	C3	3000	2	698
P2	DC1	2000	2	800	DC2	C1	6000	2	889
P2	DC2	1000	3	780	DC2	C2	4000	1	459
P2	DC3	4000	1	569	DC2	C3	2000	3	859
P3	DC1	8000	2	1120	DC3	C1	10000	3	963
P3	DC2	6000	4	790	DC3	C2	5000	6	569
P3	DC3	1000	2	799	DC3	C3	4000	4	698

Table 66.2 Capacities and construction cost of all nodes on the network

P	Capacity	Cost($)	DC	Cost ($)	Capacity	C	Demand
P1	700	45000	DC1	200000	400	C1	400
P2	600	65000	DC2	100000	800	C2	500
P3	500	90000	DC3	150000	1000	C3	300

Table 66.3 Unit processing time and carbon footprint of all nodes on the network

P	Time (h)	Carbon footprint (T)	DC	Time (h)	Carbon footprint (T)
P1	7	650	DC1	10	890
P2	9	890	DC2	13	987
P3	5	1000	DC3	12	780

66.6 Conclusion

The research on the green supply chain network optimization based on low-carbon economy's perspective should first clarify the internal mechanism of carbon emission's influence on the overall cost of the supply chain network, measure the emission accurately on the supply chain level and analyze the cost influence. Then in view of the influence of carbon emission on strategic and tactical factors of the green supply chain network design, penalty function coefficient is introduced to balance cost, response time and carbon footprint, which converts the multi-objective optimization problem to a single-objective one. By balancing the supply chain's profitability, service level, and environmental protection, a green, low-carbon supply chain network can then be built effectively.

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