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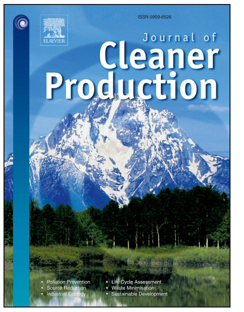


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PII: S0959-6526(17)32163-7

DOI: 10.1016/j.jclepro.2017.09.165

Reference: JCLP 10670

To appear in: *Journal of Cleaner Production*

Received Date: 19 May 2017

Revised Date: 19 August 2017

Accepted Date: 16 September 2017

Please cite this article as: Yu F, Yang Y, Chang D, Carbon footprint based green supplier selection under dynamic environment, *Journal of Cleaner Production* (2017), doi: 10.1016/j.jclepro.2017.09.165.

# Carbon footprint based green supplier selection under dynamic environment

Fang Yu[a,*], Yongsheng Yang[a], Daofang Chang[a]

[a]*Institute of logistics science & Engineering, Shanghai Maritime University, 1550 Haigang Ave, Shanghai,201306, P.R. China*

**Abstract**

Green supplier selection plays a vital role in the green supply chain management. A carbon footprint based incentive green supplier selection model, which can urge the participants in the green supply chain to initiatively make greener decisions, is proposed in this research. Both economic attributes (price, quantity, and lead time) and environmental attributes (green factors and carbon dioxide emissions ($CO_2$)) are considered during the selection. The green factors of the selected suppliers and the environmental investment are taken into account during the determinations of the green factors. The $CO_2$ emissions from the transportation and production processes are considered. Moreover, three models are put forward to maximize the total profits, maximize the green factors, and minimize the $CO_2$ emissions. Numerical calculations and comparisons are provided to verify the feasibility and superiority of the proposed models.

*Keywords:* Green supply chain, supplier selection, multi-agent systems, carbon footprint, order allocation
*2014 MSC:* 00-01, 99-00

## 1. Introduction

Integrating environmental issues into an organization's purchasing activities becomes necessary due to the escalating deterioration of the environment and the increased awareness about environmental concerns(Govindan and Sivakumar (2016); Luthra et al. (2017)). It has become increasingly imperative for organizations facing competitive, regulatory and community pressures to search for a balance between the economic and environmental performance (Yazdani et al. (2017)). Green supplier selection plays a crucial role for enterprises in the green supply chain (GSC) (Qin et al. (2017)). Consequently, the green related supplier selection catches more and more attentions.

*Corresponding author
*Email address:* fangyu1985@hotmail.com (Fang Yu)

Main environmental criteria for green supplier selections are related to the level of waste water discharge, level of solid waste generation, noise level, recycling utilization level of waste material, carbon dioxide ($CO_2$) emissions, level of harmful material utilization, and so on. Both researchers and practitioners make efforts to contribute to the green supplier selection. Although various evaluation and selection methods were proposed, there is few work focused on proposing an incentive mechanism which urges the participants in the GSC initiatively improve their strategies to reduce the harm to the environment. Yu et al. proposed an incentive selection mechanism which was verified to be useful in reducing the harmful effects on the environment (Yu et al. (2016)). The determinations of green factors were only related to the selected suppliers' green factors, the determination of $CO_2$ emissions were only related to the product transportation distances, and the purpose was to maximize the participants' profits. However, the participant's investment on the environment protection and the $CO_2$ emissions during production processes are important factors to evaluate the participant's green degree as well. Moreover, each participant in the GSC has a different preference on the profit, green factor, and $CO_2$ emissions. Thus, different models are required to satisfy the personalized demands. In this research, the work of (Yu et al. (2016)) was extended. Both the selected suppliers' green factors and the environmental investments will be considered during the determinations of green factors. The $CO_2$ emissions during production processes will be taken into account as well. In addition, three selection models will be proposed to maximize the profit, maximize the green factor, and minimize $CO_2$ emissions,.

Main contributions of this research can be summarized as follows. Firstly, an incentive supplier selection mechanism based on the carbon footprint is proposed, which can urge participants in the GSC to make greener decisions initiatively. Secondly, both economic attributes (i.e. price and quantity) and environmental attributes (i.e. green factors and $CO_2$ emissions) are considered in the calculations of profits. A reward function and a penalty function are introduced into awarding the participants with high green factors, and punishing the participants with high $CO_2$ emissions, respectively. Thirdly, new determination mechanisms for the green factor and the $CO_2$ emissions are proposed to promote participants to select greener suppliers. Fourthly, three models are proposed for different preferences on the profit, green factor, and $CO_2$ emissions. Moreover, the proposed models provide top management with flexibility in giving more or less importance weight to the economic or environmental attributes according to the participants' preferences. On the other hand, this research contributes to construct a simple but effective mathematical model which is good at reducing $CO_2$ emissions and increasing the green factors of participants. In addition, the proposed models can be used for the government to verify the effects of the determined reward/penalty threshold values to the reduction of the harmful impact on the environment.

The remainder of this research is organized as follows. A literature review relates to the supplier selection is discussed in Section 2. Section 3 describes the details of proposed models. A carbon footprint based incentive supplier selection mechanism is addressed in Section 4. The numerical calculations and analyzes are shown in Section 5. The conclusion and future research opportunities are addressed in the final section.

## 2. Literature review

### *2.1. Green supplier selection criteria*

Supplier selection is described as one of the most significant processes in the purchasing and supply management function, and widely understood as a crucial management responsibility (Wetzstein et al. (2016)). Organizations considered criteria such as cost, quality, and delivery to evaluate the performance of their suppliers (Trapp and Sarkis (2016); Hlioui et al. (2017)). However, environmental deteriorations have forced public and private sectors to think over environmental and sustainable issues. Therefore, green or sustainable supplier selection attracts more and more attentions. The environmental criteria such as pollution production (i.e. air emissions pollutant, level of waste water discharge, level of solid waste generation, etc.)(Hashemi et al. (2015); Hu et al. (2015); Kannan et al. (2015); Huang et al. (2016); Rezaei et al. (2016); Qin et al. (2017); Luthra et al. (2017); Kumar et al. (2017)), noise level(Hu et al. (2015)), recycling utilization level of waste material(Hu et al. (2015); Kannan et al. (2015); Govindan and Sivakumar (2016); Yazdani et al. (2017)), level of poisonous and harmful material utilization(Hu et al. (2015); Kannan et al. (2015); Rezaei et al. (2016); Gupta and Barua (2017)), level of clean energy utilization(Hu et al. (2015); Yazdani et al. (2017)), level of environmental protection input(Hu et al. (2015); Shabanpour et al. (2017); Qin et al. (2017)), level of environmental management(Hu et al. (2015); Hashemi et al. (2015); Rezaei et al. (2016); Yazdani et al. (2017); Qin et al. (2017); Kumar et al. (2017); Gupta and Barua (2017)) were mainly considered in previous works. However, these researches focused on the determinations of weights for the environmental attributes rather than the determinations of strategies for the environmental attributes. This research will contribute to the determination of the strategies for the environmental attributes.

### *2.2. Green supplier evaluation method*

The main modeling method can be divided into qualitative, mathematical programming (linear programming, MILP, goal programming, nonlinear programming), mathematical analytical (AHP, ANP, DEA, TOPSIS, VIKOR, etc.), artificial intelligence (fuzzy logic, grey system theory, neural networks, genetic algorithm, game theory, etc.), and combined models (Zimmer et al. (2016)). Hashemi et al. integrated the ANP with an improved GRA to weight the criteria and rank the suppliers (Hashemi et al. (2015)). Kannan proposed a fuzzy axiomatic design approach to select the best green supplier for a Singapore-based plastic manufacturing company (Kannan et al. (2015)). Hu et al. present a multi-attribute group decision making method with 2-tuple linguistic assessments for green supplier selection under a fuzzy uncertain information environment (Hu et al. (2015)). Govindan and Sivakumar proposed an integrated fuzzy TOPSIS and fuzzy MOLP methodology to elucidate the ranking of green suppliers and the order allotment problem in paper industry (Govindan and Sivakumar (2016)). Huang et al. established a game-theoretic model to investigate the impact of supplier selection and other factors (Huang et al. (2016)). Lious et al. proposed a hybrid model which combined DEMATEL, INRM, ANP and GRA approaches to address dependent relationships between various criteria (Liou et al. (2016)). Yazdani et al. combined the DEMATEL and QFD for the green supplier selection by considering various environmental performance requirements and criteria (Yazdani et al. (2017)). Shabanpour et al. combined the artificial neural network with dynamic DEA to forecast future efficiency of the green supplier (Shabanpour et al. (2017)). Qin et al. extended the TODIM technique to solve the multiple criteria group decision making problem within the context of interval type-2 fuzzy sets and applied into the green supplier selection (Qin et al. (2017)). Luthra et al. proposed a framework to evaluate the sustainable supplier selection by using an integrated analytical hierarchy process, VIKOR, multi-criteria optimization and compromise solution approach (Luthra et al. (2017)). Kummar et al. used the fuzzy-extended elimination and choice expressing reality approach to evaluate the suppliers' performance (Kumar et al. (2017)). Hamdan and Cheaitou proposed an MCDM and multi-objective optimization approach to solve a multi-period green supplier selection and order allocation problem (Hamdan and Cheaitou (2017)). Ghadimi et al. proposed a fuzzy inference system to rank the suppliers and a practical decision making approach to evaluate and select the most sustainable suppliers (Ghadimi et al. (2017)). Bakeshlou et al. developed a multi-objective fuzzy linear programming model for a green supplier selection problem, and a hybrid fuzzy multi-objective decision making is employed to solve it (Bakeshlou et al. (2017)).

Most of them aimed to assign weights to the criteria, and then rank the available suppliers. The main purposes were to evaluate the suppliers. No work focused on providing an incentive mechanism which can urge the participants in the GSC to initiatively improve their strategies to reduce the harm to the environment. This research contributes to provide a carbon footprint based supplier selection mechanism which urges the participants in the GSCN initiatively make greener decisions to reduce the harm on the environment.

## 3. Model

### *3.1. Nomenclatures:*

$\omega_g$: weight on the green factors of the suppliers
$\omega_e$: weight on the environment protection invest
$\eta_k$: proposition of item $k$ for one unit product
$\Delta_g$: average green factor of all items for $s_{ijl}$
$\varepsilon_1$: metric ton $CO_2$ emissions per kilometer
$\varepsilon_2$: metric ton $CO_2$ emissions per kilowatt-hours
$\pi^C_{zi}$: profit of CA $z$ for MA $i$

$\pi_{ij}^{M}$: profit of MA $i$ by selecting MSA $j$
$\pi_{ijl}^{S}$: profit of MSA $j$ by belonging to $s_{ijl}$
$\pi_{ij'l}^{SC}$: profit of MSA $j'$ ($j' \neq j$)by belonging to $s_{ijl}$
$\overline{\pi}_{zi}^{C}$: profit of CA $z$ by selecting MA $i$ in traditional model
$\overline{\pi}_{ij}^{M}$: profit of MA $i$ by selecting MSA $j$ in traditional model
$\overline{\pi}_{ijl}^{S}$: profit of MSAs $j$ by belonging to $s_{ijl}$ in traditional model
$A_{ijk}$: ability of item $k$ of MSA $j$ for MA $i$
$C_{jk}^{S}$: cost of item $k$ of MSA $j$
$CE_{zi}^{C}$: $CO_2$ emissions if CA $z$ selects MA $i$
$CE_{ij}^{M}$: $CO_2$ emissions if MA $i$ selects MSA $j$
$CE_{ijl}^{SS}$: $CO_2$ emissions if MSA $j$ selects $s_{ijl}$
$CET_{z}^{C}$: total $CO_2$ emissions of CA $z$
$CET_{i}^{M}$: total $CO_2$ emissions of MA $i$
$CET_{j}^{S}$: total $CO_2$ emissions of MSA $j$
$CS_{i}$: setup cost of MA $i$
$d_{zi}^{CM}$: distance from MA $i$ to CA $z$
$d_{ij}^{SM}$: distance from MSA $j$ to MA $i$
$EI_{j}^{S}$: environmental protection invest of MSA $j$
$EI_{i}^{M}$: environmental protection invest of MA $i$
$gd_{jk}^{S}$: green degree of item $k$ of MSA $j$
$gf_{z}^{C}$: green factor of CA $z$
$gf_{zi}^{CM}$: green factor of CA $z$ if it selects MA $i$
$gf_{ij}^{MS}$: green factor of MA $i$ if it selects MSA $j$
$gf_{i}^{M}$: green factor of MA $i$
$gf_{j}^{S}$: green factor of MSA $j$
$gf_{ijl}^{SS}$: green factor of MSA $j$ if it selects $s_{ijl}$
$p_{ijk}^{M}$: price of MA $i$ for MSA $j$ to buy item $k$
$P_{jk}^{S}$: unit electricity use to produce item $k$ of MSA $j$
$P_{i}^{M}$: unit electricity use to of MA $i$
$q_{zi}^{C}$: quantity of CA $z$ for MA $i$
$q_{ij}^{M}$: quantity the final product of MA $i$ for MSA $j$
$Q_{z}^{C}$: total bought quantity of CA $z$
$Q_{i}^{M}$: total bought quantity of MA $i$
$QS_{ij'k}$: acquired quantity of item $k$ for MSA $j' \in s_{ijl}$
$QST_{j}^{S}$: total produced quantity of MSA $j$
$s_{ijl}$: the $l^t h$ coalition of MSA $j$ for MA $i$
$T_{jk}^{S}$: unit production time of item $k$ of MSA $j$
$T_{i}^{M}$: unit production time of product of MA $i$.
($x_{i}^{M}$, $y_{i}^{M}$): coordinate of MA $i$
($x_{j}^{S}$, $y_{j}^{S}$): coordinate of MSA $j$
($x_{z}^{C}$, $y_{z}^{C}$): coordinate of CA $z$

*3.2. Model description*

Consider a three-echelon supply chain, which consists of multiple material supplier agents (MSAs, $j = 1, .., J$), multiple manufacturer agents (MAs, $i = 1, ..., I$), and multiple consumer agents (CAs, $z = 1, ..., Z$). MAs buy raw materials from MSAs, and CAs buy final products from MAs. We assume that each final product consists of multiple items ($k = 1, ..., K$), and each agent has a coordinate ($x$,$y$). Moreover, we assume that each MSA $j$ is allowed to establish coalitions ($s_{ijl}$, $l = 1, ..., L$) when the order of MA $i$ exceed its ability. We assume each participant in the supply chain has a green factor to record the carbon footprint during its production and consumption processes and each raw material has a green degree to show its friendliness to the environment. Both economic attributes (price $p$, quantity $q$, and lead time $lt$) and environmental attributes (green factor $g$, and $CO_2$ emissions $CE$) are considered in this research in order to reduce the harm to the environment. In this research, we only consider the $CO_2$ emissions. However, the research can also be generalized to consider the $SO_2$, NOX, PM and so on. A product transportation distance based supplier selection model was proposed in the previous work (Yu et al. (2016)), in which the green factor of the participant was only affected by the green factor of the selected supplier. In this research, green factors of participants not only affected by their selected suppliers, but also influenced by their investments to protect the environment. The green factor of each agent in this research is defined as follows:

- For each MSA $j$: relates to the green degree of its produced material, its selected partners' green factors, and its investment on the environment protection (e.g. recycle);
- For each MA $i$: relates to its selected suppliers'(MSA) green factors, and its investment on the environment protection;
- For each CA $z$: relates to its selected suppliers'(MA) green factors.

On the other hand, the carbon footprint of each agent is defined as follows:

- For each MSA $j$: relates to $CO_2$ emissions during its production process;
- For each MA $i$: relates to $CO_2$ emissions during the transportation from its selected suppliers (MSAs), and the $CO_2$ emissions during the production process;
- For each CA $z$: relates to $CO_2$ emissions during the transportation from its selected suppliers (MAs).

This research focuses on supplier selections of CAs, MAs, and MSAs. CAs want to find the optimal MAs which can supply their needed products. MAs seek the optimal MSAs which can supply their needed raw materials. MSAs want to find the optimal partners to establish coalitions when orders of MAs exceed their abilities. In addition, the coalitions dynamically change according to the specific orders rather than keep unchanging. Interactions among CAs, MAs, and MSAs can be included as follows:

- Step 1: CA $z$ makes an order to MAs;
- Step 2: Each MA $i$ evaluates the order from CA $z$ and makes an order to MSAs;
- Step 3: Each MSA $j$ evaluates the order from MA $i$, if it is out of its ability, then goes to Step 4, otherwise goes to Step 5;
- Step 4: MSA $j$ tries to find a coalition, if it successes then goes to Step 5, otherwise reject the order;
- Step 5: MSA $j$ accepts the order from MA $i$ and gives a feedback to MA $i$;
- Step 6: MA $i$ checks whether all MSAs have given responses, if yes then determines the final supplier and gives a feedback to CA $z$, otherwise waits until all feedbacks are received;
- Step 7: CA $z$ checks whether all MAs have given responses, if yes then determines the final supplier, otherwise waits until all the feedbacks are received.

The sequence diagram is shown as Figure 1. It can be generalized into the situation when there are multi-tier suppliers, or multi-tier manufacturers, or multi-tier consumers as well.

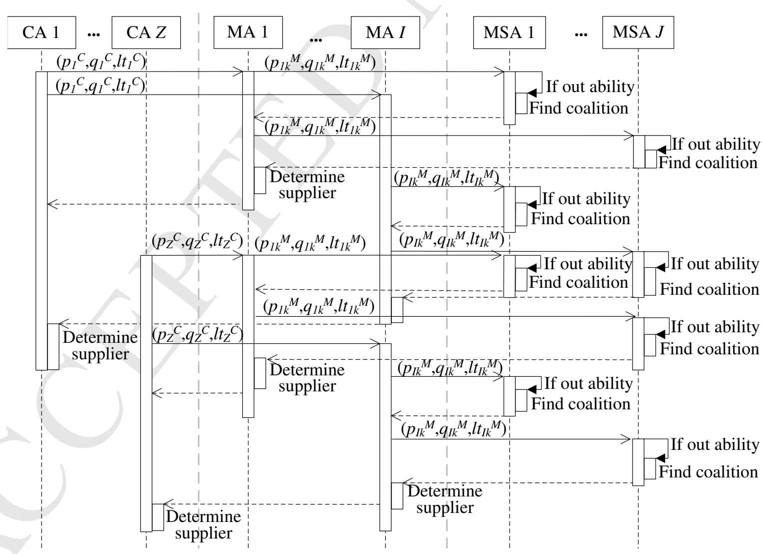


Figure 1: Sequence diagram of the model

## 4. Carbon footprint based incentive supplier selection

In this research, we try to establish a carbon footprint based incentive supplier selection mechanism, which urges agents to improve their decisions to reduce the harm to the environment. In other words, we aim to prompt the agents to select greener suppliers with higher green factors and lower $CO_2$ emissions. However, the agent in the supply chain normally tends to select the suppliers with which it has the highest profit regardless of the green factor. Thus, in this research we assume that the final profit of the participant is not only related to economic attributes, but also related to environmental attributes. As we have mentioned in Section 3.2, the green factor of the agent is affected by its selected suppliers. The green factor of the agent will be decreased if the green factor of the selected supplier is lower than the agent's green factor, and vice versa. We define a reward function $\varrho(g)$ and a penalty function $\varphi(CE)$ to encourage agents to select suppliers with higher green factors and lower $CO_2$ emissions, where

$$\varrho(g) = \begin{cases} 0, & \text{if } g \leq g^{min} \\ \theta_i, & \text{if } g_{i-1} \leq g \leq g_i \\ \theta^{max}, & \text{if } g \geq g^{max} \end{cases}, \tag{1}$$

$$\varphi(CE) = \begin{cases} 0, & \text{if } CE \leq e^{min}, \\ \delta_i, & \text{if } e_{i-1} \leq CE \leq e_i \\ \delta^{max}, & \text{if } CE \geq e^{max} \end{cases}. \tag{2}$$

The reward and penalty functions are piece-wise functions related to green factors ($g$) and $CO_2$ emissions ($CE$). The higher green factors agents gain, the higher rewards they will acquired. The lower $CO_2$ emissions agents emit, the lower penalty they will be charged. The threshold values ($\theta$ and $\delta$) for reward and penalty functions can be determined according to the preferences of agents.

### *4.1. Determinations of green factors and $CO_2$ emissions*

In this section, determinations of green factors and $CO_2$ emissions of MSAs, MAs, and CAs will be discussed.

#### *4.1.1. Green factors and $CO_2$ emissions of MSAs*

For each MSA $j$, it tries to establish a coalition if the order of MA $i$ exceeds its ability. The order is allocated according to both abilities and green factors of the members in the coalition. Thus, if coalition $s_{ijl}$ is determined as the final coalition, then according to the definition of green factor mentioned in Section 3.2 we have

$$gf_{ijl}^{SS} = \omega_g \frac{gf_j^S QST_j^S + \Delta_g \sum_{k=1}^{K} \eta_k q_{ij}^M}{QST_j^S + \sum_{k=1}^{K} \eta_k q_{ij}^M} + \omega_e EI_j^S, \tag{3}$$

$$\Delta_g = \left( \sum_{k=1}^{K} \sum_{j' \in s_{ijl}} \frac{QS_{ij'k} gd^S_{j'k}}{\eta_k q^M_{ij}} \right) / K, \tag{4}$$

$$CE^{SS}_{ijl} = \varepsilon_2 \sum_{j' \in s_{ijl}} \sum_{k=1}^{K} T^S_{j'k} P^S_{j'k} QS_{ij'k}, \tag{5}$$

$$QS_{ij'k} = \frac{A_{ij'k} g^S_{j'k}}{\sum\limits_{j \in s_{ijl}} A_{ijk} gd^S_{jk}} \eta_k q^M_{ij}, \forall j' \in s_{ijl}. \tag{6}$$

where the first part of equation (3) is related to green degrees of items (raw materials), and the second part is related to the environmental investment of MSA $j$. The importance of the selected supplier's green factor and environmental investment can be adjusted by setting the related weight ($\omega_g$ and $\omega_e$). Equation (4) is used to calculate the average green factor of MSA $j$ if it select coalition $s_{ijl}$. Equation (5) is used to calculate total $CO_2$ emissions during the production process if MSA $j$ selects coalition $s_{ijl}$ as the final supplier for MA $i$. Equation (6) is used to calculate quantity allocations of members in coalition $s_{ijl}$. The profit of MSA $j$ if it selects coalition $s_{ijl}$ is defined as

$$\begin{aligned} \pi^S_{ijl} = \sum_{k=1}^{K} p^M_{ijk} \eta_k q^M_{ij} - \sum_{k=1}^{K} \sum_{j' \in s_{ijl}} C^S_{j'k} QS_{ij'k} - \varphi(CE^{SS}_{ijl}) CE^{SS}_{ijl} \\ + \varrho(gf^{SS}_{ijl})(gf^{SS}_{ijl} - \frac{1}{K} \sum_{k=1}^{K} gd^S_{jk}), \end{aligned} \tag{7}$$

where the first part of equation (7) is the payment from MA $i$, the second part is the cost for the coalition to produce the order of MA $i$, the third part is the penalty for $CO_2$ emissions of the coalition to produce the required order, and the last part is the reward related to the final green factor. We can see from the last part of (7) that the reward will be negative if the final green factor of MSA $j$ after selecting coalition $s_{ijl}$ as supplier is less than its initial green factor. In other words, if MSA $j$ wants to increase its profit, it needs to select the supplier with which its green factor will be increased.

#### *4.1.2. Green factors and $CO_2$ emissions of MAs*

For each MA $i$, if it selects MSA $j$ as the final supplier, then we have

$$gf^{MS}_{ij} = \omega_g \Big( \frac{Q^M_i gf^M_i}{Q^M_i + \sum_{k=1}^{K} \eta_k q^M_{ij}} + \sum_{k=1}^{K} \frac{\eta_k q^M_{ij} gd^S_{jk}}{Q^M_i + \sum_{k'=1}^{K} \eta_{k'} q^M_{ij}} \Big) + \omega_e EI^M_i, \tag{8}$$

$$CE^M_{ij} = \varepsilon_1 \sqrt{\left| x^M_i - x^S_j \right|^2 + \left| y^M_i - y^S_j \right|^2} + \varepsilon_2 T^M_i P^M_i q^M_{ij}, \tag{9}$$

where the first part of equation (8) is used to calculate the green factor of MA $i$ if it selects MSA $j$ as the final supplier, and the second part is related to the environmental investment. Equation (9) is used to calculate total $CO_2$ emissions if MA $i$ selects MSA $j$ as the final supplier. The first part of (9) is the $CO_2$ emissions during the transportation from MSA $j$ to MA $i$, and the second part is the $CO_2$ emissions during the production process. The profit of MA $i$ can be included as

$$\pi_{ij}^{M} = -\sum_{k=1}^{K} p_{ijk}^{M} \eta_k q_{ij}^{M} - CS_i - \varphi(CE_{ij}^{M})CE_{ij}^{M} + \varrho(gf_{ij}^{MS})(gf_{ij}^{MS} - gf_i^{M}) \quad (10)$$

where the first part of equation (10) is the payment MA $i$ needs to pay for the product, the second part is the setup cost, the third part is the penalty related to $CO_2$ emissions, and the last part is the reward related to the green factor.

#### *4.1.3. Green factors and $CO_2$ emissions of CAs*

For each CA $z$, if it selects MA $i$ as the final supplier, then we have

$$gf_{zi}^{CM} = \frac{Q_z^C}{Q_z^C + q_{zi}^C} gf_z^C + \frac{q_{zi}^C}{Q_z^C + q_{zi}^C} gf_i^M, \quad (11)$$

$$CE_{zi}^{C} = \varepsilon_1 \sqrt{\left|x_z^C - x_i^M\right|^2 + \left|y_z^C - y_i^M\right|^2}, \quad (12)$$

where the first part of (11) is related to the initial green factor of CA $z$, and the second part is related to the green factor of MA $i$. Equation (12) is used to calculate $CO_2$ emissions during the transportation from MA $i$ to CA $z$. The profit of CA $z$ selecting MA $i$ can be concluded as

$$\pi_{zi}^{C} = -p_{zi}^{M} q_{zi}^{C} - \varphi(CE_{zi}^{C})CE_{zi}^{C} + \varrho(gf_{zi}^{CM})(gf_z^C - gf_{zi}^{CM}), \quad (13)$$

where the first part of (13) is the payment CA $z$ needs to pay for MA $i$, the second part is the penalty related to $CO_2$ emissions, and the last part is the reward related to the green factor.

### *4.2. Supplier determination*

In this section, determinations of final suppliers for MSAs, MAs, and CAs will be discussed. Each agent has an individual preference on the profit, the green factor, and total $CO_2$ emissions. Some agents care more about their profits, while the others may pay more attentions to their environmental performances (eg. green factors and/or $CO_2$ emissions). Thus, three models, which respectively aim to maximize total profits, maximize green factors of agents, and minimize total $CO_2$ emissions, are proposed. The objective function for Model 1, Model 2, and Model 3 is defined as $OBJ1$, $OBJ2$, and $OBJ3$, respectively. There are multiple agents in the GSCN, and each agent strives to select the supplier, with which it has the optimal objective function. Thus, an optimal allocation scheme is required to solve the conflicts among agents. In Model 1, the final allocation scheme is related to the profits of MSAs, MAs, and CAs. However, the profits of agents (see (7), (10), and (13)) are not only related to their economic attributes (price and quantity), but also depend on their environmental attributes (green factor and $CO_2$ emissions). Moreover, green factors of agents rely heavily upon the green factors of their selected suppliers, and $CO_2$ emissions of agents rely on the transportation distances from their selected suppliers. Thus, agents will tend to select suppliers with higher green factors and lower transportation distances in order to maximize their profits. In Model 2, the final allocation scheme is related to green factors of agents, and the green factors of agents (see (3), (8), and (11)) depend on the green factors of their selected suppliers. Therefore, agents will tend to select suppliers with higher green factors in order to increase their own green factors. In Model 3, the final allocation scheme is related to $CO_2$ emissions of agents, and the $CO_2$ emissions of MAs and CAs (see (9), and (12)) depend on the transportation distances of their selected suppliers. Thus, MAs and CAs will tend to select the suppliers with shorter transportation distances to decrease their own $CO_2$ emissions. From above analysis, we can see that all the proposed three models will urge agents to make greener decisions. $m^1_{zijl}$, $m^2_{zijl}$, and $m^3_{zijl}$ are defined to record the final allocation for Model 1, Model 2, and Model 3, respectively. The variables $m^1_{zijl}$, $m^2_{zijl}$, and $m^3_{zijl}$ equal to 1 if CA $z$ is allocated to MA $i$, and MA $i$ is allocated to coalition $s_{ijl}$ in Model 1, Model 2, and Model 3, respectively. Otherwise, $m^1_{zijl}$, $m^2_{zijl}$, and $m^3_{zijl}$ equal to 0. Consequently, we have

$$OBJ1 \qquad \max \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L} m^1_{zijl}(\pi^M_{ij} + \pi^S_{ijl}) + \sum_{z=1}^{Z}\sum_{i=1}^{I} m^1_{zijl}\pi^C_{zi} \tag{14}$$

$$\text{s.t.} \quad \sum_{j' \in s_{ijl}} A_{ij'k} \geq \eta_k q^M_{ij}, \forall k \tag{15}$$

$$\pi^{SC}_{ij'l} > 0, \forall j' \in s_{ijl}, j' \neq j \tag{16}$$

$$\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L} m^1_{zijl} = 1 \tag{17}$$

$$OBJ2 \qquad \max\{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L} m^2_{zijl}(gf^{MS}_{ij} + gf^{SS}_{ijl}) + \sum_{z=1}^{Z}\sum_{i=1}^{I} m^2_{zijl} gf^{CM}_{zi}\} \tag{18}$$

$$\text{s.t.} \quad \sum_{j' \in s_{ijl}} A_{ij'k} \geq \eta_k q^M_{ij}, \forall k \tag{19}$$

$$\pi^{SC}_{ij'l} > 0, \forall j' \in s_{ijl}, j' \neq j \tag{20}$$

$$\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L} m^2_{zijl} = 1 \tag{21}$$

$$OBJ3 \qquad \min\{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L} m^3_{zijl}(CE^M_{ij} + CE^{SS}_{ijl}) + \sum_{z=1}^{Z}\sum_{i=1}^{I} m^3_{zijl} CE^C_{zi}\} \tag{22}$$

$$\text{s.t.} \sum_{j' \in s_{ijl}} A_{ij'k} \geq \eta_k q_{ij}^M, \forall k \tag{23}$$

$$\pi_{ij'l}^{SC} > 0, \forall j' \in s_{ijl}, j' \neq j \tag{24}$$

$$\sum_{z=1}^{Z} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{l=1}^{L} m_{zijl}^3 = 1 \tag{25}$$

where (14), (18), and (22) are objective functions for three models. Equations (15), (19) , and (23) are used to ensure the final determined coalition is in ability. Equations (16), (20), and (24) are used to ensure all members in coalition $s_{ijl}$ are profitable. Equations (17), (21), and (25) are used to ensure each order can only be allocated to one supplier. Moreover, the final green factors and total $CO_2$ emissions of the agents will be accumulated once the final supplier is determined. We have

$$gf_j^S = \sum_{l=1}^{L} m_{zijl}^e gf_{ijl}^{SS}, \tag{26}$$

$$CET_j^S = CET_j^S + \sum_{l=1}^{L} m_{zijl}^e CE_{ijl}^{SS}, \tag{27}$$

$$Q_j^S = Q_i^S + \sum_{l=1}^{L} m_{zijl}^e \sum_{k=1}^{K} \eta_k q_{ij}^M, \tag{28}$$

$$gf_i^M = \sum_{j=1}^{J} m_{zijl}^e gf_{ij}^{MS}, \tag{29}$$

$$CET_i^M = CET_i^M + \sum_{j=1}^{J} m_{zijl}^e CE_{ij}^M, \tag{30}$$

$$Q_i^M = Q_i^M + \sum_{j=1}^{J} m_{zijl}^e \sum_{k=1}^{K} \eta_k q_{ij}^M, \tag{31}$$

$$gf_z^C = \sum_{i=1}^{I} m_{zijl}^e gf_{zi}^{CM}, \tag{32}$$

$$CET_z^C = CET_z^C + \sum_{i=1}^{I} m_{zijl}^e CE_{zi}^C, \tag{33}$$

$$Q_z^C = Q_z^C + \sum_{i=1}^{I} m_{zijl}^e q_{zi}^C, \tag{34}$$

where $e$ = 1, 2, and 3. We can see that both green factors and $CO_2$ emissions of MSAs, MAs, and CAs will be affected by their final determined suppliers. Thus, all agents should make their decisions from a long term consideration in order to obtain more orders.

## 5. Numerical Cases

In this section, calculations are provided to verify the feasibility and superiority of the proposed model. It is assumed that there are five MSAs, five MAs, and five CAs in the GSCN, and each product needs five items. The variable $\varepsilon_1$ equals to $6.683 \times 10^{-4}$ metric ton/km, and $\varepsilon_2$ equals to $6.89551 \times 10^{-4}$ metric ton/kwh according to the conversion between the distance and $CO_2$ emissions proposed by EPA (United States Environmental Protection Agency). If the research is generalized to consider $SO_2$, NOX, and PM, the values of $\varepsilon_1$ and $\varepsilon_2$ will change to the other values. The maximum and minimum green factor of a agent is set to 100 and 0, respective. We assume the initial values of green factors for agents obey to the uniform distribution $U(0, 100)$. The green factors will be changed according to the proposed selection mechanism during iterations. The other parameters (such as: price, cost, quantity ) in the calculations are randomly set obey to uniform distributions. Users can set the upper and lower bounds of distributions according to their own preferences (e.g. actual trading data). One example of initial green factors of MSAs, MAs, and CAs are shown in Table 1. The initial values of $CO_2$ emissions of MSAs, MAs, and CAs are set as 0. Eclipse IDE for Java Developers and ILOG CPLEX 12.0 are used to execute the calculations.

Table 1: Initial values of the green factors of the agents.

| | MSA | | | | | MA | CA |
|---|---|---|---|---|---|---|---|
| | $k$=1 | $k$=2 | $k$=3 | $k$=4 | $k$=5 | | |
| 1 | 64.80 | 27.56 | 15.54 | 25.47 | 57.38 | 50 | 60 |
| 2 | 20.76 | 88.17 | 37.13 | 66.39 | 55.22 | 40 | 40 |
| 3 | 36.39 | 34.99 | 70.92 | 68.03 | 69.39 | 30 | 70 |
| 4 | 87.79 | 94.35 | 49.87 | 49.64 | 88.12 | 45 | 55 |
| 5 | 38.47 | 32.99 | 10.47 | 56.70 | 6.18 | 35 | 69 |

We provide two cases in this section:

- Case 1: aims to find allocation schemes for three models, and check the evolutions of green factors and $CO_2$ emissions in three models;
- Case 2: compares proposed models with the traditional model which didn't consider environmental attributes.

### 5.1. Case 1

In this case, we try to find the optimal allocation schemes for three models. Allocations among the agents in three models are shown as Table 2. We can see that MA 1 in Model 1 is allocated to coalition {12} of MSA 1, and CA 1 is allocated to MA 4. Coalition {12} means the coalition consists of MSA 1 and MSA 2, and the MSA 1 is the leader of the coalition. MA 2 in Model 1 is allocated to coalition {51} of MSA 5, and CA 2 is allocated to MA 1. MA 3 in Model 1 is allocated to coalition {21} of MSA 2, and CA 3 is allocated to MA 4.

MA 4 in Model 1 is allocated to coalition {12} of MSA 1, and CA 4 is allocated to MA 2. MA 5 in Model 1 is allocated to coalition {12} of MSA 1, and CA 5 is allocated to MA 4. The allocations of Model 2 are shown as the $5^{th}$ column to the $9^{th}$ column of Table 2. We can see that MA 1 in Model 2 is allocated to coalition {21} of MSA 2, and CA 1 is allocated to MA 1. MA 2 in Model 2 is allocated to coalition {12} of MSA 1, and CA 2 is allocated to MA 1. MA 3 in Model 2 is allocated to coalition {31} of MSA 3, and CA 3 is allocated to MA 1. MA 4 in Model 2 is allocated to coalition {41} of MSA 4, and CA 4 is allocated to MA 4. MA 5 in Model 2 is allocated to coalition {41} of MSA 4, and CA 5 is allocated to MA 1. The allocations of Model 3 are shown as the $10^{th}$ column to the $14^{th}$ column of Table 2. We can see that MA 1 in Model 3 is allocated to coalition {41} of MSA 4, and CA 1 is allocated to MA 2. MA 2 in Model 3 is allocated to coalition {12} of MSA 1, and CA 2 is allocated to MA 1. MA 3 in Model 3 is allocated to coalition {51} of MSA 5, and CA 3 is allocated to MA 5. MA 4 in Model 3 is allocated to coalition {12} of MSA 1, and CA 4 is allocated to MA 2. MA 5 in Model 3 is allocated to coalition {12} of MSA 1, and CA 5 is allocated to MA 1.

Table 2: Allocations among the agents of three models

| Model 1 | | | | Model 2 | | | | Model 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MA | MSA | CA | MA | MA | MSA | CA | MA | MA | MSA | CA | MA |
| 1 | {12} | 1 | 4 | 1 | {21} | 1 | 1 | 1 | {41} | 1 | 2 |
| 2 | {51} | 2 | 1 | 2 | {12} | 2 | 1 | 2 | {12} | 2 | 1 |
| 3 | {21} | 3 | 4 | 3 | {31} | 3 | 1 | 3 | {51} | 3 | 5 |
| 4 | {12} | 4 | 2 | 4 | {41} | 4 | 4 | 4 | {12} | 4 | 2 |
| 5 | {12} | 5 | 4 | 5 | {41} | 5 | 1 | 5 | {12} | 5 | 1 |

Moreover, average green factors, total $CO_2$ emissions, and total profits of the GSCN in three models are shown in Figure 2. We can see that Model 1 has the highest total profit (see Figure 2(a)), because the objective of Model 1 is to maximize the total profit. Model 2 has the highest green factor (see Figure 2(b)), because the objective of Model 2 is to maximize the green factors. Model 3 has the lowest $CO_2$ emissions (see Figure 2(c)), because the objective of Model 3 is to minimize the total $CO_2$ emissions. .

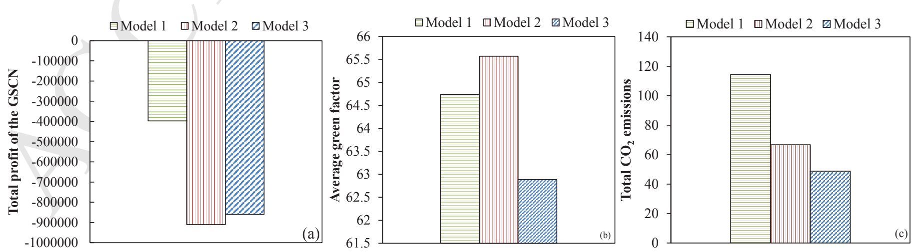


Figure 2: Average green factor, total $CO_2$ emissions, and total profits

Then, we repeat the calculation 100 times to see the evolutions of the green factors and $CO_2$ emissions in three models. The numbers and individual values of MSAs, MAs, and CAs keep unchanging. However, the procurement price, quantity, and lead time of MAs and CAs for each calculation will change. In that case, the green factor and $CO_2$ emissions of each agent will be accumulated. The vibrations of the green factors of MSAs, MAs, and CAs are shown in Figure 3. We can see from Figure 3 (a) - (c) that the green factors vibrate with the iterations. It's verified that the green factors will finally converge to a certain value when $t$ is long enough.

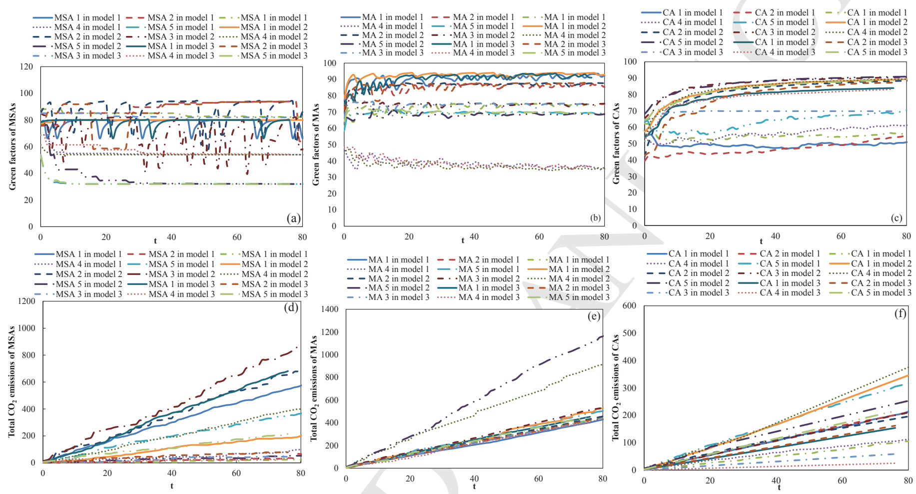


Figure 3: Vibrations of green factors and total $CO_2$ emissions of MAs and CAs in three models

If we repeat the calculation 1000 times and take MA 1 as an example to show the detailed vibrations of the green factor. The result is shown as Figure 4. We can see that the final green factors of all three models will asymptotically converge to a certain value after enough iterations. That's because the numbers of the participants in the GSCN are fixed.

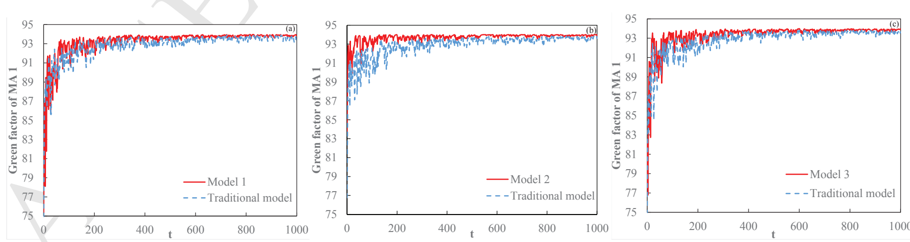


Figure 4: Green factor evolutions of MA 1 in three models

Moreover, we can see from Figure 3 (a) that the green factors of some MSAs are not converging to a certain value. The reasons lead to this situation can be concluded as follows:

- MSA's green factor is partly related to the green degree of its raw materials, and the green degree keeps unchanging during the iteration;
- Those MSAs are not selected for their limited abilities (cannot produce the items or the expected prices are too high to satisfied).

On the other hand, the total $CO_2$ emissions of MSAs, MAs, and CAs at each iteration are shown in Figure 3 (d) - (f). We can see that the total $CO_2$ emissions increase as the iteration goes by. However, we cannot see whether the proposed models urge the agents to make decisions to increase their green factors and reduce $CO_2$ emissions. Thus, a comparison between the proposed models and the other model is required.

### *5.2. Case 2*

In Case 2, we will compare the proposed model with the traditional model. In traditional model, only economic attributes (price, quantity, and lead time) are considered, and the objective is to maximize the total profit. The profits of MSAs, MAs, and CAs in traditional model are calculated as

$$\overline{\pi}_{ijl}^{S} = \sum_{k=1}^{K} p_{ijk}^{M} \eta_k q_{ij}^{M} - \sum_{k=1}^{K} \sum_{j' \in s_{ijl}} C_{j'k}^{S} QS_{ij'k}, \tag{35}$$

$$\overline{\pi}_{ij}^{M} = - \sum_{k=1}^{K} p_{ijk}^{M} \eta_k q_{ij}^{M} - CS_i, \tag{36}$$

$$\overline{\pi}_{zi}^{C} = -p_{zi}^{M} q_{zi}^{C}. \tag{37}$$

Then, we compare the proposed three models with the traditional model. Parameter settings of the traditional model and proposed models are the same. The purpose is to see the evolutions of green factors and total $CO_2$ emissions in the traditional model and proposed models. The results are shown as Figure 5. We can see from Figure 5 (a) and (d) that both the average green factor and total $CO_2$ emissions of Model 1 is lower than those of the traditional model. That's because Model 1 aims to maximize the total profit, and the total profit is related to the green factors and total $CO_2$ emissions. The maximum value of green factor is set to 100, and there is no upper bounder for the $CO_2$ emissions. Thus, the agents strive to reduce $CO_2$ emissions to decrease the penalties. If we decrease the penalty $\varphi(\cdot)$ and increase the reward $\varrho(\cdot)$, then Model 1 will have higher green factor than the traditional model. The average green factor of Model 2 is higher than that of the traditional model (see Figure 5 (b)), and the total $CO_2$ emissions in Model 2 are less than those in the traditional model (see Figure 5(e)). In Model 3, the average green factor is higher than those in the traditional model (see Figure 5 (c)), and the total $CO_2$ emissions are less than those in the traditional model (see Figure 5 (f)) as well.

We can see from the above analysis that all proposed three models have merits on reducing the harm to the environment. In other words, the proposed

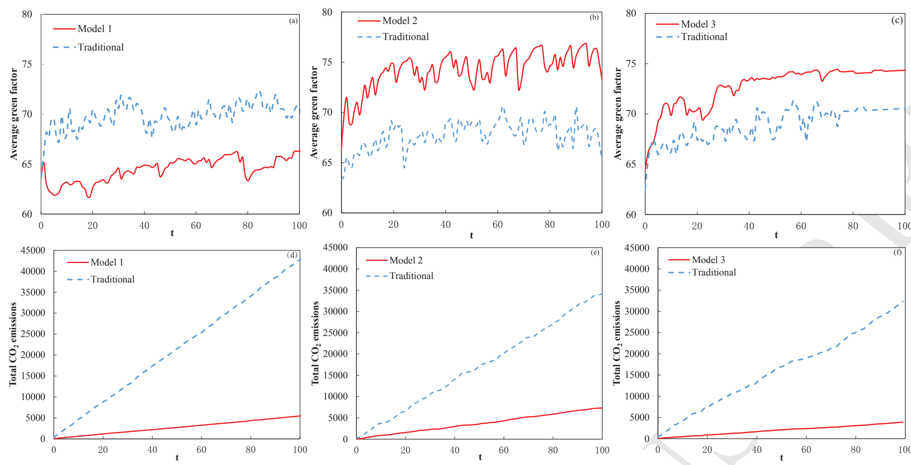


Figure 5: Comparison of the proposed three models and the traditional model

models urges the participants in the GSCN to improve their strategies to select the suppliers with greener green factors and lower $CO_2$ emissions. Moreover, we can see that Model 2 is good at increasing green factors, and Model 3 is good at reducing the $CO_2$ emissions. One can select its preferred model according to its own preference.

## 6. Conclusions

In this research, based on a carbon footprint involving economic and environmental attributes, a supplier selection mechanism was proposed to reduce the harm to the environment. We proposed a novel way to determine the strategies for environmental attributes. The profits of the participants strongly depended on both the economic and environmental attributes, which promotes the participants to preferably select the greener suppliers. This research provided not only an evaluation and selection mechanism, but also an effective incentive selection model which urges the participants initiatively improve their strategies. On the other hand, three supplier determination models are proposed for different purposes. Participants can choose models according to their own preferences on profits, green factors, and $CO_2$ emissions. It was verified that Model 2 has the best performance on increasing the green factors, and Model 3 has the best performance on reducing $CO_2$ emissions. Moreover, it is verified that the proposed models urge the agents to improve their strategies after several iterations. The proposed models can be applied into the e-commerce (online shopping) when the products are free shipping. The supervisor of the market platform can force consumers to select suppliers with the shortest distance and highest green factor, and force suppliers to supply greener products by adopting the proposed model.

In this research, the agents improve their strategies in a simple way. Adopting learning algorithms will be a next step for this research. In this research, the dynamic refers to the unfixed of the coalitions, however, it also can be generalized to the situation that the numbers of MSAs, MAs, and CAs are not fixed. Moreover, the joint-delivery model will be considered to reduce the $CO_2$ emissions for the next step.

**Acknowledgment**

This work was supported by National Natural Science Foundation of China [61540045]. This work was also supported by Shanghai Science and Technology Commission [14170501500, 14DZ2280200, 17595810300], and Shanghai Talent Development Fund [201508].

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