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A strategic decision-making model considering the social costs of carbon dioxide emissions for sustainable supply chain management

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A B S T R A C T

Incorporating sustainability into supply chain management has become a critical issue driven by pressures from governments, customers, and various stakeholder groups over the past decade. This study proposes a strategic decision-making model considering both the operational costs and social costs caused by the carbon dioxide emissions from operating such a supply chain network for sustainable supply chain management. This model was used to evaluate carbon dioxide emissions and operational costs under different scenarios in an apparel manufacturing supply chain network. The results showed that the higher the social cost rate of carbon dioxide emissions, the lower the amount of the emission of carbon dioxide. The results also suggested that a legislation that forces the enterprises to bear the social costs of carbon dioxide emissions resulting from their economic activities is an effective approach to reducing carbon dioxide emissions.

1. Introduction

In the past decade, supply chain management (SCM) has received a great deal of attention from practitioners and scholars because of globalization. Mentzer et al. (2001) have defined SCM as the systemic, strategic coordination of traditional business functions with the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole. Usually, studies of SCM have concentrated on economic issues (Goetschalcks and Fleischmann, 2008), such as finding ways to minimize the operational costs (Nagurney, 2010a) or to maximize profits (Nagurney, 2010b).

However, with increasing awareness of the need for environmental protection and sustainability, companies are urged to effectively incorporate sustainability issues into their SCM schemes, prompted by the pressures from governments, customers, and various stakeholder groups (Gold et al., 2010). Carter and Rogers (2008) defined sustainable supply chain management (SSCM) as the strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of an individual company and its supply chain. Many approaches have been observed for addressing sustainability issues in supply chain management, including green design (Lin, 2013), green purchasing (Bai and Sarkis, 2010), green manufacturing (Lin, 2013; Shang et al., 2010), reverse logistics (Eltayeb et al., 2011), etc.

Nevertheless, what previous studies have neglected to consider are the environmental, social, and economic threats resulting from climate changes (Marchant, 2010). The direct effects of climate changes include changes in temperature, precipitation, soil moisture, and sea level. The main cause of climate changes is global warming, which is mainly brought on by greenhouse gas emissions, with carbon dioxide (CO_2) as the main man-made greenhouse gas (Karl and Trenberth, 2003; Lashof and Ahuja, 1990). Damages caused by the CO_2 emissions are spread across time and space (Anthoff et al., 2009a). Thus, the reduction of CO_2 emissions has become an urgent global issue in the last decade for mitigating global warming (Morath, 2010). Several approaches, such as emission trading scheme, agreed emissions targets, and carbon tax have been proposed for reducing CO_2 emissions (Forster et al., 2006; Zhang and Folmer, 1998). Emission trading scheme has been applied in the European Union, but have failed because of the unequal access to information and market inefficiency (Andrew, 2008). The Kyoto Protocol provided for agreed emissions targets, but the evidence available to date indicates that most countries will not meet its targets. This is because of the need to sustain and grow economic activities (Andrew, 2008). Compared to emission trading scheme and agreed emissions targets, carbon tax is considered to be more transparent and visible, and hence harder to evade or

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avoid (Andrew, 2008). The carbon tax levy has been considered as one of the most common market-based approaches from the aspect of economic incentives in carbon emission regulation (Oreskes, 2011). The optimal carbon tax is the tax on carbon emissions that balances the incremental costs of reducing carbon emissions with the incremental benefits of reducing climate damages. In an optimal regime, the carbon tax could equal the social costs resulting from carbon emissions (Nordhaus, 2007).

As mentioned above, many unrecoverable damages caused by CO_2 emissions could result in tremendous social costs. Yet, most producers of CO_2 emissions do not pay attention to these social costs while societies pay for them. CO_2 emissions adversely affect everyone, regardless of their location and source, whether or not people are willing to pay to avoid the resulting costs. To mitigate the damages caused by CO_2 emissions, it is necessary to take the social costs of CO_2 emissions into consideration for all economic activities. In this study, the authors propose a model considering both the operational costs and social costs of CO_2 emissions in SCM. The objective of this study is to provide a useful model for decision-makers of SCM for planning a sustainable supply chain. This study was organized as follows: first, a literature review regarding SSCM, as well as the estimation of the social costs caused by CO_2 emissions, was offered. Second, the research problem of this study was provided. Third, a mathematical model with an illustrative case was developed. Finally, the conclusion, discussion, recommendations, and limitations for this study were presented.

2. Literature review

In this section, the authors of the present study review past literature related to SSCM and the estimation of the social costs of CO_2 emissions. The authors also aim to demonstrate the significance of incorporating the social costs of CO_2 emissions into SSCM.

2.1. Sustainable supply chain management (SSCM)

The literature about SCM has increasingly focused on issues relating to sustainability, driven by governments and both profit and nonprofit organizations in the past decades (Ageron et al., 2012). SSCM is seen as the integration of environmental, social, and economic goals in the systematic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual company and its chains for sustainable development (Carter and Rogers, 2008). Previous studies have addressed sustainability in supply chain management from various perspectives, including product design, materials purchasing, supplier selection, manufacturing, remanufacturing, reverse logistics, waste management, etc.

For example, Alves et al. (2009) developed a sustainable design procedure for employing green materials in product design procedure. Zsidisin and Siferd (2001) concentrated on green purchasing for addressing the sustainability issue in SCM. Bai and Sarkis (2010) introduced a multi-stage, multi-method approach considering economic, environmental, and social factors for selecting sustainable suppliers. Govindan et al. (2013) applied a fuzzy multi criteria approach for measuring sustainability performance of a supplier based on the triple bottom line approach. Manzini and Accorsi (2013) proposed an integrated approach to control quality, safety, sustainability, and logistics efficiency of food products and processes along the whole food supply chain, from farm to fork simultaneously. Michelsen et al. (2006) applied eco-efficiency as an instrument to measure sustainability of furniture production supply chains. Zhu et al. (2010) used empirical research to examine if different types of manufacturing enterprises with environmental-oriented supply chain cooperation (ESCC) exist. Mancini et al. (2012) used the MIPS (Material Input per Service Unit) methodology to assess the sustainability along the supply chains of three Italian foodstuffs. Liu et al. (2012) proposed a new hub-and-spoke integration model to integrate green marketing and sustainable supply chain management from six dimensions: product, promotion, planning, process, people, and project. Gold et al. (2013) used three case studies to address the question of how sustainable supply chain management (SSCM) applied to BoP (Base of the Pyramid) projects can help multinational corporations achieve their sustainability goals. Caniato et al. (2012) used a multiple case study methodology to analyze different kinds of companies tackling the environmental sustainability issue. Shaverdi et al. (2013) applied the fuzzy AHP approach for evaluating supply chain management sustainability in the publishing industry. Srivastava (2007) made a much wider attempt to address SSCM, including product design, material source and selection, manufacturing process, delivery of the final product to the consumer, and end-of-life management of the product after its useful life.

In recent years, several studies addressed the CO_2 emission issue in SCM. For example, Sundarakani et al. (2010) employed the Eulerian and Lagrangian transport models to estimate carbon emissions across the supply chain, including emissions from material processing, manufacturing, warehousing, inbound logistics, and outbound logistics. They suggested that carbon emissions across stages in a supply chain can constitute a significant threat that requires careful attention in the design phase of supply chains. Lee (2011) integrated carbon emission as an indicator for automobile supply chain management. Chaabane et al. (2012) proposed a model to design a sustainable supply chain under the carbon emission trading scheme. However, the carbon emission trading scheme has been applied in the European Union, but has failed because of its serious shortcomings in design (Andrew, 2008; Sovacool, 2011). Emissions credits were distributed for free as a rough function of past emissions, yet such a concession provided enterprises an incentive to emit more during the early years of the program to receive a larger allocation in the future (Hepburn, 2007). Furthermore, most European countries allow their enterprises to determine their own baselines and to set their own abatement cost curves, so most enterprises have a tendency to revise their estimates upward to obtain more generous allowances (Sovacool, 2011).

Compared to the emission trading scheme, carbon tax is considered to be more transparent and visible, and thus harder to evade or avoid (Andrew, 2008). The optimal carbon tax is equal to the social costs of carbon emissions (Nordhaus, 2007). Thus, in this study, the authors developed a mathematical model through integrating social costs of CO_2 emissions into supply chain management to reduce CO_2 emissions for sustainability.

2.2. The social costs of CO_2 emission

Kapp (1963) defined social costs as all direct and indirect losses sustained by third persons or the general public as a result of unrestrained economic activities. These social losses may take the form of damages to human health, the destruction of property values, and the premature depletion of ecosystems. The social costs of CO_2 emissions might be defined as the monetary value of the damage made by the emission of one extra ton of CO_2 at some point of time (Etchart et al., 2012; Guo et al., 2006; Pearce, 2003).

Owing to a great number of negative impacts in physical, biological, and human systems caused by CO_2 emissions, many studies have tried to estimate the social costs of CO_2 emissions. Existing studies that have attempted to place a value on the social costs of emitting CO_2 have employed one of two alternative approaches. They are the cost-benefit analysis (CBA) approach and the marginal cost (MC) approach (Clarkson and Deyes, 2002).

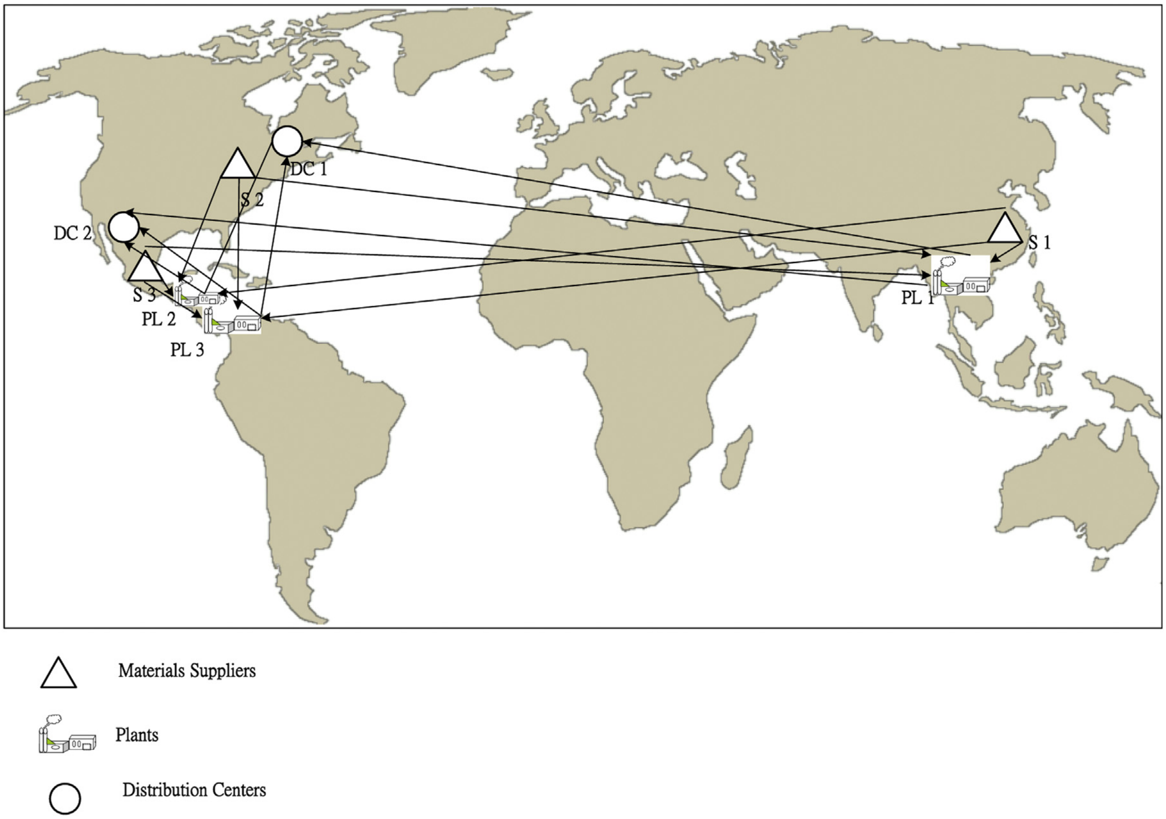

Fig. 1. Illustration of a supply chain management problem.

Under the CBA approach, the social costs of CO_2 emissions are expressed as the level of carbon tax necessary to achieve the optimum level of emissions. In the cost-benefit framework, emissions are at their optimal level where the incremental social costs of reducing emissions by one ton are equal to the additional social benefits of avoided damages (Clarkson and Deyes, 2002). The CBA would set the optimal amount of CO_2 emissions reduction at the point where these social costs exactly equal the incremental costs of controlling emissions. The higher the value for the social costs of CO_2 emissions, the more control is needed (Pearce, 2003). The larger the social costs of CO_2 emissions, the more attractive the investment in CO_2 emissions reductions is (Guo et al., 2006). In contrast, the MC approach is to estimate marginal damage costs of CO_2 emissions, the damage done by emitting an additional ton of CO_2 emissions, or the

Table 1
Demand requirements of each distribution center.

Distribution center	Location	Requirements
DC1	New York	90,000
DC2	Los Angeles	90,000

Table 2
Materials purchasing cost of plants from suppliers ($/garment).

Plant	Supplier		
	S1 (China)	S2 (USA)	S3 (Mexico)
PL1	4.5	5.1	4.9
PL2	4.67	4.85	4.62
PL3	4.68	4.9	4.77

Retrieved from Benchmarking the Competitiveness of Nicaragua's Apparel Industry (O'Rourke Group Partners, LLC, 2011)

Table 3
Production capacity, product cost, and CO_2 emissions of each plant.

Plant	Production capacity (garments/month)	Production cost ($/garment)	CO_2 equivalents emission of production process (kg/Garment)
PL1	84,000	1.908	18
PL2	72,000	2.755	14
PL3	66,000	2.41	16

Retrieved from Benchmarking the Competitiveness of Nicaragua's Apparel Industry (O'Rourke Group Partners, LLC, 2011) and Levi Strauss & Co. Life Cycle Approach to Examine the Environmental Performance of its Products (Levi Strauss & Co.).

Table 4
Materials supply capacity of each supplier.

Supplier	Supply capacity (garment/month)
S1 (China)	78,000
S2 (USA)	72,000
S3 (Mexico)	60,000

Table 5
Transportation distance between suppliers and plants (miles).

Material supplier	Transportation type	Plant		
		PL1	PL2	PL3
S1	Ship	3949	7179	7855
	Truck	450	400	350
S2	Ship	10,621	5644	4916
	Truck	350	300	250
S3	Ship	10,653	0	789
	Truck	350	300	250

Transportation distance of cargo ship is retrieved from http://www.searates.com/reference/portdistance/.
Transportation distance of truck is assumed by the authors.

damage avoided by reducing emissions by one ton of CO_2 emissions (Anthoff et al., 2009b; Clarkson and Deyes, 2002; Tol, 2011).

Many studies have applied either the CBA or MC approach to estimate the social costs of CO_2 emissions. For example, Cline (1992) used the CBA approach to estimate the social costs of CO_2 emissions and had results ranging from $3.6 to $68.5.2/t$CO_2$ emission in 2011–2020 prices (Clarkson and Deyes, 2002). In 1996, the IPCC (Intergovernmental Panel on Climate Change) Working Group III published a review and reported that the social costs of CO_2 ranged from $1.6 to $43.6/t$CO_2$ in 2000 prices (Guo et al., 2006). Stern (2007) has reported marginal damage costs of CO_2 emissions and a result about $85/t$CO_2$.

Recently, Tol (2011) reviewed previous studies and calculated the social costs of carbon emissions and found the average cost to be $31/t$CO_2$. Hope (2011) applied the PAGE09 Model to estimate the social costs of CO_2 emissions and found the average cost of CO_2 emissions to be $100/t$CO_2$. Etchart et al. (2012) also reviewed previous studies and found that the social costs of CO_2 emissions ranged from $5/t$CO_2$ to $200/t$CO_2$.

The broad ranges of estimated results for the social costs of CO_2 emissions could be because of the sheer size of the uncertainties of future climate changes, future socioeconomic variables, particular ethical parameters adopted in each model, different representations of the carbon cycle, different estimates of the rate of warming, etc. (Guo et al., 2006; Tol, 2011) The present authors also found that the estimated results of social costs rates of CO_2 emissions tended to increase gradually through literature reviews.

3. Problem description

This study emphasized the optimal operations of global production and distribution supply chain networks, considering both the operational costs and social costs of CO_2 emissions caused by operating such networks for minimizing the total costs. The network consists of a number of materials suppliers, manufacturing plants, and distribution centers (DCs). In this study, the authors assumed that the materials suppliers and DCs locations are given in advance, and the potential plants, as well as their capacities, are also identified. In addition, the authors assumed that the production of one unit of a product requires one unit of production capacity, regardless of type of product. For each materials supplier and plant and distribution center (DC), decisions must be made on the amount of materials purchased from each supplier for each plant, the total units of products that need to be produced in each plant, and the amounts of products shipping from each plant to each DC.

Operational costs include those costs associated with materials purchasing, production, and transportation. CO_2 emissions include the emissions resulting from the production process and transportation. The decisions to be determined include the demand requirement of every DC. The objective is to minimize the total costs by taking both operational costs and social costs of CO_2 emissions into account.

4. The sustainable supply chain management model and model formation

The authors developed a mixed integer, nonlinear optimization model to provide decision makers of enterprises a guideline for SSCM, with consideration of the operational costs, as well as the social costs of CO_2 emissions.

4.1. Parameter notations and definitions

Before the model is formulated, the basic parameter notations and definitions are introduced. In this study, the authors use the following indices: $j \in J$, a set of candidate suppliers; $k \in K$, a set of potential plants; $l \in L$, a set of possible distribution centers; $m \in M$, a set of materials needed for production, and, $i \in I$, a set of products. The problem parameters and decision variables are defined as follows:

4.1.1. Parameters

MC_{mjk} unit cost of material m ordered from supplier j to plant k
SC_{mj} capacity limit of material m of supplier j
CP_k capacity limit of plant k
PC_{ik} unit production cost of product i in plant k
TC_{ikl} unit transportation cost of product i shipped from plant k to DC l
LC_{ik}, UC_{ik} lower, and upper production capacity limits of product i in plant k
CO_{2ik} unit CO_2 emission of product i produced in plant k
CO_{2r} CO_2 emission of unit weight, unit distance using transportation mode r
W_m unit weight of material m
W_i unit weight of product i

4.1.2. Decision variables

G_{mjk} total units of material m purchased from supplier j to plant k
H_{ikl} total units of product i transported from plant k to DC l
TD_{mr} material m transportation distance of mode r
TD_{ir} product i transportation distance of mode r
SCR_{CO_2} social cost rate of CO_2 emission

4.2. The objective function

The total costs of the objective function include the operational costs and social costs of CO_2 emissions. The operational costs of the supply chain include purchasing costs, production costs, and transportation costs. The social costs of carbon emissions of the supply chain include the carbon emissions caused by the process of products production and transportation of products. Therefore, the objective function to be minimized is given by:

$$\text{Min } Z = \text{Min}\left[\sum_{m,j,k} MC_{mjk}G_{mjk} + \sum_{i,k,l} PC_{ik}H_{ikl} + \sum_{i,k,l} TC_{ikl}H_{ikl} + \left(\sum_{i,k,l} CO_{2ik}H_{ikl} + \sum_{m,j,k,r} CO_{2r}W_mG_{mjk}TD_{mr} + \sum_{i,k,l,r} CO_{2r}W_iH_{ikl}TD_{ir}\right)SCR_{CO_2}\right] \quad (1)$$

The first term in the objective function is the total purchasing cost of materials from all suppliers (including transportation costs of materials). The second term is the total production costs in all plants. The third term is the total transportation costs of all products. The last term is the total social costs of CO_2 emissions (including emissions caused by products production, materials transportation, and products transportation).

4.3. Constraints

For a supply chain management model, there are many generic constraints to be considered, including balance constraints of materials and products, the capacity limit constraint, and the throughput limit constraints. These constraints are discussed below.

Table 6
Transportation distance between plants and DCs (miles).

Plant	Transportation type	Distribution center	
		DC1	DC2
PL1	Ship	9654	9232
	Truck	150	230
PL2	Ship	3440	1488
	Truck	200	180
PL3	Ship	2692	2272
	Truck	150	130

Transportation distance of cargo ship is retrieved from http://www.searates.com/reference/portdistance/.
Transportation distance of truck is assumed by the authors.

Table 7
CO_2 emission of transportation.

Transportation type	CO_2 emission (kg ton^{-1} mile^{-1})
Ship	0.04374
Truck	0.08217

Retrieved from an environmental impact assessment of exported wood pellets from Canada to Europe (Magelli et al., 2009).

4.3.1. *Material requirements*

R_{mi}: Units of material m required to produce one unit of product i.

The materials balance constraint is

$$\sum_{i,l} H_{ikl}R_{mi} \le \sum_j G_{mjk} \quad \text{for all } k,\ m \tag{2}$$

4.3.2. *Supplier's capacity limits*

The capacity limits, for supplier j, can be formulated as

$$\sum_k G_{mjk} \le SC_{mj} \quad \text{for all } m \tag{3}$$

4.3.3. *Production capacity limits of plants*

There are lower and upper production capacity limits of product i in plant k. So, for each plant k, the production capacity limits constraints are

$$LC_{ik} \le \sum_l H_{ikl} \le UC_{ik} \quad \text{for all } I \tag{4}$$

4.3.4. *The throughput limit constraints*

For plant k, the throughput limit is

$$\sum_{i,l} H_{ikl} \le CP_k \tag{5}$$

(Note: In each plant, we must have $\sum UC_{ik} = CP_k$)

5. An illustrative case

The proposed mathematical model has been developed, validated, and used in a preliminary study of a supply chain from the apparel manufacturing industry to illustrate the potential application as a decision making tool for SSCM under different social cost rates of CO_2 emissions.

5.1. *Data*

The potential management of a supply chain network being considered by a textile company of Taiwan is illustrated in Fig. 1, which includes three cotton fabrics suppliers, three jeans production plants, and two DCs. These three cotton fabric suppliers are located in China, U.S.A., and Mexico, respectively. The three jeans production plants are located in Bangladesh, Mexico, and Nicaragua, respectively. The two DCs are located in New York and Los Angeles.

The objective of our SCM model is to decide the optimal amount of cotton fabrics purchased from different suppliers to each plant, jeans production in different plants, and jeans shipping from each plant to each DC under different social cost rates of CO_2 emissions, to consider both the operational costs and the socials costs of CO_2 emissions to minimize the total costs.

The authors assumed that the total demand requirements are 180,000 pairs of men's basic 100% cotton, 5 pocket denim jeans ordered from two DCs. The demand requirements of each DC are shown in Table 1. The raw material of denim jeans is cotton fabric and provided by three potential suppliers. The unit purchasing costs

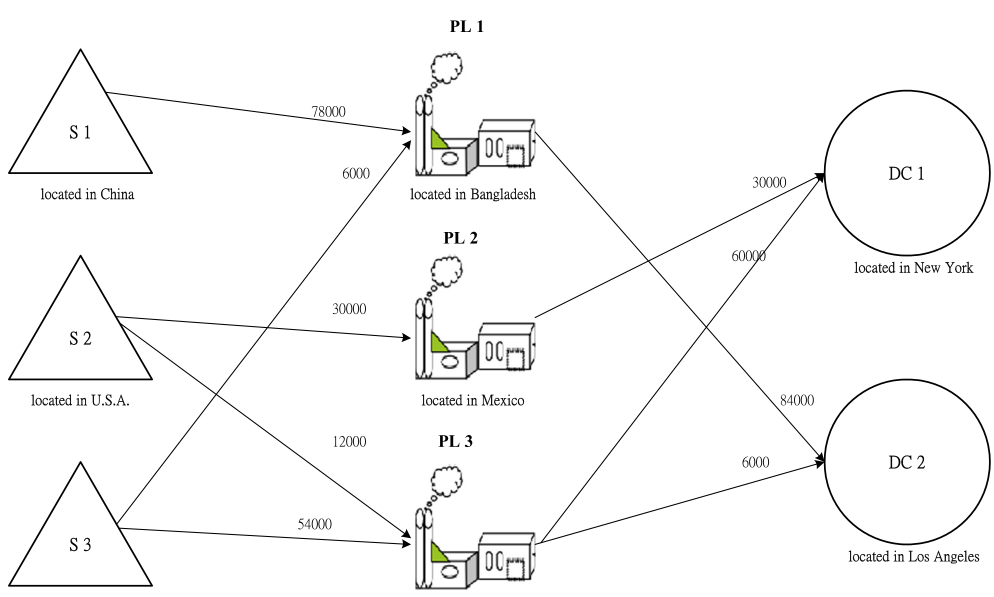

Fig. 2. Results of scenario 1 (Taking only operational costs into consideration).

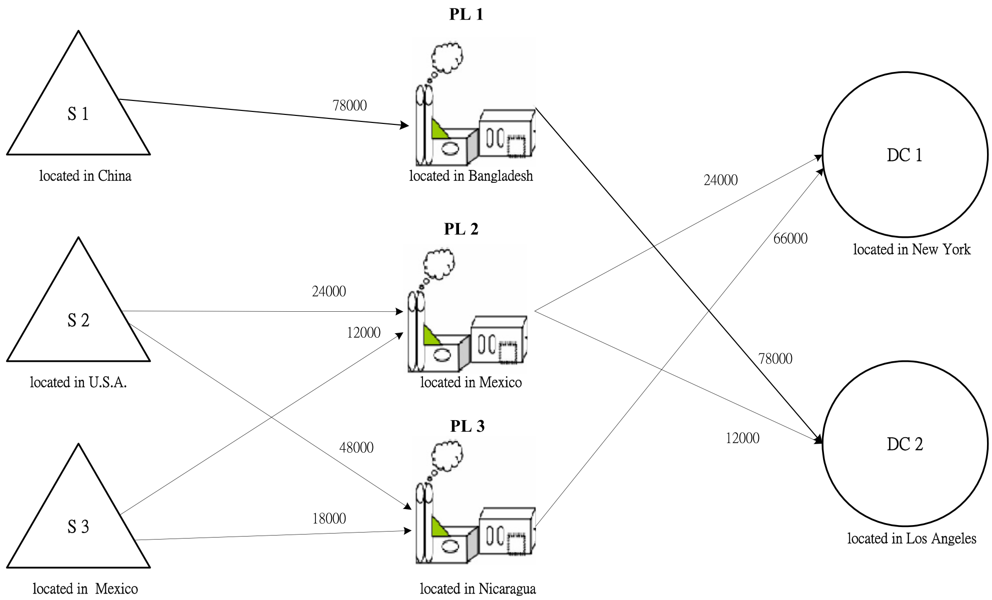

Fig. 3. Results of scenario 5 (The social costs of CO_2 emissions = \$ 100/ton CO_2 eq).

(including transportation costs of raw materials) of raw materials from each supplier to each plant is shown in Table 2. The production capacity, unit production costs (including trimming costs, packing costs, labor costs, and so on), and the amount of CO_2 emissions throughout the production process of a pair of jeans produced in each plant are shown in Table 3. The materials supply capacity of each supplier is shown Table 4. The transportation distances of raw materials shipped from suppliers to plants and products shipped from plants to DCs are shown in Tables 5 and 6, respectively, while CO_2 emissions caused by transportation are shown in Table 7 (Magelli et al., 2009). A pair of men's basic 100% cotton, 5 pocket denim jeans weighs about 0.6 kg, which requires about 0.75 kg of cotton fabric. The authors assume the sipping weight of a pair of men's basic 100% cotton, 5 pocket denim jeans is 0.75 kg (including packaging). It is assumed that raw material purchasing lot size, garment production lot size, and garment transportation lot size are 6000 garments based on the 20 feet container capacity of jeans.

5.2. Results and discussion

Nine scenarios were considered and used to analyze the results. In scenario one, the authors take only the operational costs into consideration. From scenario two to scenario nine, eight different social cost rates were considered: \$25/tCO_2, \$50/tCO_2, \$75/tCO_2, \$100/tCO_2, \$125/tCO_2, \$150/tCO_2, \$175/tCO_2, and \$200/tCO_2 of CO_2 emissions, respectively, to decide the optimal material purchasing size from each supplier, the optimal product production size in each plant, and the optimal amount of products shipping from each plant to each DC. In addition, the LINGO was applied to solve the proposed model of this study.

The amounts of cotton fabrics purchased from each supplier to each plant, jeans produced in each plant, and jeans shipping from each plant to each DC of some scenarios are shown in Figs. 2 to 4. For instance, in scenario 5, plant 3 purchased 48,000 garments' cotton fabrics from supplier 2 and 18,000 garments' cotton fabrics

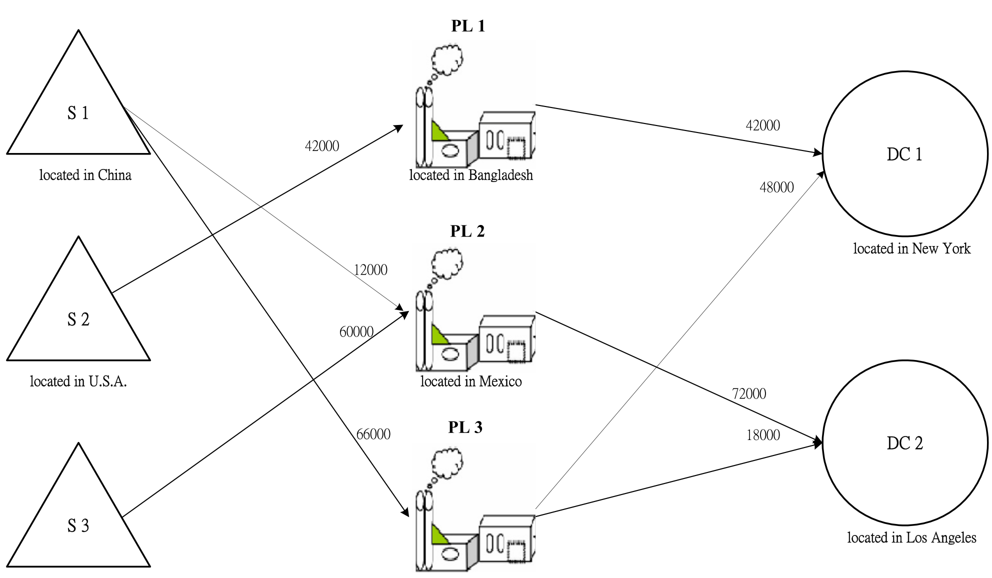

Fig. 4. Results of scenario 9 (The social costs of CO_2 emissions = \$ 200/ton CO_2 eq).

Table 8
Comparison of different scenarios.

Scenario	Unit cost of CO_2 emissions ($/ton)	Amount of CO_2 emissions (tons)	Social costs of CO_2 emissions ($)	Operation costs ($)	Total costs ($)
1	0	3049.687	0	1,368,687	1,368,687
2	25	3049.687	76242.2	1,368,687	1,444,929
3	50	3049.284	152464.2	1,368,997	1,521,461
4	75	3047.632	228572.4	1,366,547	1,595,119
5	100	3021.430	302143.0	1,368,814	1,670,957
6	125	2984.351	373043.9	1,372,294	1,745,338
7	150	2969.646	445446.9	1,366,414	1,811,861
8	175	2919.165	510853.9	1,374,518	1,885,372
9	200	2882.374	576474.8	1,400,056	1,976,531

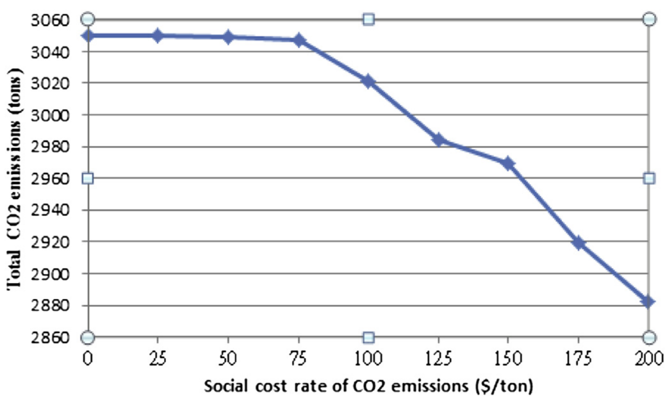

Fig. 5. Total CO_2 emissions versus social cost rate of CO_2 emissions.

from supplier 3 for producing 66,000 garments' jeans; and shipping 66,000 garments' jeans to DC 1.

Table 8 was used to compare the results obtained from the four scenarios. It was found that total CO_2 emissions decrease as the social costs rates of CO_2 emissions increase. The results showed that if enterprises have to pay the social costs of CO_2 emissions caused by their operations of supply chain networks, the decision makers of these enterprises will make optimal strategies to make tradeoffs between the operational costs and CO_2 emissions. Therefore, the decision-makers of enterprises would choose plants that emit less CO_2 gas, even though those plants have higher costs for production. This is because the overall amount of costs would be less than those of plants that do not take CO_2 emissions into serious account. Thus, the authors of this study suggest that governments should impose rules to force enterprises to pay for the social costs of CO_2 emissions. This would cause enterprises to invest money in reducing CO_2 emissions.

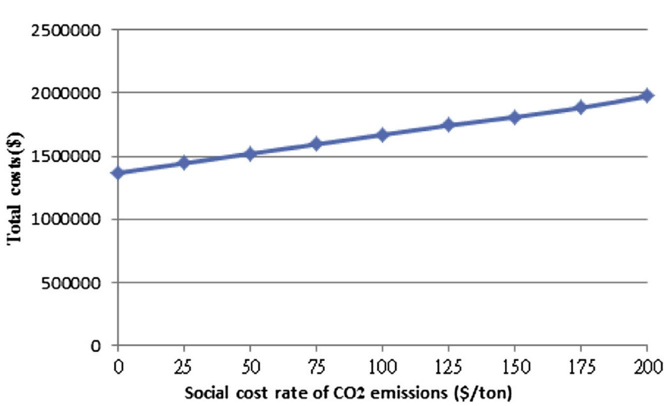

Fig. 6. Total costs versus social cost rate of CO_2 emissions.

5.3. Sensitivity analysis under different social cost rates of CO_2 emissions

We investigate the change in total CO_2 emissions based on different social cost rates of CO_2 emissions. Thus, a sensitivity analysis considering social cost rate of CO_2 was carried out. We observed the change of total CO_2 emissions and total costs by varying the social cost rate of CO_2 emissions. The results are given as graphs in Figs. 5 and 6 for the total CO_2 emissions, and total costs, respectively. The social cost of CO_2 emissions varies from 0 to $ 200/ton. In these two figures, we can see how the social cost rate of CO_2 emissions impacts total CO_2 emissions and total costs under different social cost rates of CO_2 emissions. Also, we can see that as the social cost rate of CO_2 emissions increases, the total CO_2 emissions decreases and total costs increases, respectively.

6. Conclusion

The reduction of CO_2 emissions to mitigate the impacts of global warming has become an urgent issue globally. Bearing this in mind, the authors of this study have highlighted the significance of taking social costs of CO_2 emissions into consideration in supply chain management, and have presented a generic mathematical model considering both operational costs and social costs of CO_2 emissions to assist decision makers in supply chain management.

The inclusion of social costs in supply chain management could allow decision-makers of enterprises to estimate more practical costs in the operations of supply chain networks. The proposed model has the potential to become a useful tool that facilitates the understanding of optimal supply chain strategies with consideration for social costs of CO_2 and other wastes emissions resulting from operating such a supply chain network. In addition, the proposed model could serve as a useful reference for legislators in estimating the monetary loss resulting from CO_2 emissions in the operations of supply chain networks. Furthermore, the legislators could refer this model to propose legislations to enforce the enterprises to pay for the social costs of CO_2 emissions. Therefore, the enterprises must invest money in reducing CO_2 emissions from the operations of such supply chain networks.

Although the proposed mathematical model has made a noteworthy contribution to current studies on SSCM, it also has its limitations. First, the estimation that we did regarding the calculation of the social costs of CO_2 emissions in supply chain management can only be seen as tentative at this preliminary stage. Second, as showed in our illustrative case where we took an apparel manufacturing supply chain network as an example, further studies can apply this model to other industries. Third, the proposed model is particularly suitable for the multinational enterprises that own many manufacturing plants located in different countries. Last, the social costs of other wastes emissions caused by the operations of supply chain network could be considered in further studies.

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