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The Carbon Cost Influences Research on Supply Chain Network Design

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Abstract: In recent years, reducing carbon emissions from the supply chain has become an increasingly important issue. As a result, the necessity and desirability of carbon management has become a key cost element in the supply chain in the future. Supply chain network design is not only an important part of managing the supply chain, but also has a significant impact on carbon emissions. Therefore, this paper formulates a mathematical model to optimize the supply chain network design (SCND), which takes carbon emissions into account. It also reviews the influence of the cost of carbon management on the supply chain network design and then builds a Low Carbon Emission Supply Network Design model for a specific case study. This model helps to enhance the core competitiveness of the supply chain and promote an in-depth analysis of low-carbon supply chain management.

Keywords: Low Carbon Emission; Carbon emission control; Network design; Supply chain.

1. INTRODUCTION

In recent years, there has been increasing concern with regards to the worldwide rise of greenhouse gases (GHG) emissions into the atmosphere, particularly its effects on global warming and climate change (Yang et al., 2021; Fahimnia et al., 2015). In 2020, the annual rate of the heat-trapping GHGs in the atmosphere has increased above the 2011-2020 average. That trend has continued in 2021 (WMO, 2021). With the concerted effort of the international community, several international agreements have been signed by developing and developed countries aiming reducing GHG emissions collectively (European Parliament, 2020; UNFCCC, 2016). Among all GHGs, Carbon dioxide (CO_2) emissions show the greatest impact on global warming compared with that of the other GHGs (Robinson et al., 2016). To control carbon emissions, many countries have enforced emission regulations and policies, such as carbon tax, carbon cap-and-trade, and carbon offset (Luo et al., 2022; De & Giri, 2020). The carbon tax policy imposes a fee on a firm for each unit of CO_2 emission (Saxena et al., 2018). The cap-and-trade policy sets a limit, or caps, the total level of CO_2 emission, as a result of industrial activity and allows the industry to sell or purchase emissions in a trading market (Zakeri et al. 2015). A carbon offset policy allows industries to provide investments to projects that offsets their higher carbon emissions (Palak et al., 2014), Correspondingly, the enterprises will pay for carbon dioxide emissions, which will encourage them to change their model of supply chain management. Therefore, there will be an economic incentive for companies to reduce the carbon footprint of the supply chain. There are three main methods to control the carbon emissions of a supply chain when facing the SCND problem (Wang et al., 2020). The first method is to incorporate the costs of CO_2 emissions into the economic objectives, which leads to a research interest in investigating the impact of the carbon pricing mechanism on the supply chain (Li et al., 2017). The second method is to treat the minimisation of the CO_2 emissions as an extra objective and the traditional SCND problem is converted to a multi-objective problem (Zhang et al., 2020). The third method is to impose constraints on the carbon emission (Xu et al., 2017). All these three methods may affect the supply chain management decisions at both strategic and operational levels.

This paper will mainly focus on the environmental issues in the field of supply chain management, and discuss the impact of carbon cost on the SCND using the first method as aforementioned. A discussion of the method of optimizing the supply chain with CO_2 emission control will be provided based on the experimental result.

2. LITERATURE REVIEW

Due to extensive attention paid to the sustainability issues, many researchers have addressed sustainable supply chain management problems in recent years (Wang et al. 2020; Li et al. 2020). An extensive review for the green supply chain management trends and future challenges was done by Tsenga et al. (2019). The review covered the literature works published from 1998 to 2017. A growing trend of applying mathematical optimization models has been identified for enhancing decision making in pursuit of environmental performance. Further, Joshi (2022) delivered a comprehensive literature review for the sustainable SCND publications under the year frame from 2010 to 2021. The review pointed out that integrating both resilience and sustainability elements in the SCND is one of the important future research directions.

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This review firstly concentrates on the studies on the impact of the carbon pricing mechanism on supply chain management. The aforementioned main carbon pricing policies in practice are carbon tax, carbon cap-and-trade and carbon offset. To apply these policies, two key research issues need to be addressed, which are how to measure the carbon emission and how to reduce the carbon cost in the supply chain. For example, Cholette and Venkat (2009) analyzed the carbon and energy profile for a red wine SCND case study and pointed out that different supply chain designs had different effects on the total energy and carbon emissions. Sundarakani et al. (2010) carried out modeling based on Lagrange and Euler's Box method to estimate the carbon emissions. Li et al. (2020) extracts the influencing factors of low-carbonization in coal supply chain and builds an optimization model with the objective of minimizing its low-carbon production costs. Wang et al. (2020) studied competitive and sustainable SCND problem. They first studied the retail price and carbon emission equilibrium at the competition stage. They then apply the equilibrium results to the SCND as constraints. The goal is to minimize the total costs while reducing the carbon emissions by strategically making decisions on the locations of the manufactures and distribution centers within the supply chain. Zhang et al. (2021) examined a supply chain with multiple competitive manufacturers, multiple competitive retailers and multiple demand markets. They analyzed the impacts of progressive carbon tax mechanism on equilibrium decisions and profits of manufacturers, retailers and the whole SCN and provided managerial insights based on numerical results. Overall, we can see that an eco-friendly supply chain can not only enhance its economic and environmental performance (Barzinpour and Taki, 2016), but also can greatly influence both strategic and operational decisions.

Secondly, the review concentrates on the studies on green SCND problems, where strategic decisions need to be made for long-term efficient operations of the whole supply chain. Wang et al. (2011) put forward the concept of green SCND and introduced environmental protection variables into a mixed-integer programming model. In their model, decisions on facility location and capacity allocation have been integrated with the decision on environmental protection level. Martí et al. (2015) built a model for a SCND problem, which took demand uncertainty into account and included decisions on facility locations, market allocation and transport mode under different carbon policies. The model captured operational and environmental trade-offs arising from the interaction between different supply chain processes. Talaei et al. (2016) have proposed a robust fuzzy model for carbon-efficient closed-loop SCND with demand uncertainties. The numerical results show that the model is applicable to Copiers Industry and is capable of controlling the network uncertainties. Moreover, some researchers consider carbon emission constraints. Rahmani and Mahoodian (2017) proposed a mixed integer linear programming model for a three-echelon supply chain network with uncertain demand and costs as well as the risk of facilities' disruption. The carbon emission cap was imposed as a constraint in their model. They developed a Benders decomposition algorithm to solve the model. Both operational and strategic decisions are made. Boskabadi et al. (2022) extended green supply chain management concepts to green SCND problem by taking hub network design into consideration. The model considered A multi-product, multi-period, multi-echelon, multi-plant, multi-retailer SC system. The model aims at controlling CO_2 emission throughout the network by incorporating CO_2 emission cost into the total cost as a single objective. Another objective is to maximize net profit per capita for each human resource emission cost is incorporated into the total cost as a single objective.

3. A CONCEPTUAL MODEL FOR THE SUPPLY CHAIN CARBON EMISSION COST

When we introduce the carbon cost into the supply chain network design, we need to add changes brought by introducing the carbon pricing mechanism into the supply chain network design (Figure 1).

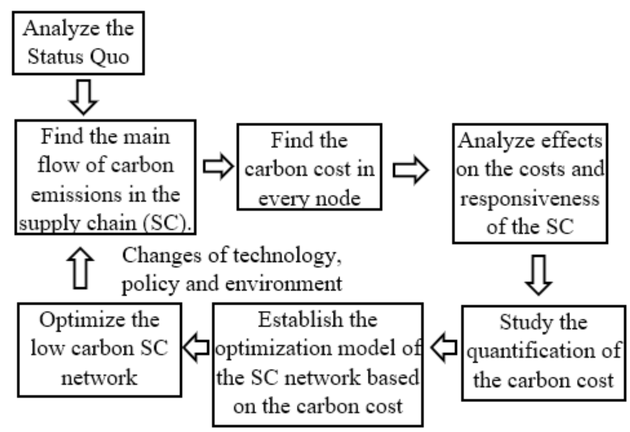

Figure 1: Analysis of Carbon Cost in the Supply Chain Network Design

Figure 1 shows that the key step in the low-carbon supply chain network design is to find important nodes of carbon emissions which affect the supply chain and then carry out a detailed analysis.

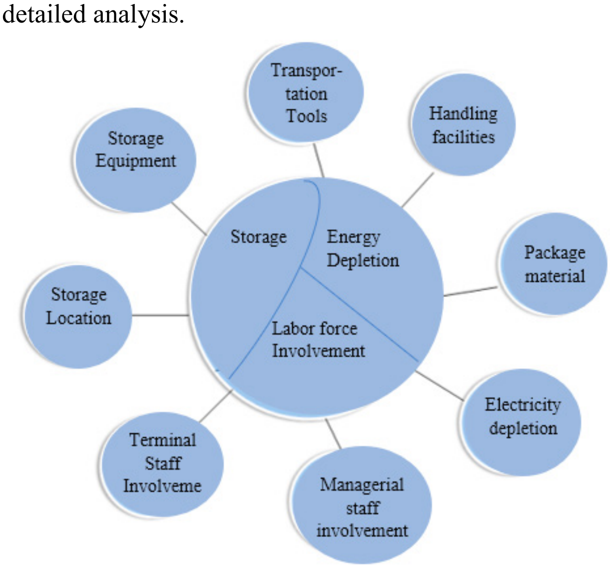

Figure 2: Factors Affecting Carbon Emissions in the Supply Chain

Many factors influence carbon emissions from the perspective of the whole supply chain (Figure 2). Therefore, we need to consider all the elements as a whole and carry out trade-offs with regards to the performance of the supply chain. These elements have impact on both the traditional supply chain performance and the newly-added cost of carbon. During the process of managing carbon emissions in the supply chain, the more detailed analysis of these elements will more likely lead to a better supply chain performance.

Figure 2 shows that among the factors that affect carbon emissions, location of supply chain facilities, determination of facility capacity, determination of transport modes and frequency and other factors all belong to the supply chain network design. Therefore, we should fully consider the impact of these factors on the performance of the supply chain. We conclude from the above discussions that we need to treat the supply chain as a whole, reanalyze the modes of transport, location of facilities, frequency of transport, routes, etc. based on the cost of carbon and strike a balance which meets the requirement of supply chain performance.

4. SUPPLY CHAIN NETWORK OPTIMIZATION MODEL INTRODUCING THE CARBON COST

Optimization decisions of the supply chain network have great influence on supply chain operations, namely, providing a control mechanism when they make use of stocks, transportation and other facilities to reduce the cost of the supply chain and enhance responsiveness. However, carbon emissions bring new variables; different facility locations, transportation route design and production decisions which will all have different impact on these emissions. In contrast, the cost of carbon will also influence the performance of the supply chain. From the analysis of related literature, we can see that studies about the supply chain network model mainly focus on supply chain equilibrium models, supply chain design and supply chain network optimization, but they are mostly based on a total cost model. For that reason, our research mainly focuses on the impact of the carbon cost on total cost in the supply chain network design.

4.1 Symbols

Linear Programming has been used to formulate a model to represent a basic supply chain network. To simplify the complexity of the problem, the model considers a single product and presumes that one unit of raw material can produce one unit of product. The entire supply chain network consists of the following four basic components: suppliers, manufacturers, warehouses and retailers (demand side). The model includes the following variables:

m: The number of retailers
w: The number of warehouses
f: The number of manufacturers
s : The number of suppliers
D_j: Annual demand of retailer $j, j = 1,2, \dots m$
S_h: Annual supply capacity of supplier $h, h = 1,2, \dots, s$,
K_i: Annual productivity of manufacturer $i, i = 1,2, \dots, f$
W_e: Annual storage capacity of the warehouse located in $e, e = 1,2, \dots, w$
W'_e : Annual handling capacity of the warehouse located in $e, e = 1,2, \dots, w$
F_i : Annual fixed costs of manufacturer located $i, i = 1,2, \dots, f$
F_e: Annual fixed costs of the warehouse located in $e, e = 1,2, \dots, w$
C_{ie}: Transportation cost per product from manufacturer i to warehouse e, $i = 1,2, \dots, f$, $e = 1,2, \dots, w$
C_{ej}: Transportation cost per product from warehouse e to retailer j, $e = 1,2, \dots, w$, $j = 1,2, \dots m$
C_{hi}: Transportation cost per raw material unit from supplier h to manufacturer $i, h = 1,2 \dots, s$, $i = 1,2, \dots, f$
C_i: Manufacturing cost per product of manufacturer, $i, i = 1,2, \dots, f$
C_e: Storage cost per product in warehouse $e, e = 1,2, \dots, w$
C'_e: Handling cost per product in warehouse $e, e = 1,2, \dots, w$
Cc_t: Additional transportation carbon cost per product (or raw material) in every stage (assuming that they are the same in every stage),
Cc_i: Additional manufacturing carbon cost per product of manufacturer $i, i = 1,2, \dots, f$
Cc_e: Additional storage carbon cost per product of warehouse $e, e = 1,2, \dots, w$
Cc'_e: Additional carbon handling cost per product in warehouse $e, e = 1,2, \dots, w$
X_{ej}: The annual number of products transported from warehouse e to retailer j, $e = 1,2, \dots, w$, $j = 1,2, \dots m$
X_{ie}: The annual number of products transported from manufacturer i to warehouse e, $i = 1,2, \dots, f$, $e = 1,2, \dots, w$
X_{hi}: The annual number of raw materials transported from supplier h to manufacturer i, $h = 1,2, \dots, s$, $i = 1,2, \dots, f$
Y_i: Variables 0-1: 1 means that the factory is located in i, and 0 means otherwise, $i = 1,2, \dots, f$
Y_e: Variables 0-1: 1 means that the warehouse is located in e, and 0 means otherwise, $e = 1,2, \dots, w$

4.2 Illustration of the calculating the carbon cost

There are two options for the carbon emission pricing Cc_k (Carbon cost). The first option is that the cost of each kind of carbon factor doesn't change along with the volume changes of carbon emissions in the supply chain and that the unit carbon cost is fixed. The second option is that the costs of carbon increase along with the increase in the volume of carbon emissions, according to special rules or government policy and have the features of a step function with $Cc_k \in \{Cc_t, Cc_i, Cc_e, Cc'_e\}, k = t \text{ or } i \text{ or } e$.

Let Cc_k be the unit cost of carbon of different supply chain stages, Q be the volume of carbon emissions in certain stages of the supply chain, we have

$$Cc_k = \begin{cases} C_1, & 0 \le Q < a_1 \\ C_2, & a_1 \le Q < a_2 \\ \dots\dots & \dots\dots\dots \\ C_n, & Q \ge a_n \end{cases}$$

The two pricing strategies have different impacts on the total cost of the supply chain, so we need to fully understand and consider different carbon emission pricing strategies, and produce an appropriate supply chain network model when we design the supply chain network.

5. TOTAL COST MODEL OF SUPPLY CHAIN CONSIDERING CARBON COST

5.1. Total cost model not considering carbon cost

If we don't consider carbon cost elements, the model minimizes the total cost of the supply chain as its optimization objective. The total cost model of the supply chain is:

$$min\left(\sum_{i=1}^{f} Y_i F_i + \sum_{e=1}^{w} Y_e F_e\right) + \left(\sum_{i=1}^{f}\sum_{h=1}^{s} C_{hi} X_{hi} + \sum_{i=1}^{f}\sum_{e=1}^{w} C_{ie} X_{ie} + \sum_{e=1}^{w}\sum_{j=1}^{m} C_{ej} X_{ej}\right) + \left(\sum_{i=1}^{f}\sum_{h=1}^{s} C_i\ X_{hi} + \sum_{e=1}^{w}\sum_{i=1}^{f} C_e\ X_{ie} + \sum_{e=1}^{w} C'_e\left(\sum_{i=1}^{f} X_{ie} + \sum_{j=1}^{m} X_{ej}\right)\right) \quad (1)$$

s.t.

$$\sum_{e=1}^{w} X_{ie} \le \sum_{h=1}^{s} X_{hi} \le K_i Y_i, \qquad i = 1,2,\dots,f \quad (2)$$

$$\sum_{j=1}^{m} X_{ej} \le \sum_{i=1}^{f} X_{ie} \le W_e Y_e, \qquad e = 1,2,\dots,w \quad (3)$$

$$\sum_{i=1}^{f} X_{ie} + \sum_{j=1}^{m} X_{ej} \le W'_e Y_e, \qquad e = 1,2,\dots,w \quad (4)$$

$$\sum_{i=1}^{f} X_{hi} \le S_h, \qquad h = 1,2\dots,s \quad (5)$$

$$\sum_{e=1}^{w} X_{ej} = D_j \qquad j = 1,2,\dots m \quad (6)$$

$$Y_i, Y_e \in \{0,1\} \quad (7)$$

$$X_{ej}, X_{ie}, X_{hi} \ge 0, \qquad integer \quad (8)$$

There are three main brackets in the the objective function (1). The terms in the bracket stand for the fixed costs of supply chain facilities (manufacturers and distributing warehouses), the terms in the second bracket stand for the supply chain transportation costs and the terms in the third bracket stand for the other variable costs (including manufacturing costs of manufacturers, storage costs of warehouses, and handling costs of warehouses). Constraint (2) guarantees that the volume of raw material and output will not exceed the manufacturer's production capacity, constraint (3) guarantees that output and volume of storage will not exceed the total storage capacity, constraint (4) guarantees that the sum of inbound and outbound volume will not exceed the total handling capacity of the factory, constraint (5) guarantees that the shipments of raw materials will not exceed the supply capacity, constraint (6) guarantees that all retailer demands are met, constraint (7) justifies the usage of the binary variables to indicate whether the facilities are built or not and constraint (8) is the sign restriction.

5.2. Total cost model considering carbon cost

In this paper, we take carbon cost into consideration by incorporating the carbon cost elements into the total economic cost of the supply chain, then the objective function (1) will be converted to (1)':

$$min\left(\sum_{i=1}^{f} Y_i F_i + \sum_{e=1}^{w} Y_e F_e\right) + \left(\sum_{i=1}^{f}\sum_{h=1}^{s}(C_{hi} + Cc_t\ )X_{hi} + \sum_{i=1}^{f}\sum_{e=1}^{w} C_{ie} + Cc_t\ X_{ie} + \sum_{e=1}^{w}\sum_{j=1}^{m}(C_{ej} + +Cc_t\ )X_{ej}\right) + \left(\sum_{i=1}^{f}\sum_{h=1}^{s}(C_i\ + Cc_i\ )X_{hi} + \sum_{e=1}^{w}\sum_{i=1}^{f}(C_e\ + Cc_e\ )X_{ie} + \sum_{e=1}^{w}(C'_e + Cc'_e)\left(\sum_{i=1}^{f} X_{ie} + \sum_{j=1}^{m} X_{ej}\right)\right) \quad (1)'$$

6. CASE STUDIES

Based on the mathematical model proposed in Section 5.1 and 5.2, a case study has been used to assess the impact of carbon cost on supply chain network design. This case study is derived from a real need of a company from a consulting project. The company produces a kind of cosmetic with health benefit. There are several manufacturers and suppliers providing raw materials to the company. In general, one unit of raw material may produce one unit of finished product. The company also hires a few warehouses to store finished products. They want to know the differences of supply chain performance with or without considering the carbon emissions. Table 1 lists the "Basic Data Input" provided by the company, and we are to run the mathematical model proposed in Section 5.1 and 5.2 with Gurobi optimization software and provide advice based on results. The analysis is divided into two steps: firstly, in section 6.1, we compare the total cost of different supply chain network design with or without taking carbon cost into consideration; secondly, in section 6.2, we discuss the impact of the change of carbon cost on supply chain network design.

6.1. Supply chain network design with or without taking carbon cost into consideration

The case proposed by the cosmetic company has been solved using Gurobi. The first scenario is to set the values of all the carbon costs to 0: namely, we don't consider the impact of carbon cost on supply chain network design. The second scenario is to set a certain value for the carbon cost and observe the impact on the decisions of the supply chain network infrastructure. Table 1 shows the basic input data while Table 2 shows the optimized supply and distribution results.

Table 1. Basic Input Data

	Supplier *h=1,2*	Manufacturer *i=1,2,3*			Retailer *j=1,2,3*
	Supply capacity (unit)	Productivity (unit)	Fixed cost (RMB)	Manufacturing cost per product (RMB)	Demand (unit)
1	50,000	15,000	500,000	15	12,000
2	30,000	12,000	750,000	20	8,000
3		30,000	600,000	30	20,000
3		30,000	600,000	30	20,000

Warehouse *e=1,2,3,4*				
Storage capacity (uint)	Handling capacity (uint)	Storage cost per product (RMB)	Handling cost per product (RMB)	Fixed cost (RMB)
21,000	10,000	12	5	80,000
30,000	22,000	8	5	60,000
25,000	18,000	7	4	45,000
30,000	20,000	6	9	50,000

Manufacturer ***i***	Warehouse e	
Extra Manufacturing carbon cost per product (RMB)	Extra handling carbon cost per product (RMB)	Extra storage carbon cost per produt(RMB)
10	15	10
9	10	7
8	20	9
	9	8

Table 2. Different Results of Considering and not Considering Carbon Cost

Supply Chain Network Design Considering Carbon Cost				
The Number of Raw Material from Suppliers to Manufacturers (unit)				
	Manufacturer 1	M 2	M 3	
Supplier 1	0	0	10000	
Supplier 2	15000	0	15000	
The Number of Product from Manufacturers to Warehouses (unit)				
	Warehouse 1	W 2	W 3	W 4
Manufacturer 1	0	5000	0	10000
M 2	0	0	0	0
M 3	0	25000	0	0
The Number of Product from Warehouses to Retailers (unit)				

	Retailer 1	R 2	R 3
Warehouse 1	0	0	0
W 2	10000	0	20000
W 3	0	0	0
W 4	2000	8000	0

Supply Chain Network Design not Considering Carbon Cost				
The Number of Raw Material from Suppliers to Manufacturers (unit)				
	Manufacturer 1	M 2	M 3	
Supplier 1	0	0	10000	
Supplier 2	15000	0	15000	
The Number of Product from Manufacturers to Warehouses (unit)				
	Warehouse 1	W 2	W 3	W 4
Manufacturer 1	0	5000	9000	1000
M 2	0	0	0	0
M 3	0	25000	0	0
The Number of Product from Warehouses to Retailers (unit)				
	Retailer 1	R 2	R 3	
Warehouse 1	0	0	0	
W 2	10000	0	20000	
W 3	2000	7000	0	
W 4	0	1000	0	

We can see from Table 2 that there are great differences between the supply chain network design that does or doesn't take carbon cost into consideration. For example, when we don't consider the carbon cost, Warehouse 3 needs to supply products to Retailer 1 and Retailer 2; when we consider carbon cost, Warehouse 3 is unused.

6.2. Impact of changes of carbon cost on supply chain network design

The changes in carbon cost also affect the supply chain network design, which is illustrated in another example. The basic data is shown in Table 3.

Table 3: Basic Data of the Supply Chain

I	Supplier *h*	Manufacturer *i*			Retailer *j*
	Supply capacity (unit)	Productivity (unit)	Fixed cost (RMB)	Manufacturing cost per product (RMB)	Demand (unit)
1	50,000	12,000	500,000	20	12,000
2	30,000	30,000	550,000	15	8,000
3		28,000	600,000	25	20,000

i	Warehouse *e*				
	Storage capacity (unit)	Handling capacity (unit)	Storage cost per product (RMB)	Handling cost per product (RMB)	Fixed cost (RMB)
1	21,000	10,000	12	5	80,000
2	30,000	22,000	8	5	60,000
3	25,000	18,000	7	4	45,000
4	30,000	20,000	6	9	50,000

We add storing carbon cost and handling carbon cost (as is shown in Table 4) to the above data, and run the mathematical model proposed in Section 5.2. Figure 3 and Figure 4 show the optimized supply chain network infrastructures after adding these two costs. We find that we have different optimized supply chain infrastructure when we add different carbon costs factors into our model. For example, as shown Figure 3, if we only add storing carbon costs, the optimized supply network infrastructure does not include the node M_3 and W_1. But, if we add another handling carbon cost, as shown Figure 4, the optimized supply network infrastructure already includes the node W_1, and the optimized transportation volumes are changed between the two adjacent stages. Therefore, when we design the supply chain network, we need to pay more attention to the impact of different carbon cost elements. We need to do some sensitivity analysis to our supply chain network model by adjusting the carbon costs factors.

Table 4: Changes of carbon costs

Warehouse *e*	New Storage Carbon Cost Per Product (RMB)	New Handling Carbon Cost Per Product (RMB)
1	5	5
2	5	20
3	20	20
4	5	5

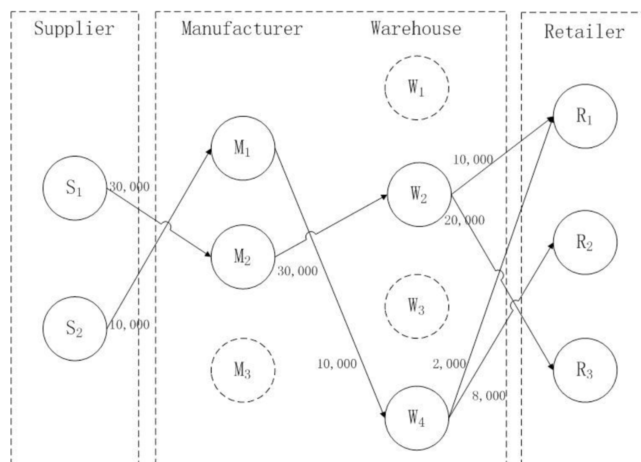

Figure 3: Supply Chain Infrastructure

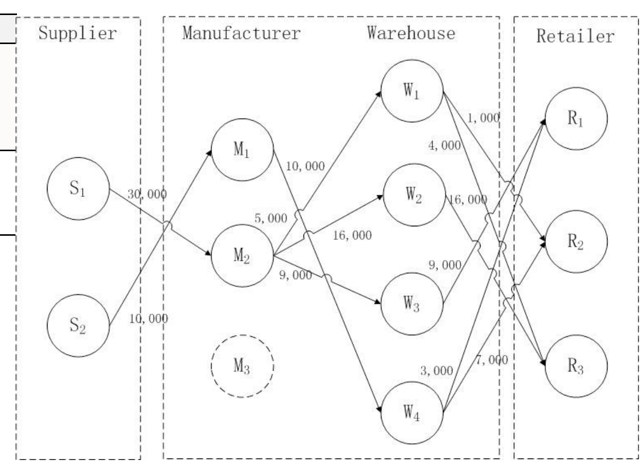

Figure 4: Supply Chain Infrastructure after taking Carbon Cost into consideration

7. CONCLUSION

In this paper, we have analyzed the carbon cost and its impact on the infrastructure of the supply chain network, established a supply chain optimization model based on carbon cost and applied the model to a case study. The results of the case study show that taking carbon cost into consideration or not generates different results when we are designing a supply chain network. Therefore, in future supply chain network design, we not only need to consider the general cost elements, but also need to fully consider the new impact of the carbon cost, so as to understand the impact of the carbon charging mechanism on the supply chain infrastructure. Only in this way can we achieve a satisfactory supply chain network infrastructure. In the future, the model can be extended to take more manufacturers, suppliers and/or retailers into consideration. Some risk in transportation route and facility disruptions, variable pricing strategies and demand uncertainties can also be taken into consideration.

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