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Uncertain Network DEA Models with Imprecise Data for Sustainable Efficiency Evaluation of Decentralized Marine Supply Chain

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Abstract: With the expansion of global trade and the deterioration of the marine environment, research on the sustainability of marine transport has drawn increasing scientific attention. This study takes the marine supply chain composed of Maersk and ports in 17 coastal cities in China as decision-making units (DMUs). It then chooses indicators from the three dimensions of economy, environment and society to evaluate the sustainable efficiency of the marine supply chain, Maersk and ports. In order to deal with the uncertain variables of the sustainability evaluation index, this study develops an uncertain network DEA model based on the uncertainty theory, and the computable equivalent form and proof are also provided. In addition, this study divides the decentralized marine supply chain into two modes, i.e., Maersk as leader and the port as leader, and it calculates their sustainable efficiency, respectively. These results suggest that the sustainable performance of ports is superior to that of Maersk, and the sustainable performance of the marine supply chain is better under the lead of ports, but most of the sustainable efficiencies of marine supply chains are inefficient. Therefore, ports should act as a catalyst for the development of the marine supply chain, and the management implications and suggestions for the economic, environmental, and social dimensions are also outlined at the conclusion.

Keywords: uncertain network DEA model; uncertainty theory; sustainable efficiency; decentralized marine supply chain

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1. Introduction

Marine transport accounts for more than 90% of global trade by volume [1], and it becomes an indispensable link to support the development of international trade. However, marine transport also aggravates environmental pollution. According to the third greenhouse gas study of the International Marine Organization, the carbon emissions caused by marine transport account for about 3% of the total carbon emissions from human activities [2]. In addition, the European Parliament (2015) [3] predicted that the share of emissions from marine transport will rise to 17% of the total international carbon emissions. The increasing demand for marine transportation will undoubtedly be one of the main causes of global warming and climate change in the future. Therefore, the sustainable development of marine transportation has become a hot issue of concern for scholars.

In recent years, with the development of information and intelligent technology, all aspects of supply chain and shipping industry operation will be assisted by digital technology [4,5]. Since maritime security largely depends on network systems, Kechagias et al. [6] focused on the network security of the maritime industry, introduced the internal views of maritime network security, and provided a detailed case study based on the method of a real company. In addition to the marine supply chain, some scholars have studied the impact of industry 4.0 on Supply Chain Innovation (SCI) in the context of industry 4.0 [5]. Manavalan and Jayakrishna [7] explored the potential opportunities provided by the embedded sustainable supply chain of the Internet of Things (IOT) for the transformation of industry 4.0 through a literature review, and they proposed a framework to evaluate the organizational readiness of the supply chain from different perspectives so as to evaluate the readiness of enterprises to realize the transformation of industry 4.0.

It has been widely known that shipping companies and ports are regarded as the two main bodies of a marine supply chain [8]. To this end, the research on sustainability for marine transportation mainly focuses on the aspects of ports and shipping companies. In the research of port sustainability, it mainly focuses on the research fields of influencing factors, index system and efficiency evaluation. Although the sustainability has been broadly considered important to the port, Ashrafi [9] found that they do not fully integrate sustainability into its development and operation, even if they also agree with the importance of sustainability. Therefore, scholars have conducted a lot of research on the driving factors of port sustainability, in which Ashrafi [10] reviewed from various research perspectives and determined 30 driving factors of enterprise sustainable development. With the contribution of the above research, the sustainability evaluation index based on the triple bottom line method was proposed and widely used in the evaluation of port sustainability [11,12]. On the other hand, shipping companies also play a vital role in the sustainable development of maritime transportation. Various studies have shown that a sustainable strategy can promote the operating performance of shipping companies and provide a competitive advantage [13,14]. However, through the research on the environmental and sustainability information disclosure of shipping companies, it was found that there is a lack of specific indicators to measure and evaluate the sustainability performance at the company level, and the information source is unknown, which will be detrimental to the evaluation of shipping sustainability [15,16]. To sum up, whether they are ports or shipping companies, as profit-making enterprises, business performance is still their main goal. In addition, sustainable information is not easy to obtain and there is little quantitative evaluation, so the the sustainability of marine transport is unknown.

Sustainability is regarded as the simultaneous achievement of the economic, environmental and social objectives that support an organization for long-term competitiveness [17]. It is worth noting that the study of the efficiency evaluation of sustainability has attracted extensive reseachers' attention because it involves three aspects: economy, environment and society. As one of the mainstream methods to evaluate efficiency, DEA has been widely used in the evaluations of sustainability, carbon emission and environment. Chen [18] takes carbon emissions as unexpected output and calculates the emission efficiency of Chinese provinces through the Super-SBM model. In order to solve the problem that the weight of DEA model is not unique, Han [19] proposed an improved environmental DEA cross model based on information entropy to analyze and evaluate the carbon emission efficiency of industrial departments in China. For the decision-making unit that needs to analyze the internal structure, such as a supply chain, network DEA is usually used to evaluate its efficiency [20,21]. The DEA method will be used in this study to measure the efficiency of marine supply chains by choosing evaluation indexes that reflect their economic, environmental and social performance, and the efficiency is defined as sustainable efficiency.

Although the above research has made a lot of beneficial attempts to evaluate sustainable efficiency by using DEA methods, it did not take into account the problem that some indexes cannot be accurately observed. When it comes to sustainable efficiency, there will inevitably be imprecise observation data of index, such as carbon emissions, social benefits and so on, and the traditional DEA models will lose their applicability. These quantities ought to be ascribed to uncertain variables in accordance with the uncertainty theory introduced by [22] in 2007. Subsequently, many uncertain DEA models with imprecise inputs and outputs were proposed based on uncertainty theory, including Wen [23], Lio and Liu [24], Jiang et al. [25], etc. Motivated by this, we attempt to propose a new uncertain

DEA model that can deal with imprecise data, which will also be one of the important research objectives of this paper.

In addition, as the upstream and downstream of the shipping supply chain, ports and shipping companies work together in the sustainable development of the shipping supply chain, which needs to be considered at the same time. However, in the sustainable research of ports and shipping companies, most of them only focus on one aspect [9,26,27]. More importantly, affected by the external environment such as policy and market, ports and shipping companies have different corporate strategies in terms of sustainability. In the shipping supply chain composed of ports and shipping companies, the powerful party will take the highest sustainable efficiency as the primary goal so as to affect the sustainable efficiency of the other party and the whole supply chain. Therefore, it is necessary to consider the position of ports and shipping companies in the supply chain and comprehensively evaluate the sustainable efficiency of ports, shipping companies and the whole shipping supply chain.

The overall structure of this paper takes the form of six parts, including this introduction. In the second part, the relative axioms of uncertainty theory will be introduced in order to construct uncertain DEA models. The third part will construct the uncertain network DEA model when the core firm is the upstream and downstream member, respectively. The fourth part will verify the model through a practical problem, and the variables and original data will be given at the same time. Last but not least, the results and the conclusion will be shown in part five and six.

2. Preliminaries

In this section, the essential and fundamental knowledge of uncertainty theory will be brought forth in light of which to deal with uncertain variables and establish models in the next section.

There are a number of measurable sets in $\mathcal{L}$, each of which are also called element Λ, composing a nonempty set Γ. Accordingly (Γ, $\mathcal{L}$, M) is set as a measure space where the uncertain measure M is defined as a set function on a σ-algebra $\mathcal{L}$ and satisfies the following axioms proposed by Liu [22].

Normality Axiom: $M\{\Gamma\} = 1$ *satisfied the universal set* Γ.

Duality Axiom: $M\{\Lambda\} + M\{\Lambda^c\} = 1$ *satisfied any event* Λ.

Subadditivity Axiom: *For every countable sequence of events* $\Lambda_1, \Lambda_2, \cdots$, *we obtain*

$$M\left\{\bigcup_{i=1}^{\infty} \Lambda_i\right\} \leq \sum_{i=1}^{\infty} M\{\Lambda_i\}.$$

Then, Liu [28] proposed the fourth axiom to define the product uncertain measure in 2009.

Product Axiom: *The product uncertain measure* M *in uncertainty spaces* $(\Gamma_k, \mathcal{L}_k, M_k)$ *is an uncertain measure meeting*

$$M\left\{\prod_{k=1}^{\infty} \Lambda_k\right\} = \bigwedge_{k=1}^{\infty} M_k\{\Lambda_k\}$$

where Λ_k *are arbitrarily chosen events from* $\mathcal{L}_k$ *for* $k = 1, 2, \cdots$, *respectively.*

Subsequently, some notions, symbols and theorems will be elucidated, which are germane to the modeling and calculation in the next section.

Assume the uncertain variable ξ exists and the uncertainty distribution is expressed as Φ. According to uncertainty theory [22],

$$\Phi(x) = M\{\xi \leq x\}$$

for any real number x.

With respect to a regular uncertainty distribution $\Phi(x)$, which is greater than 0 and less than 1, there exists the inverse function $\Phi^{-1}(\alpha)$ on the range of open interval $(0, 1)$. The expected value shows the measurement of uncertain variables and can be regarded as the average from the point of uncertain measure. The expected value of uncertain variable ξ can be calculated by the following formula:

$$E[\xi] = \int_0^1 \Phi^{-1}(\alpha)\mathrm{d}\alpha.$$

Since a linear uncertain variable labeled with $\xi \sim L(a, b)$ is the most common to express imprecise data in uncertain models, the uncertainty distribution is as follows

$$\Phi(x) = \begin{cases} 0, & \text{if } x \leq a \\ \dfrac{x-a}{b-a}, & \text{if } a < x \leq b \\ 1, & \text{if } x > b, \end{cases}$$

which has an expected value

$$E[\xi] = \frac{a+b}{2}.$$

As we know, efficiency is the ratio of inputs and outputs in data envelopment analysis, but when it contains uncertain variables, it is necessary to depend on the expected value to express the measurement of the efficiency.

Theorem 1 (Liu [29])**.** *For uncertain variables ξ and η possessing regular uncertainty distributions Φ and Ψ, they are set to be independent and positive. The expected value of $\frac{\xi}{\eta}$ is shown as follows,*

$$E[\frac{\xi}{\eta}] = \int_0^1 \frac{\Phi^{-1}(\alpha)}{\Psi^{-1}(1-\alpha)}\mathrm{d}\alpha.$$

The above includes all the essential and fundamental knowledge of uncertainty theory required for modeling in the next section.

3. The Uncertain Network DEA Models with Decentralized Modes

Assume that the marine supply chain mainly includes upstream shipping enterprises and downstream ports, both of which consume some inputs to produce some outputs. For example, the containers of cargo transported by a shipping enterprise will stop and be loaded at a port. As the upstream entity of the marine supply chain, the shipping enterprise will deliver the containers as outputs to downstream ports. The structure of the marine supply chain and its input–output relationship are shown in Figure 1.

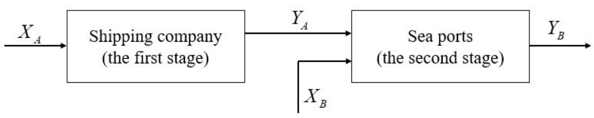

Figure 1. Marine Supply Chain.

In Figure 1, X_A is the inputs of the shipping company (the first stage) and Y_A is the output of it. The inputs of the second stage not only include the intermediate products from the first stage Y_A but also the additional inputs X_B. In the decentralized supply chain, the different leaders cause different efficiencies, because when one part in the supply chain takes the lead, its first consideration is to maximize its own interests. Therefore, the following will be modeled from two cases.

3.1. The Core Firm Is Upstream Member

Assume each marine supply chain is a DMU and the number of DMUs is n. For each j with $1 \leq j \leq n$, the jth DMU consumes uncertain input vector $\tilde{\boldsymbol{X}}_{Aj}$ to produce uncertain output vector $\tilde{\boldsymbol{Y}}_{Aj}$ in the first stage, and consumes uncertain input vector $\tilde{\boldsymbol{Y}}_{Aj}$ and $\tilde{\boldsymbol{X}}_{Bj}$ to produce uncertain output vector $\tilde{\boldsymbol{Y}}_{Bj}$ in the second stage.

When the upstream member is the core firm, we need to consider the first stage's efficiency beforehand. For every DMU, we define the sustainability efficiency of the first stage, denoted as E_{AA}, as the expected ratio of weighted uncertain outputs to weighted uncertain inputs, and we artificially set it to be always less than or equal to unity, i.e.,

$$E_{AA} = E\left[\frac{\boldsymbol{U}_A^T \tilde{\boldsymbol{Y}}_{Aj}}{\boldsymbol{V}_A^T \tilde{\boldsymbol{X}}_{Aj}}\right] \leq 1, \quad j = 1, 2, \ldots, n, \tag{1}$$

where $\boldsymbol{V_A}$ and $\boldsymbol{U_A}$ are non-negative weight vectors of $\tilde{\boldsymbol{X}}_{\boldsymbol{Aj}}$ and $\tilde{\boldsymbol{Y}}_{\boldsymbol{Aj}}$, respectively. A target DMU$_o$ is regarded as efficient in the first stage if it can find out a set of favorable weights $(\tilde{\boldsymbol{V_A}}^*, \tilde{\boldsymbol{U_A}}^*)$ such that the expected ratio of DMU$_o$ reaches up to 1, i.e.,

$$E_{AA}^* = E\left[\frac{\boldsymbol{U^*}_A^T \tilde{\boldsymbol{Y}}_{Ao}}{\boldsymbol{V^*}_A^T \tilde{\boldsymbol{X}}_{Ao}}\right] = 1$$

subject to constraint (1). In order to verify if DMU$_o$ is efficient in the first stage, we may solve the following model:

$$\begin{cases} \max\limits_{\boldsymbol{U},\boldsymbol{V}} & E_{AA} = E\left[\dfrac{\boldsymbol{U}_A^T \tilde{\boldsymbol{Y}}_{Ao}}{\boldsymbol{V}_A^T \tilde{\boldsymbol{X}}_{Ao}}\right] \\ \text{s.t.} & E\left[\dfrac{\boldsymbol{U}_A^T \tilde{\boldsymbol{Y}}_{Aj}}{\boldsymbol{V}_A^T \tilde{\boldsymbol{X}}_{Aj}}\right] \leq 1, \quad j = 1, 2, \ldots, n \\ & \boldsymbol{U}_A^T \geq 0 \\ & \boldsymbol{V}_A^T \geq 0. \end{cases} \tag{2}$$

Definition 1. *(Efficiency of the first stage) DMU$_o$ is considered to be efficient in the first stage if the optimal values of E_{AA}^* of (2) reach up to 1.*

When calculating the efficiency of the second stage of the marine supply chain, the inputs of the second stage not only include the intermediate products from the first stage Y_A but also the additional inputs X_B. Therefore, the efficiency of the second stage can be obtained similarly as the following model,

$$\begin{cases} \max\limits_{\boldsymbol{U},\boldsymbol{V}} & E_{AB} = E\left[\dfrac{\boldsymbol{U}_B^T \tilde{\boldsymbol{Y}}_{Bo}}{\boldsymbol{V}_B^T \tilde{\boldsymbol{X}}_{Bo} + \boldsymbol{U^*}_A^T \tilde{\boldsymbol{Y}}_{Ao}}\right] \\ \text{s.t.} & E\left[\dfrac{\boldsymbol{U}_B^T \tilde{\boldsymbol{Y}}_{Bj}}{\boldsymbol{V}_B^T \tilde{\boldsymbol{X}}_{Bj} + \boldsymbol{U^*}_A^T \tilde{\boldsymbol{Y}}_{Aj}}\right] \leq 1 \\ & \boldsymbol{U}_B^T \geq 0 \\ & \boldsymbol{V}_B^T \geq 0. \end{cases} \tag{3}$$

Definition 2. *(Efficiency of the second stage) DMU$_k$ is considered to be efficient in the second stage if the optimal values of E_{AB}^* of (3) reach up to 1.*

For calculation, models (2) and (3) should be transformed into accurate models, and the equivalent forms of models (2) and (3) are proved as follows:

Theorem 2. *For each j, let inputs $\tilde{X}_{A1}, \tilde{X}_{A2}, \cdots, \tilde{X}_{Am}$ and outputs $\tilde{Y}_{A1}, \tilde{Y}_{A2}, \cdots, \tilde{Y}_{As}$ be independent uncertain variables with regular uncertainty distributions $\Phi_{j1}, \Phi_{j2}, \cdots, \Phi_{jm}$ and $\Psi_{j1}, \Psi_{j2}, \cdots, \Psi_{js}$, respectively. Then, the model (2) is equivalent to the following form:*

$$\begin{cases} \max\limits_{u,v} \quad E_{AA} = \displaystyle\int_0^1 \frac{\sum_{r=1}^{s} U_{Ar}\Psi^{-1}_{Aor}(\alpha)}{\sum_{i=1}^{m} V_{Ai}\Phi^{-1}_{Aoi}(1-\alpha)} \mathrm{d}\alpha \\ \textit{subject to:} \\ \quad \displaystyle\int_0^1 \frac{\sum_{r=1}^{s} U_{Ar}\Psi^{-1}_{Ajr}(\alpha)}{\sum_{i=1}^{m} V_{Ai}\Phi^{-1}_{Aji}(1-\alpha)} \mathrm{d}\alpha \le 1, \quad j=1,2,\ldots,n, \\ \quad \boldsymbol{U_A} = (U_{A1}, U_{A2}, \cdots, U_{As}) \ge 0, \\ \quad \boldsymbol{V_A} = (V_{A1}, V_{A2}, \cdots, V_{Am}) \ge 0, \end{cases} \tag{4}$$

where $\Phi_{Ao1}, \Phi_{Ao2}, \cdots, \Phi_{Aom}$ and $\Psi_{Ao1}, \Psi_{Ao2}, \cdots, \Psi_{Aos}$ are the regular uncertainty distributions of $\tilde{X}_{Ao1}, \tilde{X}_{Ao2}, \cdots, \tilde{X}_{Aom}$ and $\tilde{Y}_{Ao1}, \tilde{Y}_{Ao2}, \cdots, \tilde{Y}_{Aos}$, respectively.

Proof. On the basis of Theorem 1, since the function $(\boldsymbol{U_A}^T\tilde{\boldsymbol{Y}}_{Aj})/(\boldsymbol{V_A}^T\tilde{\boldsymbol{X}}_{Aj})$ is strictly increasing as to $\tilde{\boldsymbol{Y}}_{\boldsymbol{Aj}}$ and strictly decreasing as to $\tilde{\boldsymbol{X}}_{\boldsymbol{Aj}}$ for each j, it can be obtained that the inverse uncertainty distribution of $(\boldsymbol{U_A}^T\tilde{\boldsymbol{Y}}_{Aj})/(\boldsymbol{V_A}^T\tilde{\boldsymbol{X}}_{Aj})$ is

$$F_k^{-1}(\alpha) = \int_0^1 \frac{\sum_{r=1}^{s} U_{Ajr}\Psi^{-1}_{Ajr}(\alpha)}{\sum_{i=1}^{m} V_{Aji}\Phi^{-1}_{Aji}(1-\alpha)} \mathrm{d}\alpha.$$

According to Theorem 1, we prove

$$E\left[\frac{\boldsymbol{U_A}^T\tilde{\boldsymbol{Y}}_{Aj}}{\boldsymbol{V_A}^T\tilde{\boldsymbol{X}}_{Aj}}\right] = \int_0^1 \frac{\sum_{r=1}^{s} U_{Ajr}\Psi^{-1}_{Ajr}(\alpha)}{\sum_{i=1}^{m} V_{Aji}\Phi^{-1}_{Aji}(1-\alpha)} \mathrm{d}\alpha, \quad j = 1,2,\ldots,n.$$

The theorem is then verified. Similarly, Formula (3) for the efficiency of the second stage is equivalent to the following form:

$$\begin{cases} \max\limits_{u,v} \quad E_{AB} = \displaystyle\int_0^1 \frac{\sum_{r=1}^{s} U_{Br}\Psi^{-1}_{Bor}(\alpha)}{\sum_{i=1}^{m} V_{Bi}\Phi^{-1}_{Boi}(1-\alpha) + \sum_{r=1}^{s} U^*_{Ar}\Psi^{-1}_{Aor}(1-\alpha)} \mathrm{d}\alpha \\ \text{subject to:} \\ \quad \displaystyle\int_0^1 \frac{\sum_{r=1}^{s} U_{Br}\Psi^{-1}_{Bjr}(\alpha)}{\sum_{i=1}^{m} V_{Bi}\Phi^{-1}_{Bji}(1-\alpha) + \sum_{r=1}^{s} U^*_{Ar}\Psi^{-1}_{Ajr}(1-\alpha)} \mathrm{d}\alpha \le 1, \quad j=1,2,\ldots,n, \\ \quad \boldsymbol{U_B} = (U_{B1}, U_{B2}, \cdots, U_{Bs}) \ge 0, \\ \quad \boldsymbol{V_B} = (V_{B1}, V_{B2}, \cdots, V_{Bm}) \ge 0, \end{cases} \tag{5}$$

where $\Phi_{Bo1}, \Phi_{Bo2}, \cdots, \Phi_{Bom}$ and $\Psi_{Bo1}, \Psi_{Bo2}, \cdots, \Psi_{Bos}$ are the regular uncertainty distributions of $\tilde{X}_{Bo1}, \tilde{X}_{Bo2}, \cdots, \tilde{X}_{Bom}$ and $\tilde{Y}_{Bo1}, \tilde{Y}_{Bo2}, \cdots, \tilde{Y}_{Bos}$, respectively. □

Taking all the above-mentioned into account, we can delineate the overall efficiency of the marine supply chain as the mean value of the two optimal values considering the upstream firm as the leader, which enjoys the priority in the supply chain:

$$e_{AB} = \frac{1}{2}(E^*_{AA} + E^*_{AB}). \tag{6}$$

3.2. The Core Firm Is Downstream Member

Similarly, it is also feasible to invent a procedure for the scenario when the downstream firm is operating as the core firm. Herein, we can obtain another two models. The difference from the previous model is that when the downstream member is the core firm, the efficiency of the downstream member should be maximized first. Therefore, the efficiency of the downstream member should be calculated first when modeling. In order to verify if DMU$_o$ is efficient in the second stage, we may solve the following model:

$$\begin{cases} \max\limits_{U,V,\mu} & E_{BB} = E\left[\dfrac{\boldsymbol{U}_B^T\tilde{\boldsymbol{Y}}_{Bo}}{\boldsymbol{V}_B^T\tilde{\boldsymbol{X}}_{Bo} + \boldsymbol{U}_A^T\tilde{\boldsymbol{Y}}_{Ak}}\right] \\ \text{s.t.} & E\left[\dfrac{\boldsymbol{U}_B^T\tilde{\boldsymbol{Y}}_{Bj}}{\boldsymbol{V}_B^T\tilde{\boldsymbol{X}}_{Bj} + \boldsymbol{U}_A^T\tilde{\boldsymbol{Y}}_{Aj}}\right] \le 1 \\ & \boldsymbol{U}_B^T \ge 0 \\ & \boldsymbol{V}_B^T \ge 0 \end{cases} \tag{7}$$

DMU$_o$ is considered to be efficient in the second stage if the optimal values of E_{BB}^* of (7) reach up to 1.

Then, in order to verify whether the upstream member is efficient, we can solve the following model:

$$\begin{cases} \max\limits_{V} & E_{BA} = E\left[\dfrac{\boldsymbol{U}{*}_A^T\tilde{\boldsymbol{Y}}_{Ak}}{\boldsymbol{V}_A^T\tilde{\boldsymbol{X}}_{Ak}}\right] \\ \text{s.t.} & E\left[\dfrac{\boldsymbol{U}{*}_A^T\tilde{\boldsymbol{Y}}_{Aj}}{\boldsymbol{V}_A^T\tilde{\boldsymbol{X}}_{Aj}}\right] \le 1, \quad j = 1, 2, \ldots, n \\ & \boldsymbol{V}_A^T \ge 0. \end{cases} \tag{8}$$

DMU$_k$ is considered to be efficient in the second stage if the optimal values of E_{BA}^* of (8) reach up to 1.

Then, we can calculate the overall efficiency of the marine supply chain where the downstream participant is the leader:

$$e_{BA} = \frac{1}{2}(E_{BB}^* + E_{BA}^*). \tag{9}$$

4. Research Design

The growth of world trade has led to the economic benefits of the marine industry growing at an increasing rate, but it has also caused serious environmental and social problems. Because these problems aggravate global warming and climate change and pose a threat to public health and safety, it is urgent to study the sustainable efficiency of the marine supply chain. This study chooses the shipping supply chain composed of Maersk and ports in major 17 coastal cities in China as the DMUs, and it selects indicators from the three dimensions of economy, environment and society to evaluate the sustainable efficiency using the data collected from 2017.

4.1. Decision Making Units

The marine supply chains of 17 coastal cities in China are regarded as the DMUs, and each DMU has the internal structure that includes the upstream shipping company Maersk and the downstream port. Figure 2 shows the structure of each DMU, which generates outputs from inputs.

Maersk is a crucial link in the marine supply chain because it transforms input into output, which is then provided as input to the downstream port. The downstream port also makes use of additional inputs and the output of Maersk to convert them into output for the whole marine supply chain.

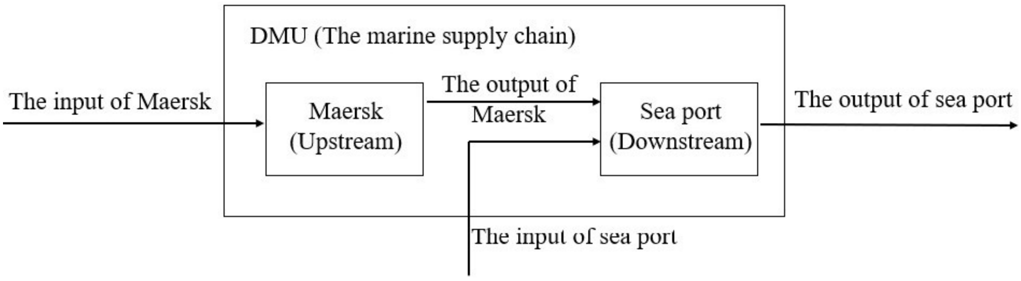

Figure 2. The structure of marine supply chain.

4.2. Evaluation Indexes and Variables

The selection of evaluation indexes in this study is mainly considered from the following three perspectives. Firstly, in order to improve the reliability and accuracy of the evaluation results, the number of input and output indexes should not exceed one-third of the number of DMUs. Secondly, since there is an obvious relationship between supply and demand between the upstream Maersk and the downstream ports, there should be an intermediate index which is both the output of Maersk and the input of the port. Last but not least, the selected indexes should comprehensively reflect the sustainability from the three dimensions of economy, environment and society. According to the above three principles and combined with the characteristics of the marine supply chain, "labor population", "exhaust emission", "social benefit", and "standard container volume" are selected as the evaluation indexes shown in Table 1.

Table 1. The evaluation indexes of sustainable efficiency.

The Index	Input or Output	Variable
Labor population	The input of Maersk	Uncertain variable
Exhaust emission	The input of the port	Uncertain variable
Standard container volume	The output of Maersk	Certain variable
Social benefit	The output of the port	Uncertain variable

Firstly, the number of employees in Maersk and standard container traffic volume are selected as the input and output variables of the upstream Maersk. The number of employees and standard container traffic volume reflect the economic dimension, but the difference is that the number of employees is an uncertain variable, while the standard container traffic volume is a certain variable. In a certain period of time, employees may leave or join, so it is impossible to have an accurate number. Although we cannot obtain the accurate number, it always fluctuates in a range anyway. Since the distribution function of the interval number is inconsistent with the real frequency, we take the number of employees as an uncertain variable.

Since Maersk transports containers to the ports, the standard container traffic volume is used as an input for the downstream ports. In addition, we select exhaust emission as an index to reflect the environmental dimension of sustainable efficiency. The exhaust emission is treated as an uncertain input variable of the port because it is an unexpected output whose data cannot be accurately observed. Finally, the ports exist not only to produce economic benefits but also achieve customer satisfaction and assume social responsibilities that include promoting regional development, providing employment and so on. Therefore, we attribute all these to the index of social benefit to reflect the social dimension of sustainable efficiency. Social benefit is the embodiment of the satisfaction of the government, enterprises and individuals in all aspects, so it is difficult to quantify it with accurate data. Therefore, social benefit is also an uncertain variable whose data can be obtained by investigating or inviting relevant experts to score.

4.3. Data Collection and Description

The standard container volume is regarded as an accurate variable whose data collection comes from the statistical data of the Ministry of Transport of the People's Republic of China (Ministry of Transport of the People's Republic of China 2017), iimedia data center and Maersk 2017 annual report. The standard container volume of Maersk in each port is calculated by the percentage of each port in China's national transportation volume in 2017 and the market share and transportation volume of Maersk shipping container transportation. The final results are shown in Table 2.

Table 2. The inputs and outputs of the marine supply chain in 17 coastal cities in China, 2017.

The Cities of DMUs	Labor Population	Exhaust Emission	Social Benefit	Standard Container Volume
Tianjin	$\mathcal{L}(45,65)$	$\mathcal{L}(10,16)$	$\mathcal{L}(78,82)$	1,031,588
Shanghai	$\mathcal{L}(200,500)$	$\mathcal{L}(30,41)$	$\mathcal{L}(83,87)$	2,755,255
Shenzhen	$\mathcal{L}(150,250)$	$\mathcal{L}(20,25)$	$\mathcal{L}(77,83)$	1,726,205
Zhoushan	$\mathcal{L}(200,300)$	$\mathcal{L}(20,24)$	$\mathcal{L}(75,85)$	1,685,821
Guangzhou	$\mathcal{L}(150,500)$	$\mathcal{L}(15,24)$	$\mathcal{L}(90,94)$	1,381,101
Dalian	$\mathcal{L}(40,60)$	$\mathcal{L}(10,19)$	$\mathcal{L}(68,72)$	1,094,884
Lianyungang	$\mathcal{L}(10,50)$	$\mathcal{L}(4,5)$	$\mathcal{L}(67,73)$	322,508
Qingdao	$\mathcal{L}(300,475)$	$\mathcal{L}(15,17)$	$\mathcal{L}(69,73)$	1,253,056
Yantai	$\mathcal{L}(15,30)$	$\mathcal{L}(2,3)$	$\mathcal{L}(55,65)$	184,877
Fuzhou	$\mathcal{L}(15,25)$	$\mathcal{L}(1,4)$	$\mathcal{L}(65,75)$	206,104
Dongguan	$\mathcal{L}(200,500)$	$\mathcal{L}(2,5)$	$\mathcal{L}(71,75)$	267,730
Xiamen	$\mathcal{L}(40,60)$	$\mathcal{L}(5,14)$	$\mathcal{L}(70,74)$	710,750
Zhuhai	$\mathcal{L}(5,10)$	$\mathcal{L}(1,3)$	$\mathcal{L}(67,73)$	155,434
Northern Gulf of Guangxi	$\mathcal{L}(40,50)$	$\mathcal{L}(1,3)$	$\mathcal{L}(68,72)$	156,119
Suzhou	$\mathcal{L}(40,75)$	$\mathcal{L}(2,8)$	$\mathcal{L}(69,75)$	402,621
Fuoshan	$\mathcal{L}(200,250)$	$\mathcal{L}(3,4)$	$\mathcal{L}(75,79)$	267,730
Nanjing	$\mathcal{L}(40,50)$	$\mathcal{L}(2,4)$	$\mathcal{L}(77,79)$	215,690

For environmental and social indexes that cannot obtain accurate data, we treat them as uncertain variables by using an expert scoring method to obtain a confidence function based on uncertainty theory. Taking social benefits as an illustration, we did not have the data at first to estimate the social benefit variables. In order to assess the level of social benefits in this circumstance, we are compelled to consult some port-related experts. Through the literature, research and interviews, we first identified some aspects of the evaluation of social benefits, such as service quality, customer satisfaction, the degree of impact on regional economic development, social image, etc. to provide reference for expert evaluation. However, it is nearly impossible for port experts to accurately describe the confidence of every possible event. Instead, they are limited to making purely subjective decisions. Therefore, we ask experts to rate the variables of social benefits on a scale of 0 to 100 based on the available data and their personal experience. Since 100 is very good in this case and 0 is very poor, no improvement is required. The situation is more satisfactory the higher the score. Taking the social benefits of the Qingdao port as an example, the consultation procedure is as follows:

(Q) What do you think is the minimum score reflecting the social benefits in Qingdao Port?
(A) 70 points. (We received a set of the expert's experimental data (70, 0))
(Q) What do you think is the maximum score representing the social benefits in Qingdao Port?
(A) 80 points. (We received a set of the expert's experimental data (80, 1))

Thus far, we acquired two of the expert's experimental data (70, 0) and (80, 1) about the amount of air pollutants in Qingdao Port. These data enable us to obtain the linear distribution of air pollutants, of which the variable is $\mathcal{L}(70, 80)$ and its uncertainty distribution is

$$\Phi(x) = \begin{cases} 0, & \text{if } x \leq 70 \\ (x-70)/10, & \text{if } 70 < x \leq 80 \\ 1, & \text{if } x > 80. \end{cases}$$

We can use the same process to obtain the linear distribution of the social benefits of each seaport. The same approach also allows us to obtain the linear distribution of uncertain variables of labor population and exhaust emission, which shown in Table 2.

5. Results, Discussions and Implications

There are two situations in the decentralized marine supply chain: that shipping enterprises are leaders or ports are leaders. In order to identify the sustainable efficiency of the marine supply chain and find out the reasons for the inefficiency, we will measure the sustainable efficiency of Maersk, ports and the whole supply chain, respectively, under different modes. The lower the sustainable efficiency value, the worse the sustainable performance. On the contrary, the higher the sustainable efficiency value, the better the sustainable performance. When the sustainable efficiency reaches up to 1, it can be considered that the sustainable level is the best without improvement.

Therefore, this section will use the models proposed in Section 3 and the data listed in Section 4 to calculate the sustainable efficiencies of the marine supply chain, Maersk and ports, respectively, to identify whether they are efficient. Subsequently, we will discuss and make suggestions and implications according to the results from the three perspectives of economy, environment and society.

5.1. Results and Discussions

First of all, the sustainable efficiencies of the marine supply chain when Maersk and the port are the leader are calculated, respectively, and compared, which is shown in Table 3. It can be seen from Table 3 that the sustainable performance of marine supply chains in Qingdao and Zhuhai are the best, whose sustainable efficiency reaches up to 1 under the lead of both Maersk and the port. The second is the marine supply chain in Guangzhou, whose sustainable efficiency reaches up to 1 when the port is the leader. In addition, only the sustainable efficiency of the marine supply chain in the northern gulf of Guangxi is lower than 0.9 under the lead of both Maersk and the port. In addition, the sustainable efficiency of other supply chains is higher than 0.9 in at least one case. By comparing the sustainable efficiencies of marine supply chains under the lead of Maersk and the port, it can be found that the sustainable efficiencies of most supply chains are higher when ports are leaders, which is shown in Figure 3.

Table 3. The sustainable efficiency of the marine supply chain with different leaders.

The Cities of DMUs	The Efficiency of DMUs with Maersk as Leader	The Efficiency of DMUs with the Port as Leader
Tianjin	0.8742	0.9261
Shanghai	0.9652	0.9609
Shenzhen	0.9277	0.9307
Zhoushan	0.9447	0.9423
Guangzhou	0.9416	1.0000
Dalian	0.9442	0.9689
Lianyungang	0.8873	0.9014
Qingdao	1.0000	1.0000
Yantai	0.8596	0.9469
Fuzhou	0.8818	0.9343
Dongguan	0.9155	0.9693
Xiamen	0.9188	0.9010
Zhuhai	1.0000	1.0000
Northern Gulf of Guangxi	0.8646	0.8556
Suzhou	0.9345	0.9156
Fuoshan	0.9531	0.9587
Nanjing	0.9493	0.9721

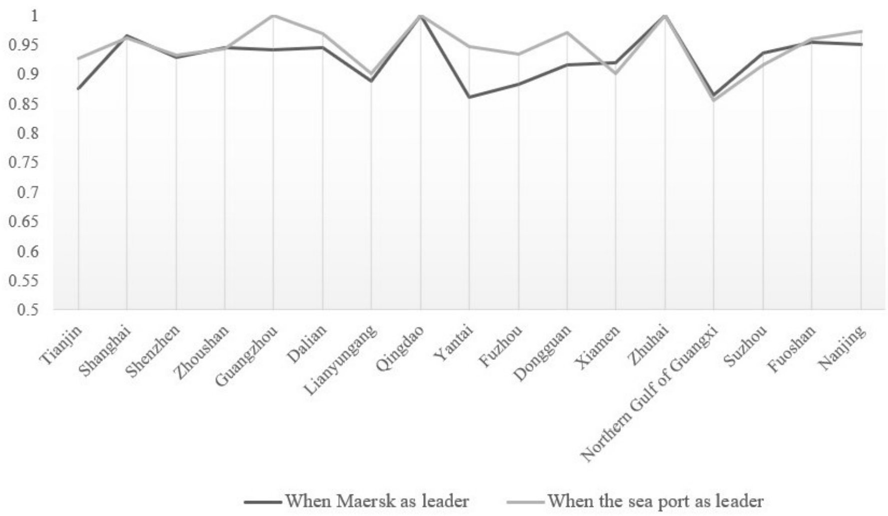

Figure 3. The sustainable efficiency of the marine supply chain under different leaders.

Afterwards, the sustainable efficiencies of Maersk with different leaders are calculated, and the results are shown in Table 4. As can be seen from Table 4, Maersk's sustainable performance in Zhuhai and Guangzhou are the best, whose sustainable efficiency reaches up to 1 under the lead of both Maersk and the port. However, it is noteworthy that compared with the sustainable efficiency of the marine supply chain, Maersk's sustainable level is significantly lower, because the sustainable efficiencies of Maersk in five regions (Lianyungang, Fuzhou, Xiamen, Suzhou and Northern Gulf of Guangxi) are lower than 0.9 under the lead of both Maersk and the port. By comparing the sustainable efficiency of Maersk with different leaders, it can be found that the sustainable efficiencies of Maersk vary little, which is displayed in Figure 4.

Similarly, the sustainable efficiencies of ports under the lead of both Maersk and the port are calculated through the model introduced in Section 3 and the results are shown in Table 5. According to the results, the ports of Zhuhai and Qingdao have the best sustainable performance, as the sustainable efficiency reaches up to 1 when both Maersk and the port are the leader. In addition, the sustainable efficiency of Guangzhou port reaches up to 1 when the port is the leader. The sustainable efficiencies of Suzhou port and Nanjing port reach up to 1 when Maersk is the leader and when the port is the leader, respectively.

By comparing the sustainable efficiency of ports under the lead of both Maersk and the port, it can be found that the sustainable efficiencies of ports are higher when the port is the leader, as demonstrated in Figure 5.

Table 4. The sustainable efficiency of Maersk with different leaders.

The Cities of DMUs	The Efficiency of Maersk When Maersk is Leader	The Efficiency of Maersk When the Port is Leader
Tianjin	0.9229	0.8563
Shanghai	0.9387	0.9277
Shenzhen	0.9127	0.8691
Zhoushan	0.9342	0.8923
Guangzhou	1.0000	1.0000
Dalian	0.9284	0.9459
Lianyungang	0.8747	0.8797
Qingdao	0.9956	0.9956
Yantai	0.8327	0.9116
Fuzhou	0.8254	0.8756
Dongguan	0.8942	0.9434
Xiamen	0.8376	0.8122
Zhuhai	1.0000	1.0000
Northern Gulf of Guangxi	0.7881	0.7262
Suzhou	0.8689	0.8383
Fuoshan	0.9144	0.9186
Nanjing	0.9179	0.9442

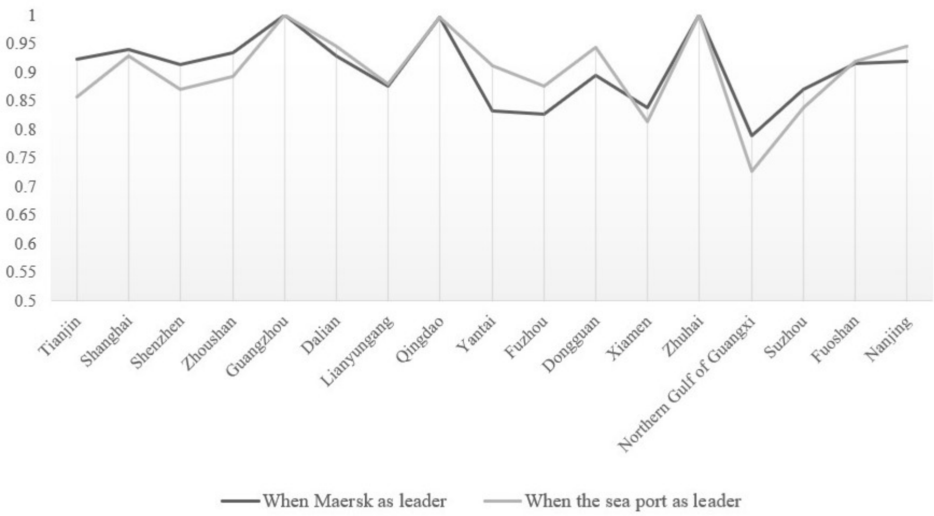

Figure 4. The sustainable efficiency of Maersk under different leaders.

In general, from the perspective of different leaders, it can assist each port, Maersk, and marine supply chain in determining the most sustainable mode for themselves according to the results. Furthermore, the marine supply chain's sustainable performance is better when the port is the leader. As a result, ports and shipping companies should play the roles of guidance and cooperation in the marine supply chain, respectively. Finally, most marine supply chains are inefficient, so it is necessary to increase the sustainable efficiency of shipping enterprises and ports to enhance the sustainable performance of shipping supply chains.

Table 5. The sustainable efficiency of ports with different leaders.

The Cities of DMUs	The Efficiency of Ports When Maersk is Leader	The Efficiency of Ports When the Port is Leader
Tianjin	0.8255	0.9958
Shanghai	0.9916	0.9940
Shenzhen	0.9427	0.9923
Zhoushan	0.9552	0.9923
Guangzhou	0.8832	1.0000
Dalian	0.9600	0.9918
Lianyungang	0.8998	0.9230
Qingdao	1.0000	1.0000
Yantai	0.8864	0.9821
Fuzhou	0.9381	0.9930
Dongguan	0.9367	0.9952
Xiamen	1.0000	0.9898
Zhuhai	1.0000	1.0000
Northern Gulf of Guangxi	0.9410	0.9850
Suzhou	1.0000	0.9929
Fuoshan	0.9918	0.9987
Nanjing	0.9807	1.0000

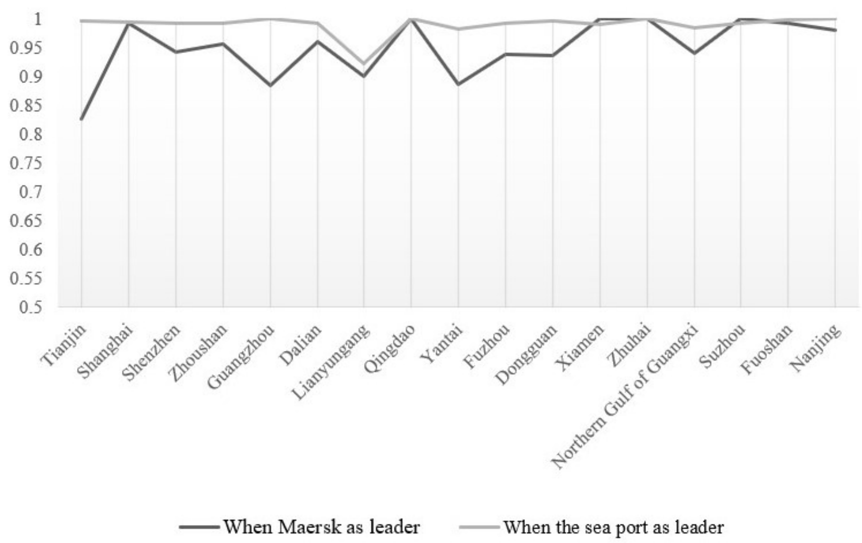

Figure 5. The sustainable efficiency of ports under different leaders.

5.2. Suggestions and Implications

According to the results, ports have a greater influence to ensure the sustainability of the marine supply chain, so the ports and shipping companies should play the role of guidance and cooperation, respectively. This study advances some management suggestions and implications for shipping companies and ports to promote the sustainable development of the marine supply chain from the perspectives of the economy, environment and society.

Although the port economy and regional economic growth are inextricably linked, port operations also use a lot of energy and pollute the environment. Some emerging technologies, such as automation, artificial intelligence, the Internet of Things, and 5G technology, need to be applied to ports in order to realize the common progress of the economy, environment and society and to support the sustainable development of ports. These technologies can not only improve operational efficiency and economic output but also promote rational resource allocation and reduce energy waste by automating wharf operations, building monitoring systems, power supply systems, digital platforms, and so on. Simultaneously, the use of digital technology enables real-time information exchange, allowing shipping companies and ports to collaborate more deeply and provide better services to enterprises and customers.

Furthermore, some relevant policies must be implemented and promoted. Ports should actively collaborate with shipping companies to promote the implementation of ship emission control zone policies and reduce harmful gas emissions. While taking advantage of good locations and terrain advantages to develop, ports should also actively participate in social responsibilities, drive regional industrial upgrading, and realize port-city integration.

As an important component of the marine supply chain, shipping companies' behavior has an impact on the sustainable development of the marine supply chain; especially from the results, the sustainable efficiency of shipping companies is significantly lower than that of ports. First of all, the shipping companies should introduce talents, improve the quality of employees, and strengthen their learning of new technologies and new equipment, so as to cooperate with the application of emerging technologies in ports. Second, to lessen the burning of fossil fuels and exhaust emissions, shipping companies should work with ports, follow emission control area regulations, and implement clean energy technology. Finally, shipping companies should accelerate the digitalization process in order to provide customers with more efficient and convenient services, as well as form strong partnerships with downstream ports, in order to improve the marine supply chains' operational efficiency and customer satisfaction.

6. Conclusions

The purpose of this study is to evaluate the sustainable efficiency of the marine supply chain by constructing an uncertain network DEA model, which is used to deal with uncertain variables and considers the internal structure of the DMU. This study defines the marine supply chain composed of Maersk and ports as the DMU, and it selects the labor population of Maersk, exhaust emission, standard container volume and social benefits as the evaluation indexes to evaluate the sustainable efficiency of the marine supply chain in 17 cities in China. The results show that the sustainable performance of ports is better than that of Maersk, and the marine supply chains perform better when the port is the leader, but most of the marine supply chains are inefficient, which needs to be improved.

A series of measures need to be taken to ensure the sustainability of the marine supply chain. First, realize port automation and build information platforms through the construction of smart ports to improve port operational efficiency and customer satisfaction. Second, establish emission control zones and implement boundary energy technology to reduce pollutants and fossil fuel combustion. Finally, strengthen the cooperation between upstream and downstream enterprises in the marine supply chain and the cooperation between ports to drive marine supply chain and regional economic development.

In general, the main contributions of this study are reflected in two aspects. First of all, the traditional DEA model is not applicable because the relevant sustainable data can not be accurately observed, such as social benefits, carbon emissions, etc. Therefore, this study constructs an uncertain network DEA model to deal with imprecise data and applies it to evaluate the sustainable efficiency of the marine supply chain, which is expected to improve the methods in the field of sustainable efficiency evaluation. Second, by identifying the internal structure of the DMU and simultaneously taking into account the upstream and downstream of the marine supply chain, this study analyzes the causes of the inefficiency and offers management recommendations. This study is therefore meaningful, which can provide methodological support for the evaluation of DMUs with uncertain variables and internal structure, and it can also expand the evaluation of sustainable efficiency involving not only shipping but also other industries.

Although we have calculated the sustainable efficiency of the marine supply chain in most coastal cities in China, there are still some limitations that need further research. Firstly, due to the limitation of the number of DMUs, the selection of evaluation indexes is not comprehensive. Although the evaluation indexes of this study involve three dimensions of economy, environment and society, they cannot comprehensively reflect sustainable performance. Other limitations are that the marine supply chain usually has a more complex structure, and there may also be cooperative relationships between shipping companies and ports. Therefore, future research needs to consider the internal structure of the marine supply chain and the relationship between upstream and downstream, and it needs to build a more comprehensive evaluation index system for evaluation.

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