

## Article

# Evaluating Global Container Shipping Companies: A Novel Approach to Investigating Both Qualitative and Quantitative Criteria for Sustainable Development

Chia-Nan Wang <sup>1</sup>, Thanh-Tuan Dang <sup>1,2,\*</sup>, Ngoc-Ai-Thy Nguyen <sup>1,2</sup>, Chien-Chang Chou <sup>3,\*</sup>,  
Hsien-Pin Hsu <sup>4,\*</sup> and Le-Thanh-Hieu Dang <sup>1</sup>

- <sup>1</sup> Department of Industrial Engineering and Management, National Kaohsiung University of Science and Technology, Kaohsiung 807618, Taiwan
- <sup>2</sup> Department of Logistics and Supply Chain Management, Hong Bang International University, Ho Chi Minh 72320, Vietnam
- <sup>3</sup> Department of Shipping Technology, National Kaohsiung University of Science and Technology, Kaohsiung 807618, Taiwan
- <sup>4</sup> Department of Supply Chain Management, National Kaohsiung University of Science and Technology, Kaohsiung 81157, Taiwan
- \* Correspondence: tuandt@hiu.vn (T.-T.D.); ccchou@nkust.edu.tw (C.-C.C.); hphsu@nkust.edu.tw (H.-P.H.)

**Abstract:** The COVID-19 pandemic has implications for the container shipping industry and global supply chains. Measuring the efficiency of major international container shipping companies (CSCs) is an important issue that helps them make strategic decisions to improve performance, especially in the context that all businesses and governments are adapting to build back better the post-pandemic world. This paper develops a new integrated approach using both a qualitative assessment tool and a performance assessment tool as a systematic and flexible framework for evaluating the container shipping industry. This new methodology is implemented in two phases to consider both qualitative and quantitative criteria for assessing the performance of CSCs based on efficiency. In the first phase, qualitative performance evaluation is performed using spherical fuzzy analytical hierarchical process (AHP-SF) to find criteria weights and then the grey complex proportional assessment methodology (COPRAS-G) is used to find the ranking of CSCs. Qualitative variables are converted into a quantitative variable for use in the data envelopment analysis (DEA) model as an output called an output variable called expert-based qualitative performance (EQP). Then, DEA is performed to identify efficient and inefficient CSCs with the EQP variable and other quantitative parameters (i.e., capacity, lifting, expenses, revenue, and CO<sub>2</sub> emissions). The efficiency of 14 major global CSCs is empirically evaluated, and the scores for CSCs' efficiency in all dimensions are measured and examined. The results show that the average cargo efficiency of the CSCs is lower than their eco-efficiency performance, revealing the operational disruption caused by the pandemic. Moreover, by identifying efficient and inefficient CSCs, our findings provide practical implications for decision-makers in the maritime field and assist in modifying applicable policies and strategies to achieve sustainable performance.

**Keywords:** shipping industry; decision-making; AHP-SF; COPRAS-G; data envelopment analysis; undesirable output; cargo efficiency; eco-efficiency

**MSC:** 62C05; 90B50; 91B06; 68T35; 49N05



**Citation:** Wang, C.-N.; Dang, T.-T.; Nguyen, N.-A.-T.; Chou, C.-C.; Hsu, H.-P.; Dang, L.-T.-H. Evaluating Global Container Shipping Companies: A Novel Approach to Investigating Both Qualitative and Quantitative Criteria for Sustainable Development. *Axioms* **2022**, *11*, 610. <https://doi.org/10.3390/axioms11110610>

Academic Editors: Darko Božanić, Adis Puška and Radko Mesiar

Received: 5 September 2022

Accepted: 25 October 2022

Published: 1 November 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

### 1.1. Research Background

Globalization has enhanced the importance of maritime transportation in recent decades as global trade has grown [1]. The container shipping business is an important aspect of the worldwide supply chain's flow of commodities. It is the most efficient

and cost-effective method of long-distance transportation of large goods. Thanks to efficient equipment and technology, container shipping services have grown relatively convenient, especially for intermodal transit. Meanwhile, the container shipping sailing network grows and is refined, improving connectivity between ports worldwide. As a result, container shipping has surpassed all other modes of freight transportation on a global scale [2]. According to the United Nations Conference on Trade and Development (UNCTAD), international containerized trade has continuously risen over decades [3].

Noticeably, maritime transport defied the COVID-19 disruption. Volumes fell less sharply than anticipated in 2020, and by the end of the year, they had rebounded, laying the framework for a change in global supply networks and new maritime trade patterns. Even though the worldwide crisis hampered maritime transport, the consequences were less severe than previously anticipated. Containerized trade dropped only 1.1 percent to 149 million twenty-foot equivalent units (TEU), compared to an 8.4 percent drop in 2009 after the financial crisis. Global container port throughput declined similarly, reaching 815.6 million TEU in 2020. Following the early 2020 shock, volumes quickly rebounded as stimulus packages and income-supporting measures strengthened consumer demand. Nonetheless, maintaining this worldwide transportation system is rather expensive [4]. Global container shipping firms (CSCs) must deploy a huge fleet of ships that sail according to fixed schedules. In addition, each vessel must be equipped with a number of empty containers for loading products. The turnaround ratio determines the necessary number of empty containers. A global CSC must budget for fuel, anchoring, canal fees, and other expenses in addition to these high fixed costs. The worldwide container shipping market is dominated by only a few CSCs due to the above-mentioned high entrance hurdles [5]. As a result, expertise and strategies are critical for CSCs to survive and thrive. Shipping companies must measure efficiency in order to improve their efficiency prospects.

### *1.2. CSCs' Efficiency Measurements*

Running a CSC is difficult due to the lack of significant distinctions in the essential services supplied by CSCs. Shippers may be enticed to move their cargo to another CSC due to a minor difference in freight rates [4]. Global economic volatility, problems in relocating empty containers, and extra capacity brought on by enlarged ships all add to the complexity and challenges of running a container shipping business. Despite these enormous expenses and hurdles, CSCs can survive and improve the operational efficiency of their shipping service production by leveraging their experience and tactics. A production system's function can be defined as transforming input into output [6]. This transformation can be thought of as a process of change—the operand results in extra values to meet the requirements of such changes. Shipping services are a function of both capital and labor [7]. In operational efficiency analysis, CSCs' performance is defined as a process that transforms inputs such as fleet capacity, workforce, and expenses to containers carried. Then, the volume of cargo carried (or so-called lifting) becomes a source of earnings (revenue) as a good output. The efficiency measures for CSCs' performance using different input–output combinations can be different. If lifting is used as an output, named cargo efficiency, this only reflects the relative ability of a company in carrying cargoes. Meanwhile, measuring efficiency using financial indicators of a CSC as outputs, called economic efficiency (or financial efficiency), can give insights into the financial performance of each company. Along with revenue gains, a CSC also causes harmful emissions from operation to the environment and society, which is seen as a bad output in the evaluation system. This leads to the need to consider the ecological efficiency of CSCs.

Due to its operating consequences on the maritime and air environments, the shipping sector has been at the center of attention on a worldwide scale. The impact of shipping activities on environmental pollution is highlighted in various discussions [8–14]. The global crisis has once again reminded the public of environmental sustainability trends. These trends have been steadily developing over the last decade, but they have accelerated during the epidemic and are continuing to revolutionize maritime transportation and trade.

Maritime transportation is under increasing pressure to decarbonize and operate more sustainably; additional challenges have also surfaced in the aftermath of the pandemic. According to the International Maritime Organization (IMO), the share of shipping emissions in global anthropogenic emissions reached nearly 3% in 2018 [15]. Despite maritime transportation being the safest and most energy-efficient mode of transportation compared to other modes, especially when considering transported volumes, the industry's contribution to global CO<sub>2</sub> emissions is expected to increase by 50–250% due to increased international trade until 2050. Global shipping must thus strike the right balance between its role as a private company and its social obligations to protect the environment. CSCs are concentrating on boosting eco-efficiency due to growing worries about climate change and growing knowledge of the detrimental effects of hazardous compounds on human health. The eco-efficiency idea, which is essentially the performance of the economics and the environment combined, has been examined in a number of recent studies and is regarded as the top research for future trends, not least for the shipping sector. To incorporate negative environmental impacts into CSCs' efficiency analysis, the eco-efficiency model investigates how operating costs, workforce, and liftings transform into one desirable output (revenue) and undesirable output (CO<sub>2</sub> emissions) [16].

### 1.3. Objectives of Present Study

As for each CSC, its relative performance compared to other firms is measured using several methods. For studying the overall performance of the CSCs, we view the global CSCs as production units and calculate the CSCs' performance in translating their resources into specific forms of outputs. As previously outlined, the efficiency of CSCs concerns the utilization of resources in multiple dimensions and generates different types of outcomes such as lifting (cargo-efficiency model), revenue, and CO<sub>2</sub> emissions (eco-efficiency model). Therefore, assessment should take multiple inputs and outputs into account simultaneously. With this being the case, data envelopment analysis (DEA) is a useful tool for estimating the production frontier and determining the efficiency of different organizations. It has been widely used in studies of relative port and shipping efficiency and, more recently, for efficiency analysis while considering the negative effects of emissions. In existing DEA-related articles, cargo efficiency and economic efficiency of specific CSCs have been investigated, including in studies such as [4,7,17–20]. Eco-efficiency has been discussed in the most recent articles [2,16,21].

In addition, the determination of the performance efficiency of a CSC is complicated further by the fact that while considering inputs and outputs that are quantitative (fleet capacity, expenses, workforce, revenue, the amount of CO<sub>2</sub> emissions, etc.) by the DEA models, it is vital to explore the qualitative criteria influencing a shipping enterprise's competitive advantage toward sustainable development. Numerous qualitative factors have recently become increasingly complex as strategic operations, environmental, social, political, counterparty, and customer satisfaction concerns have been discussed in various studies on CSC performance evaluation [22–28]. In light of this, the multi-criteria decision making (MCDM) techniques are used through experts' judgments or questionnaire surveys. As a result, a method is required to optimize the decision maker's attitude toward each criterion's importance while incorporating multiple aspects [29]. This study develops an integrated AHP-SF (spherical fuzzy analytical hierarchical process), COPRAS-G (grey complex proportional assessment), and DEA methodologies evaluation framework for global CSCs' performances, considering qualitative and quantitative factors. The inputs, outputs, and criteria have been determined by means of reviewing the literature review and experts' discussions. Qualitative assessment results could be integrated as a novel parameter for the quantitative analysis using the DEA model. This framework is comprehensive because, while decision-makers of CSCs can consider expert judgements of qualitative performance, the final efficiency scores from the DEA model suggest that inefficient CSCs make strategic decisions to improve their performance toward sustainable development.

The remaining sections are arranged as follows: Section 3 elaborates on the AHP-SF, COPRAS-G, and slack-based measure DEA (SBM-DEA) techniques. Section 2 gives a review of the literature. The empirical analysis is presented in Section 4. Section 5 concludes by outlining the discussions, limits, and possible directions for further research.

## 2. Literature Review

### 2.1. Literature Review on Efficiency Analysis of CSCs

In many industries, for relating efficiency outcomes to features of decision-making organizations, the application of DEA is regarded as an appropriate methodology. DEA was first introduced by Charnes et al. [30,31] to assess the efficiency and productivity of a decision-making unit (DMU) through multiple inputs–outputs. For efficiency analysis in the shipping industry based on quantitative dimensions, DEA models are used so that CSCs can understand their strengths and weaknesses and increase their performance. Two DEA models that are widely used are the Charnes, Cooper, and Rhodes (CCR), and the Banker, Charnes, and Cooper (BCC). Lun and Marlow [17] used two inputs (shipping capacity and operating costs) and two outputs to calculate the efficiency of major global CSCs (profit and revenue). With three inputs (total assets, workforce, and capital expenditures) and sales as an output, Panayides et al. [18] conducted an efficiency analysis of important international shipping corporations. Using a two-stage DEA technique, Bang et al. [7] investigated the operational and financial efficiencies of 14 liner shipping enterprises. In order to assess the effectiveness of international container shipping lines, Gutiérrez et al. [19] developed a bootstrap DEA approach: labor force, the number of ships, and fleet capacity were used as input variables, and containers carried and annual turnover were used as output variables, respectively. Chao et al. [4] used a dynamic network DEA with shared inputs to assess the cargo efficiency and economic efficiency of 13 major global CSCs. Chen et al. [2] considered the environmental efficiency of Taiwanese shipping firms using the network centralized DEA model for resource allocation. The correlations between economic and cargo efficiencies, environmentally adjusted efficiencies, and environmental efficiencies were determined by Gong et al. [16] using the DEA-SBM (slack-based model) for various input–output combinations. Their proposed model was applied for international shipping companies as their business units. Kuo et al. [21] developed two separate DEA models to obtain the cargo and eco-efficiency scores of 10 global CSCs and explore the determinants of the CSCs' efficiencies.

The existing literature reveals that most CSCs' efficiency evaluation approaches have filtered out efficient CSCs on measurable factors (capacity, expenses, workforce, emissions, etc.). In some cases, conducting only quantitative analysis in assessing organizational performance in the shipping industry is insufficient due to the need to investigate a CSC's efficiency from other aspects that are intangible and unmeasurable, such as their impacts on society and their counterparty, or strategy-related efficiency. In this case, experts' involvement is a practical method to provide qualitative judgments for CSCs based on their knowledge. To prioritize the competitive advantages of container shipping liner companies, Bao et al. [28] developed a multi-attribute decision making (MADM) model with intuitionistic fuzzy linguistic variables to evaluate both quantitative and qualitative data with experts' judgments. Each business's efficiency of technological upgrading, workplace safety, gender quality, personnel training, and other quantitative criteria are investigated in this study. The AHP method is most recognized in handling qualitative and subjective measurements of experts through pairwise comparison [32]. Yoon et al. [24] used the AHP method with fuzzy logic for uncertain information to evaluate the performance of CSCs in Vietnam under five main criteria: service, operation, service cost, counterparty, and financial status. The decision-making trial and evaluation laboratory (DEMATEL) method also uses pairwise comparison for collaborative decision-making to evaluate the relative importance of criteria. Based on the experience and knowledge of appropriate shipping industry experts obtained through an effective questionnaire, Hsu and Ho [27] determined key factors toward the performance of CSCs in Taiwan from the perspective of domestic

high-tech industry shippers. For evaluating the suitability and relevance of customer demands, customer expenses, customer communication, and customer convenience, the fuzzy Delphi technique and the improved DEMATEL model were suggested. Table 1 summarizes studies on CSCs' efficiency assessment.

**Table 1.** Overview of studies on CSCs' efficiency evaluation.

No	Author	Year	Inputs/Outputs/Criteria	Methodology Approach
1	Lun and Marlow [17]	2011	Operating costs, shipping capacity, profit, revenue	DEA-CCR
2	Panayides et al. [18]	2011	Number of employees, total assets, capital expenditures, sales	DEA-CCR DEA-BCC
3	Bang et al. [7]	2012	Total assets, capital expenditure, revenue, operating profits, number of ships, capacity, cargo carried	DEA-CCR DEA-BCC
4	Gutiérrez et al. [19]	2014	Labor, number of ships, fleet capacity, containers carried, turnover	Bootstrap DEA
5	Chao [20]	2017	Fleet capacity, operating expenses, number of port calls, container lifting, revenue	Network DEA
6	Chao et al. [4]	2018	Fleet capacity, operating expenses, employees, lifting, revenue	Dynamic network DEA
7	Yoon et al. [24]	2018	Service, operation, cost, counterparty, financial status	Fuzzy AHP
8	Gong et al. [16]	2019	Capital expenditure, total assets, capacity, number of ships, employees, fuel cost, revenue, cargo carried, CO <sub>2</sub> emissions, SOx emissions, NOx emissions	DEA-SBM
9	Kuo et al. [21]	2020	Fleet capacity, employees, operating costs, revenue, lifting, CO <sub>2</sub> emissions	Two-stage double bootstrap DEA
10	Hsieh et al. [33]	2020	Fleet capacity, employees, operating costs, revenue, lifting, CO <sub>2</sub> emissions	Two-stage network DEA
11	Bao et al. [28]	2021	Capacity, number of ships, revenue, tax, technological upgrading, workplace safety, gender equality, personnel training, CO <sub>2</sub> emissions, SOx emissions, NOx emissions	MADM with intuitionistic fuzzy linguistic variables
12	Hsu and Ho [27]	2021	Quality of services, costs, communication, convenience	Fuzzy Delphi and DEMATEL
13	Liu et al. [34]	2022	Revenue, average ship size, tax, technological upgrading, safe production, talent training, gender equality, GHG emission, emissions of SOx, NOx	AHP and Particle Swarm Optimization (PSO)

Table 1 summarizes the methods used for global shipping evaluation in papers published from the years 2011–2021. It can be observed that DEA is a common method used for quantitative assessments. Traditional DEA models are CCR (Charnes, Cooper, and Rhodes) [30] and BCC (Banker, Charnes, Cooper) [35] employ radial and orientated techniques. However, the relative efficiency of the radial DEA efficiency measurement will be exaggerated when the input or output has nonzero slacks, and the efficiency result of the orientated DEA measuring technique is equally unreliable. Thus, the slacks-based measure model (SBM) was proposed by Tone [36] to overcome this problem. The SBM is a non-radial DEA model, as opposed to the radial CCR and BCC models. All inputs and outputs change proportionally as a result of the improvement of invalid DMU in the radial DEA model. The main advantage of the SBM model is that it improves inaccurate DMU in a way that directly addresses input or output slacks in addition to equal proportion improvement [37]. Additionally, traditional DEA models usually aim for the highest possible output, but when evaluating an economic system's production or operation efficiency, unexpected outputs are always present alongside expected ones. It is challenging to prevent negative effects, such the release of contaminants. The approach for evaluating efficiency should take into consideration any unfavorable externalities brought on by the production process. As a con-

sequence, Tone suggested expanding the SBM model to examine the connection between production and pollution and to take unexpected output into account. SBM has gained popularity as a method of addressing environmentally unfavorable results in efficiency evaluation [38–41].

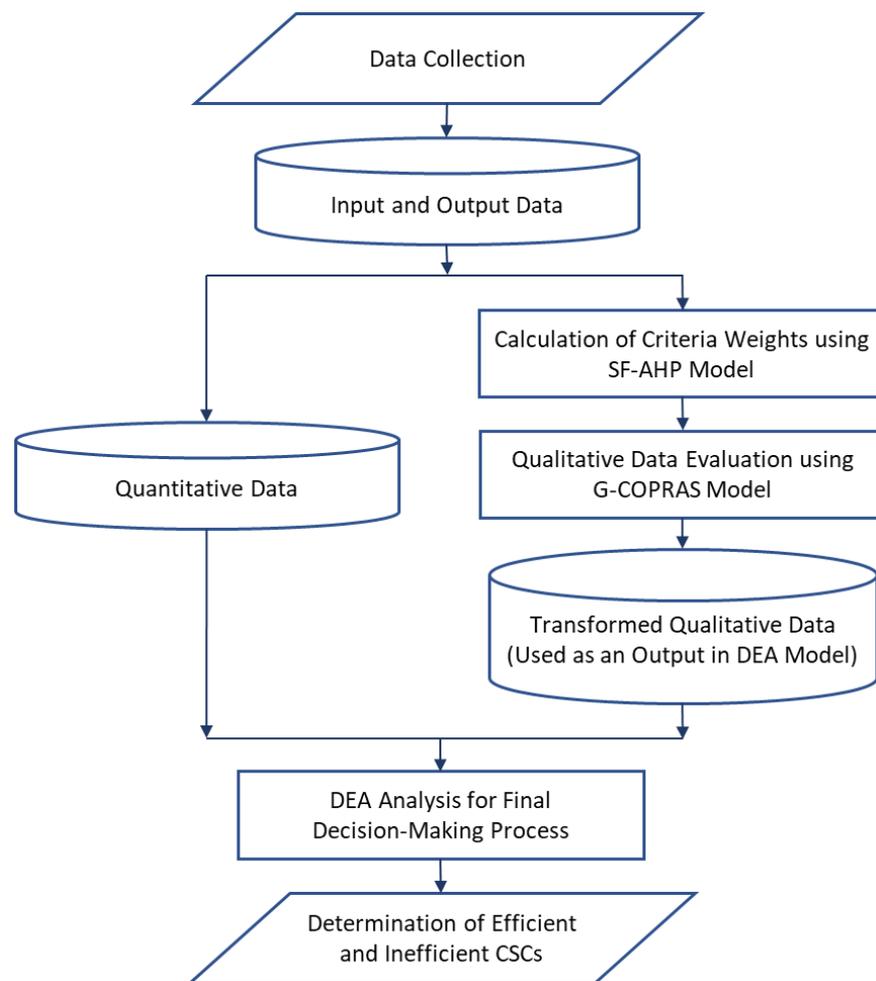
However, it is evident that the AHP-SF and COPRAS-G methods have almost been missed in the literature of global shipping evaluation, although they are among the latest MCDM methods. The novel spherical fuzzy sets theory (SFS) combined with AHP for calculating the spherical criteria weights is proposed, while the COPRAS technique under grey theory is utilized for alternative ranking. These methods are among the latest MCDM methods, yet they have been almost missing in the literature of global shipping evaluation. Spherical fuzzy set (SFS) developed in 2019 [42] is a three-dimensional fuzzy set that was created as an extension of the intuitionistic fuzzy set, PFS, and neutrosophic logics, specifically to handle uncertainty during the quantification of expert judgments. SFS improves decision-making over its predecessors by making it more intelligent (comparable to human judgment), which can lead to a decision-making process that is more accurate when evaluating options. Because of this benefit, SFS has lately been used in a variety of applications, including location selection [43,44], renewable energy evaluation [45], supplier selection [46–49], systems management [50–56], technology evaluation [57], and strategies selection [58].

The COPRAS-G method ranks alternatives based on their significance and utility degree using a stepwise evaluation procedure [59,60]. The parameters of the alternatives are determined using the grey relational grade and expressed in terms of intervals in this method. The grey systems theory is concerned with the investigation of problems involving small samples and limited information [61]. It is concerned with uncertain systems with only a portion of the information known. Situations in which there is no information are categorized as black, whereas those in which all the information is excellent are categorized as white. On the other hand, these hypothetical situations are rarely present in real-world problems. The areas between these two extremes are described as being grey, ambiguous, or fuzzy. As a result, a grey system is one in which some information is certain and some is unknown. One is constantly in the middle, between the black and white extremes, as there is always some degree of uncertainty (i.e., somewhere in the grey area). Recent applications of COPRAS-G are integrated with other MCDM methods as a more systematic and comprehensive framework. Aghdaie et al. [62] implemented market segment evaluation and selection based on application of fuzzy AHP and COPRAS-G methods. Tavana et al. [63] proposed a novel hybrid social media platform selection model using fuzzy ANP and COPRAS-G. Caisucar et al. [64] used fuzzy-TOPSIS and COPRAS-G approach for validation of portfolio allocation in New Product Development. Kayapinar Kaya and Aycin [65] presented an integrated interval type 2 fuzzy AHP and COPRAS-G methodologies for supplier selection in the era of Industry 4.0.

## 2.2. Research Gaps

It is deduced that many previous approaches have suffered from certain shortcomings, such as only considering quantitative parameters or being too subjective in evaluating the shipping businesses. While the problem of evaluating CSCs has been investigated by many scholars, mostly under quantitative variables in the container shipping context (fleet capacity, employees, expenses, revenue, greenhouse gas emissions, etc.), the assessment of the competitive advantage benefits of CSCs is meager. In this direction, evaluation dimensions are often difficult-to-quantify qualitative criteria such as counterparty, strategies, and social and environmental aspects, to name a few. Therefore, it is also essential and instructive to evaluate CSCs' competitive advantages and this can be done using multi-attribute analysis employing expert panels. An integrated approach using both a qualitative assessment tool and a performance assessment tool can be developed as a systematic and flexible framework for evaluating the container shipping industry.

To fulfill the research gap, we used three MCDM methods to find efficient and inefficient international CSCs sensitively. In the first step, the CSCs were evaluated with expert judgments on the sustainability criteria of strategic operation, service level, social and environmental aspects, and counterparty. The spherical fuzzy analytical hierarchical process (AHP-SF) was used to determine the criteria weights. Then, the grey complex proportional assessment (COPRAS-G) method was utilized to find the ranking of CSC. Qualitative variables were transformed into a quantitative variable for use in the DEA model, as an output variable called expert-based qualitative performance (EQP). Then, DEA was performed to identify efficient and inefficient CSCs with the EQP variable and other quantitative parameters (i.e., capacity, lifting, expenses, revenue, emissions, etc.). All steps are explained step by step in Figure 1.



**Figure 1.** Flow chart of proposed methodology.

The paper contributes to the existing literature with different concepts of efficiency measures within the shipping industry. To the best of the authors' knowledge, this is the first attempt to utilize the merits of AHP-SF, COPRAS-G, and SBM-DEA for global shipping evaluation. The performance of CSCs is evaluated under both quantitative and qualitative dimensions in terms of sustainability, which is a significant advantage of this study. There is a need for a more systematic and analytical framework for global shipping evaluation; this study is the first integration of AHP-SF, COPRAS-G, and DEA, with the qualitative variables being transformed into a new quantitative variable for the typical CSCs' efficiency model. Thus, the proposed approach and implications are significant materials for decision-makers in the ocean transportation industry to run their CSCs in a

sustainable manner, especially in reducing emissions from shipping, along with devising strategies for the industry stakeholders.

### 3. Methodology

#### 3.1. Spherical Fuzzy Analytical Hierarchy Process (AHP-SF)

Spherical fuzzy set (SFS) was created by Kutlu Gündođdu and Kahraman [45] as the most current emergence of the fuzzy sets, which can better manage uncertainties and ambiguities in the decision-making process. As shown in Figure 2, each spherical fuzzy number contains the membership, non-membership, and hesitancy functions associated with the interval [0, 1].

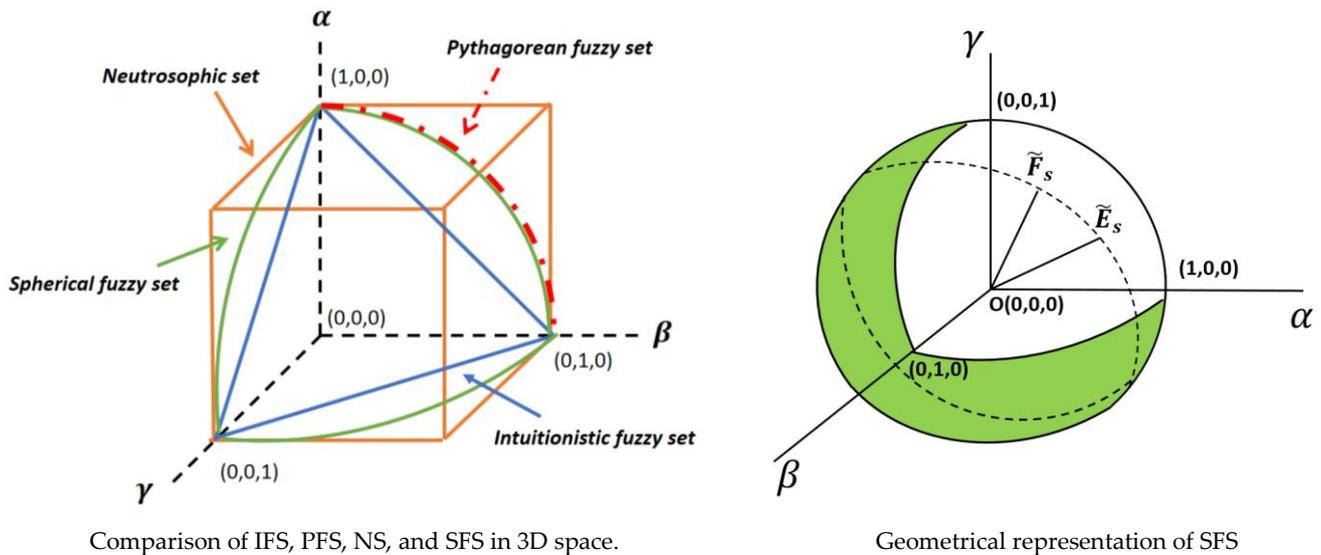


Figure 2. Geometric representation of SFS in 3D space [42].

**Definition 1:** Singer value SFS  $\tilde{F}_S$  of the universe of discourse  $X$  is presented by Equations (1)–(3).

$$\tilde{F}_S = \{x, (\alpha_{\tilde{F}_S}(x), \beta_{\tilde{F}_S}(x), \gamma_{\tilde{F}_S}(x)) | x \in X\} \tag{1}$$

$$\alpha_{\tilde{F}_S}(x) : X \rightarrow [0, 1], \beta_{\tilde{F}_S}(x) : X \rightarrow [0, 1], \gamma_{\tilde{F}_S}(x) : X \rightarrow [0, 1] \tag{2}$$

$$0 \leq \alpha_{\tilde{F}_S}^2(x) + \beta_{\tilde{F}_S}^2(x) + \gamma_{\tilde{F}_S}^2(x) \leq 1 \tag{3}$$

with  $\forall x \in X$ ; for each  $x$ ,  $\alpha_{\tilde{F}_S}(x)$ ,  $\beta_{\tilde{F}_S}(x)$ , and  $\gamma_{\tilde{F}_S}(x)$  denote membership, non-membership, and hesitancy levels of  $x$  to  $\tilde{F}_S$ , respectively.

**Definition 2:** For convenience, let  $\tilde{F}_S = (\alpha_{\tilde{F}_S}, \beta_{\tilde{F}_S}, \gamma_{\tilde{F}_S})$  and  $\tilde{E}_S = (\alpha_{\tilde{E}_S}, \beta_{\tilde{E}_S}, \gamma_{\tilde{E}_S})$  be two SFSs. Some arithmetic operations of SFS are presented in Equations (4)–(9).

- Union operation

$$\tilde{F}_S \cup \tilde{E}_S = \left\{ \max\{\alpha_{\tilde{F}_S}, \alpha_{\tilde{E}_S}\}, \min\{\beta_{\tilde{F}_S}, \beta_{\tilde{E}_S}\}, \min\left\{1 - \left(\left(\max\{\alpha_{\tilde{F}_S}, \alpha_{\tilde{E}_S}\}\right)^2 + \left(\min\{\beta_{\tilde{F}_S}, \beta_{\tilde{E}_S}\}\right)^2\right)^{1/2}, \max\{\gamma_{\tilde{F}_S}, \gamma_{\tilde{E}_S}\}\right\} \right\} \tag{4}$$

- Intersection operation

$$\tilde{F}_S \cap \tilde{E}_S = \left\{ \min\{\alpha_{\tilde{F}_S}, \alpha_{\tilde{E}_S}\}, \max\{\beta_{\tilde{F}_S}, \beta_{\tilde{E}_S}\}, \max\left\{1 - \left(\left(\min\{\alpha_{\tilde{F}_S}, \alpha_{\tilde{E}_S}\}\right)^2 + \left(\max\{\beta_{\tilde{F}_S}, \beta_{\tilde{E}_S}\}\right)^2\right)^{1/2}, \min\{\gamma_{\tilde{F}_S}, \gamma_{\tilde{E}_S}\}\right\} \right\} \tag{5}$$

- Addition operation

$$\tilde{F}_S \oplus \tilde{E}_S = \left\{ \left( \alpha_{\tilde{F}_S}^2 + \alpha_{\tilde{E}_S}^2 - \alpha_{\tilde{F}_S}^2 \alpha_{\tilde{E}_S}^2 \right)^{1/2}, \beta_{\tilde{F}_S} \beta_{\tilde{E}_S} \left( \left( 1 - \alpha_{\tilde{E}_S}^2 \right) \gamma_{\tilde{F}_S}^2 + \left( 1 - \alpha_{\tilde{F}_S}^2 \right) \gamma_{\tilde{E}_S}^2 - \gamma_{\tilde{F}_S}^2 \gamma_{\tilde{E}_S}^2 \right)^{1/2} \right\} \tag{6}$$

- Multiplication operation

$$\tilde{F}_S \otimes \tilde{E}_S = \left\{ \alpha_{\tilde{F}_S}^2 \alpha_{\tilde{E}_S}^2 \left( \beta_{\tilde{F}_S}^2 + \beta_{\tilde{E}_S}^2 - \beta_{\tilde{F}_S}^2 \beta_{\tilde{E}_S}^2 \right)^{1/2}, \left( \left( 1 - \beta_{\tilde{E}_S}^2 \right) \gamma_{\tilde{F}_S}^2 + \left( 1 - \beta_{\tilde{F}_S}^2 \right) \gamma_{\tilde{E}_S}^2 - \gamma_{\tilde{F}_S} \gamma_{\tilde{E}_S} \right)^{1/2} \right\} \tag{7}$$

- Multiplication by a scalar;  $\sigma > 0$

$$\sigma \cdot \tilde{F}_S = \left\{ \left( 1 - \left( 1 - \alpha_{\tilde{F}_S}^2 \right)^\sigma \right)^{1/2}, \beta_{\tilde{F}_S}^\sigma, \left( \left( 1 - \alpha_{\tilde{F}_S}^2 \right)^\sigma - \left( 1 - \alpha_{\tilde{F}_S}^2 - \gamma_{\tilde{F}_S}^2 \right)^\sigma \right)^{1/2} \right\} \tag{8}$$

- Power of  $F_S$ ;  $\sigma > 0$

$$\tilde{F}_S^\sigma = \left\{ \alpha_{\tilde{F}_S}^\sigma, \left( 1 - \left( 1 - \beta_{\tilde{F}_S}^2 \right)^\sigma \right)^{1/2}, \left( \left( 1 - \beta_{\tilde{F}_S}^2 \right)^\sigma - \left( 1 - \beta_{\tilde{F}_S}^2 - \gamma_{\tilde{F}_S}^2 \right)^\sigma \right)^{1/2} \right\} \tag{9}$$

**Definition 3:** For these SFSs,  $\tilde{F}_S = (\alpha_{\tilde{F}_S}, \beta_{\tilde{F}_S}, \gamma_{\tilde{F}_S})$  and  $\tilde{E}_S = (\alpha_{\tilde{E}_S}, \beta_{\tilde{E}_S}, \gamma_{\tilde{E}_S})$ ; the following is valid under the condition  $\sigma, \sigma_1, \sigma_2 > 0$ , Equations (10)–(15).

$$\tilde{F}_S \oplus \tilde{E}_S = \tilde{E}_S \oplus \tilde{F}_S \tag{10}$$

$$\tilde{F}_S \otimes \tilde{E}_S = \tilde{E}_S \otimes \tilde{F}_S \tag{11}$$

$$\sigma(\tilde{F}_S \oplus \tilde{E}_S) = \sigma \tilde{F}_S \oplus \sigma \tilde{E}_S \tag{12}$$

$$\sigma_1 \tilde{F}_S \oplus \sigma_2 \tilde{F}_S = (\sigma_1 + \sigma_2) \tilde{F}_S \tag{13}$$

$$(\tilde{F}_S \otimes \tilde{E}_S)^\sigma = \tilde{F}_S^\sigma \otimes \tilde{E}_S^\sigma \tag{14}$$

$$\tilde{F}_S^{\sigma_1} \otimes \tilde{F}_S^{\sigma_2} = \tilde{F}_S^{\sigma_1 + \sigma_2} \tag{15}$$

**Definition 4:** Spherical weighted arithmetic mean (SWAM) with respect to  $w = (w_1, w_2, \dots, w_n)$ ;  $w_i \in [0, 1]$ ;  $\sum_{i=1}^n w_i = 1$ , SWAM is defined by Equation (16).

$$\begin{aligned} SWAM_w(\tilde{F}_{S1}, \dots, \tilde{F}_{Sn}) &= w_1 \tilde{F}_{S1} + w_2 \tilde{F}_{S2} + \dots + w_n \tilde{F}_{Sn} \\ &= \left\{ \left[ 1 - \prod_{i=1}^n \left( 1 - \alpha_{\tilde{F}_{Si}}^2 \right)^{w_i} \right]^{1/2}, \right. \\ &\quad \left. \prod_{i=1}^n \beta_{\tilde{F}_{Si}}^{w_i} \left[ \prod_{i=1}^n \left( 1 - \alpha_{\tilde{F}_{Si}}^2 \right)^{w_i} - \prod_{i=1}^n \left( 1 - \alpha_{\tilde{F}_{Si}}^2 - \gamma_{\tilde{F}_{Si}}^2 \right)^{w_i} \right]^{1/2} \right\} \end{aligned} \tag{16}$$

Compared to the traditional AHP model, the AHP-SF model offers numerous benefits. While the method collects data from experts, it may not accurately reflect the expressed opinions. As a result, AHP-SF may readily eliminate the uncertainty caused by expert opinion in the comparison matrix. The AHP-SF model was used to calculate the weights of the criteria in this paper. The AHP-SF process has six steps, as follows [57].

Step 1: Define the hierarchical structure of the problem.

The hierarchical structure is organized with the research goal (level 1) and the list of criteria  $C = \{C_1, C_2, \dots, C_n\}$  (level 2) *within*  $n \geq 2$ .

Step 2: Construct pairwise comparison matrices.

As demonstrated in Table 2, the pairwise comparison matrices are built in consideration of spherical fuzzy linguistic scales. The score indices (SI) are determined by Equations (17) and (18).

$$SI = \sqrt{\left| 100 * \left[ (\alpha_{\tilde{F}_S} - \gamma_{\tilde{F}_S})^2 - (\beta_{\tilde{F}_S} - \gamma_{\tilde{F}_S})^2 \right] \right|} \tag{17}$$

for the AMI, VHI, HI, SMI, and EI.

$$\frac{1}{SI} = \frac{1}{\sqrt{\left| 100 * \left[ (\alpha_{\tilde{F}_S} - \gamma_{\tilde{F}_S})^2 - (\beta_{\tilde{F}_S} - \gamma_{\tilde{F}_S})^2 \right] \right|}} \tag{18}$$

for the EI, SLI, LI, VLI, and ALI.

**Table 2.** AHP-SF linguistic scales and spherical fuzzy number  $(\alpha, \beta, \gamma)$  [57].

Linguistics Terms	Spherical Fuzzy Number	Score Index
Absolutely more importance (AMI)	(0.9, 0.1, 0.0)	9
Very high importance (VHI)	(0.8, 0.2, 0.1)	7
High importance (HI)	(0.7, 0.3, 0.2)	5
Slightly more importance (SMI)	(0.6, 0.4, 0.3)	3
Equally importance (EI)	(0.5, 0.4, 0.4)	1
Slightly low importance (SLI)	(0.4, 0.6, 0.3)	1/3
Low importance (LI)	(0.3, 0.7, 0.2)	1/5
Very low importance (VLI)	(0.2, 0.8, 0.1)	1/7
Absolutely low importance (ALI)	(0.1, 0.9, 0.0)	1/9

Step 3: Check consistency.

The corresponding SI is transformed from the linguistics scales. The consistency ratio (CR), which must be less than 10%, is next evaluated for the pairwise comparison matrices.

Step 4: Determine the spherical fuzzy local weights of the criteria.

Using the SWAM operator to determine the weight of each condition by Equation (19).

$$SWAM_w(\tilde{F}_{S1}, \dots, \tilde{F}_{Sn}) = w_1\tilde{F}_{S1} + w_2\tilde{F}_{S2} + \dots + w_n\tilde{F}_{Sn} = \left\{ \left[ 1 - \prod_{i=1}^n (1 - \alpha_{\tilde{F}_{Si}}^2)^{w_i} \right]^{1/2}, \prod_{i=1}^n \beta_{\tilde{F}_{Si}} \left[ \prod_{i=1}^n (1 - \alpha_{\tilde{F}_{Si}}^2)^{w_i} - \prod_{i=1}^n (1 - \alpha_{\tilde{F}_{Si}}^2 - \gamma_{\tilde{F}_{Si}}^2)^{w_i} \right]^{1/2} \right\} \tag{19}$$

where  $w = 1/n$ .

Step 5: Aggregate spherical fuzzy weights.

Equation (20) is used to defuzzify the criterion weights. They are then normalized using Equation (21). The final ranking scores are aggregated using the multiplication operator in Equation (22).

$$S(\tilde{w}_j^s) = \sqrt{\left| 100 * \left[ \left( 3\alpha_{\tilde{F}_S} - \frac{\gamma_{\tilde{F}_S}}{2} \right)^2 - \left( \frac{\beta_{\tilde{F}_S}}{2} - \gamma_{\tilde{F}_S} \right)^2 \right] \right|} \tag{20}$$

$$\bar{w}_j^s = \frac{S(\tilde{w}_j^s)}{\sum_{j=1}^n S(\tilde{w}_j^s)} \tag{21}$$

$$\tilde{F}_{S_{ij}} = \bar{w}_j^s \cdot \tilde{F}_{S_i} = \left\{ (1 - (1 - \alpha_{\tilde{F}_S}^2)^{\bar{w}_j^s})^{1/2}, \beta_{\tilde{F}_S}^{\bar{w}_j^s}, ((1 - \alpha_{\tilde{F}_S}^2)^{\bar{w}_j^s} - (1 - \alpha_{\tilde{F}_S}^2 - \gamma_{\tilde{F}_S}^2)^{\bar{w}_j^s})^{1/2} \right\}, \forall i \quad (22)$$

Using Equation (23), spherical fuzzy arithmetic addition over global weights is used to determine the final AHP-SF score ( $\tilde{F}$ ).

$$\begin{aligned} \tilde{F} &= \sum_{j=1}^n \tilde{F}_{S_{ij}} = \tilde{F}_{S_{i1}} \oplus \tilde{F}_{S_{i2}} \oplus \dots \oplus \tilde{F}_{S_{in}}, \forall i \\ \text{i.e., } \tilde{F}_{S_{i1}} \oplus \tilde{F}_{S_{i2}} &= \left\{ \left( \alpha_{\tilde{F}_{S_{i1}}}^2 + \alpha_{\tilde{F}_{S_{i2}}}^2 - \alpha_{\tilde{F}_{i1}}^2 \alpha_{\tilde{F}_{i2}}^2 \right)^{1/2}, \beta_{\tilde{F}_{S_{i1}}} \beta_{\tilde{F}_{S_{i2}}}, \left( (1 - \alpha_{\tilde{F}_{S_{i2}}}^2) \gamma_{\tilde{F}_{S_{i1}}}^2 + \right. \right. \\ &\quad \left. \left. (1 - \alpha_{\tilde{F}_{S_{i1}}}^2) \gamma_{\tilde{F}_{S_{i2}}}^2 - \gamma_{\tilde{F}_{S_{i1}}}^2 \gamma_{\tilde{F}_{S_{i2}}}^2 \right)^{1/2} \right\} \end{aligned} \quad (23)$$

Step 6: Defuzify the final score of each criterion.

Sort the criteria list by their defuzzified final rating: the greater the number, the better. In the following step, the criterion weights are employed for the COPRAS-G model.

### 3.2. Grey Complex Proportional Assessment (COPRAS-G)

Julong [66] created the grey theory to investigate uncertainty with ambiguous information. The grey hypothesis is separated into three categories, referred to as the “white system”, “black system”, and “grey system” depending on how much of the knowledge is “completely known”, “unknown”, and “partially known”, respectively. The grey theory notion is shown in Figure 3.

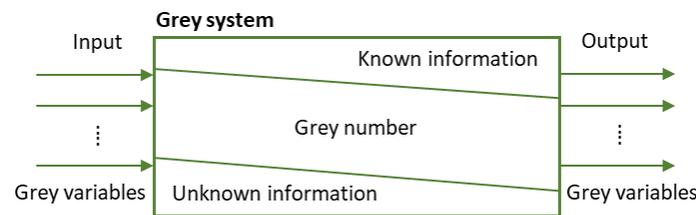


Figure 3. The concept of grey theory [67].

Let  $\otimes x = [\underline{x}, \bar{x}]$  represent a grey number with  $\underline{x}$  denoting the lower limit and  $\bar{x}$  denoting the upper limit of the membership function.

Let  $\otimes x_1 = [\underline{x}_1, \bar{x}_1]$  and  $\otimes x_2 = [\underline{x}_2, \bar{x}_2]$  be two grey numbers;  $\varepsilon$  denotes a positive real number and  $L$  denotes the length of grey number. The basic grey number arithmetic operations are shown in Equations (24)–(29).

$$\otimes x_1 + \otimes x_2 = [\underline{x}_1 + \underline{x}_2, \bar{x}_1 + \bar{x}_2] \quad (24)$$

$$\otimes x_1 - \otimes x_2 = [\underline{x}_1 - \bar{x}_2, \bar{x}_1 - \underline{x}_2] \quad (25)$$

$$\otimes x_1 * \otimes x_2 = [\min(\underline{x}_1 \underline{x}_2, \underline{x}_1 \bar{x}_2, \bar{x}_1 \underline{x}_2, \bar{x}_1 \bar{x}_2), \max(\underline{x}_1 \underline{x}_2, \underline{x}_1 \bar{x}_2, \bar{x}_1 \underline{x}_2, \bar{x}_1 \bar{x}_2)] \quad (26)$$

$$\otimes x_1 / \otimes x_2 = [\min(\underline{x}_1 / \underline{x}_2, \underline{x}_1 / \bar{x}_2, \bar{x}_1 / \underline{x}_2, \bar{x}_1 / \bar{x}_2), \max(\underline{x}_1 / \underline{x}_2, \underline{x}_1 / \bar{x}_2, \bar{x}_1 / \underline{x}_2, \bar{x}_1 / \bar{x}_2)] \quad (27)$$

$$\varepsilon \otimes x_1 = \varepsilon[\underline{x}_1, \bar{x}_1] = [\varepsilon \underline{x}_1, \varepsilon \bar{x}_1] \quad (28)$$

$$L(\otimes x_1) = [\bar{x}_1 - \underline{x}_1] \quad (29)$$

The concept of grey complex proportional assessment (COPRAS-G), which aims to lessen subjective judgements in the decision-making process, was initially created by Zavadskas et al. [59]. There are many benefits to using COPRAS-G in the decision-making process, including: (1) fewer calculation steps than TOPSIS or WASPAS methods; (2) the ability to calculate the values to be maximized and minimized separately among the criteria;

(3) usually, distribution of samples is not necessary; and (4) compared to other MCDM methods, the estimated utility degree of COPRAS-G reveals how much better the optimal alternative is than the other in percentage terms [65].

All of the evaluation criteria in this work are subjective, and it is impossible to precisely describe their values. Grey numbers are therefore a useful way for the COPRAS-G technique to communicate the actual situation during the decision-making process. According to the utility degree computation, the COPRAS-G technique prioritizes the alternative. There are six steps in the COPRAS-G method [68].

Step 1: Identify the relevant criteria and alternatives.

Suppose that  $A = \{A_1, A_2, \dots, A_m\}$  is a discrete set of  $m$  alternatives, which are ranked by a discrete set  $C = \{C_1, C_2, \dots, C_n\}$  of  $n$  criteria.

Step 2: Construct the decision matrix.

Utilize the linguistic scale with grey values in Table 3 to evaluate how well the alternatives performed in relation to the criteria. Suppose that there are  $k$  experts, and the value of alternative  $h$  in the criterion  $g$  is calculated using Equation (30). Following that, the grey decision matrix is built, as can be seen in Equation (31).

$$\otimes G_{hg} = \frac{1}{k} (\otimes G_{hg}^1 + \otimes G_{hg}^2 + \dots + \otimes G_{hg}^k) \tag{30}$$

$$\otimes G = \begin{bmatrix} \otimes G_{11} & \otimes G_{12} & \dots & \otimes G_{1n} \\ \otimes G_{21} & \otimes G_{22} & \dots & \otimes G_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \otimes G_{m1} & \otimes G_{m2} & \dots & \otimes G_{mn} \end{bmatrix} \tag{31}$$

where  $\otimes G_{hg}$  is the importance of alternative  $h$  in the criterion  $g$ .

**Table 3.** The linguistics scale with grey numbers  $[x, \bar{x}]$  [68].

Scale	Grey Number
Very Poor (VP)	[0, 1]
Poor (P)	[1, 3]
Medium Poor (MP)	[3, 4]
Fair (F)	[4, 5]
Medium Good (MG)	[5, 6]
Good (G)	[6, 9]
Very Good (VG)	[9, 10]

Step 3: Determine the important weight of each criterion.

The AHP-SF method is employed to calculate the significance level of criteria.

Step 4: Determine the weighted normalized decision matrix.

First, use Equations (32)–(34) to develop the normalized grey decision matrix.

$$\otimes G^* = \begin{bmatrix} \otimes G_{11}^* & \otimes G_{12}^* & \dots & \otimes G_{1n}^* \\ \otimes G_{21}^* & \otimes G_{22}^* & \dots & \otimes G_{2n}^* \\ \vdots & \vdots & \vdots & \vdots \\ \otimes G_{m1}^* & \otimes G_{m2}^* & \dots & \otimes G_{mn}^* \end{bmatrix} \tag{32}$$

$$\underline{G}_{hg}^* = \frac{\underline{G}_{hg}}{\frac{1}{2} (\sum_{h=1}^m \underline{G}_{hg} + \sum_{h=1}^m \bar{G}_{hg})} = \frac{2\underline{G}_{hg}}{\sum_{h=1}^m \underline{G}_{hg} + \sum_{h=1}^m \bar{G}_{hg}} \tag{33}$$

$$\bar{G}_{hg}^* = \frac{\bar{G}_{hg}}{\frac{1}{2} (\sum_{h=1}^m \underline{G}_{hg} + \sum_{h=1}^m \bar{G}_{hg})} = \frac{2\bar{G}_{hg}}{\sum_{h=1}^m \underline{G}_{hg} + \sum_{h=1}^m \bar{G}_{hg}} \tag{34}$$

where  $\otimes G_{hg}$  represents the pairwise comparison from a group of decision-makers with respect to the  $h^{th}$  alternative in the  $g^{th}$  criterion.

Weighted normalized grey decision matrix is then created, as shown in Equation (35).

$$\otimes X = \begin{bmatrix} \otimes X_{11} & \otimes X_{12} & \cdots & \otimes X_{1n} \\ \otimes X_{21} & \otimes X_{22} & \cdots & \otimes X_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \otimes X_{m1} & \otimes X_{m2} & \cdots & \otimes X_{mn} \end{bmatrix} \text{ where } \otimes X_{hg} = \otimes G_{hg}^* \times w_g \quad (35)$$

where  $w_g$  is the important weight of each criterion.

Step 5: Determine the relative significance of each alternative.

First, we compute the sums  $P_h$  of the criterion values (the larger values are better) using Equation (36).

$$P_h = \frac{1}{2} \sum_{g=1}^o (\underline{X}_{hg} + \overline{X}_{hg}), h = 1, 2, \dots, m; g = 1, 2, \dots, o \quad (36)$$

Next, we compute the sums  $R_h$  of the criterion value (the smaller values are better) using Equation (37).

$$R_h = \frac{1}{2} \sum_{g=o+1}^n (\underline{X}_{hg} + \overline{X}_{hg}), h = 1, 2, \dots, m; g = o + 1, o + 2, \dots, n \quad (37)$$

After that, Equation (38) is used to calculate the relative relevance of each alternative.

$$Q_h = P_h + \frac{\sum_{h=1}^m R_h}{R_h \sum_{h=1}^m \frac{1}{R_h}}, h = 1, 2, \dots, m \quad (38)$$

Step 6: Calculate the utility degree of each alternative.

First, Equation (39) is used to derive the optimality criterion  $K$ . The utility degree of each alternative  $N_h$  is then determined by contrasting them with the best alternative (which has a utility degree of 100%), as shown in Equation (40).

$$K = \text{Max}_h Q_h, h = 1, 2, \dots, m \quad (39)$$

$$N_h = \frac{Q_h}{Q_{max}} \times 100\%, h = 1, 2, \dots, m \quad (40)$$

### 3.3. Data Envelopment Analysis (DEA)

Data envelopment analysis (DEA), which does not rely on the premise that the data are normal, is an effective non-parametric methodology. In the DEA model, homogeneity and isotonicity are two essential premises. Before using the DEA model, the correlation between the inputs and outputs must be confirmed, and it must be a complete positive linear correlation. The correlation of Pearson’s ( $r$ ) of two variables ( $x$ ) and ( $y$ ) is calculated, as can be seen in Equation (41) [69].

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (41)$$

where  $n$  is the sample size;  $x_i$  and  $y_i$  denote the individual sample points indexed with  $i$ ; and  $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$  is the mean of the sample which is analogous for  $\bar{y}$ .

Slacks-based measure (SBM) is one of the many widely utilized DEA models. It can be used for efficiency analysis either without taking into account the negative environmental impact [36] or by adjusting for the negative outputs, a so-called DEA undesirable output model [70]. This paper analyzes the economic efficiency and environmental efficiency of the shipping companies at the same time. Hence, the adjusted DEA model ensures consistency and enables comparability.

The list of symbols and notations used in the adjusted DEA model is presented as follows [16].

- $n$ : number of decision-making units (DMUs), as shipping companies in this paper
- $DMU_j$ : the  $j^{th}$  DMU,  $j = 1, 2, \dots, n$ , has  $m$  inputs,  $s_1$  desirable outputs,  $s_2$  undesirable outputs
- $x_{ij}$  ( $i = 1, 2, \dots, m$ ): the  $i^{th}$  input of the  $j^{th}$  DMU, the matrix as  $X \in R^{m \times n}$
- $y_{grj}$  ( $r = 1, 2, \dots, s_1$ ): the  $r^{th}$  desirable output, the matrix as  $y_g \in R^{s_1 \times n}$
- $y_{bjj}$  ( $q = 1, 2, \dots, s_2$ ): the  $q^{th}$  undesirable output, the matrix as  $y_b \in R^{s_2 \times n}$
- $\delta = 1$ : the model adjusts the desirable output by the negative impact of shipping emissions (i.e., undesirable output model)
- $\delta = 0$ : otherwise

The adjusted DEA model with or without considering the negative impact of shipping emissions can be written as:

$$\begin{aligned} \min \rho &= \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_{io}^-}{x_{io}}}{1 + \frac{1}{s_1 + \delta s_2} \left( \sum_{r=1}^{s_1} \frac{s_{ro}^g}{y_{gro}} + \delta \sum_{q=1}^{s_2} \frac{s_{qo}^b}{y_{bro}} \right)} \\ \text{Subject to} & \\ & x_o = X\lambda + s^-; \\ & y_{go} = Y_g\lambda - s^g; \\ & y_{bo} = Y_b\lambda + s^b; \\ & s^- \geq 0, s^g \geq 0, s^b \geq 0, x_{ij} \geq 0, y_{grj} \geq 0, y_{bjj} \geq 0 \end{aligned} \tag{42}$$

where  $s^- = (s_{1o}^-, \dots, s_{mo}^-)$ ,  $s^g = (s_{1o}^g, \dots, s_{s_1o}^g)$ ,  $s^b = (s_{1o}^b, \dots, s_{s_2o}^b)$  denote slack variables of inputs, desirable outputs, and undesirable outputs, respectively.  $\lambda = (\lambda_1, \dots, \lambda_n)$  denotes a positive weight vector. The subscript  $o$  represents the DMU evaluated.

Through the Charnes–Cooper transition [70], Equation (42) can be transformed into Equation (43) with an integer  $t$  (linear programming model) as follows.

$$\begin{aligned} \min \rho &= t - \frac{1}{m} \sum_{i=1}^m \frac{s_{io}^-}{x_{io}} \\ \text{Subject to} & \\ t + \frac{1}{s_1 + \delta s_2} \left( \sum_{r=1}^{s_1} \frac{s_{ro}^g}{y_{gro}} + \delta \sum_{q=1}^{s_2} \frac{s_{qo}^b}{y_{bro}} \right) &= 1; \\ & x_o t = X \wedge + S^-; \\ & y_{go} t = Y_g \wedge - S^g; \\ & y_{bo} t = Y_b \wedge + S^b; \\ & S^- \geq 0, S^g \geq 0, S^b \geq 0, \wedge \geq 0, t \geq 0 \end{aligned} \tag{43}$$

where  $S^- = ts^-$ ,  $S^g = ts^g$ ,  $S^b = ts^b$ ,  $\wedge = t\lambda$ .

The adjusted DEA model can be applied for situations either without considering the environmental impact or by adjusting for the bad outputs and can be solved as a linear programming model. The optimal value of the objective function is at 1, or the efficiency score is 100%. Otherwise, the DMU is inefficient.

#### 4. Empirical Analysis

This study analyzes 14 publicly traded shipping companies, including Maersk, CMA-CGM, COSCO, and Hapag-Lloyd. Data from 30 CSCs were obtained because they now own 80% of the worldwide container vessel fleet [16,71], but 16 CSCs were excluded from the analysis due to missing data. Their primary operations are container transportation and dry bulk freight. Most of them also offer logistics and shipping-related services, and others own or operate ports. As displayed in Table 4, each CSC is regarded as a DMU. During the evaluation period, the selected CSCs in this analysis controlled more than 70% of the overall fleet capacity in the world liner shipping industry.

**Table 4.** The list of container shipping companies.

DMUs	Container Shipping Companies	Symbol	Headquarters	Total TEU	Total Ships	Market Share (%)
CSC-01	COSCO Shipping Lines	COSCO	China	2,934,447	480	11.6
CSC-02	Orient Overseas Container Line	OOCL	China	781,779	113	3.1
CSC-03	Sinotrans	Sinotrans	China	45,006	31	0.2
CSC-04	SITC Container Lines	SITC	China	142,602	95	0.6
CSC-05	A.P. Moller-Maersk	Maersk	Denmark	4,279,305	736	17.0
CSC-06	CMA-CGM Group	CMA-CGM	France	3,171,456	568	12.6
CSC-07	Hapag-Lloyd	Hapag-Lloyd	Germany	1,746,772	252	6.9
CSC-08	ZIM Integrated Shipping Services	ZIM	Israel	413,862	109	1.6
CSC-09	Ocean Network Express	ONE	Japan	1,542,261	210	6.1
CSC-10	Hyundai Merchant Marine	HMM	South Korea	819,790	75	3.3
CSC-11	Evergreen Marine	Evergreen	Taiwan	1,477,644	204	5.9
CSC-12	Wan Hai Lines	Wan Hai	Taiwan	422,910	149	1.7
CSC-13	Yang Ming Marine Transport	Yang Ming	Taiwan	662,047	90	2.6
CSC-14	Matson	Matson	United States	68,670	29	0.3

Toward the comprehensive evaluation implementation for CSCs' performances, the aggregation of qualitative and quantitative data for efficiency analysis is proposed. The concepts of quantitative and qualitative variables are described in the forthcoming sub-sections. Steps of the defined method are applied in the upcoming two phases.

#### 4.1. Phase 1: Qualitative Efficiency Analysis

It is vital to investigate the elements that influence CSCs' competitive advantage and deepen understanding of the mechanisms that underpin their influence because CSCs account for a large amount of the shipping industry's market share. When CSCs are faced with globalized competition, the following dimensions are their standard potential advantages: service quality requirements, logistics capabilities, technology upgrading, maintenance of business relationships, flexible operations, and market orientation, to name a few. Fanam et al. [72] reported that freight costs, service quality, scheduling, equipment handling, and information technology (IT) would influence container liner shipping advantages. Magnus et al. [73] claimed that economies of scale, pricing, network coordination, cost reduction, regulation, and shipper relationships were all key factors affecting the competitiveness of a CSC. When evaluating CSCs discussed by Hsu and Ho [27], other influential factors are transport reliability and security, corporate reputation, professional expertise, and integrated logistics operations. Notably, in rapidly evolving market circumstances where the focus is on green and sustainable development, social and environmental factors in the container shipping context have recently received increasing attention. For container shipping operators to improve their green performance, Yang [25] indicated that environmental conventions/directives/regulations, internal green practices, and external green collaborations are noteworthy dimensions.

According to previous research, many factors influence the competitive advantage of a shipping liner. Based on the literature review and expert's opinions, a list of criteria was selected in this study to evaluate CSCs' competitive advantage benefits (see Table 5). These factors are frequently described using difficult-to-quantify qualitative descriptions. When evaluating organizational performance in the shipping business, it can be challenging to undertake a quantitative study in some circumstances. As a result, experts are frequently asked to provide qualitative descriptions based on their knowledge and expertise. However, one of the major drawbacks of using expert panels is that their recommendations are frequently accompanied by ambiguity and hesitancy. Thus, the use of proposed methodologies AHP-SF and COPRAS-G is an effective way to handle this problem, presented in the upcoming sub-sections. For this analysis, a panel of 15 experts with at least ten years of professional experience in the maritime industry was invited to evaluate criteria and DMUs, as shown in Table 6. Some of the experts are well-experienced port state

control officers, master mariners, senior lecturers, shipping administration professionals, and freight forwarders. The others are managers and executives in the shipping industry.

**Table 5.** The list of criteria and their explanation.

Dimension	Criteria	Explanation	References
Counterparty (C)	External green collaborations (C1)	Relates to green partnerships and collaborations with suppliers, partners, and clients to jointly decrease environmental impact, reach shared environmental goals, and make collaborative actions.	Yang [25], Di Vaio et al. [26], Lirn et al. [74]
	Relationship (C2)	Refers to stable cooperation between CSC and their partners, suppliers, and customers to share risks and rewards, regarding reliability, truth, dependence, alliance, compatibility, reciprocity.	Hsu and Ho [27], Yang et al. [75], Tiwari et al. [76]
	Corporate reputation and image (C3)	CSC creates a better reputation and brand equity can increase the differentiation advantages of the firm.	Yoon et al. [24], Hsu and Ho [27], Fanam and Ackerly [77]
Social and Environmental aspects (SE)	Workplace safety and equity (SE1)	Refers to the assurance of a safe and equitable workplace for all employees.	Bao et al. [28]
	Internal green practices (SE2)	Defined as many internal green shipping practices and operations that a CSC can implement and manage independently to reduce the environmental impacts of daily activities.	Yang [25], Di Vaio et al. [26], Lirn et al. [74]
	Environmental institutional pressures (SE3)	The adoption and implementation of conventions, directives, regulations, and strategies on container transport to protect the environment.	Yang [25], Di Vaio et al. [26], Lirn et al. [74]
Service Level (SL)	Reliability (SL1)	Refers to on-time performance, responsibility display to customers, accuracy of transshipment, ability to handle cargo at the destination in safe and sound condition, and lower probability of shutting out or roll-over of containers at transshipment port.	Iqbal and Siddiqui [23], Hsu and Ho [27]
	Flexibility and responsiveness (SL2)	Defined as how fast a shipping line is to cater and adapt to the changing needs and requirements.	Iqbal and Siddiqui [23], Čirjevskis [78]
	Quality of service (SL3)	Refers to quality control and inspection for a variety of available and value-added services of a CSC can provide, commitment to continuous improvement.	Yoon et al. [24], Hsu and Ho [27], Yuen and Thai [79]
	Security performance (SL4)	Refers to security and safety performance regarding information and cargo during transport.	Hsu and Ho [27], Fanam and Ackerly [77]
Operation (O)	Market orientation (O1)	The ability to gather, share, and respond to market insights with cross-functional coordination to access consumer demands and competitive information.	Tseng and Liao [22]
	Network and schedule (O2)	This criterion refers to domestic and international service networks, schedule reliability, sufficient sailings, transit timeframe, etc.	Yoon et al. [24], Hsu and Ho [27], Fanam and Ackerly [77], Vernimmen et al. [80]
	Integrated logistics operations (O3)	If a CSC effectively integrates logistics operations it means it can reduce transit time and enhance timely delivery, cargo transport security, and flexible tariffs, integrate freight forwarding, logistics operations, customs brokerage, warehousing, and distribution.	Tseng and Liao [22], Hsu and Ho [27], Fanam and Ackerly [77], Vernimmen et al. [80]
	Equipment system and IT application (O4)	Capabilities of regular and continuous upgrading the equipment systems, services, and IT applications.	Iqbal and Siddiqui [23], Tseng and Liao [22]

**Table 5.** Cont.

Dimension	Criteria	Explanation	References
	Professionalism (O5)	This dimension is characterized by attributes such as maritime expertise, competence, and experience of an organization.	Hsu and Ho [27]

**Table 6.** Experts’ profiles.

Category	Profile	No. of Respondents
Education level	Undergraduate	8
	Graduate	4
	Ph.D.	3
Work experience	Between five to ten years	10
	More than ten years	5
Work field	Shipping and logistics companies	6
	Port services companies	2
	Research	7

4.1.1. The Use of AHP-SF for Determination Criteria Weights and Results

The AHP-SF model is employed to weight the qualitative performance criteria of CSCs. In this stage, four selected dimensions including Counterparty (C), Social and Environmental aspects (SE), Service Level (SL), Operation (O), and their sub-criteria for qualitative performance evaluation were determined as shown in Table 5. Figure 4 depicts the decision problem’s hierarchical structure. Figure 4 shows a hierarchy of the significance of the criteria as determined by the decision-makers using the linguistic weighting factors.

The computation of the four primary dimensions shown below serves as an example of the AHP-SF methodology. The pairwise comparison matrix utilizing linguistic terms, the non-fuzzy comparison matrix, and the normalized comparison matrix of the four primary dimensions are all displayed in Tables 7–9. The consistency ratio of the pairwise comparison for experts was calculated as follows. Note that *WSV* denotes weighted sum value, *CV* denotes consistency vector, *D* denotes a considered dimension, *SI* denotes score index.

$$D_{12} = \frac{SI_{D_{12}}}{SUM_{D_2}} = \frac{1.171}{4.423} = 0.265$$

$$MEAN_{D_1} = \frac{0.159 + 0.265 + 0.139 + 0.128}{4} = 0.173$$

$$WSV = \begin{bmatrix} 1.000 & 1.171 & 0.417 & 0.491 \\ 0.854 & 1.000 & 0.904 & 0.873 \\ 2.399 & 1.107 & 1.000 & 1.467 \\ 2.036 & 1.145 & 0.681 & 1.000 \end{bmatrix} \times \begin{bmatrix} 0.173 \\ 0.223 \\ 0.337 \\ 0.268 \end{bmatrix} = \begin{bmatrix} 0.705 \\ 0.908 \\ 1.390 \\ 1.104 \end{bmatrix}$$

$$CV = \begin{bmatrix} 0.705 \\ 0.908 \\ 1.390 \\ 1.104 \end{bmatrix} / \begin{bmatrix} 0.173 \\ 0.223 \\ 0.337 \\ 0.268 \end{bmatrix} = \begin{bmatrix} 4.085 \\ 4.079 \\ 4.127 \\ 4.124 \end{bmatrix}$$

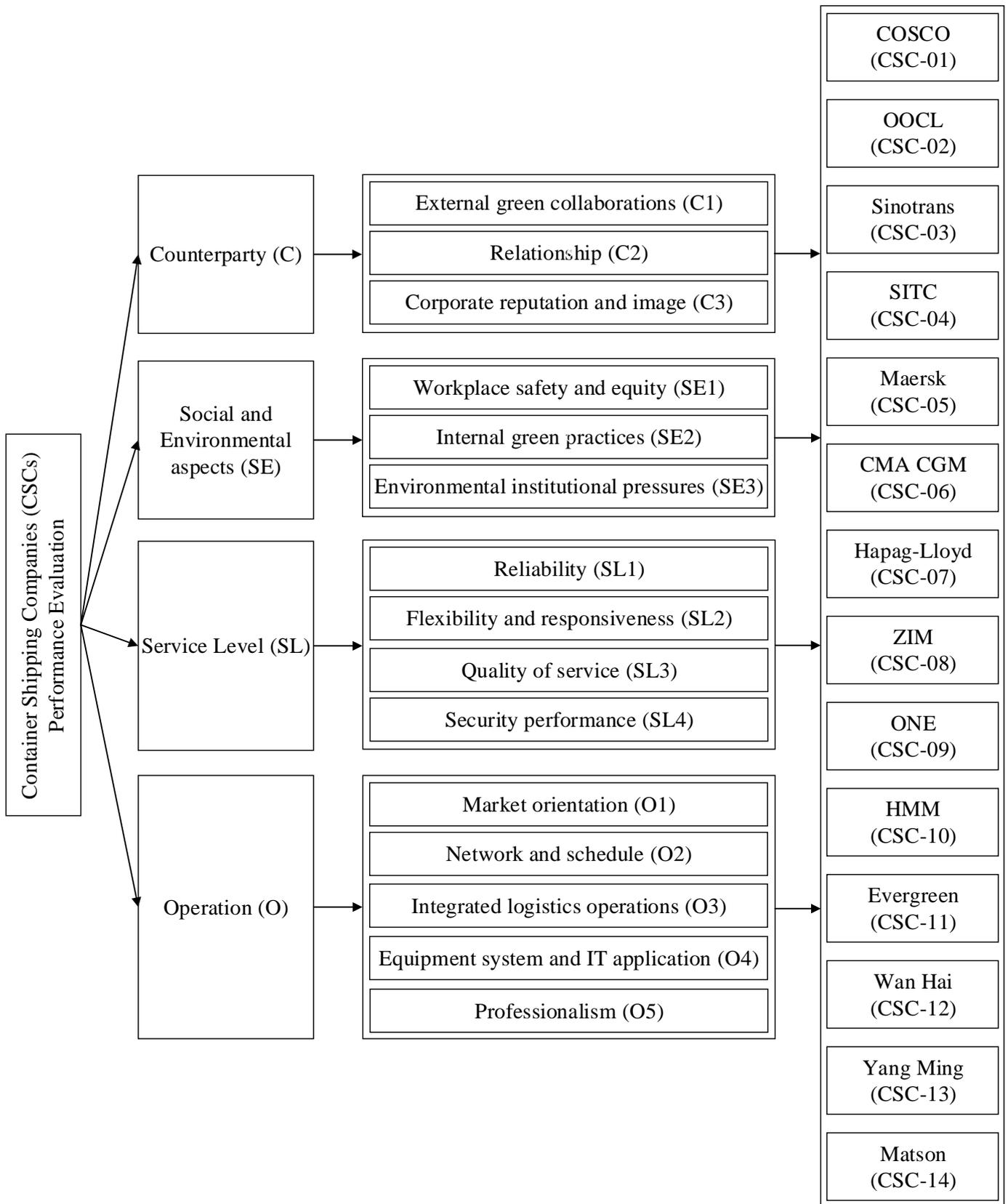


Figure 4. Hierarchical structure for qualitative performance analysis.

**Table 7.** The pairwise comparison matrix of the AHP-SF model.

Dimension	Left Criteria Is Greater				Right Criteria Is Greater				Dimension	
	AMI	VHI	HI	SMI	EI	SLI	LI	VLI		ALI
C			4	3	3	2	2	1		SE
C				3	2	2	4	4		SL
C			1	2	3	2	4	3		O
SE			3	3	3	2	1	3		SL
SE			2	4	3	2	1	3		O
SL		1	4	3	3	1	3			O

**Table 8.** The non-fuzzy comparison matrix of the AHP-SF model.

Dimension	C	SE	SL	O
C	1.000	1.171	0.417	0.491
SE	0.854	1.000	0.904	0.873
SL	2.399	1.107	1.000	1.467
O	2.036	1.145	0.681	1.000
SUM	6.288	4.423	3.002	3.832

**Table 9.** The normalized comparison matrix of the AHP-SF model.

Dimension	C	SE	SL	O	MEAN	WSV	CV
C	0.159	0.265	0.139	0.128	0.173	0.705	4.085
SE	0.136	0.226	0.301	0.228	0.223	0.908	4.079
SL	0.381	0.250	0.333	0.383	0.337	1.390	4.127
O	0.324	0.259	0.227	0.261	0.268	1.104	4.124

With the four main dimensions ( $n = 4$ ), the largest eigenvector ( $\lambda_{max}$ ) was calculated to identify the consistency index ( $CI$ ), the random index ( $RI$ ), and consistency ratio ( $CR$ ) as follows:

$$\lambda_{max} = \frac{4.085 + 4.079 + 4.127 + 4.124}{4} = 4.104$$

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{4.104 - 4}{4 - 1} = 0.035$$

Such that  $n = 4$ ,  $RI = 0.9$ , and the  $CR$  value is calculated as follows:

$$CR = \frac{CI}{RI} = \frac{0.035}{0.9} = 0.038$$

As shown in  $CR = 0.038 < 0.1$ , the pairwise comparison matrix was consistent, and the result was satisfactory.

Following that, Table 10 calculates the integrated spherical fuzzy comparison matrix. The resulting spherical fuzzy weights for each dimension were then determined and are displayed in Table 11 as a result. For explanation, the following calculation was presented for the spherical fuzzy weights of criteria D1, which is Counterparty (C), with spherical fuzzy weights  $(\alpha, \beta, \gamma) = (0.432, 0.542, 0.304)$ , as follows:

$$\alpha_{D1} = \left[ 1 - \prod_{i=1}^n (1 - \alpha_{F_{Si}}^2)^{w_i} \right]^{1/2} = \left[ 1 - (1 - 0.500^2)^{\frac{1}{4}} * (1 - 0.484^2)^{\frac{1}{4}} * (1 - 0.344^2)^{\frac{1}{4}} * (1 - 0.369^2)^{\frac{1}{4}} \right]^{1/2} = 0.432$$

$$\beta_{D1} = \prod_{i=1}^n \beta_{F_{Si}}^{w_i} = 0.400^{\frac{1}{4}} * 0.518^{\frac{1}{4}} * 0.659^{\frac{1}{4}} * 0.631^{\frac{1}{4}} = 0.542$$

$$\begin{aligned} \gamma_{D1} &= \left[ \prod_{i=1}^n (1 - \alpha_{\tilde{F}_{Si}}^2)^{w_i} - \prod_{i=1}^n (1 - \alpha_{\tilde{F}_{Si}}^2 - \gamma_{\tilde{F}_{Si}}^2)^{w_i} \right]^{1/2} \\ &= \left[ (1 - 0.500^2)^{\frac{1}{4}} * (1 - 0.484^2)^{\frac{1}{4}} * (1 - 0.344^2)^{\frac{1}{4}} * (1 - 0.369^2)^{\frac{1}{4}} - (1 - 0.500^2 - 0.400^2)^{\frac{1}{4}} \right. \\ &\quad \left. * (1 - 0.484^2 - 0.276^2)^{\frac{1}{4}} * (1 - 0.344^2 - 0.232^2)^{\frac{1}{4}} * (1 - 0.369^2 - 0.248^2)^{\frac{1}{4}} \right]^{1/2} = 0.304 \\ S(\tilde{w}_{D1}^s) &= \sqrt{\left| 100 * \left[ (3\alpha_{\tilde{F}_S} - \frac{\gamma_{\tilde{F}_S}}{2})^2 - (\frac{\beta_{\tilde{F}_S}}{2} - \gamma_{\tilde{F}_S})^2 \right] \right|} = \sqrt{\left| 100 * \left[ (3 * 0.432 - \frac{0.304}{2})^2 - (\frac{0.542}{2} - 0.304)^2 \right] \right|} \\ &= 11.443 \\ \bar{w}_{D1}^s &= \frac{S(\tilde{w}_j^s)}{\sum_{j=1}^n S(\tilde{w}_j^s)} = \frac{11.443}{11.443 + 12.001 + 14.151 + 13.103} = 0.226 \end{aligned}$$

Table 10. The integrated spherical fuzzy comparison matrix.

Dimension	C			SE			SL			O		
	$\alpha$	$\beta$	$\gamma$									
C	0.500	0.400	0.400	0.484	0.518	0.276	0.344	0.659	0.232	0.369	0.631	0.248
SE	0.441	0.553	0.282	0.500	0.400	0.400	0.433	0.573	0.259	0.429	0.576	0.264
SL	0.590	0.413	0.270	0.475	0.523	0.281	0.500	0.400	0.400	0.521	0.480	0.276
O	0.552	0.443	0.280	0.484	0.512	0.288	0.406	0.588	0.270	0.500	0.400	0.400

Table 11. The spherical weights from the AHP-SF model.

Dimension	AHP-SF Weight			Calculations to Obtain Crisp Weights	Crisp Weights
	$\alpha$	$\beta$	$\gamma$	$S(\tilde{w}_j^s)$	$\bar{w}_j^s$
C	0.432	0.542	0.304	11.443	0.226
SE	0.452	0.520	0.311	12.001	0.237
SL	0.525	0.451	0.312	14.151	0.279
O	0.490	0.481	0.317	13.103	0.258

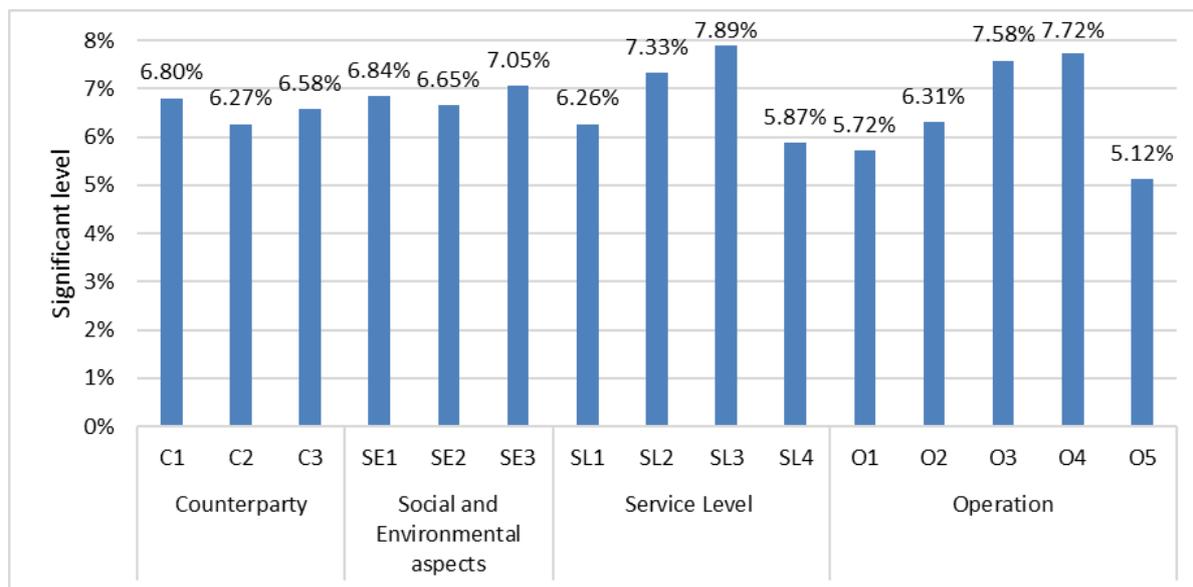
The AHP-SF weights of the four main dimensions consist of three parameters: the membership function ( $\alpha$ ), non-membership function ( $\beta$ ), and hesitancy function ( $\gamma$ ) of the element  $x \in X$ . The crisp weights of the four main dimensions were calculated based on the abovementioned calculation. The most significantly correlated dimension to qualitative performance is Service Level (SL) with a value of 0.279, followed by Operation (O) with a value of 0.258, Social and Environmental aspects (SE) with a value of 0.237, and Counterparty (C) is the last significantly dimension with a value of 0.226. Therefore, the same procedures are used to determine the importance level for 15 criteria. Table A1 presents the integrated spherical fuzzy comparison matrix with 15 criteria (Appendix A).

Table 12 shows the spherical fuzzy weights and crisp weights of the AHP-SF model. The significant level of each criterion is calculated based on the geometrical mean, defuzzification, and normalization procedures. For example, the spherical fuzzy weights of the criteria External green collaborations (C1) have a membership function ( $\alpha$ ) at 0.496, non-membership function ( $\beta$ ) at 0.478, and hesitancy function ( $\gamma$ ) at 0.342. Similar to the procedure, the spherical fuzzy weights of the criteria Relationship (C2) have membership function ( $\alpha$ ), non-membership function ( $\beta$ ), and hesitancy function ( $\gamma$ ) of 0.458, 0.529, and 0.325, respectively. The significance levels of 15 criteria of the AHP-SF model are displayed in Figure 5. The results indicate that the five most significant criteria for qualitative performance evaluation of CSCs are Quality of service (SL3), Equipment system and IT application (O4), Integrated logistics operations (O3), Flexibility and responsiveness (SL2), and Environmental institutional pressures (SE3), with significance levels of 7.89%, 7.72%,

7.58%, 7.33%, and 7.05%, respectively. Meanwhile, Professionalism (O5) is specified as the least significant criterion, with a value of 5.12% compared to other considered criteria. The findings suggest that decision-makers focus on “SL3”, “O4”, “O3”, “SL2”, and “SE3” for improving the qualitative performance of CSCs.

**Table 12.** Spherical fuzzy weights and crisp weights 15 criteria of the AHP-SF model.

Criteria	Geometric Mean			Spherical Fuzzy Weights			Crisp Weights
	$\alpha$	$\beta$	$\gamma$	$\alpha$	$\beta$	$\gamma$	
External green collaborations (C1)	0.754	0.478	0.117	0.496	0.478	0.342	0.068
Relationship (C2)	0.790	0.529	0.106	0.458	0.529	0.325	0.063
Corporate reputation and image (C3)	0.772	0.515	0.101	0.477	0.515	0.318	0.066
Workplace safety and equity (SE1)	0.758	0.502	0.094	0.492	0.502	0.307	0.068
Internal green practices (SE2)	0.769	0.506	0.096	0.480	0.506	0.310	0.066
Environmental institutional pressures (SE3)	0.740	0.482	0.107	0.510	0.482	0.327	0.071
Reliability (SL1)	0.794	0.544	0.091	0.454	0.544	0.301	0.063
Flexibility and responsiveness (SL2)	0.719	0.458	0.113	0.530	0.458	0.336	0.073
Quality of service (SL3)	0.678	0.415	0.120	0.568	0.415	0.346	0.079
Security performance (SL4)	0.817	0.568	0.090	0.428	0.568	0.300	0.059
Market orientation (O1)	0.826	0.579	0.084	0.417	0.579	0.290	0.057
Network and schedule (O2)	0.789	0.524	0.099	0.459	0.524	0.314	0.063
Integrated logistics operations (O3)	0.705	0.444	0.104	0.543	0.444	0.323	0.076
Equipment system and IT application (O4)	0.690	0.434	0.121	0.557	0.434	0.348	0.077
Professionalism (O5)	0.859	0.624	0.075	0.376	0.624	0.274	0.051



**Figure 5.** The significant level of 15 criteria of the AHP-SF model.

Next, the COPRAS-G approach will employ the crisp numbers discovered at the conclusion of the AHP-SF stage as weight values for qualitative criteria.

4.1.2. The Use of COPRAS-G and Results

In this step, COPRAS-G will convert qualitative inputs into a single quantitative output variable termed “expert-based qualitative performance” (EQP). Using COPRAS-G methodology, CSCs are graded according to how well they handle qualitative data. The AHP-SF model is used to determine the preference weight for each criterion. The integrated grey decision matrix of alternatives regarding criteria, in accordance with the COPRAS-G method, is shown in Table A2 (Appendix A). Table 13 provides an evaluation of the COPRAS-G model’s utility level. Maersk (CSC-05) attains the best qualitative performance

with a utility degree of 100% consequently. COSCO (CSC-01) comes in second with a utility degree of 96.97%, while Evergreen (CSC-11) comes in third with a utility degree of 94.41%. Meanwhile, with a utility degree of 53.75%, Sinotrans (CSC-03) has the lowest qualitative performance.

**Table 13.** The evaluation of the utility degree of the COPRAS-G model.

DMUs	Companies	$P_h$	$R_h$	$Q_h$	EQP, $N_h$ (%)
CSC-01	COSCO	0.0773	0.0042	0.0819	96.97
CSC-02	OOCL	0.0512	0.0025	0.0590	69.83
CSC-03	Sinotrans	0.0377	0.0026	0.0454	53.75
CSC-04	SITC	0.0723	0.0054	0.0760	89.97
CSC-05	Maersk	0.0807	0.0052	0.0845	100
CSC-06	CMA-CGM	0.0711	0.0061	0.0743	87.96
CSC-07	Hapag-Lloyd	0.0732	0.0059	0.0765	90.57
CSC-08	ZIM	0.0570	0.0061	0.0603	71.32
CSC-09	ONE	0.0733	0.0054	0.0769	91
CSC-10	HMM	0.0725	0.0050	0.0765	90.50
CSC-11	Evergreen	0.0771	0.0074	0.0798	94.41
CSC-12	Wan Hai	0.0677	0.0053	0.0714	84.46
CSC-13	Yang Ming	0.0663	0.0024	0.0746	88.35
CSC-14	Matson	0.0562	0.0029	0.0630	74.59

At the end of the second step, firstly, criteria weights based on 15 qualitative criteria are calculated with AHP-SF methodology as fuzzy numbers and then calculated into crisp numbers. Secondly, according to the COPRAS-G method, qualitative variables are transformed into only one quantitative variable as an output called expert-based qualitative performance (EQP) and will be used in DEA as an output.

#### 4.2. Phase 2: Finding the Ranking of Efficient and Inefficient CSCs with DEA and Final Results

The qualitative performance values obtained from COPRAS-G analysis are considered an output variable called EQP. In this phase, we select quantitative variables for efficiency analysis after reviewing the existing literature in the container shipping industry. Two efficiency measurement models are established for this analysis, as shown in Figure 6. First is the cargo efficiency model of CSCs, which is measured by using four inputs (owned-in and chartered-in fleet capacity, employee, and operating costs) to produce one output (lifting). Then, the eco-efficiency model with the EQP output variable is developed by using three inputs (employee, operating costs, and lifting) and three outputs (revenue, CO<sub>2</sub> emissions, and EQP). Data collection of input and output variables is shown in Table A3 (Appendix A). Table 14 shows the description and data sources of inputs and outputs (data values of 2020) used in the DEA analysis. Data on chartered-in fleet capacity, owned fleet capacity, employees, operating costs, lifting, revenue, and CO<sub>2</sub> emissions were collected from two main sources: the Alphaliner website [78] and related reports of each CSC. The statistical analysis of input and output variables is shown in Table 15. The variables have a positive connection as in Table A4 (Appendix A), with all correlation coefficients between input/output items being significant, indicating a sound isotonicity of our DEA model.

The efficiency scores and rankings of 14 CSCs in both models were obtained, as shown in Table 16, after the DEA analysis of this system was performed in the DEA Solver software package. In total, five out of 14 CSCs (Sinotrans, SITC, ZIM, Evergreen, and Yang Ming) obtained cargo efficiency. Eight out of 14 CSCs (COSCO, Sinotrans, SITC, ZIM, ONE, HMM, Evergreen, and Matson) obtained eco-efficiency with EQP. On the other hand, Maersk, CMA-CGM, and Hapag-Lloyd were the least efficient CSCs among 14 CSCs, having the lowest overall efficiency scores (0.2622, 0.2862, and 0.4758, respectively). For cargo efficiency, Maersk had the lowest score of 0.2902, CMA-CGM ranked 13th at 0.3443, and Matson ranked 12th at 0.3480. For eco-efficiency with EQP, Maersk, CMA-CGM, and Hapag-Lloyd obtained the lowest scores, at 0.2341, 0.2281, and 0.5331, respectively.

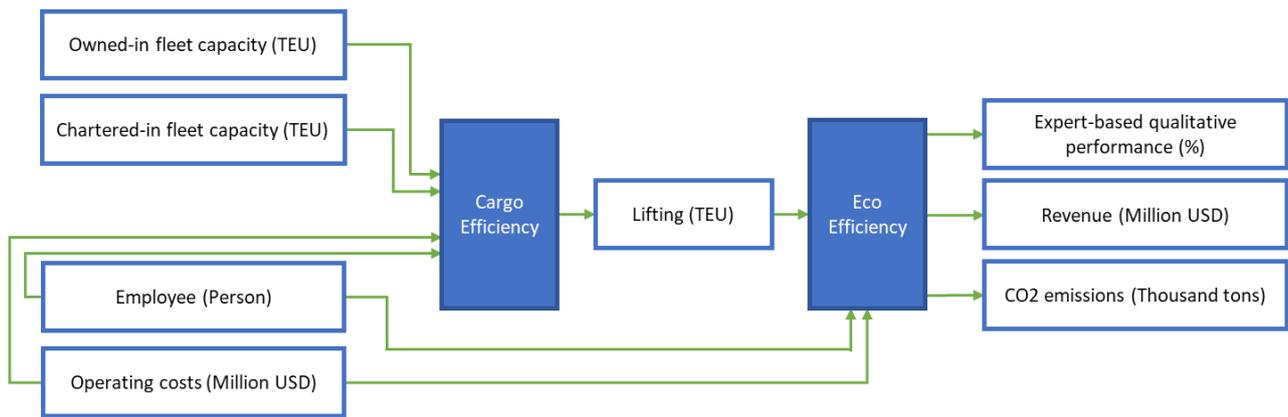


Figure 6. Efficiency models of CSCs.

Table 14. Description of input and output variables.

Variables	Type	Abbreviation	Description	Data Sources
Owned-in fleet capacity	Input to cargo model	I1	Fleet capacity owned by the container carriers (TEU)	Alphaliner website
Chartered-in fleet capacity	Input to cargo model	I2	Fleet capacity of the container carriers chartered from other ship owners (TEU)	Alphaliner website
Employee	Input to cargo/eco model	I3	Number of full-time employees (person)	Annual reports, website, and related reports of each company
Operating costs	Input to cargo model	I4	Cost of goods (services) sold, operating expenses, and overhead expenses (USDm)	Annual reports, website, and related reports of each company
Lifting	Output from cargo model/input to eco model	O1/I5	Measured in terms of volume, through the number of TEUs carried annually (TEU)	Annual reports, website, and related reports of each company
EQP	Desirable output from eco model	O2	Qualitative performance values	COPRAS-G results
Revenue	Desirable output from eco model	O3	Total operating revenue of the companies (USDm)	Annual reports, website, and related reports of each company
CO <sub>2</sub> emissions	Undesirable output from eco model	O-Bad	Total carbon dioxide emissions released from the companies (thousand tons)	Corporate social responsibility, sustainability reports, website and related reports of each company

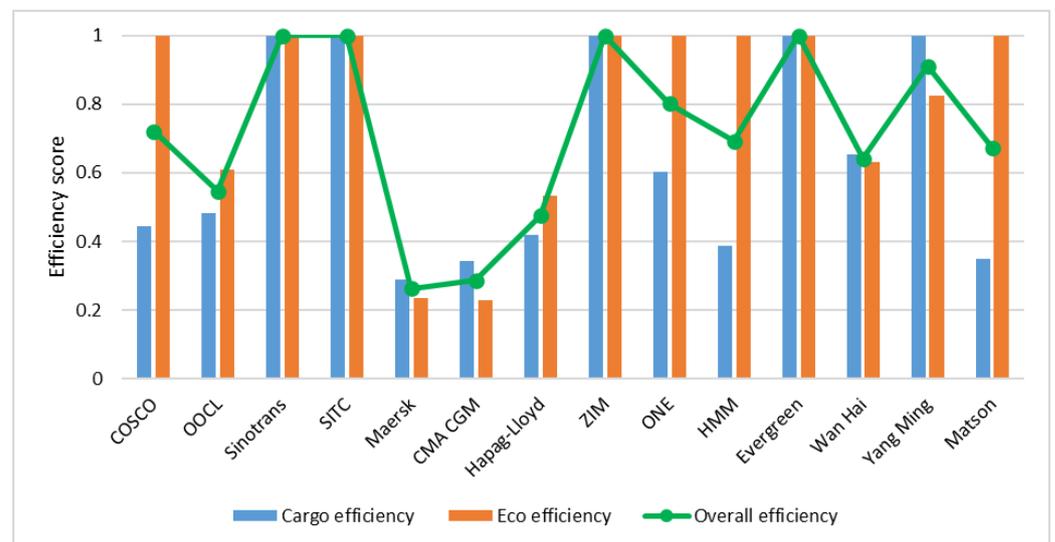
Table 15. Statistical analysis of input and output variables.

Variables	Unit	Max	Min	Avg	SD
Owned-in fleet capacity (I1)	TEU	2,480,020	9247	691,761	686,332
Chartered-in fleet capacity (I2)	TEU	1,843,166	22,982	630,278	608,074
Employee (I3)	Person	83,624	1652	19,180	27,016
Operating costs (I4)	Million USD	31,804	1240	10,351	9366
Lifting (O1/I5)	TEU	25,268,000	747,200	9,056,751	7,398,825
Qualitative performance (O2)	%	100	53.75	84.55	12.24
Revenue (O3)	Million USD	39,740	1685	12,657	11,514
CO <sub>2</sub> emissions (O-Bad)	Thousand tons	34,207	134	9701	10,334

**Table 16.** Cargo and eco-efficiency of each CSC of the DEA model.

DMUs	Companies	Cargo Efficiency	Ranking	Eco-Efficiency with EQP	Ranking	Overall Efficiency	Ranking
CSC-01	COSCO	0.4434	9	1.0000	1	0.7217	7
CSC-02	OOCL	0.4832	8	0.6098	11	0.5465	11
CSC-03	Sinotrans	1.0000	1	1.0000	1	1.0000	1
CSC-04	SITC	1.0000	1	1.0000	1	1.0000	1
CSC-05	Maersk	0.2902	14	0.2341	13	0.2622	14
CSC-06	CMA-CGM	0.3443	13	0.2281	14	0.2862	13
CSC-07	Hapag-Lloyd	0.4185	10	0.5331	12	0.4758	12
CSC-08	ZIM	1.0000	1	1.0000	1	1.0000	1
CSC-09	ONE	0.6036	7	1.0000	1	0.8018	6
CSC-10	HMM	0.3863	11	1.0000	1	0.6931	8
CSC-11	Evergreen	1.0000	1	1.0000	1	1.0000	1
CSC-12	Wan Hai	0.6530	6	0.6304	10	0.6417	10
CSC-13	Yang Ming	1.0000	1	0.8233	9	0.9116	5
CSC-14	Matson	0.3480	12	1.0000	1	0.6740	9
	Average	0.6407		0.7899		0.7153	

Figure 7 shows a visual image of cargo efficiency scores against eco-efficiency scores and their overall efficiency scores. Four CSCs (Sinotrans, SITC, ZIM, and Evergreen) performed the best in both models, achieving cargo efficiency, eco-efficiency, and overall efficiency scores of 1, meaning they are the most efficient CSCs in all investigated dimensions. Moreover, as we can see, while most CSCs have relatively even efficiency scores in both models, COSCO, ONE, HMM, and Matson only performed better on the eco-efficiency model with scores of 1, while achieving quite low cargo efficiency scores (0.4434, 0.6036, 0.3863, and 0.3480, respectively). Figures of Maersk, CMA-CGM, and Hapag-Lloyd are the lowest in both cargo and eco-efficiencies, suggesting that they are the inefficient CSCs among 14 CSCs.



**Figure 7.** Comparison of the CSCs efficiency scores.

### 5. Discussions and Conclusions

Measuring the efficiency of major global CSCs is a contentious issue for both academics and practitioners. More significantly, in the case of maritime transportation, businesses and governments realize that adapting to the post-pandemic world and rebuilding better entails providing economic, social, and environmental value and developing new business opportunities. Compared to most of the previous studies, mainly quantitative-oriented approaches, this study enables the inclusion of both quantitative and qualitative factors in

the evaluation process for the container shipping sector. A more systematic and analytical framework for global shipping evaluation that integrates AHP-SF, COPRAS-G, and DEA has been proposed in this paper for the first time in the literature. In terms of qualitative performance analysis, the criteria weights from AHP-SF results indicated that quality of service, equipment system and IT application, integrated logistics operations, flexibility and responsiveness, and environmental institutional pressures are the most important criteria that influence CSCs' competitive advantage. COPRAS-G indicated efficient and inefficient CSCs under experts' qualitative evaluation. Expert-based qualitative performance (EQP) is considered an output variable for the DEA performance analysis. The DEA analysis indicated that only a few CSCs were efficient concerning all dimensions.

From the final results, it is found that the average cargo efficiency score of all CSCs (0.6407) is lower than the average score in the eco-efficiency model with EQP (0.7899). Our result implies that, during the COVID-19 pandemic, CSCs have had a positive impact on the environment. This can be explained by the fact that the COVID-19 pandemic has crippled the global shipping industry in its initial stages. Although preliminary calculations for 2020 show a significant fall in transportation emissions due to lower activity during the COVID-19 outbreak, there is no doubt that emissions will rebound after 2020. As a result, CSC decision-makers should focus on strengthening environmental strategies as soon as possible. Rather, it is indicated that Maersk, CMA-CGM, and Hapag-Lloyd, three of the largest shipping companies in the world in terms of capacity, have the worst efficiencies during the research period, indicating that they have not been maximizing their resources to obtain the best possible outcomes in both operational and environmental performance. Thus, there is a lot of opportunities for them to enhance efficiency performance. The improvement can be achieved by making better use of their current resources rather than intensifying the resources. Moreover, CSCs that are efficient in only one dimension (COSCO, ONE, HMM, and Matson) should dissect the weaknesses and redevelop their strategies for improving both efficiencies.

The integrated method used in this study to evaluate the container shipping sector aids in the synthesis of several criteria in various CSCs to provide sustainable performances that take operational, economic, environmental, and social factors into account. This study suggests that inefficient CSCs make strategic steps to improve their performance, which typically helps to evaluate relative efficiency in the literature on the shipping industry. Our findings can assist the managers of CSCs in identifying their respective strengths and weaknesses in running businesses. On the other hand, identifying the efficient CSCs is very important from the perspectives of shippers and logistics service providers to select appropriate shipping suppliers. Due to the incompleteness of data, our study's limitation is that we only considered 14 CSCs as a sample, despite the fact they owned more than 70% fleet capacity of the container shipping market during the evaluation period. Therefore, it is advised that researchers examine as many DMUs as they can. Additionally, due to lacking data, this study only takes CO<sub>2</sub> emissions into account as an unwanted output in the eco-efficiency model. Future research may incorporate other emissions (SO<sub>x</sub>, NO<sub>x</sub>, etc.) as unwanted outputs in the eco-efficiency model. Furthermore, it is possible to look at external variables affecting CO<sub>2</sub> and other emissions. In terms of methodology, sensitivity analysis and/or comparative analysis with other MCDM techniques are suggested for researchers to validate the results.

**Author Contributions:** Conceptualization, T.-T.D.; data curation, C.-C.C.; formal analysis, N.-A.-T.N.; funding acquisition, C.-N.W.; investigation, L.-T.-H.D.; methodology, T.-T.D.; project administration, C.-N.W.; software, T.-T.D.; validation, H.-P.H.; writing—original draft, T.-T.D. and N.-A.-T.N.; writing—review and editing, C.-N.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors received no specific funding for this work.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors appreciate the support from the National Kaohsiung University of Science and Technology, Taiwan; and Hong Bang International University, Vietnam.

**Conflicts of Interest:** The authors have declared that no competing interests exist.

**Appendix A**

**Table A1.** The integrated spherical fuzzy comparison matrix of the SF-AHP model.

Criteria	C1			C2			C3			SE1			SE2		
	$\alpha$	$\beta$	$\gamma$												
C1	0.500	0.400	0.400	0.569	0.412	0.311	0.495	0.468	0.349	0.535	0.454	0.310	0.562	0.412	0.319
C2	0.381	0.603	0.296	0.500	0.400	0.400	0.485	0.498	0.314	0.485	0.502	0.311	0.557	0.415	0.321
C3	0.446	0.509	0.352	0.450	0.525	0.297	0.500	0.400	0.400	0.423	0.564	0.307	0.382	0.617	0.268
SE1	0.421	0.567	0.303	0.459	0.522	0.061	0.526	0.449	0.321	0.500	0.400	0.400	0.404	0.583	0.300
SE2	0.381	0.597	0.303	0.391	0.584	0.187	0.429	0.544	0.324	0.546	0.427	0.317	0.500	0.400	0.400
SE3	0.422	0.546	0.327	0.470	0.498	0.354	0.453	0.527	0.318	0.605	0.388	0.279	0.466	0.513	0.321
SL1	0.391	0.587	0.303	0.398	0.600	0.278	0.398	0.603	0.264	0.395	0.565	0.336	0.458	0.534	0.291
SL2	0.512	0.464	0.321	0.573	0.409	0.442	0.640	0.350	0.263	0.572	0.411	0.302	0.536	0.441	0.315
SL3	0.557	0.418	0.311	0.577	0.396	0.526	0.557	0.418	0.311	0.466	0.505	0.329	0.566	0.423	0.299
SL4	0.410	0.565	0.317	0.498	0.484	0.150	0.381	0.603	0.296	0.402	0.583	0.296	0.363	0.625	0.282
O1	0.354	0.631	0.282	0.526	0.460	0.200	0.357	0.640	0.262	0.288	0.710	0.216	0.360	0.632	0.265
O2	0.463	0.491	0.349	0.417	0.556	0.143	0.422	0.546	0.327	0.450	0.525	0.318	0.399	0.576	0.316
O3	0.552	0.422	0.313	0.536	0.441	0.329	0.527	0.444	0.321	0.557	0.429	0.302	0.551	0.434	0.307
O4	0.677	0.324	0.237	0.659	0.334	0.549	0.557	0.429	0.302	0.516	0.462	0.314	0.507	0.483	0.304
O5	0.476	0.497	0.321	0.433	0.541	0.035	0.370	0.607	0.302	0.338	0.658	0.255	0.399	0.590	0.282
Criteria	SE3			SL1			SL2			SL3			SL4		
C1	0.515	0.456	0.328	0.547	0.429	0.319	0.435	0.553	0.307	0.386	0.604	0.286	0.537	0.438	0.325
C2	0.480	0.497	0.335	0.548	0.455	0.283	0.383	0.610	0.280	0.365	0.625	0.279	0.431	0.562	0.289
C3	0.496	0.488	0.321	0.538	0.467	0.282	0.320	0.678	0.234	0.386	0.604	0.286	0.569	0.412	0.311
SE1	0.351	0.648	0.253	0.548	0.408	0.343	0.380	0.614	0.280	0.476	0.504	0.324	0.539	0.446	0.311
SE2	0.482	0.504	0.318	0.479	0.518	0.288	0.404	0.586	0.293	0.363	0.637	0.265	0.598	0.387	0.298
SE3	0.500	0.400	0.400	0.583	0.412	0.289	0.386	0.604	0.286	0.331	0.668	0.246	0.584	0.387	0.314
SL1	0.357	0.637	0.262	0.500	0.400	0.400	0.451	0.538	0.303	0.404	0.586	0.293	0.575	0.406	0.307
SL2	0.557	0.418	0.311	0.489	0.491	0.314	0.500	0.400	0.400	0.331	0.667	0.240	0.646	0.353	0.263
SL3	0.599	0.390	0.286	0.536	0.441	0.315	0.606	0.383	0.279	0.500	0.400	0.400	0.608	0.381	0.295
SL4	0.363	0.615	0.296	0.373	0.611	0.289	0.302	0.696	0.229	0.338	0.655	0.268	0.500	0.400	0.400
O1	0.354	0.626	0.289	0.584	0.400	0.292	0.357	0.635	0.269	0.323	0.676	0.242	0.388	0.580	0.322
O2	0.403	0.566	0.320	0.425	0.550	0.314	0.462	0.520	0.310	0.381	0.597	0.303	0.502	0.477	0.314
O3	0.471	0.509	0.317	0.562	0.425	0.300	0.537	0.439	0.313	0.399	0.576	0.316	0.589	0.396	0.289
O4	0.527	0.452	0.311	0.475	0.514	0.303	0.588	0.410	0.285	0.462	0.520	0.310	0.583	0.402	0.295
O5	0.302	0.696	0.229	0.354	0.636	0.275	0.381	0.597	0.303	0.308	0.687	0.242	0.347	0.641	0.269
Criteria	O1			O2			O3			O4			O5		
C1	0.596	0.383	0.304	0.472	0.494	0.341	0.396	0.592	0.293	0.293	0.708	0.208	0.458	0.526	0.310
C2	0.382	0.617	0.268	0.531	0.443	0.329	0.404	0.586	0.293	0.297	0.702	0.215	0.507	0.471	0.321
C3	0.601	0.397	0.283	0.515	0.456	0.328	0.399	0.589	0.293	0.390	0.604	0.280	0.578	0.393	0.319
SE1	0.659	0.342	0.254	0.485	0.498	0.314	0.390	0.604	0.280	0.427	0.561	0.303	0.623	0.373	0.279
SE2	0.582	0.413	0.283	0.552	0.421	0.325	0.398	0.596	0.286	0.433	0.564	0.290	0.524	0.469	0.294
SE3	0.589	0.383	0.312	0.535	0.435	0.325	0.473	0.515	0.311	0.407	0.585	0.286	0.646	0.353	0.263
SL1	0.366	0.629	0.266	0.513	0.467	0.317	0.380	0.616	0.273	0.470	0.524	0.300	0.603	0.383	0.296
SL2	0.593	0.397	0.291	0.477	0.511	0.307	0.407	0.582	0.293	0.351	0.652	0.252	0.562	0.412	0.319
SL3	0.654	0.344	0.262	0.562	0.412	0.319	0.552	0.421	0.325	0.477	0.511	0.307	0.632	0.360	0.279
SL4	0.560	0.402	0.332	0.439	0.549	0.303	0.356	0.640	0.260	0.363	0.633	0.266	0.591	0.393	0.297
O1	0.500	0.400	0.400	0.396	0.595	0.286	0.390	0.604	0.280	0.352	0.644	0.265	0.527	0.451	0.317
O2	0.542	0.436	0.311	0.500	0.400	0.400	0.368	0.624	0.273	0.454	0.528	0.317	0.599	0.377	0.309
O3	0.557	0.429	0.302	0.567	0.410	0.304	0.500	0.400	0.400	0.489	0.490	0.325	0.670	0.325	0.259
O4	0.572	0.407	0.303	0.484	0.487	0.325	0.454	0.518	0.328	0.500	0.400	0.400	0.660	0.340	0.250
O5	0.414	0.562	0.313	0.329	0.656	0.275	0.286	0.711	0.223	0.291	0.707	0.216	0.500	0.400	0.400

**Table A2.** The integrated grey decision matrix of the G-COPRAS model.

Criteria	C1		C2		C3		SE1		SE2	
CSCs	$\underline{x}$	$\overline{x}$								
COSCO	3.800	4.933	4.333	5.667	4.133	5.400	5.733	7.133	3.533	4.733
OOCL	2.867	4.067	2.400	3.467	2.000	3.333	2.467	3.800	1.800	3.133
Sinotrans	1.933	3.133	1.733	3.000	1.867	3.533	1.600	2.800	1.800	3.200
SITC	4.267	5.533	4.667	6.067	3.933	5.267	6.133	7.667	4.533	5.933
Maersk	4.333	5.600	4.467	5.867	4.600	6.133	3.600	4.667	4.200	5.867
CMA-CGM	3.333	4.533	2.467	3.733	1.933	3.267	2.933	4.267	5.267	6.667
Hapag-Lloyd	3.533	4.800	3.667	4.733	2.800	4.200	1.800	3.200	5.000	6.533
ZIM	2.467	3.667	3.200	4.400	4.000	5.400	2.533	3.733	5.200	6.733
ONE	2.933	4.133	2.733	3.933	3.467	5.000	4.533	6.200	4.533	6.067
HMM	4.467	5.933	2.600	3.867	3.667	4.867	2.200	3.467	4.133	5.600
Evergreen	5.000	6.400	3.800	4.867	3.533	4.667	4.333	5.733	6.467	8.000
Wan Hai	3.467	4.600	3.800	4.800	4.733	6.400	4.933	6.467	4.400	6.000
Yang Ming	4.333	5.667	4.200	5.200	2.333	3.800	2.733	4.067	1.667	2.933
Matson	2.133	3.467	2.533	3.733	2.333	3.533	1.933	3.200	2.200	3.400
CSCs	SE3		SL1		SL2		SL3		SL4	
COSCO	2.867	4.067	3.733	4.800	4.533	6.067	5.267	6.667	4.800	6.467
OOCL	2.200	3.267	1.867	3.133	3.200	4.533	2.267	3.333	1.000	2.400
Sinotrans	1.667	3.000	1.400	2.800	1.467	2.867	1.867	3.133	2.333	3.533
SITC	2.600	4.000	3.467	4.667	4.600	6.133	3.600	4.667	4.200	5.867
Maersk	3.333	4.533	3.733	5.000	4.467	5.867	5.667	7.067	5.267	6.667
CMA-CGM	3.533	4.800	4.733	6.133	5.600	7.000	4.400	5.800	5.000	6.533
Hapag-Lloyd	3.733	5.000	5.800	7.200	5.400	6.933	2.800	4.000	5.200	6.733
ZIM	2.933	4.133	2.733	3.933	3.467	5.000	2.733	3.933	3.067	4.200
ONE	3.333	4.467	2.600	3.867	5.667	6.867	4.800	6.200	4.133	5.600
HMM	5.000	6.400	4.867	6.400	4.200	5.467	4.333	5.733	3.133	4.467
Evergreen	5.867	7.800	4.800	6.200	4.733	6.400	4.933	6.467	6.000	7.533
Wan Hai	4.333	5.667	4.200	5.200	3.400	4.600	3.533	4.667	1.667	2.933
Yang Ming	6.000	7.667	2.533	3.733	2.333	3.533	1.933	3.200	2.200	3.400
Matson	3.600	4.800	2.333	3.533	4.467	5.867	5.667	7.067	5.267	6.667
CSCs	O1		O2		O3		O4		O5	
COSCO	6.067	7.867	4.400	5.800	3.200	4.533	3.733	4.933	3.800	5.000
OOCL	2.800	3.867	3.200	4.333	4.267	5.933	3.267	4.400	3.533	4.733
Sinotrans	1.867	3.400	1.400	2.800	2.067	3.200	1.800	3.067	1.733	3.000
SITC	4.000	5.333	3.867	5.267	3.200	4.533	4.067	5.400	2.600	3.800
Maersk	4.267	5.533	4.667	6.067	3.933	5.267	6.133	7.667	4.533	5.933
CMA-CGM	4.333	5.600	4.467	5.867	4.600	6.133	3.600	4.667	4.200	5.867
Hapag-Lloyd	3.333	4.533	3.733	5.000	4.467	5.867	5.667	7.067	5.267	6.667
ZIM	3.533	4.800	4.733	6.133	2.800	4.200	1.800	3.200	2.467	3.733
ONE	6.067	8.000	1.800	3.200	5.400	6.933	4.000	5.400	5.200	6.733
HMM	4.133	5.800	2.733	3.933	5.000	6.400	3.933	5.333	5.867	7.267
Evergreen	4.467	5.933	2.600	3.867	3.667	4.867	2.200	3.467	4.133	5.600
Wan Hai	2.400	3.467	2.533	3.800	3.533	4.667	3.333	4.533	6.467	8.000
Yang Ming	2.200	3.467	4.800	6.200	4.733	6.400	4.933	6.467	4.400	6.000
Matson	2.733	3.933	2.400	3.600	2.067	3.267	2.533	3.667	1.667	2.933

**Table A3.** Data collection of input and output variables.

CSCs	Owned-in Fleet Capacity (TEU)	Chartered-in Fleet Capacity (TEU)	Employee (Person)	Operating Costs (Million USD)	Lifting (TEU)	Revenue (Million USD)	CO <sub>2</sub> Emissions (Thousand Tons)
COSCO	1,553,344	1,381,103	17,080	22,559	18,882,522	26,945	15,934
OOCL	595,330	186,449	10,552	6602	7,462,000	8191	5539
Sinotrans	22,024	22,982	33,751	12,525	3,645,600	13,302	134

Table A3. Cont.

CSCs	Owned-in Fleet Capacity (TEU)	Chartered-in Fleet Capacity (TEU)	Employee (Person)	Operating Costs (Million USD)	Lifting (TEU)	Revenue (Million USD)	CO <sub>2</sub> Emissions (Thousand Tons)
SITC	117,302	25,300	1652	1240	2,614,203	1685	1508
Maersk	2,480,020	1,799,285	83,624	31,804	25,268,000	39,740	34,207
CMA-CGM	1,328,290	1,843,166	80,780	25,336	21,000,000	31,445	30,900
Hapag-Lloyd	1,049,546	697,226	13,117	12,963	11,838,000	14,600	12,800
ZIM	9247	404,615	3794	2835	2,841,000	3992	2932
ONE	711,491	830,770	7736	10,446	11,964,000	14,397	11,727
HMM	545,134	274,656	3715	4346	3,894,000	5435	4916
Evergreen	759,891	717,753	2009	5849	7,054,400	7496	5836
Wan Hai	262,784	160,126	4369	2332	4,509,000	2969	3218
Yang Ming	211,684	450,363	2194	3978	5,074,587	4625	4316
Matson	38,573	30,097	4149	2103	747,200	2383	1842

Table A4. The correlation matrix of input and output variables of the DEA model.

Variables	Correlations	I1	I2	I3	I4	O1/I5	O2	O3	O-Bad
Owned-in fleet capacity (I1)	Pearson Correlation	1	0.895 **	0.722 **	0.901 **	0.953 **	0.640 *	0.914 **	0.916 **
	Sig. (2-tailed)		0	0.004	0	0	0.014	0	0
	N	14	14	14	14	14	14	14	14
Chartered-in fleet capacity (I2)	Pearson Correlation	0.895 **	1	0.773 **	0.900 **	0.959 **	0.597 *	0.919 **	0.954 **
	Sig. (2-tailed)	0		0.001	0	0	0.024	0	0
	N	14	14	14	14	14	14	14	14
Employee (I3)	Pearson Correlation	0.722 **	0.773 **	1	0.882 **	0.796 **	0.147	0.884 **	0.875 **
	Sig. (2-tailed)	0.004	0.001		0	0.001	0.616	0	0
	N	14	14	14	14	14	14	14	14
Operating costs (I4)	Pearson Correlation	0.901 **	0.900 **	0.882 **	1	0.953 **	0.353	0.997 **	0.919 **
	Sig. (2-tailed)	0	0	0		0	0.215	0	0
	N	14	14	14	14	14	14	14	14
Lifting (O1/I5)	Pearson Correlation	0.953 **	0.959 **	0.796 **	0.953 **	1	0.555 *	0.966 **	0.961 **
	Sig. (2-tailed)	0	0	0.001	0		0.039	0	0
	N	14	14	14	14	14	14	14	14
Qualitative performance (O2)	Pearson Correlation	0.640 *	0.597 *	0.147	0.353	0.555 *	1	0.386	0.538 *
	Sig. (2-tailed)	0.014	0.024	0.616	0.215	0.039		0.172	0.047
	N	14	14	14	14	14	14	14	14
Revenue (O3)	Pearson Correlation	0.914 **	0.919 **	0.884 **	0.997 **	0.966 **	0.386	1	0.938 **
	Sig. (2-tailed)	0	0	0	0	0	0.172		0
	N	14	14	14	14	14	14	14	14
CO <sub>2</sub> emissions (O-Bad)	Pearson Correlation	0.916 **	0.954 **	0.875 **	0.919 **	0.961 **	0.538 *	0.938 **	1
	Sig. (2-tailed)	0	0	0	0	0	0.047	0	
	N	14	14	14	14	14	14	14	14

Note: \*\* denotes correlation is significant at the 0.01 level (2-tailed), \* denotes correlation is significant at the 0.05 level (2-tailed).

## References

- Cano, J.A.; Campo, E.A.; Baena, J.J. Application of DEA in International Market Selection for the Export of Goods. *Dyna* **2017**, *84*, 376–382. [CrossRef]
- Chen, M.-C.; Yu, M.-M.; Ho, Y.-T. Using Network Centralized Data Envelopment Analysis for Shipping Line Resource Allocation. *Int. J. Environ. Sci. Technol.* **2018**, *15*, 1777–1792. [CrossRef]
- Review of Maritime Transport. 2021. Available online: [https://unctad.org/system/files/official-document/rmt2021\\_en\\_0.pdf](https://unctad.org/system/files/official-document/rmt2021_en_0.pdf) (accessed on 19 January 2022).
- Chao, S.L.; Yu, M.M.; Hsieh, W.F. Evaluating the Efficiency of Major Container Shipping Companies: A Framework of Dynamic Network DEA with Shared Inputs. *Transp. Res. Part A Policy Pract.* **2018**, *117*, 44–57. [CrossRef]
- Notteboom, T.; Pallis, T.; Rodrigue, J.-P. Disruptions and Resilience in Global Container Shipping and Ports: The COVID-19 Pandemic versus the 2008–2009 Financial Crisis. *Marit. Econ. Logist.* **2021**, *23*, 179–210. [CrossRef]
- Bellgran, M.; Säfssten, K. *Production Development*; Springer: London, UK, 2010; ISBN 978-1-84882-494-2.
- Bang, H.-S.; Kang, H.-W.; Martin, J.; Woo, S.-H. The Impact of Operational and Strategic Management on Liner Shipping Efficiency: A Two-Stage DEA Approach. *Marit. Policy Manag.* **2012**, *39*, 653–672. [CrossRef]
- Cariou, P. Is Slow Steaming a Sustainable Means of Reducing CO<sub>2</sub> Emissions from Container Shipping? *Transp. Res. D Transp. Environ.* **2011**, *16*, 260–264. [CrossRef]

9. Cariou, P.; Cheaitou, A. The Effectiveness of a European Speed Limit versus an International Bunker-Levy to Reduce CO<sub>2</sub> Emissions from Container Shipping. *Transp. Res. D Transp. Environ.* **2012**, *17*, 116–123. [CrossRef]
10. Kim, S.; Lee, S. Stakeholder Pressure and the Adoption of Environmental Logistics Practices. *Int. J. Logist. Manag.* **2012**, *23*, 238–258. [CrossRef]
11. Luo, M. Emission Reduction in International Shipping—The Hidden Side Effects. *Marit. Policy Manag.* **2013**, *40*, 694–708. [CrossRef]
12. Wang, K.; Fu, X.; Luo, M. Modeling the Impacts of Alternative Emission Trading Schemes on International Shipping. *Transp. Res. Part A Policy Pract.* **2015**, *77*, 35–49. [CrossRef]
13. Shi, Y. Reducing Greenhouse Gas Emissions from International Shipping: Is It Time to Consider Market-Based Measures? *Mar. Policy* **2016**, *64*, 123–134. [CrossRef]
14. Von der Gracht, H.A.; Darkow, I.-L. Energy-Constrained and Low-Carbon Scenarios for the Transportation and Logistics Industry. *Int. J. Logist. Manag.* **2016**, *27*, 142–166. [CrossRef]
15. Fourth Greenhouse Gas Study. 2020. Available online: <https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx> (accessed on 19 January 2022).
16. Gong, X.; Wu, X.; Luo, M. Company Performance and Environmental Efficiency: A Case Study for Shipping Enterprises. *Transp. Policy* **2019**, *82*, 96–106. [CrossRef]
17. Lun, V.Y.H.; Marlow, P. The Impact of Capacity on Firm Performance: A Study of the Liner Shipping Industry. *Int. J. Shipp. Transp. Logist.* **2011**, *3*, 57. [CrossRef]
18. Panayides, P.M.; Lambertides, N.; Savva, C.S. The Relative Efficiency of Shipping Companies. *Transp. Res. E Logist. Transp. Rev.* **2011**, *47*, 681–694. [CrossRef]
19. Gutiérrez, E.; Lozano, S.; Furió, S. Evaluating Efficiency of International Container Shipping Lines: A Bootstrap DEA Approach. *Marit. Econ. Logist.* **2014**, *16*, 55–71. [CrossRef]
20. Chao, S.-L. Integrating Multi-Stage Data Envelopment Analysis and a Fuzzy Analytical Hierarchical Process to Evaluate the Efficiency of Major Global Liner Shipping Companies. *Marit. Policy Manag.* **2017**, *44*, 496–511. [CrossRef]
21. Kuo, K.-C.; Lu, W.-M.; Kweh, Q.L.; Le, M.-H. Determinants of Cargo and Eco-Efficiencies of Global Container Shipping Companies. *Int. J. Logist. Manag.* **2020**, *31*, 753–775. [CrossRef]
22. Tseng, P.-H.; Liao, C.-H. Supply Chain Integration, Information Technology, Market Orientation and Firm Performance in Container Shipping Firms. *Int. J. Logist. Manag.* **2015**, *26*, 82–106. [CrossRef]
23. Iqbal, B.; Siddiqui, D.A. Factors Influencing Selection of Container Shipping Lines in Pakistan—A Logistics Perspective. *Asian Bus. Rev.* **2017**, *7*, 35–44. [CrossRef]
24. Yoon, D.-G.; Phuong Thao, N.; Jong-Soo, K. Fuzzy AHP Evaluation for Performance of Container Shipping Companies in Vietnam (Developing on the Model of Previous Study for the Domestic Lines). *J. Korean Navig. Port Res.* **2018**, *42*, 365–370. [CrossRef]
25. Yang, C.S. An Analysis of Institutional Pressures, Green Supply Chain Management, and Green Performance in the Container Shipping Context. *Transp. Res. D Transp. Environ.* **2018**, *61*, 246–260. [CrossRef]
26. di Vaio, A.; Varriale, L.; Lekakou, M.; Stefanidaki, E. Cruise and Container Shipping Companies: A Comparative Analysis of Sustainable Development Goals through Environmental Sustainability Disclosure. *Marit. Policy Manag.* **2021**, *48*, 184–212. [CrossRef]
27. Hsu, C.-L.; Ho, T.-C. Evaluating Key Factors of Container Shipping Lines from the Perspective of High-Tech Industry Shippers. *J. Mar. Sci. Technol.* **2021**, *29*, 3. [CrossRef]
28. Bao, J.; Zhou, Y.; Li, R. Competitive Advantage Assessment for Container Shipping Liners Using a Novel Hybrid Method with Intuitionistic Fuzzy Linguistic Variables. *Neural Comput. Appl.* **2021**. [CrossRef]
29. Zeydan, M.; Çolpan, C.; Çobanoğlu, C. A Combined Methodology for Supplier Selection and Performance Evaluation. *Expert Syst. Appl.* **2011**, *38*, 2741–2751. [CrossRef]
30. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the Efficiency of Decision Making Units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444. [CrossRef]
31. Charnes, A.; Cooper, W.W.; Golany, B.; Seiford, L.; Stutz, J. Foundations of Data Envelopment Analysis for Pareto-Koopmans Efficient Empirical Production Functions. *J. Econ.* **1985**, *30*, 91–107. [CrossRef]
32. Saaty, T.L. How to Make a Decision: The Analytic Hierarchy Process. *Eur. J. Oper. Res.* **1990**, *48*, 9–26. [CrossRef]
33. Hsieh, H.P.; Kuo, K.; Le, M.; Lu, W. Exploring the Cargo and Eco-Efficiencies of International Container Shipping Companies: A Network-Based Ranking Approach. *Manag. Decis. Econ.* **2021**, *42*, 45–60. [CrossRef]
34. Liu, X.; Wang, Y.; Wang, L. Sustainable Competitiveness Evaluation of Container Liners Based on Granular Computing and Social Network Group Decision Making. *Int. J. Mach. Learn. Cybern.* **2022**, *13*, 751–764. [CrossRef]
35. Banker, R.D.; Charnes, A.; Cooper, W.W. Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis. *Manag. Sci.* **1984**, *30*, 1078–1092. [CrossRef]
36. Tone, K. A Slacks-Based Measure of Efficiency in Data Envelopment Analysis. *Eur. J. Oper. Res.* **2001**, *130*, 498–509. [CrossRef]
37. Chai, J.; Fan, W.; Han, J. Does the Energy Efficiency of Power Companies Affect Their Industry Status? A DEA Analysis of Listed Companies in Thermal Power Sector. *Sustainability* **2019**, *12*, 138. [CrossRef]
38. Lozano, S.; Gutiérrez, E. Slacks-Based Measure of Efficiency of Airports with Airplanes Delays as Undesirable Outputs. *Comput. Oper. Res.* **2011**, *38*, 131–139. [CrossRef]

39. Li, H.; Shi, J.F. Energy Efficiency Analysis on Chinese Industrial Sectors: An Improved Super-SBM Model with Undesirable Outputs. *J. Clean. Prod.* **2014**, *65*, 97–107. [[CrossRef](#)]
40. Apergis, N.; Aye, G.C.; Barros, C.P.; Gupta, R.; Wanke, P. Energy Efficiency of Selected OECD Countries: A Slacks Based Model with Undesirable Outputs. *Energy Econ.* **2015**, *51*, 45–53. [[CrossRef](#)]
41. Cecchini, L.; Venanzi, S.; Pierri, A.; Chiorri, M. Environmental Efficiency Analysis and Estimation of CO<sub>2</sub> Abatement Costs in Dairy Cattle Farms in Umbria (Italy): A SBM-DEA Model with Undesirable Output. *J. Clean. Prod.* **2018**, *197*, 895–907. [[CrossRef](#)]
42. Kutlu Gündoğdu, F.; Kahraman, C. Spherical Fuzzy Sets and Spherical Fuzzy TOPSIS Method. *J. Intell. Fuzzy Syst.* **2019**, *36*, 337–352. [[CrossRef](#)]
43. Ayyildiz, E.; Taskin Gumus, A. A Novel Spherical Fuzzy AHP-Integrated Spherical WASPAS Methodology for Petrol Station Location Selection Problem: A Real Case Study for İstanbul. *Environ. Sci. Pollut. Res.* **2020**, *27*, 36109–36120. [[CrossRef](#)]
44. Kutlu Gündoğdu, F.; Kahraman, C. A Novel VIKOR Method Using Spherical Fuzzy Sets and Its Application to Warehouse Site Selection. *J. Intell. Fuzzy Syst.* **2019**, *37*, 1197–1211. [[CrossRef](#)]
45. Kutlu Gündoğdu, F.; Kahraman, C. A Novel Spherical Fuzzy Analytic Hierarchy Process and Its Renewable Energy Application. *Soft Comput.* **2020**, *24*, 4607–4621. [[CrossRef](#)]
46. Unal, Y.; Temur, G.T. Sustainable Supplier Selection by Using Spherical Fuzzy AHP. *J. Intell. Fuzzy Syst.* **2021**, *42*, 593–603. [[CrossRef](#)]
47. Sharaf, I.M. Global Supplier Selection with Spherical Fuzzy Analytic Hierarchy Process. In *Decision Making with Spherical Fuzzy Sets: Theory and Applications*; Studies in Fuzziness and Soft Computing; Kahraman, C., Kutlu Gündoğdu, F., Eds.; Springer: Cham, Switzerland, 2021; pp. 323–348.
48. Unal, Y.; Temur, G.T. Using Spherical Fuzzy AHP Based Approach for Prioritization of Criteria Affecting Sustainable Supplier Selection. In *Intelligent and Fuzzy Techniques: Smart and Innovative Solutions, Proceedings of the INFUS 2020 Conference, Istanbul, Turkey, 21–23 July 2020*; Springer: Cham, Switzerland, 2021; pp. 160–168.
49. Sharaf, I.M.; Khalil, E.A.-H.A. A Spherical Fuzzy TODIM Approach for Green Occupational Health and Safety Equipment Supplier Selection. *Int. J. Manag. Sci. Eng. Manag.* **2021**, *16*, 1–13. [[CrossRef](#)]
50. Menekşe, A.; Camgöz Akdağ, H. Distance Education Tool Selection Using Novel Spherical Fuzzy AHP EDAS. *Soft Comput.* **2022**, *26*, 1617–1635. [[CrossRef](#)] [[PubMed](#)]
51. Kutlu Gündoğdu, F.; Kahraman, C.; Karaşan, A. Spherical Fuzzy VIKOR Method and Its Application to Waste Management. In *Intelligent and Fuzzy Techniques in Big Data Analytics and Decision Making, Proceedings of the INFUS 2019 Conference, Istanbul, Turkey, 23–25 July 2019*; Springer: Cham, Switzerland, 2020; pp. 997–1005.
52. Yildiz, D.; Temur, G.T.; Beskese, A.; Bozbura, F.T. A Spherical Fuzzy Analytic Hierarchy Process Based Approach to Prioritize Career Management Activities Improving Employee Retention. *J. Intell. Fuzzy Syst.* **2020**, *39*, 6603–6618. [[CrossRef](#)]
53. Mathew, M.; Chakraborty, R.K.; Ryan, M.J. A Novel Approach Integrating AHP and TOPSIS under Spherical Fuzzy Sets for Advanced Manufacturing System Selection. *Eng. Appl. Artif. Intell.* **2020**, *96*, 103988. [[CrossRef](#)]
54. Nguyen, T.-L.; Nguyen, P.-H.; Pham, H.-A.; Nguyen, T.-G.; Nguyen, D.-T.; Tran, T.-H.; Le, H.-C.; Phung, H.-T. A Novel Integrating Data Envelopment Analysis and Spherical Fuzzy MCDM Approach for Sustainable Supplier Selection in Steel Industry. *Mathematics* **2022**, *10*, 1897. [[CrossRef](#)]
55. Udony Oluğu, E.; Durdymammedovich Mammedov, Y.; Young, J.C.E.; Yeap, P.S. Integrating Spherical Fuzzy Delphi and TOPSIS Technique to Identify Indicators for Sustainable Maintenance Management in the Oil and Gas Industry. *J. King Saud Univ.—Eng. Sci.* **2021**; *in press*. [[CrossRef](#)]
56. Gul, M.; Fatih Ak, M. A Modified Failure Modes and Effects Analysis Using Interval-Valued Spherical Fuzzy Extension of TOPSIS Method: Case Study in a Marble Manufacturing Facility. *Soft Comput.* **2021**, *25*, 6157–6178. [[CrossRef](#)]
57. Dogan, O. Process Mining Technology Selection with Spherical Fuzzy AHP and Sensitivity Analysis. *Expert Syst. Appl.* **2021**, *178*, 114999. [[CrossRef](#)]
58. Nguyen, P.-H.; Tsai, J.-F.; Dang, T.-T.; Lin, M.-H.; Pham, H.-A.; Nguyen, K.-A. A Hybrid Spherical Fuzzy MCDM Approach to Prioritize Governmental Intervention Strategies against the COVID-19 Pandemic: A Case Study from Vietnam. *Mathematics* **2021**, *9*, 2626. [[CrossRef](#)]
59. Zavadskas, E.K.; Kaklauskas, A.; Turskis, Z.; Tamošaitienė, J. Multi-Attribute Decision-Making Model by Applying Grey Numbers. *Informatica* **2009**, *20*, 305–320. [[CrossRef](#)]
60. Zavadskas, E.K.; Kaklauskas, A.; Turskis, Z.; Tamošaitienė, J. Selection of the Effective Dwelling House Walls by Applying Attributes Values Determined at Intervals. *J. Civ. Eng. Manag.* **2008**, *14*, 85–93. [[CrossRef](#)]
61. Deng, J. Control Problems of Grey Systems. *Syst. Control Lett.* **1982**, *1*, 288–294.
62. Aghdaie, M.H.; Zolfani, S.H.; Zavadskas, E.K. Market Segment Evaluation and Selection Based on Application of Fuzzy AHP and COPRAS-G Methods. *J. Bus. Econ. Manag.* **2012**, *14*, 213–233. [[CrossRef](#)]
63. Tavana, M.; Momeni, E.; Rezaeiniya, N.; Mirhedayatian, S.M.; Rezaeiniya, H. A Novel Hybrid Social Media Platform Selection Model Using Fuzzy ANP and COPRAS-G. *Expert Syst. Appl.* **2013**, *40*, 5694–5702. [[CrossRef](#)]
64. Caisucar, M.; Naik Dessai, A.; Usgaonkar, G. Validation of Portfolio Allocation in NPD: Fuzzy-TOPSIS and COPRAS-Grey Approach. *Int. J. Syst. Assur. Eng. Manag.* **2021**, *12*, 37–43. [[CrossRef](#)]
65. Kayapinar Kaya, S.; Aycin, E. An Integrated Interval Type 2 Fuzzy AHP and COPRAS-G Methodologies for Supplier Selection in the Era of Industry 4.0. *Neural Comput. Appl.* **2021**, *33*, 10515–10535. [[CrossRef](#)]

66. Julong, D. Introduction to Grey System Theory. *J. Grey Syst.* **1989**, *1*, 1–24.
67. Li, G.D.; Yamaguchi, D.; Nagai, M. A Grey-Based Decision-Making Approach to the Supplier Selection Problem. *Math. Comput. Model.* **2007**, *46*, 573–581. [[CrossRef](#)]
68. Turanoglu Bekar, E.; Cakmakci, M.; Kahraman, C. Fuzzy COPRAS Method for Performance Measurement in Total Productive Maintenance: A Comparative Analysis. *J. Bus. Econ. Manag.* **2016**, *17*, 663–684. [[CrossRef](#)]
69. Wang, C.-N.; Dang, T.-T.; Nguyen, N.-A.-T.; Le, T.-T.-H. Supporting Better Decision-Making: A Combined Grey Model and Data Envelopment Analysis for Efficiency Evaluation in e-Commerce Marketplaces. *Sustainability* **2020**, *12*, 10385. [[CrossRef](#)]
70. Halkos, G.; Petrou, K.N. Treating Undesirable Outputs in DEA: A Critical Review. *Econ. Anal. Policy* **2019**, *62*, 97–104. [[CrossRef](#)]
71. Alphaliner TOP 100. Available online: <https://alphaliner.axsmarine.com/PublicTop100/> (accessed on 8 February 2022).
72. Dzakah Fanam, P.; Nguyen, H.-O.; Cahoon, S. Competitiveness of the Liner Operators: Methodological Issues and Implications. *J. Traffic Transp. Eng.* **2016**, *4*, 231–241. [[CrossRef](#)]
73. Basedow, J.; Magnus, U.; Wolfrum, R. (Eds.) *The Hamburg Lectures on Maritime Affairs 2009 and 2010*; Springer: Berlin/Heidelberg, Germany, 2012; Available online: <https://link.springer.com/book/10.1007%2F978-3-642-27419-0#toc> (accessed on 8 February 2022).
74. Lirn, T.-C.; Lin, H.-W.; Shang, K.-C. Green Shipping Management Capability and Firm Performance in the Container Shipping Industry. *Marit. Policy Manag.* **2014**, *41*, 159–175. [[CrossRef](#)]
75. Yang, C.-C.; Tai, H.-H.; Chiu, W.-H. Factors Influencing Container Carriers' Use of Coastal Shipping. *Marit. Policy Manag.* **2014**, *41*, 192–208. [[CrossRef](#)]
76. Tiwari, P.; Itoh, H.; Doi, M. Shippers' Port and Carrier Selection Behaviour in China: A Discrete Choice Analysis. *Marit. Econ. Logist.* **2003**, *5*, 23–39. [[CrossRef](#)]
77. Fanam, P.D.; Ackerly, L. Evaluating Ocean Carrier Selection Criteria: Perspectives of Tasmanian Shippers. *J. Shipp. Trade* **2019**, *4*, 5. [[CrossRef](#)]
78. Čirjevskis, A. Unbundling Dynamic Capabilities in Successful Asian-Pacific Shipping Companies. *J. Asia Bus. Stud.* **2017**, *11*, 113–134. [[CrossRef](#)]
79. Yuen, K.F.; Thai, V. Barriers to Supply Chain Integration in the Maritime Logistics Industry. *Marit. Econ. Logist.* **2017**, *19*, 551–572. [[CrossRef](#)]
80. Vernimmen, B.; Dullaert, W.; Engelen, S. Schedule Unreliability in Liner Shipping: Origins and Consequences for the Hinterland Supply Chain. *Marit. Econ. Logist.* **2007**, *9*, 193–213. [[CrossRef](#)]