Economic Evaluation of Safety Input-Output Efficiency of Arctic Ship Operators Based on the DEA Model

Junjie Wan, Raphael Baumler

Ship operations in the Arctic region require shipowners to increase specific safety investments due to the area's unique characteristics, such as extreme climate, remoteness, and fragile environment. From an economic perspective, shipowners must provide enhanced safety capacities through higher safety budgets while maintaining the profitability of ship operations. Therefore, economic assessments are necessary for decision-makers to determine whether safety investments are effectively allocated and to verify their adequacy. In this context, assessing safety input-output efficiency can help managers measure the efficiency of safety investments in terms of economic benefits and optimize resource allocation. This study uses Data Envelopment Analysis (DEA) to measure efficiencies over a selected period, using safety investments as inputs and economic benefits as outputs in the DEA models. The results of the empirical analysis of an Arctic ship operator indicate that safety investments were not effectively utilized in some years and show projected output targets for improvement. Additionally, recommendations for safety improvements are provided based on the DEA results and accident data. The approach in this study offers a practical tool for decision-makers to invest in Arctic shipping safety.

KEYWORDS

~ Arctic shipping
~ Data Envelopment Analysis (DEA)
~ Safety investment
~ Input-output

World Maritime University, Malmö, Sweden

e-mail: w1802972@wmu.se
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1. INTRODUCTION

1.1. Background

Ship operations in the Arctic today require enhanced risk prevention and protection measures because the probability and consequences of accidents are high and severe. The International Maritime Organization (IMO) has developed specific regulations, primarily the Polar Code, to address shipping activities in the Arctic region. The IMO's Polar Code entered into force on January 1, 2017, covering aspects of structure, machinery, safety navigation, manning and training, and pollution prevention. It includes Part I for safety measures in accordance with relevant SOLAS chapters and Part II for pollution prevention in line with relevant MARPOL Annexes. The development of the Polar Code is now in its second phase, focusing on applying the Polar Code to ships not currently covered by SOLAS (IMO 2025).

Additionally, Arctic coastal states have adopted national regulations regarding navigation safety and pollution prevention in the Arctic. For example, for the Northern Sea Route (NSR), the Russian Federation has established the Requirements for the Design, Equipment, and Supplies of Vessels Navigating the Northern Sea Route (1996), the Rules of Navigation in the Water Area of the Northern Sea Route (NSR Rules), and amendments to certain legislative acts. Arctic shipping in Canada is governed by several pieces of legislation, including the Arctic Waters Pollution Prevention Act, the Arctic Shipping Safety and Pollution Prevention Regulations (ASSPPR), the Canada Shipping Act 2001, the Marine Transportation Security Act, the Coasting Trade Act, the Marine Liability Act, and the Canada Labour Code.

The extreme climate, remoteness, and fragile environment in the region require shipowners to increase their safety investments (e.g., ice-class ships, Polar Code compliance costs) to comply with these regulations and mitigate specific risks (e.g., ice impacts, sudden weather changes) (Wan et al. 2024). Shipowners must ensure the profitability of ship operations while providing enhanced safety capacities to their vessels through ship design and operation (Christensen et al. 2022; Wan and Baumler 2025). Therefore, companies intending to navigate Arctic regions need higher safety budgets and must verify the adequacy of their investments.

In this context, appropriate economic assessment approaches are required for decision-makers to determine whether these safety investments are cost-effective, contribute to economic benefits, and are properly allocated.

To this end, this study aims to demonstrate an appropriate approach, Data Envelopment Analysis (DEA), to evaluate safety input-output efficiency for Arctic ship operators. This approach can be a valuable tool to help managers assess and allocate safety investments in terms of scale, structure, and timing. Literature reviews indicate that applications of Data Envelopment Analysis (DEA) in the area of safety have been demonstrated in industries other than shipping. This research is expected to fill the gap in its application to safety investment decision-making in the shipping industry, and the outcome can serve as a reference for ship operators in decision-making, planning, and optimizing safety investments in Arctic shipping.

1.2. Literature review

Investment strategies are essential in business and are associated with resource implications, including costs and consequences (Riaño-Casallas and Tompa 2018). Economic assessments can be used to evaluate safety investment decisions at the enterprise level (Targoutzidis et al. 2014) because some decisions affect the entire company rather than just reducing ship accidents or protecting the crew.

Safety is often viewed as a cost with no visible returns. Therefore, the extent to which organizations allocate limited resources (such as time, facilities, and money) to safety is influenced by a combination of legal, financial, and moral factors (Targoutzidis et al. 2014). Beyond legal requirements, safety investments require management commitment and a willingness to enhance operational safety.

Many studies (e.g., Jervis and Collins 2001; Riel and Imbeau 1996) have confirmed the positive impact of safety investments on safety performance (Teo and Feng 2011), including cost reductions from lower accident rates and improved corporate profitability (López-Alonso et al. 2016).

Despite the general consensus that additional safety investment can lead to better safety performance (Laufer 1987; Brody et al. 1990; Teo and Feng 2011), the claim that safety investments are always profitable is an oversimplification.

In practice, not all safety investments are financially profitable, nor should they be (Tompa et al. 2010; Targoutzidis et al. 2014). safety investments are diverse, and some benefits may be uncertain. The literature notes that certain investments, such as overly complex safety management systems, can create counterproductive bureaucracy that negatively affects safety (e.g., Dekker 2014—the bureaucratization of safety; Bhattacharya and Tang 2013—fatigue for safety).

Additionally, simply comparing the costs of safety investments with the benefits is problematic (Aven and Flage 2009). Tappura et al. (2015) review existing management accounting practices related to safety and conclude that, in addition to calculating the costs and benefits of safety investments, their efficiency and resulting improvements (such as productivity gains) should also be evaluated.

The literature identifies other types of economic evaluation that can be used to analyze the potential benefits of preventive measures, including cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), and cost-utility analysis (CUA) (Reniers and van Erp 2016). These methods primarily relate the cost of an alternative to specific program objectives, compare costs to objectives or benefits, and assess a cost-benefit ratio (Levin and McEwan 2001; Daniels et al. 2019). For example, Li and Cullinane (2003), Viertola and Storgård (2013), Giuliano et al. (2016), and Puisa et al. (2021) applied these approaches to evaluate safety regulations or measures in the maritime field. However, methods such as CBA, CEA, and CUA do not provide the efficiency measures required for this study. Furthermore, they focus on comparing different alternatives and calculating a cost-benefit ratio, but are limited in supporting further consideration of investment allocation.

2. METHODOLOGY

This study adopts the DEA method to evaluate the safety input–output efficiency for Arctic ship operators. A typical DEA process involves the following steps: 1) select DMUs; 2) select the DEA model; 3) determine input and output variables; 4) collect data and process the DEA model solution; 5) analyze results; 6) provide recommendations.

2.1. Justification of the Data Envelopment Analysis

Data Envelopment Analysis (DEA) is a non-parametric method for measuring the relative efficiency of a homogeneous set of decision-making units (DMUs), a task that has been challenging for other approaches due to the complex relationships between the multiple inputs and outputs involved in DMUs (Cooper et al. 2011, p. 3).

The DEA method can determine whether a DMU's corresponding point is located on the efficient production frontier. Additionally, this method allows decision-makers to rank DMUs by their efficiencies and gain new insights into activities and entities, such as identifying sources of inefficiency (Cooper et al. 2006), and to make project adjustments based on evaluation results to improve DMU efficiency (Tong and Ding 2008; Chen et al. 2015).

DEA offers significant advantages in evaluating an entity's efficiency with multiple inputs and outputs:

- It is objective because it does not require assumptions about any weight coefficients (Chen et al. 2015).
- DEA does not require analysis of the existing quantitative relationships between inputs and outputs (Cooper et al. 2006).
- For inefficient DMUs, it enables evaluation of how many resources should be added (Fancello et al. 2020) and the possible conservation of resources or augmentation of outputs (Boussofiane et al. 1991).

However, the limitations of the DEA method include:

- DEA is sensitive to measurement error (Avkiran and Rowlands 2008). Therefore, input and output data should be as accurate as possible.
- Its main inherent limitation is the selection of input and output variables. Thus, the validity of DEA strongly depends on the proper choice of variables (Fancello et al. 2020).

The existing literature indicates that applying the DEA method to safety investments in the shipping industry remains unexplored. However, its application in safety has been demonstrated in other industries, such as mining. For example, Sarkar et al. (2003) adopted DEA and fuzzy set theory to evaluate the safety performance of coal mines in terms of productivity, efficiency, and profitability. El-Mashaleh et al. (2010) used DEA to assess the relative efficiency of construction contractors in terms of safety performance. Tong and Ding (2008) and Shu-Ming (2011) applied the DEA model to the mining industry to assess safety input-output efficiency. Beriha et al. (2011) evaluated the safety performance of three industries using the DEA model. Suh (2025) employed DEA to calculate and evaluate both productivity and safety effectiveness. Selecting safety investments as inputs and economic performance as outputs is considered appropriate, as this selection was tested in these studies. The literature demonstrates the potential of the DEA approach. Furthermore, other economic evaluation methods cannot assess efficiencies in the presence of multiple inputs and outputs. Therefore, the DEA method is considered the most appropriate approach for this purpose.

2.2. Choice of DMU and DEA model

Generally, a Decision-Making Unit (DMU) is considered an entity whose performance is under study (Cooper et al. 2006). Entities can include organizations such as companies, governments, and non-profit organizations. DMUs must be homogeneous and share the same characteristics (i.e., objectives, constraints, background, input, and output variables). Thus, the set of DMUs can consist of a group of homogeneous organizations (e.g., several banks or several airlines). The DEA method can evaluate and compare the efficiencies of two or more different companies during the same period, with each company selected as a DMU. For example, company A is DMU1, while company B is DMU2.

Additionally, the same entity in each relevant period (e.g., one year) can be regarded as a different DMU (Charnes et al. 1978). For example, company A in 2020 can be DMU1, while company A in 2021 can be DMU2. Thus, the DEA method can also evaluate the efficiency of the same company in different years, with this company in each year as a DMU (Tong and Ding 2008). In this study, the Arctic ship operator in each year (from 2011 to 2022) is considered a DMU.

There are various models (e.g., Slack-Based Model and Additive Model) in the DEA method. DEA models should be selected based on their characteristics and evaluation objectives. The first DEA model, the

Charnes, Cooper, and Rhodes (CCR) model, was introduced by Charnes et al. (1978), based on the work of Farrell (1957), and further extended by Banker, Charnes, and Cooper (BCC model) (Banker et al. 1984). The CCR and BCC models are classic and are the most widely used DEA models in almost all applications. The CCR model (also known as the CRS model) focuses on technical efficiency (TE) under constant returns to scale, while the BCC model (also known as the VRS model) focuses on pure technical efficiency (PTE) under variable returns to scale. Both models can be further divided into input-oriented models, which aim to minimize inputs while achieving at least the given output levels, and output-oriented models, which attempt to maximize outputs without requiring more observed input values (Cooper et al. 2006).

In the empirical analysis, we focus on evaluating technical efficiency. For an Arctic ship operator, it is reasonable that maximizing safety benefits outweighs minimizing safety investments. Therefore, the CCR (output-oriented) model is chosen in this study.

2.3. CCR Model

The form of the CCR (output-oriented) model and the axioms are listed below:

We assume that there are n DMUs to be evaluated and that the relative efficiency of the DMUs is DMU_j $(j = 1, 2, \ldots, n)$; each DMU takes m different inputs, which are x_i $(i = 1, 2, \ldots, m)$ and the input "weight" is v_i $(i = 1, 2, \ldots, m)$; each DMU produces q different outputs, which are y_r $(r = 1, 2, \ldots, q)$ and the output "weight" is u_r $(r = 1, 2, \ldots, q)$. Both v_i and u_r are variables.

The fractional program (FP_k) can be written as:

$$(FP_k) \qquad \max \frac{\sum_{r=1}^{q} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}} \qquad (1)$$

$$subject\ to \quad \frac{\sum_{r=1}^{q} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1$$

$$v \geq 0; u \geq 0$$

$$i = 1,2, \ldots, m;\ r = 1,2, \ldots, q;\ j = 1,2, \ldots, n$$

The fractional program can be reduced to a linear program (LP_k) as follows:

$$(LP_k) \qquad \min \sum_{i=1}^{m} v_i x_{ik} \qquad (2)$$

$$subject\ to \quad \sum_{r=1}^{q} \mu_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0$$

$$\sum_{r=1}^{q} \mu_r y_{rk} = 1$$

$$v \geq 0; \mu \geq 0$$

$$i = 1,2, \ldots, m;\ r = 1,2, \ldots, q;\ j = 1,2, \ldots, n$$

The dual problem (DLP_k) called DEA envelopment form can be formulated as:

$$(DLP_k) \qquad \max \varphi \qquad (3)$$

$$subject\ to \quad \sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{ik}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq \varphi y_{rk}$$
$$\lambda \geq 0$$
$$i = 1,2,\dots,m;\ r = 1,2,\dots,q;\ j = 1,2,\dots,n$$

2.4. Input-output variables

The basic principles for selecting input and output variables are: (1) Use common input and output items for all DMUs (Charnes et al. 1978); (2) Reflect the focus of the evaluations (Cooper et al. 2006); (3) Use positive numerical data; and (4) Measurement units do not need to be congruent.

In this study, inputs are safety investments by Arctic ship operators, representing the value of resources (e.g., money, workforce, facilities) invested in prevention and protection (Brody et al. 1990; Rikhardsson et al. 2002). Outputs are the economic benefits to companies resulting from their safety investments, including reduced accident losses and value-added production (i.e., increased productivity).

2.4.1. Input variables

Shipping safety investments are expenditures aimed at enhancing shipping safety, promoting or maintaining health and safety standards, eliminating or mitigating risks, reducing casualties, and preventing marine accidents (Brody et al. 1990; U.S. Coast Guard 1997).

Ensuring scientific acceptability and reliability is essential to achieving a robust classification of safety investments by Arctic ship operators. Bibliographic keyword searches in academic databases (e.g., Scopus, ScienceDirect, and Google Scholar) were conducted for the period from 2000 to 2023. The researchers used a list of keywords (e.g., Arctic shipping, safety investments, polar operation) and combinations of these keywords.

Investments in five domains – infrastructure, measures, personnel, technology, and management – were identified and are listed below. Each investment is identified through literature related to Arctic shipping safety and verified with examples by examining recent safety investment activities of Arctic ship operators. For example, Gao and Erokhin (2019), Rajagopal and Zhang (2021), Wang et al. (2018), Lasserre (2014), and Lajeunesse et al. (2011) advocate investing in ice-class ships, pilotage services, weather and ice information services, seafarers with Arctic experience, and personnel training. In 2009, ships from the Beluga Shipping Group used their own meteorologists to provide the ice navigator with up-to-date data to ensure that the ice information was as reliable as possible (Østreng et al. 2013).

Safety investments in infrastructures and facilities (I_1) are costs incurred in establishing safety-related infrastructures and facilities and maintenance. For Arctic ship operators, these could be additional costs to obtain Ice Class notation, costs of upgrading the vessel's condition for safety, and vessel maintenance costs.

Safety measure investments (I_2) are costs that occurred on safety measures placed onboard the ships and expenses on external services paid by the shipowners to other parties to ensure the safety of the voyages. Examples of services are icebreaker assistance, pilotage, communication and navigation services, weather and ice information service, and insurance premiums for the vessels and crew.

Safety investments in personnel (I_3) are prevention costs spent on work personnel from the company. Examples of cost items are additional wages for crew with Arctic experience, additional hiring costs, wages of additional manning, wages of safety inspectors and safety administration staff, Polar training for crew, safety training for crew and staff, and personal protective equipment.

Safety investments in technologies (I_4) are the costs of purchasing, developing, and adopting new technologies to ensure the safety of shipping activities. Examples of new technologies include drones, autonomous underwater vehicles, ice monitoring, weather forecasting, artificial intelligence (AI), big data analytics, anti-icing solutions, icebreaking technology, Arctic voyage optimization, and Arctic oil spill response technology.

Investments in safety management (I_5) are the costs of establishing and maintaining a safety management system. Examples of cost items include inspections, audits, safety awards, safety incentives, safety meetings, and drills.

2.4.2. Output variables

To a shipowner, the economic benefits contributed by safety investments are value-added production and reduced accident losses.

1. Value-added production ($\boldsymbol{O_1}$)

Value-added production is embodied in higher productivity and better quality (European Commission 2011; Mossink 2002). Existing literature and Health and Safety Executives (HSE) have adopted the Cobb-Douglas production function in the health and safety economic evaluations. For example, (Sheikh et al. 2006) used the function to measure whether increased health and safety activities would encourage investment in human and capital, thereby increasing productivity. (Tan et al. 2012) established a multifactor production function model for the mining industry based on the function.

Based on the Cobb-Douglas production function, the value-added production can be expressed as:

$$\boldsymbol{Y = AL^{\beta}K^{\alpha}} \qquad (4)$$

Where:

- $\boldsymbol{Y}$ is the monetary value of the value-added production ($\boldsymbol{O_1}$).
- $\boldsymbol{L}$ represents labor, which is the working hours spent by safety personnel and ship maintenance staff.
- $\boldsymbol{K}$ represents capital, which is the monetary value of the total safety investment.
- $\boldsymbol{A}$ is the multifactor productivity (MFP) for the country's transportation industry in the year. Its values usually are published by the country's national statistics agency.
- $\boldsymbol{\beta}$ and $\boldsymbol{\alpha}$ are the output elasticities of labor and capital, respectively. The values usually are published by the country's national statistics agency.
- $\boldsymbol{\alpha + \beta = 1.}$

2. Reduced accident losses ($\boldsymbol{O_2}$)

In an ex-post study, this actual benefit in a period (e.g., one year) can be expressed as Equation 5. For example, reduced accident losses in 2020 equals total accident losses in 2019 minus total accident losses in 2020.

$$\begin{aligned}&\text{Reduced accident losses } (\boldsymbol{O_2}) \text{ in a year}\\ &\quad = \text{Total accident losses in last year} - \text{Total accident losses in the year} \quad (5)\end{aligned}$$

Marine accident losses are the sum of four components: injury and death costs, environmental damage costs, and other costs (U.S. Coast Guard 1997).

- ***Injury and death costs*** **(IDC)** include medical expenses, compensation costs, and absenteeism-related costs. Examples of cost items are medical charges for treatment, hospitalization, transfer of injured crew, wages for medical leave, wages for co-worker overtime, fringe benefits, and costs associated with employee replacement.
- ***Property damage costs*** **(PDC)** are costs of property (e.g., ship, quay) damage or loss in marine accidents. Examples are the costs of repairing the damaged ship, compensation for the damage to other vessels or public facilities, and expenses paid by the shipowner to deal with cargo loss or damage.
- ***Environmental damage costs*** **(EDC)** include costs to clean up the pollution, costs to remove debris, compensations to restore the damaged environment, and compensations paid to local communities.
- ***Other costs*** **(OC)** are other cost items associated with marine accidents. Cost items include operation disturbance, accident response, insurance, penalties, fines, legal, and accident investigation.

3. Empirical analysis

The empirical case study analysis on an Arctic ship operator in the United States demonstrates the data collection and the DEA's methodological steps and presents the numerical results. The currency used in this case study is the U.S. dollar.

2.5. Data

Inputs

The values of actual safety investments (I_1, I_2, I_3, I_5) (described in 4.1.1) from 2011 to 2022 were derived from the State Governor's Operating Budget Reports as the operator is state-funded. Safety investments in new technologies (I_4) have not been found in all available resources and are considered null for the period. Thus, the value of total safety investment (K) can be estimated (see Table 1).

Table 1 The values of total safety investment from 2010 to 2022. (Source: The authors)

Year	I_1	I_2	I_3	I_5	Total (K)
2011	$6,273,800	$6,680,100	$2,472,890	$229,400	$15,656,190
2012	$6,619,600	$6,764,600	$2,451,720	$218,700	$16,054,620
2013	$6,201,400	$6,893,100	$2,903,530	$230,500	$16,228,530
2014	$7,293,600	$5,929,100	$2,537,830	$220,000	$15,980,530
2015	$6,230,900	$5,978,100	$2,124,790	$308,300	$14,642,090
2016	$8,313,000	$5,570,300	$2,182,780	$130,400	$16,196,480
2017	$5,107,800	$6,191,200	$2,012,570	$310,400	$13,621,970
2018	$10,322,000	$6,226,900	$2,062,480	$256,600	$18,867,980
2019	$8,110,400	$6,979,400	$1,725,700	$682,800	$17,498,300
2020	$2,779,000	$5,714,300	$1,741,990	$67,400	$10,302,690
2021	$2,911,300	$5,664,800	$2,676,480	$110,000	$11,362,580
2022	$3,259,900	$3,179,900	$2,169,750	$34,000	$8,643,550

Outputs

The values of variables in Eq. (4) were taken from the available resources. The total number of safety personnel and ship maintenance staff (N) in each year was derived from the State Governor's Operating Budget Reports, and then the labor (L) can be estimated (see the note in Table 2). (U.S. Bureau of Labor Statistics 2023) published the multifactor productivity (A) for the water transportation industry (Index base year 2012 = 100). (Congressional Budget Office 2001) assumes that the elasticity of capital (α) equals 0.3 and the elasticity of labor ($\boldsymbol{\beta}$) equals 0.7 in the Cobb-Douglas production function to calculate Gross domestic product (GDP). Finally, the monetary value of value-added production ($\boldsymbol{Y}$) is calculated by Eq. (4) (see Table 2).

Table 2 The monetary values of value-added production from 2011 to 2022. (Source: The authors)

Year	K	N	L	A	α	β	Y	$R = Y/K$
2011	$15,656,190	12	24204	100.05	0.3	0.7	$16,879,398	1.08
2012	$16,054,620	12	24204	100.00	0.3	0.7	$16,998,125	1.06
2013	$16,228,530	13	26221	107.02	0.3	0.7	$19,301,858	1.19
2014	$15,980,530	13	26221	102.34	0.3	0.7	$18,372,521	1.15
2015	$14,642,090	11	22187	96.16	0.3	0.7	$14,961,063	1.02
2016	$16,196,480	11	22187	91.76	0.3	0.7	$14,714,926	0.91
2017	$13,621,970	11	22187	88.78	0.3	0.7	$13,515,486	1
2018	$18,867,980	11	22187	90.09	0.3	0.7	$15,123,544	0.8
2019	$17,498,300	8	16136	89.20	0.3	0.7	$11,713,762	0.67
2020	$10,302,690	8	16136	93.60	0.3	0.7	$10,485,080	1.02
2021	$11,362,580	11	22187	84.64	0.3	0.7	$12,203,450	1.07
2022	$8,643,550	11	22187	83.62	0.3	0.7	$11,107,144	1.29

Note:
(1) $L = N \times 2017$ (Estimated working hours in a year with a deduction from statutory holidays).
(2) R represents the ratio of value-added production to safety investments in the year.

A complete list of marine accidents from 2011 to 2022, along with the estimated monetary value of losses, was obtained from the Incident Investigation Report (IIR) database of the United States Coast Guard (U.S. Coast Guard 2023) and the ten-year marine claim losses report from the state's risk management department. The cost values were either estimated by the U.S. Coast Guard in the IIR or recorded in the report as actual costs. However, neither source included the costs of injury and death. Therefore, the Individual Injury Estimator (OSHA 2023) provided by the U.S. Occupational Safety and Health Administration (OSHA) was used to estimate the direct and indirect costs of injury and death based on injury types. The marine accident losses from 2010 to 2022 are summarized in Table 3. Furthermore, the values of reduced accident losses (O_2) can be calculated using Eq. (5).

Table 3 The values of total marine accident losses from 2010 to 2022. (Source: The authors)

Year	IDC			PDC				EDC	OC	Total accident losses
	Crew	Passenger	Shore employee	Vessel	Cargo	Public facilities	Private facilities		Legal	
2010	$1,039,521	$0	$0	$98,469	$13,199	$82,825	$3,884	$0	$0	$1,237,898
2011	$516,804	$71,556	$0	$334,755	$17,489	$239,158	$0	$0	$0	$1,179,762
2012	$703,936	$95,219	$391,474	$723,033	$4,682	$4,673,296	$0	$0	$0	$6,591,640
2013	$514,395	$164,096	$0	$288,469	$8,203	$120,383	$0	$0	$0	$1,095,546
2014	$444,301	$113,305	$0	$49,000	$28,729	$0	$3,336	$0	$0	$638,671
2015	$174,069	$0	$0	$2,631,943	$15,734	$327,681	$0	$0	$0	$3,149,426
2016	$180,553	$1,996	$0	$157,062	$10,911	$161,365	$102	$0	$0	$511,988
2017	$114,599	$185	$0	$51,702	$6,962	$2,128	$1,187	$0	$0	$176,763
2018	$279,462	$0	$0	$552,884	$24,168	$0	$0	$0	$0	$856,514
2019	$367,490	$0	$0	$301,047	$3,757	$0	$0	$0	$104,500	$776,794
2020	$699,822									$699,822
2021	$345,147									$345,147
2022	$1,065,102									$1,065,102

Note: The values of IDC, PDC, EDC, and OC from 2020 to 2022 are unavailable in resources. The values of the total losses in these three years were derived from the reports of the state's risk management department.

Input-Output table

After the values of inputs and outputs were obtained, the input-output table was constructed, where DMUs are the Arctic ship operator in each year from 2011 to 2022. Since DEA models require all values of input and output variables to be positive numerical data, \$5411878.01 (the absolute value of the lowest O_2) was added to all O_2 to ensure that (see Table 4).

Table 4 Input and Output table. (Source: The authors)

DMU	Year	Inputs				Outputs		O_2(unadjusted)
		I_1	I_2	I_3	I_5	O_1	O_2(Adjusted)	
DMU1	2011	\$6,273,800	\$6,680,100	\$2,472,890	\$229,400	\$16,879,398	\$5,470,014	\$58,136
DMU2	2012	\$6,619,600	\$6,764,600	\$2,451,720	\$218,700	\$16,998,125	\$0.01	-\$5,411,878
DMU3	2013	\$6,201,400	\$6,893,100	\$2,903,530	\$230,500	\$19,301,858	\$10,907,972	\$5,496,094
DMU4	2014	\$7,293,600	\$5,929,100	\$2,537,830	\$220,000	\$18,372,521	\$5,868,753	\$456,875
DMU5	2015	\$6,230,900	\$5,978,100	\$2,124,790	\$308,300	\$14,961,063	\$2,901,123	-\$2,510,755
DMU6	2016	\$8,313,000	\$5,570,300	\$2,182,780	\$130,400	\$14,714,926	\$8,049,316	\$2,637,438
DMU7	2017	\$5,107,800	\$6,191,200	\$2,012,570	\$310,400	\$13,515,486	\$5,747,103	\$335,225
DMU8	2018	\$10,322,000	\$6,226,900	\$2,062,480	\$256,600	\$15,123,544	\$4,732,127	-\$679,751
DMU9	2019	\$8,110,400	\$6,979,400	\$1,725,700	\$682,800	\$11,713,762	\$5,491,598	\$79,720
DMU10	2020	\$2,779,000	\$5,714,300	\$1,741,990	\$67,400	\$10,485,080	\$5,488,850	\$76,972
DMU11	2021	\$2,911,300	\$5,664,800	\$2,676,480	\$110,000	\$12,203,450	\$5,766,553	\$354,675
DMU12	2022	\$3,259,900	\$3,179,900	\$2,169,750	\$34,000	\$11,107,144	\$4,691,923	-\$719,955

In actual practice, decision-makers in a ship operator may make reducing accident losses the priority and target, as it is more visible in the financial sheets and safety performance reports than increased productivity. Thus, the following two tests were applied.

(1) Test 1 measures the efficiency in terms of economic benefits, where value-added production ($\boldsymbol{O_1}$) and reduced accident losses ($\boldsymbol{O_2}$) are outputs.
(2) Test 2 measures the efficiency in terms of reduced accident losses, where reduced accident losses ($\boldsymbol{O_2}$) is the only output.

2.6. Results and discussion

The DEA calculation is performed by the DEAP 2.1 software (Coelli 1996b). The results are presented below:

Test 1

Table 5 Summary of Test 1 results. (Source: The authors)

DMU	TE	Rank	Effectiveness	Input slacks				Output slacks	
				I_1	I_2	I_3	I_5	O_1	O_2
DMU1	0.979	3	Non-effective	0	860104	0	23272	0	1763725
DMU2	0.976	4	Non-effective	0	1014862	0	10384	0	6504188
DMU3	1.000	1	Strongly effective	0	0	0	0	0	0
DMU4	1.000	1	Strongly effective	0	0	0	0	0	0
DMU5	0.972	5	Non-effective	0	974126	0	121904	0	1928669
DMU6	1.000	1	Strongly effective	0	0	0	0	0	0
DMU7	0.963	6	Non-effective	0	1454671	0	142624	0	12282
DMU8	1.000	1	Strongly effective	0	0	0	0	0	0
DMU9	0.980	2	Non-effective	886698	2321093	0	544485	0	0
DMU10	1.000	1	Strongly effective	0	0	0	0	0	0
DMU11	1.000	1	Strongly effective	0	0	0	0	0	0
DMU12	1.000	1	Strongly effective	0	0	0	0	0	0

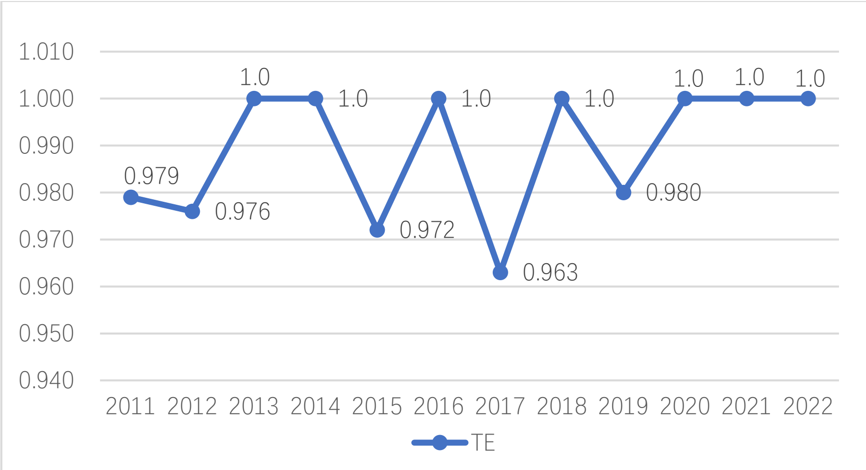

Figure 1. Trend of technical efficiency calculated in Test 1. (Source: The authors)

Table 6 Input and output targets of the non-effective DMUs in Test 1. (Source: The authors)

DMU	Target/Original	Input				Output	
		I_1	I_2	I_3	I_5	O_1	O_2
DMU1	Original	$6,273,800	$6,680,100	$2,472,890	$229,400	$16,879,398	$5,470,014
	Improvement	-$0	-$860,104	-$0	-$23,272	+$355,072	+$1,878,792
	Target	$6,273,800	$5,819,996	$2,472,890	$206,128	$17,234,470	$7,348,806
DMU2	Original	$6,619,600	$6,764,600	$2,451,720	$218,700	$16,998,125	$0.01
	Improvement	-$0	-$1,014,862	-$0	-$10,384	+$409,076	+$6,504,188
	Target	$6,619,600	$5,749,738	$2,451,720	$208,316	$17,407,201	$6,504,188
DMU5	Original	$6,230,900	$5,978,100	$2,124,790	$308,300	$14,961,063	$2,901,123
	Improvement	-$0	-$974,126	-$0	-$121,904	+$426,713	+$2,011,414
	Target	$6,230,900	$5,003,974	$2,124,790	$186,396	$15,387,776	$4,912,537
DMU7	Original	$5,107,800	$6,191,200	$2,012,570	$310,400	$13,515,486	$5,747,103
	Improvement	-$0	-$1,454,671	-$0	-$142,624	+$512,327	+$230,135
	Target	$5,107,800	$4,736,529	$2,012,570	$167,776	$14,027,813	$5,977,238
DMU9	Original	$8,110,400	$6,979,400	$1,725,700	$682,800	$11,713,762	$5,491,598
	Improvement	-$886,699	-$2,321,093	-$0	-$544,485	+$241,862	+$113,389
	Target	$7,223,701	$4,658,307	$1,725,700	$138,315	$11,955,624	$5,604,987

The explanations of the Test 1 results are listed below:

(1) Technical efficiency (TE) reflects the overall safety investment efficiency of the DMU. DMU1, DMU2, DMU5, DMU7, and DMU9 are non-effective (TE < 1), indicating there was room for possible improvements in the efficiencies of years 2011, 2012, 2015, 2017, and 2019.

(2) The input and output slacks reflect how much the inputs can be reduced and how much the outputs can be increased to achieve the targeted efficiency. DMU3, DMU4, DMU6, DMU8, DMU10, DMU11, and DMU12 were strongly effective (TE = 1, slacks = 0), indicating that the utilization of safety investments in the years 2013, 2014, 2016, 2018, 2020, 2021, and 2022 was strongly effective.

(3) The ranking of all DMUs according to TE value is given in Table 5. Among them, 2017 had the lowest efficiency.

(4) The trend of the efficiency is given in Figure 1. This reflects that efficiency fluctuated slightly during the period.

(5) Each non-effective DMU's projected values (targets) are calculated by adding slack movement and radial movement to the original values. The radial movement shows the adjusted proportionality of input and output variables and gives the value for the variables for improvement (Coelli 1996a). The input and output targets of the non-effective DMUs are

presented in Table 6. For example, in the year 2011, the shipowner could reduce $860,104 in safety measure investments and $23,272 spent on safety management while projecting an increase in value-added production ($355,072) and an increase in reduced accident losses ($1,878,792).

Test 2

Table 7 Summary of Test 2 results. (Source: The authors)

DMU	TE	Rank	Effectiveness	Input slacks				Output slacks
				I_1	I_2	I_3	I_5	O_2
DMU1	0.589	6	Non-effective	992167	809357	0	33087	0
DMU2	0.439	7	Non-effective	6619600	6764600	2451720	218700	0
DMU3	1.000	1	Strongly effective	0	0	0	0	0
DMU4	0.626	4	Non-effective	1959466	0	40359	21735	0
DMU5	0.363	8	Non-effective	1692744	933761	0	139621	0
DMU6	1.000	1	Strongly effective	0	0	0	0	0
DMU7	0.760	3	Non-effective	809325	1413276	0	150630	0
DMU8	0.611	5	Non-effective	5916926	1330487	0	92868	0
DMU9	0.847	2	Non-effective	4424626	2882517	0	545803	0
DMU10	1.000	1	Strongly effective	0	0	0	0	0
DMU11	1.000	1	Strongly effective	0	0	0	0	0
DMU12	1.000	1	Strongly effective	0	0	0	0	0

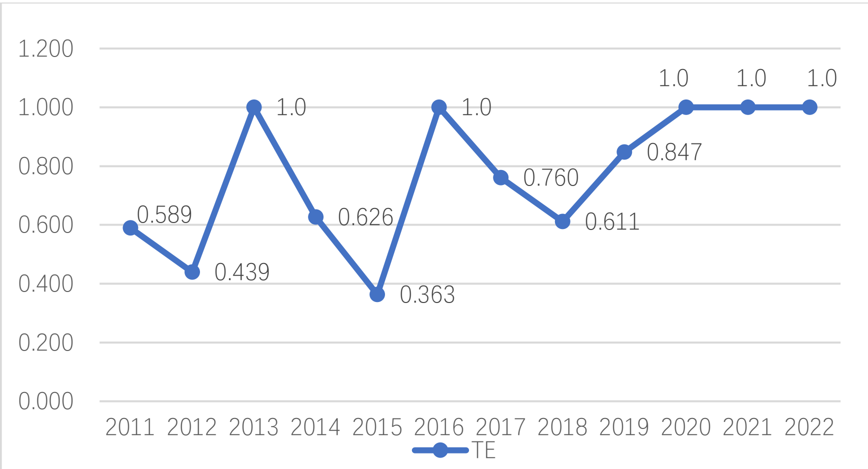

Figure 2. Trend of technical efficiency calculated in Test 2. (Source: The authors)

Table 8 Input and output targets of the non-effective DMUs in Test 2. (Source: The authors)

DMU	Target/Original	Input				Output
		I_1	I_2	I_3	I_5	O_2
DMU1	Original	$6,273,800	$6,680,100	$2,472,890	$229,400	$5,470,014
	Improvement	-$992,167	-$809,357	-$0	-$33,087	+$3,820,131
	Target	$5,281,633	$5,870,743	$2,472,890	$196,313	$9,290,145
DMU2	Original	$6,619,600	$6,764,600	$2,451,720	$218,700	$0.01
	Improvement	-$6,619,600	-$6,764,600	-$2,451,720	-$218,700	+$0.013
	Target	$0.013	$0.014	$0.006	$0	$0.023
DMU4	Original	$7,293,600	$5,929,100	$2,537,830	$220,000	$5,868,753
	Improvement	-$1,959,466	-$0	-$40,359	-$21,735	+$3,513,739
	Target	$5,334,134	$5,929,100	$2,497,471	$198,265	$9,382,492
DMU5	Original	$6,230,900	$5,978,100	$2,124,790	$308,300	$2,901,123

	Improvement	-$1,692,744	-$933,761	-$0	-$139,621	+$5,081,281
	Target	$4,538,156	$5,044,339	$2,124,790	$168,679	$7,982,404
DMU7	Original	$5,107,800	$6,191,200	$2,012,570	$310,400	$5,747,103
	Improvement	-$809,325	-$1,413,276	-$0	-$150,630	+$1,813,713
	Target	$4,298,475	$4,777,924	$2,012,570	$159,770	$7,560,816
DMU8	Original	$10,322,000	$6,226,900	$2,062,480	$256,600	$4,732,127
	Improvement	-$5,916,927	-$1,330,487	-$0	-$92,868	+$3,016,191
	Target	$4,405,073	$4,896,413	$2,062,480	$163,732	$7,748,318
DMU9	Original	$8,110,400	$6,979,400	$1,725,700	$682,800	$5,491,598
	Improvement	-$4,424,626	-$2,882,517	-$0	-$545,804	+$991,506
	Target	$3,685,774	$4,096,883	$1,725,700	$136,996	$6,483,104

The explanations of the Test 2 results are listed below:

The results show that the utilization of safety investments in the years 2013, 2016, 2020, 2021, and 2022 were strongly effective, and there was room for possible improvements in the efficiencies of years 2011, 2012, 2014, 2015, 2017, 2018, and 2019.

The ranking of all DMUs according to TE values is given in Table 7. Among them, 2015 had the lowest efficiency.

The efficiency trend shows it gradually increased from 2011 to 2022 (see Figure 2).

The input and output targets of the non-effective DMUs are presented in Table 8.

2.7. Analysis – do ovdje

The results above show the efficiency, ranking, trend, and targets in the two tests. In addition to the DEA results, a review of the available resources mentioned above (e.g., budget reports, the report of marine claim losses) provides observations on this case study as follows:

Safety issues - Several accident/incident types should be brought to the attention of the management due to the high frequency: (1) Crew injury (e.g., 8 to 11 cases from 2011 to 2014) with recent improvement (3 to 4 cases per year) (2) Cargo damage (e.g., 20 claims in 2018) with crew members involved, reflecting challenges to address loading/unloading operation. (3) Damages to docks, suggesting deployment of protective systems in ports such as tugs may not be available (4) Unforeseen mechanical failures.

Human resources - The remoteness and harsh climate present difficulty in retaining qualified, experienced seafarers for the Arctic ship operator, which has been acknowledged in the corporate management reports since 2016. Over the last five years, nearly 350 crew members have left mainly due to seeking other employment. The high turnover rate of crew members and the steady loss of senior officers are becoming major issues that the management has already realized.

Production - The ratio of value-added production to safety investments for the year ($\boldsymbol{R}$) ranges from 0.67 to 1.29 (see Table 2). The possible reason for the low ratio (lower than 1.02) from 2015 to 2020 is that the ship operator had a low figure of labor ($\boldsymbol{L}$) because of a shortage of ship maintenance staff. This is consistent with the fact revealed in budget reports that the loss of ship maintenance staff has been challenging in day-to-day operations.

Safety investments - No investments in safety-related new technologies were found in the available resources. A case related to that is the need for a new ship maintenance management system software, which was identified in 2017 by the management. However, a request for proposal was not issued until 2022.

Efficiency - Test 2 results indicate that the efficiency in terms of contribution to reduced accident losses gradually improved from 2011 to 2022. It is consistent with the observed improved safety performance, according to data on accidents and incidents. Years 2011, 2012, 2015, 2017, and 2019 are non-effective DMUs in both Test 1 and Test 2, which means the shipowner could improve production and reduce accident losses by optimizing the allocation of safety investments. Additionally, in almost all non-effective DMUs, there is no slack in investment in personnel, which means there is room for the shipowner to allocate more resources to this input.

Considering the uncertainties in marine operations and casualties, these measures can only be considered indicative and adapted to the specific context of one company during a certain period.

2.8. Recommendations

Based on the observations listed above, recommendations can be drawn as follows:

- Increase investment in assessing human and organizational factors related to injuries, loading/unloading, and docking operations. The observations reflect the need to enhance focus on elements such as human and organizational factors. Adequate research on such factors may be beneficial in finding solutions at a comparable low cost compared to other investments.
- In the same vein, striving to retain qualified and experienced seafarers and maintenance staff (e.g., hiring headhunters, attending job fairs, signing bonuses) may become a winning strategy at a low cost. Additionally, highly qualified and experienced personnel are safer, improve productivity, and help avoid operation delays due to unforeseen mechanical failures.
- Set up safety initiative programs in the organization. Promote safety awards to the crew members to enhance their safety awareness.
- Identify and invest in the new technologies that contribute to safe operation and promote their adoption.

3. CONCLUSION

The Arctic shipping industry currently lacks available methods to evaluate safety investments and their economic contributions. Empirical analysis of Arctic ship operators shows that the DEA method is a suitable and practical approach for quantitatively assessing whether the efficiency of safety investments improves over time. Furthermore, recommendations can be drawn from the analysis to support management decisions aimed at enhancing the company's safety performance by combining DEA results with data on accidents, incidents, and financial conditions.

The DEA method allows decision-makers to select various models depending on the objectives of the analysis. In future work, BCC or other models can be applied, and the results compared to provide a comprehensive view of efficiencies, improvements, and targets. Another approach is to use input-oriented models to minimize safety investments while maintaining economic benefits. Future studies can also collect qualitative data, such as in-depth interviews, to provide more incisive observations and explanations of the relationship between safety input and output variables.

The proliferation of such studies using the same methodology could help identify trends that require not only company action but also regulatory intervention. For example, practical onboard training for crew members to gain adequate experience in the Arctic is not regulated under the current Polar Code, but it may be essential for crew competency in polar operations. Additionally, such studies may serve as a tool for governments to evaluate their investments in Arctic shipping. Investments from Arctic coastal states are crucial for ensuring navigation safety, especially in infrastructure and facilities such as icebreakers, while abundant evidence shows that past safety investments from these states have been insufficient.

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