Application of DEA Method in the Evaluation of Input and Benefit of Arctic Search and Rescue

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Abstract: Search and rescue (SAR) at sea is the basis for ensuring the safety of maritime navigation and the premise and guarantee for the development of maritime transportation. With the development and utilization of the Arctic Sea route, more and more countries participate in Arctic navigation. Countries around the polar region begin to focus on maritime SAR and continue to invest in the construction of relevant infrastructure. A certain amount of economic resources are consumed while ensuring polar transportation. There are continuous discussions on the input and benefits of SAR work. SAR input in the polar region can not only achieve great economic and social benefits but also cost huge human and material resources to national governments and societies. Therefore, it is essential to analyze the input and benefits of SAR. This paper analyzed the basic concept of the DEA method, the DEA model, and its basic theory, explored the feasibility to analyze the input and benefits of SAR in the region by virtue of the DEA method, and established an index system. It is of great practical significance to guide the neighboring polar countries and near-Arctic countries to carry out the analysis of Arctic SAR inputs and benefits and then participate in the construction of polar SAR in a targeted manner.

Keywords-arctic search and rescue; DEA method; input and benefit

1 BACKGROUND

Due to the harsh climate and remote environment, coupled with complex coastlines and many unknown or unplanned transportation routes, the Arctic becomes one of the most challenging SAR areas.[1] The Arctic maritime emergency SAR is confronted with universal problems such as a broad area of responsibility, unreasonable resource distribution, inadequate equipment, and insufficient technical force. The Arctic Search and Rescue Agreement is an international treaty concluded by the member states of the Arctic Council (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States) in Nuuk, the capital of Greenland, on May 12, 2011. The Agreement regulates the scope and plans of international SAR in the Arctic by contracting parties and defines the area of SAR responsibility of each contracting party. As all countries continue to invest in SAR, it becomes a common concern, how to carry out SAR input and benefit analysis, which will also provide guidance for the construction of polar SAR in the next step.[2]

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2 INTRODUCTION OF DATA ENVELOPE ANALYSIS

Data envelope analysis (DEA) is a nonparametric system analysis and evaluation method. It is a new field of interdisciplinary research involving management science, operations research, and mathematical economics. [3] As a nonparametric evaluation method, the most important feature of DEA is especially suitable for dealing with complex system evaluation problems with multiple inputs and outputs. This method evaluates the decision-making unit (DMU) by calculating the various input and output index data to judge whether the DMU is relatively effective. It is a method to draw conclusions by comparing all DMUs. As an economic treatment, DEA can provide corresponding approaches to the problem from economic perspectives when evaluating the efficiency of DMUs and thus is applicable to the evaluation of many industries.[4] Therefore, many scholars are prone to considering this method in the selection of evaluation methods.

3 FEASIBILITY ANALYSIS

3.1 Main features of the DEA method

As a multi-objective decision-making method to deal with multiple input and output problems, DEA is especially suitable for complex systems with multiple inputs and outputs, which can be reflected in the following aspects: (1) in the DEA method, the input/output weight of DMU is a variable and the model evaluates the most powerful side of decision-making unit. The influence of subjective impressions on the input/output weight can be ignored. (2) DEA is a nonparametric method without setting relevant parameters between input and output in advance to generate functions. Therefore, the DEA method is relatively objective and capable of avoiding the influence of many subjective factors.

3.2 Features of evaluating the input and benefits of maritime SAR through DEA method

Generally, two methods can be used to analyze the evaluation efficiency index from economic perspectives, including nonparametric analysis and parametric analysis. In the use of the parametric analysis method for analysis and evaluation, the production function should be set up in advance to estimate the possible error terms. The parameters can be determined through the econometric regression model, so as to evaluate the production efficiency. However, in the use of the nonparametric analysis method, there is no need to determine production function, parameters, and error terms. Such methods compare the relative efficiency of each index to be analyzed by virtue of the linear programming approach and DEA is one of them.

As a nonparametric analysis method, DEA does not need to determine the aspects such as the production function, parameters, and error terms. It evaluates the relative efficiency of production units by analyzing the actual observed data and using an appropriate production function model. In the efficiency evaluation of the national public sector, including the SAR Center, the input of resources and the price of output products or services are usually difficult to be determined. However, DEA is a relatively effective approach to analyzing and evaluating DMU with multiple inputs and outputs without the requirement of clear input and output prices. Therefore, this method is of great advantage in the analysis of Maritime SAR input and benefits.

In this respect, DEA has the following advantages over other analysis methods:

When the SAR Center puts limited resources onto SAR activities, the input weight and resources price are not associated with each output. Given its features, the DEA method can be conducive to analyzing the DMU with an unknown relative weight of input and output. In the DEA method, the weight of input and output vectors of any DMU are uncertain and selectable, which maximizes the ratio of the weight of the output vector to the input vector. Due to this constraint condition, the input weight vector selected by any DMU shall be greater than or equal to the output weight. Any evaluation of DMU is not based on its own perspective. Therefore, the determination of the inefficiency of a DMU is not simple, and its output may be invalid by the peer review group.

(2) To date, no way has been found to clarify the relation between maritime SAR input and benefits. Nevertheless, the DEA method can carry out nonparametric evaluation without specifying the index between each maritime SAR input and benefit.

(3) Maritime SAR is a system with multiple inputs and output, and the commonly used standard parametric methods fail to come into play in this system. The appearance of the DEA method is to deal with similar problems.

(4) Other mathematical methods such as fuzzy evaluation, cost-benefit analysis, and analytical hierarchy process for the analysis of input and benefit model also have certain features. However, some of them fail to correctly determine the weight problem in the analysis of input and benefit and have strong subjectivity. Some calculations are very complicated and fail to clearly demonstrate the characteristics of SAR input and benefit. As a nonparametric statistical and analysis method, DEA is intended for “evaluation”, having great advantages in the evaluation of the relative superiority among diverse samples. It is not required to select the production function of DMU, determine whether each index can be compared in advance, and clarify the weight between each index. It helps to discover the low - efficiency parts based on the obtained analysis data. These features are in line with the characteristics and requirements of maritime SAR input and benefit evaluation.[5]

(5) Compared with other methods for the evaluation of input and benefit, DEA allows the evaluated to choose appropriate weight based on their own advantages, and construct production frontier function by the nonparametric method in accordance with the actual input and output of each DMU. Therefore, in the analysis of maritime SAR input and benefit, more effective evaluation results can be obtained by DEA than by other methods. In the use of the DEA method, the DMU with better efficiency in reality can be selected as the standard, and the convex line segment composed of such DMU can be used to form the production frontier.

To sum up, DEA is a more suitable method to analyze the input and benefit of maritime SAR.

4 APPLICATION METHOD

4.1 Related concepts of DEA

4.1.1 Basic concept of DMU

Generally, any process or system is in the appropriate range, and the production factors input can produce certain products through processing. Different production processes may be different in the input factors or products. However, any production process and the system are basically intended to produce products in the hope of using fewer production factors to improve production efficiency. Production efficiency relies on the subjective decision of producers, so we referred to any production unit as DMU. From the above definition, it can be seen that each DUM has a corresponding economic meaning and some common characteristics, namely having corresponding input and output data. The input data is transformed into output data through the whole production process to achieve the ultimate purpose of decision-making. In the same DEA model, the comparability principle can only be satisfied if the types of DMUs selected are the same. Generally, the same type of DMU is characterized by the following three [6]:

First, in the process of comparison, all DMUs shall be in the same external environment;

Second, the selected DMUs shall have a unified output objective;

Finally, the input and output index of each DMU shall share follow the same standard.

4.1.2 Basic concept of production possibility set

Assuming that the input and output vectors of a DMU in a production (economic) activity are P=(P1, P2,...Pm) and Q=(q1, q2,...qn), then all production processes of the DMU mentioned later are replace with the vector (P, Q).

According to Definition 3.1, the set T= {(P,Q)|the output Q possibility is produced by input P} is referred to as the production possibility set (PPS) consisting of all the production activities carried out in the production process.

In the process of DEA, the PPS of any DMU M (countable) to be analyzed and evaluated must follow the following four axioms:

Axiom of convexity: for any $(P_1, Q_1) \in T$ and $(P_2, Q_2) \in T$,and $\alpha \in [0,1]$, $\alpha(P_1, Q_1) + (1-\alpha)(P_2, Q_2) \in T$.

This axiom shows that if the input is carried out at the sum of the α and (1-α) multiples of P1 and P2, the sum of the α and (1-α) multiples of outputs Q1 and Q2 will also meet the above conditions.

Axiom of ineffectiveness: if $(P,Q) \in T, P' \geq P,$ then $(P',Q) \in T$; if $Q' \leq Q,$, then $(P,Q') \in T$; this axiom means that it is possible to have less input and more output in a production process.

Axiom of cone: if $(P,Q) \in T$ and $d \geq 0$, then $d(P,Q) = (dP, dQ) \in T$; this axiom means that the expansion between input and output is the same in a production process, for instance, if input P is enlarged d times, the output Q will also be enlarged d times.

Axiom of minimality: the optimal PPS obtained in the whole analysis and evaluation is the minimum value to meet the above-mentioned PPS of a - c axioms.

The above axioms are a mathematical combination, which is consistent with daily economic processes.

Definition3.2 defines $L(Q)=\{P\,|\,(P,Q)\in T\}$ as the input possibility set of Q and $K(P)=\{Q\,|\,(P,Q)\in T\}$ as the output possibility set of P. T is the whole PPS.

Definition 3.3 hypothesizes that $(P,Q)\in T$; if there is no $(P,Q')\in T$, and $Q'\geq Q$, then (P,Q) represents an effective production activity. It also hypothesizes that $(P,Q)\in T$; if there is no $(P',Q)\in T$, and $P'\leq P$, then (P,Q) is also an effective production activity.

Definition 3.4 hypothesizes that $(P,Q)\in T$; if there is no $(P',Q')\in T$, and $P'\leq P, Q'\geq Q$, then (P,Q) represents an effective production activity.

According to Definition 3.5, for all PPS T, the hyper-surface composed of all effective production activity points (P, Q) is called the production function.

The production function mentioned in Definition 3.5 refers to the functional relationship between any group of input and maximum output under the related production technical conditions. In the so-called production function, Q is an increasing function of P. This index only reflects that the output will not decrease relative to the increase of input, but the range of increase can not be determined. Therefore, it is impossible to determine the extent or magnitude of the increase in input.

4.2 Introduction of the DEA model

4.2.1 Basic DEA model

Assuming there are n units or departments (i.e., DMUs), then each DMU has s inputs and m outputs. The following table shows the input and output data of each DMU.

Table 1 Input and output data of each DMU

			1	2	$\cdots$	j	$\cdots$	n
x_1	1	–	p_{11}	p_{12}	$\cdots$	p_{1j}	$\cdots$	p_{1n}
x_2	2	–	p_{21}	p_{22}	$\cdots$	p_{2j}	$\cdots$	p_{2n}
$\cdots$	$\cdots$	–	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
x_m	m	–	p_{m1}	p_{m2}	$\cdots$	p_{mj}	$\cdots$	p_{mn}

q_{11}	q_{12}	$\cdots$	q_{1j}	$\cdots$	q_{1n}	–	1	y_1
q_{21}	q_{22}	$\cdots$	q_{2j}	$\cdots$	q_{2n}	–	2	y_2
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
q_{s1}	q_{s2}	$\cdots$	q_{sj}	$\cdots$	q_{sn}	–	s	y

Assuming that DMU $DMU_j(j=1,2...n)$; the input and output vectors are $P_j=(p_{1j},p_{2j},...,p_{mj})^T$ and $Q_j=(q_{1j},q_{2j},...,q_{nj})^T$, then the weight of s output and m input is $x=(x_1,x_2,...,x_m)^T$, $y=(y_1,y_2,...,y_n)^T$.

Assuming that the input and output of DMU DMU_{j0} is (p_0,q_0), then the efficiency evaluation index of DMU_{j0} can be expressed as:

$$k_{j0}=\frac{y^TQ_0}{x^Tp_0}$$

In the analysis of DMU_{j0}, k_{j0} is usually set as the initial value, and the obtained efficiency index of each DMU shall meet the condition $k_j=\frac{y^TQ_j}{x^TP_j}\le 1$. Then the following planning model (i.e., C^2R model) can be constructed.

$$(C^2R)^s\begin{cases}\max\frac{y^TQ_0}{x^TP_0},\\ \frac{y^TQ_j}{x^TP_j}\le 1,\ j=1,......,n\\ y\ge 0, x\ge 0\end{cases}$$

Assuming that $s=\frac{1}{x^Tp_0},\beta=sx,\gamma=sy$, the above fractional planning model can be transformed into the following linear planning model:

$$(P_{C^2R})\begin{cases}\max\gamma^TQ_0=k_0\\ \beta^TP_j-\gamma^TQ_j\ge 0,\ j=1,2,......,n\\ \beta^TP_0=1\\ \beta\ge 0,\gamma\ge 0\end{cases}$$

Its dual model can be expressed as:

$$(D_{C^2R})\begin{cases}\min\varepsilon\\ \sum_{j=1}^{n}P_j\alpha_j+t^-=\varepsilon P_0\\ \sum_{j=1}^{n}Q_j\alpha_j-t^+=Q_0\\ \alpha_j\ge 0,\ j=1,2,......,n\end{cases}$$

Definition 3.6: if the optional solution β_0 and γ_0 obtained by model (P_{C^2R}) through calculation can meet the condition $\beta^TP_0=1$, then DMU DMU_{j0} is less DEA efficient. Definition 3.7: if the optional solution β_0 and γ_0 obtained by model (P_{C^2R}) through calculation can meet the condition $\beta^TP_0=1$, in addition, $\beta_0>0,\gamma_0>0$, then DMU DMU_{j0} is DEA efficient.

Definition 3.8: if the optional solution $\varepsilon_0 = 1$ obtained by model (D_{C^2R}) through calculation, and the corresponding variable $t^-, t^+, \varepsilon_0, \alpha_{0j}(j = 1,...,n)$ of any optional solution can meet the condition $t^{0+} = 0, t^{0-} = 0$, then DMU DMU_{j0} is DEA efficient.

With the transformation of model C^2R, relaxation variables t^{0+} and t^{0-} are introduced to adjust the efficiency frontier of each DMU. In the current operation, the model is balanced by the index of relaxation variable. For an inefficient DMU, the t^{0+} and t^{0-} corresponding to its input and output are not 0, but the t^{0+} and t^{0-} corresponding to an efficient DMU's input and output are 0.

4.2.2 The effective economic meaning and scale efficiency of DEA

The equivalent linearized model of model C^2R mentioned above is:

$$T = \left\{(P,Q) \mid \sum_{j=1}^{n} P_j\alpha_j \le P, \sum_{j=1}^{n} Q_j\alpha_j \ge Q, \alpha_j \ge 0, j = 1,2,......,n \right\}$$

$$(D_{C^2R})\begin{cases} \min \in \\ \sum_{j=1}^{n} P_j\alpha_j + t^- = \in P_0 \\ \sum_{j=1}^{n} Q_j\alpha_j - t^+ = Q_0 \\ \alpha_j \ge 0, j = 1,2,......,n \end{cases}$$

Since the PPS is, the model (D_{C^2R}) can rewrite the following expression:

$$(D_{C^2R})\begin{cases} \min \varepsilon \\ (\varepsilon P_0, Q_0) \in T_{C^2R} \end{cases}$$

Model (D_{C^2R}) means that in the case of single input and output, for all PPSs, if the output Q0 is unchanged, and input P0 fails to continue to decrease in the process of scaling down by ε, then the optimal solution of the model (D_{C^2R}) can be obtained, namely $\varepsilon_0 = 1$. If P0 continues to scale down by ε, then the optimal solution of model $\varepsilon_0 < 1$ is (D_{C^2R}).

4.2.3 Super-efficiency DEA model

Generally, through model C^2R, some functions could not be realized, such as evaluating efficient DMUs. The revised model C^2R, namely the super-efficiency DEA model, can effectively compare all DMUs. It follows the basic idea that in the evaluation of the efficiency of a DMU, the evaluated DMU is not included in the DUMs combination to be considered first. Due to the DMUs without maximizing DEA efficiency, the production frontier remains unchanged and the evaluation results are consistent with model C^2R. For the DMUs with efficient DEA obtained in the model operation, the super-efficiency model will change their production frontier through recalculation, so as to produce a higher efficiency value than in model C^2R. In this case, the efficiency value obtained may be more than 1. The super-efficiency model can be obtained by modifying the formula:

$$(D_{C^2R})\begin{cases} \min \varepsilon \\ \sum_{\substack{j=1 \\ j\neq j_n}}^{n} P_j\alpha_j + t^- = \varepsilon P_{j0} \\ \sum_{\substack{j=1 \\ j\neq j_n}}^{n} Q_j\alpha_j - t^+ = Q_{j0} \\ \alpha_j \geq 0,\ j = 1,2,......,n \\ t^-, t^+ \geq 0 \end{cases}$$

The economic meaning and letters represented by this model are consistent with the meaning of the model C^2R mentioned above. The approach to improve inefficient DMUs is to project the input and output (p_0, q_0) of inefficient DMU DMU_{j0} on the effective plane, and obtain the improved value of DMU through change. This method can not only improve the inefficient DMUs, but also explain the reason why they are inefficient.

$$\begin{cases} p_0^1 = \varepsilon^0 p_0 - t^{-0} \\ q_0^1 = q_0 + t^{+0} \end{cases}$$

4.3 Application of the DEA method

Firstly, the evaluation objective shall be determined, followed by the selection of appropriate DMUs. The appropriate DEA model is selected for analysis by specifying the index system to be evaluated. The final step is to evaluate the organizations obtained by the analysis.

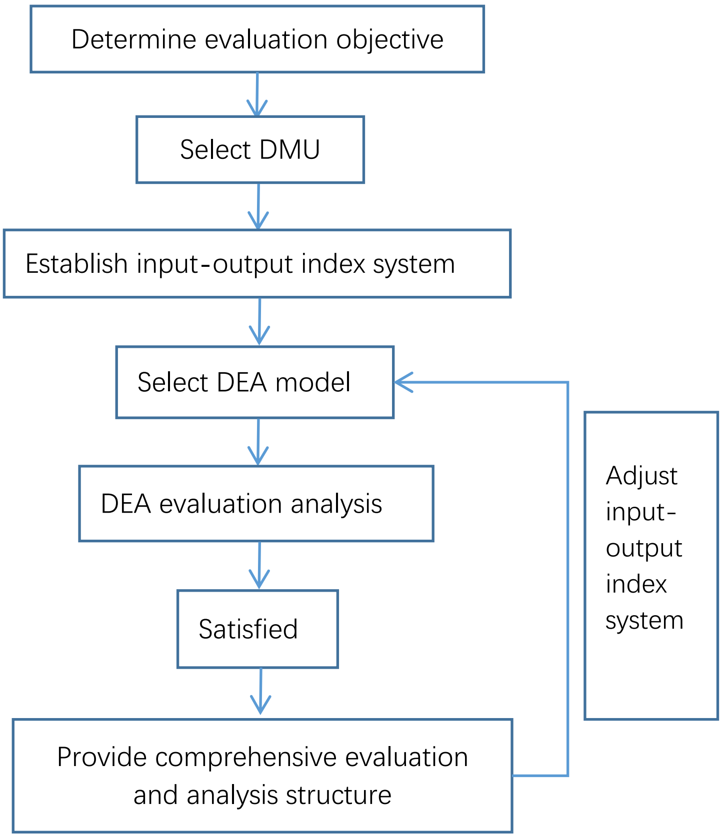

Figure1. Application of the DEA method

5 SYSTEM CONSTRUCTION

5.1 SAR input index

Manpower input: the manpower input for SAR by the SAR Center usually can be measured from different perspectives. Considering the current situation of the SAR center and the characteristics of SAR management, shore-based SAR managers and sea-and-air SAR teams should be selected.

In terms of the allocation of shore-based SAR managers, theoretically, the more shore-based SAR managers are allocated to each area on average, the more professionals with rich navigation and rescue qualifications on the shore can participate in SAR management, and the better the SAR can be.

The size of the sea-and-air SAR team is not the larger the better. Only reasonable input can achieve a more obvious SAR effect.

Material input: mainly refers to the part converted into capital input. This input is the basis of SAR management, including the daily expenditure of the maritime SAR Center, the input of special SAR equipment, the input of SAR exercises, fuel consumption, and personnel subsidies in SAR, and the input of the government for reward and compensation.

It can be divided into three aspects: basic input, input in emergency response, and compensation for non-governmental rescue forces.

5.2 SAR benefit index

Lives rescued: the most direct indicator to reflect the effectiveness of maritime SAR activities.

Ships rescued: the ship itself is of great value, and overturning will cause great damage to the waterway and environment.

SAR success rate: maritime SAR activities refer to search and rescue victims at sea with the use of SAR personnel and equipment. The maritime SAR success rate can directly reflect the SAR effect.

6 CONCLUSION

This paper introduced the basic concept of the DEA method, its application method, and the feasibility to adopt it to conduct polar SAR evaluation. In addition, this paper established an evaluation index system. In the following research, the reasonable use of the evaluation model to analyze the SAR input and benefit in different polar regions can provide guidance for different countries around the polar region to carry out SAR input in their own areas and provide a reference for navigation ships.

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