A Classification Method for Inland Navigable and Substandard Waterways

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ABSTRACT

Classification of inland navigable and substandard waterways is essential for optimal allocation of safety administration resources. It is stipulated in “Regulations on the Administration of Water Traffic Safety in Zhejiang Province” that Maritime Safety Administration (MSA) should be responsible for the Navigable waterways using professional resources whilst Local Transportation Authorities should be responsible for the safety management of the Substandard waterway. It is therefore important to classify waterways into navigable and substandard areas in order to apply for different safety administration measures. At present, the division of inland navigable and substandard waterways is not clear, and there are no systematic methods for the classification of waterways. This paper investigated the present conditions of the inland waterways in Ningbo, and a classification method is proposed which can classify waterways into navigable and substandard areas based on C²R model of data envelopment analysis (DEA). A case study was also carried out using the proposed method and the results were compared with those obtained using fuzzy comprehensive evaluation (FCE) method. It is found that unlike the FCE, the proposed method does not need to determine the exactly weights of the indicators which influence the classification of inland waterways and does not need to determine the membership function of the indicators, thus the results are more objective and reliable.
INTRODUCTION

According to “Regulations on the Administration of Water Traffic Safety in Zhejiang Province”, “inland navigable waterways” refer to the rivers, lakes, reservoirs, canals and other waters which have channels above quasi 7 grade and are available for navigation of ships. “Inland substandard waterways” refer to the waters except the inland navigable waterways, including the rivers, lakes, reservoirs, scenic areas, nature reserves, and the waters within the city landscape, which do not have channels. The regulations state that Maritime Safety Administration (MSA) is responsible for the supervision of the water traffic safety in the navigable waterways and Local Transportation Authorities are responsible for the supervision of the water activities in the substandard waterways. In order to clarify the duty of departments and implement the responsibility for supervision and ensure the safety of navigation, the classification of inland waterways is very necessary.

At present, studies of the inland navigable and substandard waterways’ classification are in their infancy, the systematic method has not been formed. Some developed countries only have conducted research on the classification of inland channels’ grades. For example, the United States divides their channels into 5 grades based on the depth of water [1]. Western Europe divides the inland channels into 6 levels based on the tonnage of ship [2]. All above are not involved in the classification of inland navigable waterways, but the channel grade is one of the important factors that affects the inland waterways attributes. In China, a few scholars have carried out the related studies, such as Huiying Zhao [1], who has studied for the classification method of inland waterways in Jiangsu province and proposed the model based on fuzzy comprehensive evaluation (FCE) method. Lin Xi [3] made a systematic discussion about the present situation and the problems of Nantong coastal navigable waterways classification, and put forward some suggestions about it. Hedi Li [4] proposed that the inland navigable waterways were the areas which were equipped with the navigation aids according to the national standard. And the Chinese inland waterways are divided into 7 classes according to the inland ships' tonnage in the “inland river navigation standard” [5]. However, in the above-mentioned research, most scholars proposed the classification suggestions according to their personal experiences, which do not have the theoretical basis. So it is difficult to apply them to classify the inland waterways in most areas. The only mathematical method proposed by Huiying Zhao was based on FCE, which should calculate the weights of the indicators in advance according to the expertise and determine the membership functions of them. So the classification results would be influenced by the human subjective factors.

The classification of inland waterways needs to consider many aspects and each aspect contains different indicators. These indicators can be divided into inputs and outputs according to their practical meaning. Therefore, to classify the inland waterways within a region is to evaluate the waterways with the same input and output indicators, which is consistent with the characteristic of the problem solved.
by data envelopment analysis (DEA). DEA does not need to anticipate any weight of the indicators or determine the production function relationship between the inputs and outputs, thus it can eliminate the influence of subjective factors on the results to a large extent [6]. Therefore, we choose this approach to classify the inland waterways in this paper.

METHODOLOGY

DEA is a non-parametric method that was originally used to evaluate the relative efficiency of a homogeneous group of decision making units (DMUs) [7]. In this paper, the evaluated inland waterways are the DMUs. The fundamental of DEA application is to keep the output or input indicators of the waterways unchanged and use the mathematical programming method to determine the relative effective production frontier which is formed by the best practices waterways, then project each waterway to the efficient frontier and measures the efficiency scores of them according to their distances to the frontier [8]. When the waterway falls on the efficient frontier, it is called DEA-efficient, and its relative efficiency score is 1, which means there is no way, through the change of its indicators, to achieve at greater navigation status. When the waterway falls inside the efficient frontier, it is called DEA-inefficient, and its relative efficiency score is between 0 and 1, which means its navigation status can be improved by changing the indicators.

In DEA, it has many significant models. Compared with these models, the classic C²R model is easier to apply, because it has a simple structure, fewer constrains and a linear solving process [9-10]. It utilizes the ratios of the weighted sum of outputs to the weighted sum of inputs to evaluate the comprehensive efficiency of DMUs[11], which means it can comprehensively reflect the navigable conditions of the inland waterways. Therefore, the C²R model is sufficient to meet the evaluation requirements of inland waterways in this study.

THE CLASSIFICATION METHOD

Classification Indicators

The determination of indicators for the inland waterways classification is the first step of DEA application. Through comparing and analyzing the various influential factors as well as discussing with Ningbo Maritime Safety Administration and the relative experts, infrastructure, safety and traffic these three factors are chosen to classify the inland waterways, which contain the navigation condition, safety and requirement three aspects. Then more indicators are developed for each of the three factors constituting a multilayer hierarchical structure. Firstly, to describe the infrastructure construction condition of the inland waterways, the channel grade and the navigation facility are considered. The channel grade is one of
the important indicators for the inland waterways classification. Whilst the navigation facilities which include the navigational aids and the traffic service to ensure the safety of navigation also have a significant influence. Secondly, the ship accident rate directly reflects the safety of the inland waterway, while the Network accessibility which embodies the convenience of river water traffic indirectly reflects it, so they are selected to describe this factor. Totally, these four indicators are specified reflecting the waterways’ construction and maintenance cost, so they are set as the input indicators, which are shown as the left part of Figure 1. On the other hand, as the outcome of the waterways traffic transportation, the main ships’ tonnage and the ship traffic volume are considered as the output indicators, which are shown as the right part of Figure 1.

In the above structure, the four input indicators are the qualitative ones. Before using the C²R model to calculate the efficiency of the inland waterways, they are required to be quantified. Since DEA has little requirement for the input and output data and is not affected by the data dimension. Therefore, in the quantization process, it is only necessary to consider the rationality of the data and the sensitivity of their impact on the results.

In this paper, we divide all the channels into 8 levels. Because the higher the channel grade, the more the cost of waterways’ construction and maintenance, we set 10 as the minimum base and the upper grade is twice the next grade. In addition, Navigation facility, ship accident rate and network accessibility are all divided into 3 classes. We also set 10 as the minimum base and the upper class is four times the next class. In this way, the sensitivity of these indicators’ impact on the results is relative high, and the specific quantization values are shown in Table I and Table II.

![Figure 1. The hierarchical framework of classification indicators.](image)

<table>
<thead>
<tr>
<th>Channel grade</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indicator value</td>
<td>1280</td>
<td>640</td>
<td>320</td>
<td>160</td>
<td>80</td>
<td>40</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>
TABLE II. NAVIGATION FACILITIES, SHIP ACCIDENT RATES AND NETWORK ACCESSIBILITY INDICATORS.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Indicator class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navigation facility</td>
<td>Complete, Relatively complete, Incomplete</td>
</tr>
<tr>
<td>Ship accident rate</td>
<td>High, Middle, Low</td>
</tr>
<tr>
<td>Network accessibility</td>
<td>Accessible, Relatively accessible, Inaccessible</td>
</tr>
</tbody>
</table>

Classification Model

Assume that there is a set of $n$ inland waterways in a region to be evaluated, each inland waterway with $m$ inputs and $s$ outputs. The input and output indicator values of the $j$th ($j=1,\ldots,n$) inland waterway are denoted by $x_{ij}(i=1,\ldots,m)$ and $y_{ij}(r=1,\ldots,s)$, respectively; $v_i$ and $u_r$ are the weights assigned to the inputs and outputs.

Let $x_j=(x_{1j},x_{2j},\ldots,x_{mj})^T$, $y_j=(y_{1j},y_{2j},\ldots,y_{sj})^T$, $v=(v_1,v_2,\ldots,v_m)^T$, $u=(u_1,u_2,\ldots,u_s)^T$, then its efficiency can be measured by the following model [12-13]:

$$h_j = \frac{\sum_{i=1}^{m} u_i y_{ij}}{\sum_{i=1}^{m} v_i x_{ij}} = \frac{u^T y_j}{v^T x_j}, \quad h_j \leq 1, \quad j = 1, 2, \ldots, n$$

(1)

where $h_j$ is the relative efficiency of the $j$th inland waterway. This equation indicates that it is the ratio of the outputs to the inputs, which constitutes the fractional programming problems as follows:

$$\max h_e = \frac{u^T y_o}{v^T x_o},$$

s.t. $\frac{u^T y_j}{v^T x_j} \leq 1, \quad j = 1, \ldots, n,$

$$u_r \geq 0, \quad v_i \geq 0, \quad r = 1, \ldots, s, \quad i = 1, \ldots, m,$$

(2)

where $(x_o, y_o)=(x_{jo}, y_{jo})$, DMU$_0$ represents the waterway under evaluation. Using Charnes-Cooper transformation and the dual conversion, the above fractional
programming model can be solved through the following linear programming model:

\[
\begin{aligned}
\min & \quad \theta_o, \\
\text{s.t.} & \quad \sum_{j=1}^{n} x_{ij} \lambda_j \leq \theta_o x_{io}, \\
& \quad \sum_{j=1}^{n} y_{ij} \lambda_j \geq y_{ro}, \\
& \quad \lambda_j \geq 0, \quad i = 1, \ldots, m, \quad r = 1, \ldots, s, \quad j = 1, \ldots, n,
\end{aligned}
\]  

(3)

Where \( \theta_o \) represents the relative efficiency of the \( j,th \) inland waterway. After introducing the slack variable \( s_i^- \), the residual variable \( s_r^+ \) and non-Archimedean \( \varepsilon \) into the above model, it can be transformed into the following form:

\[
\begin{aligned}
\min & \quad \left[ \theta_o - \varepsilon \left( \bar{e}^T s_i^- + e^T s_r^+ \right) \right], \\
\text{s.t.} & \quad \sum_{j=1}^{n} x_{ij} \lambda_j + s_i^- = \theta_o x_{io}, \\
& \quad \sum_{j=1}^{n} y_{ij} \lambda_j - s_r^+ = y_{ro}, \\
& \quad \lambda_j \geq 0, \quad j = 1, 2, \ldots, n, \\
& \quad s_i^- \geq 0, \quad i = 1, 2, \ldots, m, \\
& \quad s_r^+ \geq 0, \quad r = 1, 2, \ldots, s,
\end{aligned}
\]  

(4)

where \( s_i^- \) represents a reduced investment compared to the optimal solution, \( s_r^+ \) represents an increased output compared to the optimal solution, \( \bar{e}^T = (1 \quad 1 \quad \ldots \quad 1) \in E_m, \quad e^T = (1 \quad 1 \quad \ldots \quad 1) \in E_s \) and \( \varepsilon \) is a number less than any positive number and greater than 0.

In the model, the value of \( \theta_o \) is the main basis for classifying the inland navigable and substandard waterways. If \( \theta_o = 1 \) and \( s_i^- = 0, s_r^+ = 0 \), then the \( j,th \) inland waterway is called DEA-efficient, which indicates that this inland waterway is squarely on the efficient production frontier and its relatively navigable efficiency is highest in the all evaluated waters, so it will be directly divided into navigable ones; If \( \theta_o < 1 \), then the \( j,th \) inland waterway is DEA-inefficient, which shows that this waterway is within the effective production frontier envelope, the value is greater, the relative navigable viability of the waterway is higher, and it is more inclined to be classified into the navigable area, and vice versa. In order to optimize the allocation of safety supervision resources and put the limited maritime regulatory resources into the necessary inland waterways’ management, we use Pareto
principle to divide this kind waterways[14]. That is, arrange their values of $\theta_o$ in order from large to small, then divide the former 20% of them into navigable waterways and the remaining 80% of them into substandard waterways.

CASE STUDY

Available Data

In this paper, 11 inland waterways, 5 lakes and 2 reservoirs were selected from Ningbo, China, as the experimental sample. The relative indicator values were obtained from Ningbo Maritime Safety Administration or the local Maritime Safety Authorities. The missing data were obtained by field observations. And the qualitative indicators were quantified as specified in above section. Then in order to verify the validity of the method proposed in this paper, we decided to compare the classification results with the results based on fuzzy comprehensive evaluation (FCE) [15].

Results

On the basis of knowing the values of each indicator, the classification model was applied to calculate the relative efficiencies $\theta_o$ of these inland waterways by DEAP2.1, then classified the waterways according to their values of $\theta_o$. Among them, the values of $\theta_o$ for Yongjiang River, Dongjiang River, Yinjiang River, Dongqian Lake and Baixi Reservoir are 1, and $s_r^- = 0, s_r^+ = 0$, so these 5 waterways are directly divided into navigable ones. While the values of $\theta_o$ for other waterways are less than 1, according to Pareto principle, Fenghua River, Shanjiang River and Yaojiang River are divided into navigable ones and the rest are divided into substandard ones. The final classified results compared with those based on FCE are shown directly by the inland waterways’ number in Table III. The distribution of the classification areas is shown in the Figure 2. The green areas represent the navigable waterways, the red areas represent the substandard waterways and the yellow one represents the different regions of the two results.
Comparing the results based on the two different methods, it can be seen that the classifications of Wuyu River are different. In DEA, it was classified into the
substandard waterway. While in FCE, it was classified into the navigable waterway. When focus on the calculation results, in DEA, the $\theta$ of Wuyu river is 0.066 which is far away from 0.5, so it absolutely belongs to the navigable waterway in this method. While in FCE, this river’s membership degree to the navigable waterway is 0.387 and the membership degree to the substandard waterway is 0.355, which are very close. Because this method needs to use analytic hierarchy process (AHP) to determine the weight of each indicator, the result is likely to change because of the human subjective factors. In addition, after the field investigation, it is found that part of Wuyu River has experienced heavy sedimentation and some bridges’ headroom is insufficient, which means the navigation condition is limited and there is a certain risk. From the actual condition, the river is also not suitable for navigation. Therefore, the classification of Wuyu river based on the proposed method is more reliable and objective. What’s more, the inland waterways’ classification scheme in Ningbo which based on the proposed method in this paper has been adopted by Ningbo Maritime Safety Administration.

DISCUSSION AND CONCLUSION

A new classification method for inland navigable and substandard waterways has been proposed. The waterway indicators for classification have been determined and the classification model based upon the C2R model of DEA has been proposed. The advantage of the new method is that the weights of the indicators and the production function relationship between the inputs and outputs do not need to be determined in advance, thus simplifying the classification calculation steps and largely eliminating the impact of human subjective factors.

The application of the proposed method indicated that DEA-based approach did outperform the traditional FCE approach. The results based on available data collected in Ningbo revealed that the classification scheme using the proposed method was more consistent with the actual situation. It should be noted that the method requires a higher accuracy of the data, so to ensure the authenticity and rationality of the data is the key to apply.

Due to the related indicators of inland waterways will vary with the waterway construction situation, the actual navigation requirement, the natural environment and so on. When some indicators change, the attribute of the waterway may also be changed. Therefore, the relevant departments should adjust the scope of navigable inland waterways in time by establishing the corresponding dynamic adjustment system in order to satisfy the demand of actual navigation.
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REFERENCES