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# EVALUATING KEY ENVIRONMENTAL RISK FACTORS FOR POLLUTION AT INTERNATIONAL PORTS IN TAIWAN

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**Summary**

The main purpose of this paper is to use the fuzzy analytic hierarchy process (FAHP) approach to evaluate the key environmental risk factors for pollution at international ports in Taiwan. Relying on the literature and experts' opinions, a hierarchical structure with three risk aspects and thirteen risk factors is first constructed, and a FAHP model then proposed. Based on data from the AHP experts' questionnaires, we use the FAHP approach to determine key environmental risk factors. Finally, the results show that: (1) Air pollution is the most important aspect of environmental pollution at international ports in Taiwan. (2) In order of relative importance, the top five key environmental risk factors for pollution at international ports in Taiwan are the oil leaks from ships, volatile organic compounds (VOCs), exhaust emissions from ships at berth, harmful coatings on ships' hulls, and ships' failure to use low-pollution fuel. Furthermore, some discussions are provided for port authority in Taiwan.

*Key words:* *environmental risk; pollution; Taiwanese port; fuzzy analytic hierarchy process*

## 1. Introduction

International ports constitute a transition zone between land and sea, and are important connecting points in international trade and logistics activities [1]. As port operating efficiency increases, and more ships enter and leave a port, while this can promote prosperity by increasing economic activity in the port area, it can also disturb and harm the marine ecology and harbor environment. Responding to international environmental protection trends, the Association of Pacific Ports (APP) proposed at an international symposium [2] held in 2009 that the port of the future would emphasize efficiency, environmental protection, and safety, which enshrined the ideal of the "green port" as a goal for future port development efforts. As a consequence, while pursuing port and economic development; international ports must also give real thought to reducing port pollution and transforming themselves into green or ecological ports.

Port pollution [3, 4] includes seawater pollution, air pollution, noise pollution, and the generation of waste. In the case of seawater pollution, ships sewage, oil spills, toxic liquids released during the loading and unloading, and ballast water may all cause pollution of seawater. In particular, extreme effort must be taken to ensure that the improper discharge of ballast water does not allow exotic marine species to enter local harbors, where they may have a harmful influence on native species and the local environment. Furthermore, the incessant entry and departure of ships has made air pollution an increasingly severe problem in Taiwan's ports. Air pollution from ships consists chiefly of nitrogen oxides (NOx) and sulfur oxides (SOx) in exhaust from generators and engines, substances generated from the shipboard incineration of wastes and the burning of poor-quality fuel oil, substances harmful to the ozone layer, and volatile organic compounds (VOCs) derived from ship cargoes. Lastly, due to operations in the port area, noise from heavy loading and unloading equipment will not only affect personnel working in the port area, but also influence the lives of nearby residents. Long-term exposure to noise pollution can affect human health, such as by causing hearing damage, disturbing sleep, and causing psychological discomfort.

International ports cannot avoid producing a certain level of pollution, and the development of marine transport and related economic activities will inevitably produce external costs in the form of pollution. From the perspective of risk management [4-6], seawater pollution, air pollution, and noise pollution are the three major types of port pollution. All three types can be considered environmental risk categories, and their existence, time of occurrence, and degree of influence are uncertain to some degree.

So-called environmental risks refer to fundamental risks that may cause destruction or harm to the ecological or industrial environment. Port operations constitute a typical human activity and an industry with environmental risk factors. The entry and exit of ships and loading and unloading of cargo entail certain degrees of risk. And as a port expands in size, the volume of cargo and the types of cargo loaded, unloaded, and stored at the port will also increase and become more complex, which will also tend to increase the incidence of environmental risk factors and their degree of influence. International ports are a type of international shipping enterprise, and modern enterprises regard risk management as a management function with the goal of achieving effective management and control of risk at an optimal cost through the steps of verification, assessment, and risk management decision-making. This study consequently investigates how, in light of the green port concept, port managers should implement preventive measures and control environmental risks so as to minimize the influence of seawater pollution, air pollution, and noise pollution in the port area in the midst of conflict between port development and environmental protection [7, 8].

The assessment of environmental risks in port areas takes into consideration numerous factors, such as international marine pollution control conventions, port operations, and governmental environmental protection policies. Hence, this evaluation for key environmental risk factors poses a multiple criteria problem. Experience showed that evaluation of key factors (criteria), which involves a multiple criteria problem, is not an easy task. The issue of evaluating key environmental factors faces how to evaluate the relative weights of these multiple ones; however, the relative weights based upon this measurement in which information is subjective, e.g., phrase of ‘much more important than,’ ‘essential importance,’ or ‘equal importance.’ There are many methods to evaluate relative weights of multiple criteria problems. One of the commonly used techniques for multiple criteria problems is the Saaty’s Analytic Hierarchy Process (AHP) approach [9]. Since the AHP method is a systematic decision-making method that can be used to tackle complicated problems, and is typically applied to decision-making problems involving uncertain situations and numerous attributes; hence, the use of the AHP method would be more suitable in this paper. However, because risk factor issues tend to have qualitative aspects, and assessment personnel must make judgments that are inherently subjective and imprecise, in many cases it is very difficult to express the importance of risk factors in precise and quantitative form. That is, in view of the qualitative characteristics of risk factor questions, and the inherently fuzzy [10] nature of individuals' subjective views, it would be very difficult to express the importance of risk factors in terms of precise values. Determining the importance of risk factors constitutes a multiple criteria problem in which information is incomplete or imprecise and views may be subjective or endowed with linguistic [11] characteristics. In order to investigate the key environmental risk factors associated with port pollution, this study employed fuzzy set theory [9] in conjunction with the AHP [10] to construct a fuzzy analytic hierarchy process (FAHP) model [12, 13] of the key environmental risk factors connected with port pollution.

In summary, the main purpose of this study is to apply the FAHP approach to evaluate port environmental risks in Taiwan, and it is expected that the results of this study can provide Taiwan's international ports with risk management strategies and recommendations. The FAHP approach is designed to minimize such adverse conditions and strengthen the evaluation process in this article. We hope that the results of this study can provide green port guidance for Taiwanese green port policy. The first section provides some background information concerning this subject. The following section presents the preliminary environmental risk factors, and the third section describes the FAHP method. The fourth section consists of an empirical study, and the final section presents the research conclusions.

## 2. Preliminary environmental risk factors

The concept of risk has long pervaded all corporate business operations, and failure to confront and respond to risks will make a company vulnerable to interruption of operations. This study consequently believes that if port managers can apply the risk management concept to all port activities, this will promote the port's subsequent development and enhanced competitiveness [7]. Since pollution represents a significant risk category, control of port pollution should therefore constitute one of a port's operating activities. If an international port fails to establish required pollution control measures or regulations, or if it fails to attain pollution emission standards or targets, this can be considered a risk element jeopardizing achievement of the green port concept.

The green port concept refers to a port's ability to minimize the pollution caused by port operations, reduce the port's negative impact on the environment, and protect the port ecology and nearby residents' living environment. The issue of environmental pollution is not only a matter of global concern, but also involves the environmental protection policies of national governments, and these policies may directly or indirectly affect the effectiveness of companies' risk management measures. As a result, environmental risk management has become a key duty of corporate risk management personnel.

The major international ports in Taiwan (including the ports of Kaohsiung, Keelung, and Taichung) have already implemented green port planning and adopted environmental protection measures. Among the actions being taken are the acquisition of alternative energy sources or new technologies able to reduce the environmental impact of port operations; enhancement of harbor clean-up work and deployment of automatic port environmental quality monitoring systems enabling early warning and prompt control of environmental problems; collection and treatment of oily water in the port area, and banning the discharge of oily water into the harbor or sea; mitigation of transport vehicle exhaust emissions in the port area in order to improve air quality; provision of on-shore power systems enabling ships at berth to obtain power, sharply reducing air pollution from the operation of shipboard generators in the port area; design of wharf buildings, container yards, and wharf equipment to employ chiefly green energy equipment; and implementation of environmental education to boost the environmental and conservation consciousness of port personnel. Apart from Taiwan, these environmental measures are also being adopted by the ports of Hong Kong, Sydney, Long Beach, Seattle, Los Angeles, and New York/New Jersey, which are likewise striving to make the transformation to green and ecological ports. These measures can effectively reduce the negative impact on the environment caused by port operations.

International ports that seek to transform themselves into green ports must first pay attention to pollution risk management in the port area. This study investigated pollution risk factors under the three aspects of air pollution, seawater pollution, and noise pollution based on a review of the literature [3, 4, 7, 8, 14-33] and collection of recommendations from interviews with experts and scholars. The following Table 1 contains explanations of the assessment criteria obtained by this study.

**Table 1** Environmental risk factors for port pollution

| Risk aspect | Risk factor | Description of factor |
|---|---|---|
| Air pollution ($C_1$) | Ships' failure to use low-pollution fuel ($C_{11}$) | Air pollution risk caused by ships' failure to use low-sulfur fuel oil in accordance with regulations |
| | Exhaust emissions from ships at berth ($C_{12}$) | Air pollution risk from the port's failure to install an on-shore power system, and the continued use of fuel oil as a main power source by ships at berth |
| | Airborne dust in the port area ($C_{13}$) | Air pollution risk from particulate matter created during the loading, unloading, and transport of bulk cargo (such as coal and ore) and building materials in the port area |
| | Volatile organic compounds (VOCs) ($C_{14}$) | Air pollution risk from VOCs released during loading, unloading, and transport of petroleum |
| | Ships fail to reduce speed while underway in the port area ($C_{15}$) | Air pollution risk caused by failure of ships to reduce their speed while in the prescribed area |
| Seawater pollution ($C_2$) | Ships discharge ballast water ($C_{21}$) | Seawater pollution risk caused when the uncontrolled discharge of ballast water by ships leads to invasion by non-native species |
| | Ship sewage and wastewater ($C_{22}$) | Seawater pollution risk caused by the discharge of wastewater from ship kitchens, bathrooms, and washing machines, and sewage produced by shipboard personnel |
| | Harmful coatings on ships' hulls ($C_{23}$) | Seawater pollution risk caused by ships' use of harmful antifouling systems, specifically hull coatings containing organotin antifouling agents |
| | Oil leaks from ships ($C_{24}$) | Seawater pollution risk caused by vessels' discharge of oily water or bilge washing water in violation of regulations, and spillage of waste oil or oily water during the careless repair of vessels |
| Noise pollution ($C_3$) | Operating noise of equipment and machinery in the port area ($C_{31}$) | Noise pollution risk caused by container yard noise from the operation of equipment such as transtainers and forklifts, etc. |
| | Noise caused by vehicles and transport equipment, access road traffic ($C_{32}$) | Noise pollution risk caused by continuous noise from trucks entering and exiting port roads and machinery moving on main port roads |
| | Noise from engines on arriving and departing ships ($C_{33}$) | Ships are the chief noise source in the port area. Noise pollution risk from the operation of machinery including such shipboard noise sources as engines, diesel generators, transmission systems, propellers, ventilation and air conditioning equipment, and cargo cranes |
| | Noise from construction in the port area ($C_{34}$) | Noise pollution risk from construction and installation work, operation of equipment and drilling in the port area |

Note: The code names of each risk aspect and risk factor are shown in parentheses.

## 3. Method

The concepts and methods used in this paper are briefly introduced in this section.

### 3.1 The concept of fuzzy numbers

In a universe of discourse $X$, a fuzzy subset $A$ of $X$ is defined by a membership function $f_A(x)$, which maps each element $x$ in $X$ to a real number in the interval $[0, 1]$. The value of function $f_A(x)$ represents the grade of membership of $x$ in $A$.

A fuzzy number $A$ [34] in real line $\Re$ is a triangular fuzzy number if its membership function $f_A : \Re \to [0, 1]$ is

$$f_A(x) = \begin{cases} (x-c)/(a-c), & c \le x \le a \\ (x-b)/(a-b), & a \le x \le b \\ 0, & otherwise \end{cases}$$

with $-\infty < c \le a \le b < \infty$. A triangular fuzzy number can be denoted by $(c, a, b)$.

In this paper, Zadeh's extension principle [10] is employed to perform algebraic operations involving fuzzy numbers. Let $A_1 = (c_1, a_1, b_1)$ and $A_2 = (c_2, a_2, b_2)$ be the fuzzy numbers. The algebraic operations of any two fuzzy numbers $A_1$ and $A_2$ can be expressed as:

(1) Fuzzy addition, $\oplus$ :

$$A_1 \oplus A_2 = (c_1 + c_2, a_1 + a_2, b_1 + b_2);$$

(2) Fuzzy subtraction, $\ominus$ :

$$A_1 \ominus A_2 = (c_1 - b_2, a_1 - a_2, b_1 - c_2);$$

(3) Fuzzy multiplication, $\otimes$ :

$$k \otimes A_2 = (kc_2, ka_2, kb_2), \quad k \in \Re, \ k \ge 0;$$

$$A_1 \otimes A_2 \cong (c_1c_2, a_1a_2, b_1b_2), \quad c_1 \ge 0, \ c_2 \ge 0.$$

(4) Fuzzy division, $\varnothing$ :

$$(A_1)^{-1} = (c_1, a_1, b_1)^{-1} \cong (1/b_1, 1/a_1, 1/c_1), c_1 > 0;$$

$$A_1 \varnothing A_2 \cong (c_1/b_2, \ a_1/a_2, \ b_1/c_2), \quad c_1 \ge 0, \ c_2 > 0.$$

### 3.2 The FAHP approach

Many FAHP methods [12, 13, 16, 25, 35-38] are proposed and applied in many multiple criteria problems. Two methods proposed by Buckley [35] and Chang [36] are usually employed in the academic literature. Buckley [35] extended a hierarchical analysis using a consistency test method for fuzzy positive reciprocal matrices in which all elements are trapezoidal fuzzy numbers. Buckley et al. [37] revisited the fuzzy hierarchical analysis and proposed a new method of finding the fuzzy weights. Chang [36] used the same procedure in building fuzzy pair-wise comparison matrices. However, two important steps of Chang's extent analysis method on fuzzy AHP are added to calculate the value of the fuzzy synthetic extent and the degree of possibility of any two fuzzy numbers. In 2009, Ding [38] modified Chang's method and applied the proposed method to select a suitable partner of strategic alliance for a liner shipping company. In this paper, the FAHP approach of Ding et al. method [12] is used to evaluate relative weights. The steps are described below.

**Step 1.** Establishment of a hierarchical structure

This study employs the hierarchical framework diagram shown in Figure 1. In this framework, the problems lie on the L$^{th}$ layer, and consist of pollution risk factors with a major influence on the port area. There are $k$ risk aspects on the $L$+1 layer, and $p+\cdots+q+\cdots+r$ chief assessment criteria on the $L$+2 layer.

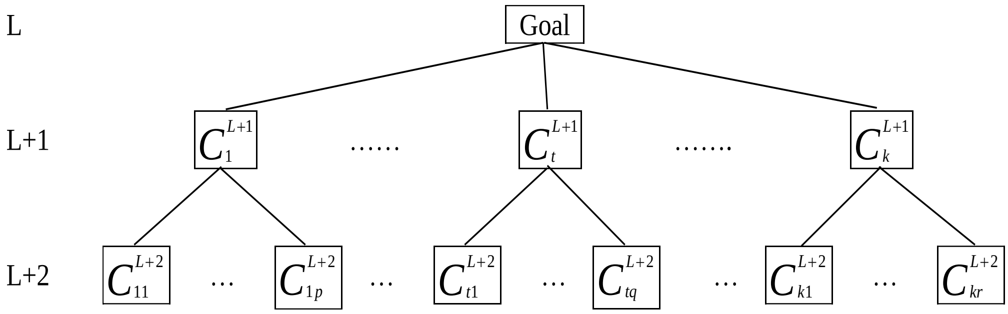


**Fig. 1** Hierarchical structure

**Step 2.** Establishment of pairwise comparison matrices for decision attributes

Pairwise comparison of questionnaire results was employed to determine the experts' views of the relative importance of paired assessment criteria.

(1) Let $x_{ij}^h$, $h=1, 2, \ldots, n$, be the relative importances assigned to any two risk aspects $i$ and $j$ by expert $h$ on the $L$+1 layer. Then, the pairwise comparison matrix is defined as $[x_{ij}^h]_{k\times k}$.

(2) Let $x_{uv}^h$, $h=1, 2, \ldots, n$, be the relative importances assigned to any two risk factors $u$ and $v$ by expert $h$ on the $L$+2 layer. Then, the pairwise comparison matrix with respect to each risk aspect, i.e. $C_1^{L+1}$, $C_t^{L+1}$, $C_k^{L+1}$, is defined as $[x_{uv}^h]_{p\times p}$, $[x_{uv}^h]_{q\times q}$, $[x_{uv}^h]_{r\times r}$.

**Step 3.** Establishing triangular fuzzy numbers

The generalized mean is a typical representation of many well-known averaging operations [39], including min, max, geometric mean, arithmetic mean, and harmonic mean, etc. The min and max represent the lower and upper bounds of generalized means. In addition, the geometric mean is most effective at representing the consensus views of multiple decision-makers [9]. To aggregate all information generated by different averaging operations, we use the grade of membership to demonstrate their strength after considering all approaches. Triangular fuzzy numbers characterized through use of min, max and geometric mean operations are therefore used to convey the views of all experts.

Let $x_{ij}^h \in [\frac{1}{9}, \frac{1}{8}, \ldots, \frac{1}{2}, 1] \cup [1, 2, \ldots, 8, 9]$, $h=1, 2, \ldots, n$, $\forall i,\ j=1, 2, \ldots, k$, be the relative importances assigned to any two risk aspects $i$ and $j$ by expert $h$ on the $L$+1 layer. After integrating the views of all $n$ experts, the triangular fuzzy numbers can be expressed as

$$\tilde{A}_{ij}^{L+1} = (c_{ij}, a_{ij}, b_{ij}),$$

$$\text{where } c_{ij} = \min\{x_{ij}^1, x_{ij}^2, \ldots, x_{ij}^n\},\ a_{ij} = \left(\prod_{h=1}^{n} x_{ij}^h\right)^{1/n},\ b_{ij} = \max\{x_{ij}^1, x_{ij}^2, \ldots, x_{ij}^n\}.$$

We can integrate the views of all $n$ experts on the $L$+2 layer in the same way, so that the triangular fuzzy numbers can be expressed as

$$\tilde{A}_{uv}^{L+2} = (c_{uv}, a_{uv}, b_{uv}),\ \ \forall u, v = 1, \ldots, p;\ \cdots;\ \forall u, v = 1, \ldots, q;\ \cdots;\ \forall u, v = 1, \ldots, r,$$

where $c_{uv} = \min\{x_{uv}^1, x_{uv}^2, \ldots, x_{uv}^n\}$, $a_{uv} = \left(\prod_{h=1}^{n} x_{uv}^h\right)^{1/n}$, $b_{uv} = \max\{x_{uv}^1, x_{uv}^2, \ldots, x_{uv}^n\}$.

**Step 4.** Constructing fuzzy positive reciprocal matrices

We use the integrated triangular fuzzy numbers to construct fuzzy positive reciprocal matrices. For the $L$+1 layer, the fuzzy positive reciprocal matrix can be expressed as

$$A = \left[\tilde{A}_{ij}^{L+1}\right] = \begin{bmatrix} 1 & \tilde{A}_{12}^{L+1} & \cdots & \tilde{A}_{1k}^{L+1} \\ 1/\tilde{A}_{12}^{L+1} & 1 & \cdots & \tilde{A}_{2k}^{L+1} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{A}_{1k}^{L+1} & 1/\tilde{A}_{2k}^{L+1} & \cdots & 1 \end{bmatrix},$$

where $\tilde{A}_{ij}^{L+1} \otimes \tilde{A}_{ji}^{L+1} \cong 1, \quad \forall i, j = 1, 2, \ldots, k.$

The equations of the fuzzy positive reciprocal matrices on the $L$+2 layer can be obtained using an analogous method.

**Step 5.** Calculation of the fuzzy weights of the fuzzy positive reciprocal matrices

Let $\tilde{Z}_i^{L+1} \cong \left(\tilde{A}_{i1}^{L+1} \otimes \tilde{A}_{i2}^{L+1} \otimes \cdots \otimes \tilde{A}_{ik}^{L+1}\right)^{1/k}, \quad \forall i = 1, 2, \ldots, k,$ be the geometric mean of triangular fuzzy number of the $i^{th}$ risk aspect on the $L$+1 layer. The fuzzy weight of the $i^{th}$ risk aspect can then be expressed as

$$\tilde{W}_i^{L+1} \cong \tilde{Z}_i^{L+1} \otimes \left(\tilde{Z}_1^{L+1} \oplus \tilde{Z}_2^{L+1} \oplus \cdots \oplus \tilde{Z}_k^{L+1}\right)^{-1}$$

For convenience, the fuzzy weight is expressed as $\tilde{W}_i^{L+1} = (w_{ic}, w_{ia}, w_{ib})$. The equations of fuzzy weights on the $L$+2 layer can be obtained using an analogous method.

**Step 6.** Defuzzifying the fuzzy weights to obtain crisp weights

To perform defuzzification in an effective manner, the graded mean integration representation (GMIR) method proposed by Chen and Hsieh [40] is used to defuzzify the fuzzy weights.

Let $\tilde{W}_i^{L+1} = (w_{ic}, w_{ia}, w_{ib})$, $\forall i = 1, 2, \ldots, k,$ be $k$ triangular fuzzy numbers. The GMIR of crisp weights $k$ can then be expressed as

$$W_i^{L+1} = \frac{w_{ic} + 4w_{ia} + w_{ib}}{6},\ \forall i = 1, 2, \ldots, k\ .$$

The defuzzification of fuzzy weights on the $L$+2 layer can be performed using an analogous method.

**Step 7.** Normalizing the crisp weights

To facilitate comparison of the relative importance of risk aspects on different layers, the crisp weights are normalized and expressed as

$$NW_i^{L+1} = \frac{W_i^{L+1}}{\sum_{i=1}^{k} W_i^{L+1}}$$

**Step 8.** Calculating the integrated weights for each layer

Let $NW_i^{L+1}$ and $NW_u^{L+2}$ be the normalized crisp weights on the $L$+1 and $L$+2 layers. Then,

(1) The integrated weight of each risk aspect on the $L$+1 layer is

$$IW_i^{L+1} = NW_i^{L+1}, \forall i = 1, 2, \ldots, k .$$

(2) The integrated weight of each risk factor on the $L$+2 layer is

$$IW_u^{L+2} = NW_i^{L+1} \times NW_u^{L+2}, \ \forall i = 1, 2, \ldots, k ;$$

$$\forall u = 1, \ldots, p; \ \cdots; \ \forall u = 1, \ldots, q; \ \cdots; \ \forall u = 1, \ldots, r .$$

## 4. Empirical study

This section describes an empirical study conducted to evaluate key environmental risk factors for pollution at international ports in Taiwan.

### 4.1 Data collection

The AHP expert questionnaire was based on the risk aspects and risk factors shown in Table 1, and was used to investigate the relative weights of all risk factors. In this paper, an AHP questionnaire with three risk aspects and 13 risk factors was used to compile the pair-wise comparison matrices of each layer and express the relative importance of each risk factor. To check whether the expressions were clear or important questions were missed, some experts and scholars were invited to pre-test the questionnaire. Finally, two rounds of correction based on questionnaire design principles were carefully performed, and the final AHP questionnaire was completed. Furthermore, for saving space, the AHP questionnaire example of 3 risk aspects on the $L$+1 layer is shown as Table 2.

**Table 2** The AHP questionnaire example of 3 risk aspects

<table>
<tr><td colspan="19">Regarding the three risk aspects on the L+1 layer, in your opinion what is the relative importance of “Air pollution,” “Seawater pollution” and “Noise pollution?”</td></tr>
<tr><td rowspan="2">Risk aspect</td><td colspan="8">← Increasing importance</td><td></td><td colspan="8">Increasing importance →</td><td rowspan="2">Risk aspect</td></tr>
<tr><td>9</td><td>8</td><td>7</td><td>6</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td></tr>
<tr><td>Air pollution</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>Seawater pollution</td></tr>
<tr><td>Air pollution</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>Noise pollution</td></tr>
<tr><td>Seawater pollution</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>□</td><td>Noise pollution</td></tr>
</table>

To ensure that the international port pollution risk assessment results in this study appropriately meshed with practical needs, the questionnaire was issued to key working personnel at Taiwan's three major international ports. The questionnaire sought to assess the relative importance of port pollution sources affecting green port risk factors.

The AHP questionnaires were distributed during a two-month period in 2016. The port authorities, experts and scholars were invited to fill in the AHP questionnaires. The surveys were completed through e-mails, phone calls, and in-person interviews conducted by the authors. The returned questionnaires were checked to determine whether the consistency index (C.I.) of each matrix of every layer was lower than 0.1 [10]. When the C.I. value of a matrix is higher than 0.1, this implies that the respondent had made an inconsistent pair-wise comparison of two risk aspects (or risk factors). To prevent the occurrence of errors, the authors helped such respondents to correct their judgments until the C.I. value of each matrix was lower than 0.1.

A total of 30 questionnaires were issued, of which 27 valid questionnaires were recovered, for an effective recovery rate of 90%. In view of Robinson's recommendation [41] that 5-7 experts ideally be enlisted in research on group decision-making problems, the 27 valid recovered questionnaires should be sufficient to provide a representative range of views. As a result, after the 27 questionnaires were checked for validity, the number of responses was deemed acceptable.

## 4.2 Results

In our case, with three risk aspects and 13 risk factors, there were five (1+3) pair-wise comparison matrices to compile. We integrated twenty-seven valid questionnaires to compute the fuzzy positive reciprocal matrices for three risk aspects and 13 risk factors, as shown in Table 3 to Table 6.

**Table 3** The fuzzy positive reciprocal matrices of three risk aspects

| | $C_1$ | $C_2$ | $C_3$ |
|---|---|---|---|
| $C_1$ | (1, 1, 1) | (0.20, 1.50, 7) | (0.20, 2.56, 8) |
| $C_2$ | (0.14, 0.67, 5) | (1, 1, 1) | (0.20, 2.03, 7) |
| $C_3$ | (0.13, 0.39, 5) | (0.14, 0.49, 5) | (1, 1, 1) |

**Table 4** The fuzzy positive reciprocal matrices of five risk factors under the ‘air pollution’ aspect

| | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | $C_{15}$ |
|---|---|---|---|---|---|
| $C_{11}$ | (1, 1, 1) | (0.17, 0.73, 5) | (0.20, 0.85, 7) | (0.13, 0.53, 7) | (0.50, 1.74, 6) |
| $C_{12}$ | (0.20, 1.50, 6) | (1, 1, 1) | (0.25, 2.03, 5) | (0.14, 0.98, 8) | (0.20, 2.55, 9) |
| $C_{13}$ | (0.14, 1.18, 5) | (0.20, 0.49, 4) | (1, 1, 1) | (0.11, 0.64, 5) | (0.14, 1.48, 5) |
| $C_{14}$ | (0.14, 1.90, 8) | (0.13, 1.02, 7) | (0.20, 1.57, 9) | (1, 1, 1) | (0.25, 3.16, 8) |
| $C_{15}$ | (0.17, 0.58, 2) | (0.11, 0.39, 5) | (0.20, 0.68, 7) | (0.13, 0.32, 4) | (1, 1, 1) |

**Table 5** The fuzzy positive reciprocal matrices of four risk factors under the ‘seawater pollution’ aspect

| | $C_{21}$ | $C_{22}$ | $C_{23}$ | $C_{24}$ |
|---|---|---|---|---|
| $C_{21}$ | (1, 1, 1) | (0.20, 0.92, 4) | (0.14, 0.62, 4) | (0.13, 0.35, 6) |
| $C_{22}$ | (0.25, 1.08, 5) | (1, 1, 1) | (0.14, 0.61, 4) | (0.11, 0.32, 3) |
| $C_{23}$ | (0.25, 1.62, 7) | (0.25, 1.67, 7) | (1, 1, 1) | (0.13, 0.38, 4) |
| $C_{24}$ | (0.17, 2.87, 8) | (0.33, 3.12, 9) | (0.25, 2.66, 8) | (1, 1, 1) |

**Table 6** The fuzzy positive reciprocal matrices of four risk factors under the 'noise pollution' aspect

| | $C_{31}$ | $C_{32}$ | $C_{33}$ | $C_{34}$ |
|---|---|---|---|---|
| $C_{31}$ | (1, 1, 1) | (0.25, 1.18, 5) | (0.11, 1.53, 5) | (0.25, 0.86, 5) |
| $C_{32}$ | (0.20, 0.85, 4) | (1, 1, 1) | (0.33, 1.34, 6) | (0.14, 1.28, 6) |
| $C_{33}$ | (0.20, 0.65, 9) | (0.17, 0.75, 3) | (1, 1, 1) | (0.17, 0.64, 4) |
| $C_{34}$ | (0.20, 1.16, 4) | (0.17, 0.78, 7) | (0.25, 1.55, 6) | (1, 1, 1) |

In this paper, the authors use three risk aspects ($C_1 - C_3$) from the twenty-seven valid questionnaires as an example to illustrate the computational procedures used in the FAHP method. The other three pair-wise comparison matrices are omitted by reasoning of analogy. The computational process and empirical results are shown as follows.

At first, the relative importance data from the twenty-seven valid questionnaires are used to collect a pairwise comparison matrix (*i.e.* Step 2). We then transformed these data into triangular fuzzy numbers through geometric mean method (*i.e.* Step 3). These triangular fuzzy numbers are employed to construct a fuzzy positive reciprocal matrix (*i.e.* Step 4). The geometric means of the triangular fuzzy number ($\tilde{Z}_i^{L+1}$) and the fuzzy weights ($\tilde{W}_i^{L+1}$) of three assessment aspects are calculated (*i.e.* Step 5). Using the Step 6 to defuzzy the fuzzy weights, we can obtain the crisp weights ($W_i^{L+1}$). Finally, the normalized weights ($NW_i^{L+1}$) of three assessment aspects by using Step 7 are obtained. The computational results are shown in Table 7.

**Table 7** The computational results of three assessment aspects

| | $C_1$ | $C_2$ | $C_3$ |
|---|---|---|---|
| $C_1$ | (1, 1, 1) | (0.20, 1.50, 7) | (0.20, 2.56, 8) |
| $C_2$ | (0.14, 0.67, 5) | (1, 1, 1) | (0.20, 2.03, 7) |
| $C_3$ | (0.13, 0.39, 5) | (0.14, 0.49, 5) | (1, 1, 1) |
| $\tilde{Z}_i^{L+1}$ | (0.34, 1.57, 3.83) | (0.31, 1.11, 3.27) | (0.26, 0.58, 2.92) |
| $\tilde{W}_i^{L+1}$ | (0.03, 0.48, 4.21) | (0.03, 0.34, 3.60) | (0.03, 0.18, 3.22) |
| $W_i^{L+1}$ | 1.027 | 0.832 | 0.662 |
| $NW_i^{L+1}$ | 0.407 | 0.330 | 0.263 |

In summary, we used the same computational process of the proposed FAHP approach for each risk factor to obtain the normalized weights and integrated weights. The empirical results are summarized in Table 8.

**Table 8** Normalized weights and integrated weights of each layer

| **Risk aspect** | **Normalized / Integrated weights (A)** | **Risk factors** | **Normalized weights (B)** | **Integrated weights (C)=(A)*(B)** |
|---|---|---|---|---|
| Air pollution | 0.407 (1) | Ships' failure to use low-pollution fuel | 0.199 (3) | 0.0810 (5) |
| | | Exhaust emissions from ships at berth | 0.234 (2) | 0.0952 (3) |
| | | Airborne dust in the port area | 0.166 (4) | 0.0676 (8) |
| | | VOCs | 0.261 (1) | 0.1062 (2) |
| | | Ships fail to reduce speed while underway in the port area | 0.140 (5) | 0.0570 (13) |

**Table 8** Normalized weights and integrated weights of each layer (continued)

| **Risk aspect** | **Normalized / Integrated weights (A)** | **Risk factors** | **Normalized weights (B)** | **Integrated weights (C)=(A)*(B)** |
|---|---|---|---|---|
| Seawater pollution | 0.330 (2) | Ships discharge ballast water | 0.199 (3) | 0.0657 (10) |
| | | Ship sewage and wastewater | 0.181 (4) | 0.0597 (11) |
| | | Harmful coatings on ships' hulls | 0.248 (2) | 0.0818 (4) |
| | | Oil leaks from ships | 0.372 (1) | 0.1228 (1) |
| Noise pollution | 0.263 (3) | Operating noise of equipment and machinery in the port area | 0.253 (3) | 0.0665 (9) |
| | | Noise caused by vehicles and transport equipment, access road traffic | 0.258 (2) | 0.0679 (7) |
| | | Noise from engines on arriving and departing ships | 0.223 (4) | 0.0586 (12) |
| | | Noise from construction in the port area | 0.266 (1) | 0.070 (6) |

The questionnaire survey's findings were as follows:

(1) ‘Air pollution’ ranked highest, indicating that it is the most important risk aspect affecting environmental pollution at international ports in Taiwan. ‘Seawater pollution’ and ‘noise pollution’ ranked in the second and third places. This study believes that, because the respondents consisted of personnel at port companies, the questionnaire results reflected the fact that, compared with the aspects of ‘seawater pollution’ and ‘noise pollution,’ ‘air pollution’ has a more widespread influence, and its effects are not limited to the harbour area; in contrast, the influence of ‘noise pollution’ tends to be limited to the harbour and nearby area, which accounts for this aspect's lowest weight rank.

(2) The most important risk factors were ‘VOCs’ in the risk aspect of ‘air pollution,’ ‘oil leaks from ships’ in the aspect of ‘seawater pollution,’ and ‘noise from construction in the port area’ in the aspect of ‘noise pollution.’

(3) The top five key environmental risk factors for pollution at international ports in Taiwan were, in order of importance, ‘oil leaks from ships,’ ‘VOCs,’ ‘exhaust emissions from ships at berth,’ ‘harmful coatings on ships' hulls,’ and ‘ships' failure to use low-pollution fuel.’

4.3 Discussions

This study provides a detailed explanation of only the top five environmental risk factors as reflected in their overall weighting rank. Because the top five environmental risk factors account for 77% of factor loading, however, they can preliminarily express most of the issues addressed in this study. These environmental risk factors are discussed as follows:

– *Oil leaks from ships*

This risk factor was the most important risk factor in terms of its overall weighting rank, and was also the most important risk factor in the aspect of seawater pollution. Seawater pollution caused by the discharge of oily water or bilge washing water by ships in violation of regulations, or the spillage of waste oil or oily water through negligence during ship repair work, can do severe harm to the marine environment and marine ecology. Among current response measures, oil booms are commonly deployed around ships taking on oil to prevent the dispersal of pollution if any oil leaks occur. In addition, methods currently used to deal with accidental oil spills at sea include the use of oil absorbents, oil skimmers, and oil dispersants. With regard to other countries' measures to control oil spills from ships, for example, the United States' Oil Pollution Act 1990 (OPA1990) has the chief goal of resolving disputes involving accidental oil spills from vessels traveling in US waters. Moreover, such countries as Britain, Norway, the Netherlands, and even Japan generally rely on response plans drafted after the fact to control oil spills from ships.

– *VOCs*

This risk factor was the second risk factor in terms of its overall weighting rank, and was also the most important risk factor in the aspect of air pollution. Petroleum loading, unloading, and transport processes entail the release of VOCs, which include ozone precursors, and ozone will be produced via photochemical reactions. Ozone is a highly reactive oxidizing agent, and many studies have shown that it is harmful to humans, crops, and many materials. In particular, is harmful to the human respiratory system, and long-term exposure to ozone will cause such symptoms as headache, fatigue, coughing, and shortness of breath. Apart from harm to humans and crops, ozone also causes acid rain, which occurs due to the increased formation of hydrogen peroxide ($H_2O_2$) and the reaction of ozone with $SO_2$ in clouds. Thus far, nine photochemical assessment monitoring stations have been established in Taiwan to monitor ozone, ozone precursors, and some oxygenated volatile organic compounds (OVOCs), as well as to analyze emission sources, in order to provide information to guide the drafting of ozone control strategies.

– *Exhaust emissions from ships at berth*

This risk factor was third in terms of its overall weighting rank, and was also the second risk factor in the aspect of air pollution. Because ships do not necessarily cease all operations while at berth, they still require power in order to maintain their basic functions. As a consequence, ships that continue to power themselves through the combustion of fuel oil will cause air pollution while at port. And because ships stay in a fixed location while at berth, they can cause very large amounts of air pollution. In particular, the exhaust emissions from several ships at berth at the same time cannot be easily overlooked. Furthermore, when large commercial vessels, particularly container ships and bulk carriers, are at berth, in order to conserve costs, they typically use poor-quality fuel oil to run their generators and obtain power to meet their basic operating needs. The combustion of poor-quality fuel oil creates large quantities of harmful $NO_X$, $SO_X$, and particulate matter. At present, some international ports require ships to turn off their onboard generators while at berth, and instead use onshore electricity as their main source of power. This practice can reduce ships' exhaust emissions while in port.

– *Harmful coatings on ships' hulls*

This risk factor was fourth in terms of its overall weighting rank, and was also the most important assessment criterion in the aspect of seawater pollution. Harmful antifouling systems used by ships, specifically underwater hull coatings containing organotin antifouling agents, will cause seawater pollution. Antifouling systems are employed on ships chiefly to prevent the growth of organisms (such as algae) on their hulls and the surfaces of their underwater facilities; organisms growing on ships' hulls will increase drag and force the vessels to consume more fuel. Nevertheless, antifouling coatings are harmful to the environment. For instance, some antifouling agents cause sex abnormalities in marine organisms and also severely disturb the ecological balance in the sea. Various countries are currently researching new types of antifouling coatings that are nontoxic and environmentally benign. Some scientists are searching for natural antifouling substances in marine organisms such as corals, algae, and dolphins; these substances have anesthetic, repellent, and antiadhesion properties, but have few negative effects on the marine environment or marine organisms.

– *Ships fail to use low-pollution fuel*

This risk factor was fifth in terms of its overall weighting rank, and was also the third assessment criterion in the aspect of air pollution. This risk factor concerns the fuel used by ships, and specifically whether the sulfur content of fuel oil used by ships is below the level specified by MARPOL 73/78 (Protocol of 1978 Relating to the International Convention for the Prevention of Pollution From Ships 1973), which prescribes that the sulfur content of any fuel oil used by ships may not exceed 4.5% by weight, and may not exceed 1.5% when ships are in emission control zones. If the sulfur content of their fuel is excessively high, ships will discharge $SO_2$, which readily dissolves in water and forms sulfurous acid, which yield sulfates after oxidation in the air and is a main cause of acid rain. For its part, acid rain causes soil acidification, degrades water quality, and corrodes buildings and equipment.

## 5. Conclusions

Port pollution will have a negative impact on port activities. From the green port perspective, it is important to determine how a port authority should implement risk management to minimize the influence of port pollution. What environmental risks do ports in Taiwan face? What are the key environmental risk factors involved? This study seeks to analyze the key environmental risk factors for pollution at international ports in Taiwan, and has employed the FAHP method to evaluate such risk factors.

The study's empirical survey employed an AHP expert questionnaire to systematically assess the importance attached to individual environmental risk factors, and obtained the following results:

(1) Air pollution is the most important aspect affecting environmental pollution at international ports in Taiwan.

(2) VOCs is the most important risk factor in the aspect of air pollution. Oil leaks from ships is the most important risk factor in the aspect of seawater pollution, and noise from construction in the port area is the most important risk factor in the aspect of noise pollution.

(3) The top five environmental risk factors for pollution at international ports in Taiwan are, in order of importance, oil leaks from ships, VOCs, exhaust emissions from ships at berth, harmful coatings on ships' hulls, and ships' failure to use low-pollution fuel.

Due to time constraints, this study only investigated 13 assessment criteria in the three major aspects of air, seawater, and noise pollution. Future research may address such issues as radiation pollution indirectly caused by Japan's tsunami, or may investigate assessment criteria connected with other types of pollution sources. Moreover, if dependent relationships exist between risk aspects or risk factors, the analytic network process (ANP) approach [42] or the decision making trial and evaluation laboratory (DEMATEL) approach [43] can be used to make clear those situations.

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