A novel model for the quantitative evaluation of green port development – A case study of major ports in China

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Abstract

Environmental problems that seriously affect both natural systems and social development of human beings have drawn extensive attention from governing authorities all around the world, and become an urgent issue to be addressed. Ports play a significant role in the international shipping which inevitably influence the global environment. Thus, the concept of green port is developed to mitigate the negative impacts of inappropriate port operations on environment. This paper analyzes the current status of green port development worldwide. An evaluation model for quantitative measurement of green port development is established based on the Drivers, Pressures, States, Impacts and Responses (DPSIR) framework. The weight of each index composing the evaluation model is calculated through an analytical hierarchy process method, and the evaluation results of the investigated ports with respect to each index are aggregated using an evidential reasoning approach. The evaluation model is further demonstrated through a comparative analysis of five major ports in China. The novel model developed along with the methods applied in this paper can provide significant insights for the comparative evaluation on the development of green ports in other countries and/or regions, as well as a powerful tool to conduct self-assessment of green port development.

Keywords: Green port development, DPSIR framework, evidential reasoning, maritime transport

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1. Introduction

As crucial nodes in international transport networks, ports play a significant role in promoting regional and global trade and economic development. For example, the cargo throughput of Ningbo-Zhoushan Port reached at 0.87 billion tons in 2014, ranking the first in the world (Wei, 2015). Meanwhile, a large amount of capital was invested in port infrastructure construction, reconstruction and maintenance due to the rapid development of ports. Due to such facts, more attention needs to be paid on the environmental protection urgently to ensure ports' sustainability while facilitating the development of port logistics in the coming decades. In spite of the fact that ports are not the direct places for production processing, nor it has a large amount of material consumption, it, however, is an important distribution center for various goods allowing a large number of vehicles and ships to be engaged in transport operations, which can be a source of contamination (discharge of waste gas and rubbish) (Chen, 2009; Chang and Wang, 2012). Apart from these traffic conveyances, there is certain pollution from goods themselves like coal dust, dangerous materials and chemicals, etc. A recent accident caused by chemical goods explosions in Tianjin Port (China) provides supporting evidence. A study (Ma *et al*., 2014) showed that in 2011, emissions of carbon dioxide (CO_2), nitrogen dioxide (NO_2) and dust from harbor districts in China reached about 127 thousand tons, 146 thousand tons and 1.2 million tons, respectively. They significantly contribute to the environmental deterioration in the country. Pollution from port operations will not only damage the ecological balance of nature and urban environment, but also cause adverse effect on global climate change, which further increases the risk associated with port operations. Development of low-carbon economy is considered to be a fundamental way to solve environmental problems. Nevertheless, port and shipping are still in absence of effective control measures for emissions of greenhouse gas, and the importance of sustainable development is still being ignored by many port authorities (Wang, 2014). In view of this ignorance, the concept of green port (or low-carbon port) was officially proposed in the United Nations Climate Change conference in 2009 (Wu and Ji, 2013). On the basis of organic combination of port development, utilization of resources and environmental protection, green port refers to the one characterized by healthy ecological environment, reasonable utilization of resources, low energy consumption and low pollution (Chen, 2009).

Started early in United States, Japan and other developed countries, prominent achievements have been obtained through active exploration and implementation of the planning and construction of green port (Gupta *et al*., 2005; Cai, 2010). As one of the advocates of green port, the Port of Long Beach has made remarkable achievements. The "green port" policy was launched in Port of Long Beach in January 2005 for the first time with a series of environmental protection plans developed from seven aspects, namely water quality protection, improvement of air quality, soil conservation, wildlife and habitat protection, alleviating traffic pressure, sustainable development and community participation (Lv, 2005). Since the implementation of the above environmental protection plans, the water quality of Long Beach has been much improved. Sydney Harbor carried out the Green Port Guidelines from other aspects, focusing on the importance of quality of the water and air, biological diversity, noise control, rubbish and dangerous cargo management, and environmental education and training, etc. (Lu and Hu, 2009). Strengthening legislation and enforcement was one of their main measures. In Italy, a shore power supply system was equipped in both Venetian Harbor and Port of La Spezia in 2010, leading to about 30% reduction of the CO_2 emissions, 95% reduction of the nitric oxide (NO) emissions, as well as significant noise reduction (Cai, 2010). In Tokyo Harbor, when planning the layout of the port, its influence on the environment is considered in terms of both ecological and living environment. It is also required that the port construction project and the environmental protection planning should be implemented simultaneously (Liu, 2004). The aforementioned countries apply "green" to their port operations and the future design of the port construction to strengthen the port infrastructure and its capability in dealing with emergency response.

In China, research on green port started relatively late. Shanghai Port actively explored the environmental protection measures for the port administration and listed the construction of ecological port as an important research subject. Based on the research of ecological development and countermeasures in Shanghai Port, an evaluation index system of green port development was proposed (Lin, 2010). Tianjin Port officially launched the research project related to green port development in October 2007, elaborating the concrete measures of development of green port from aspects of environmental protection, infrastructure, environmental pollution control, environmental risk prevention and management, development of environmental management system as well as the construction of green logistics networks (Wan *et al*., 2011). Lianyungang Port took the advantages of shore power technology in the control of pollutant emissions, energy saving and noise reduction, which brought considerable economic and social benefits (Yu, 2012). Qingdao Port introduced new equipment and new technologies to improve the working efficiency and to reduce the energy consumption.

Due to the great environmental impact from port operations and development, an increasing attention has been drawn from both industry and academia. Taking the situation of Kaohsiung Port as an example, Berechman and Tseng (2012) study the environmental costs of port related emissions with emphases on particular matter and volatile organic compounds. The results show that the combined environmental costs of ships and trucks are estimated to be more than 100 million USD per year. Lam and Notteboom (2014) investigate the role of port management tools in the development of green port from the perspective of policy and management. The situation from four leading ports in both developing and developed countries are also studied and compared. Song (2001) reveals that the problems associated with green port development, particularly in the developing countries.

a) There are a lot of old ports that came into service a few decades ago. Generally speaking, theses ports are lack of financial support and under the management with outdated techniques.

b) Weak consciousness of environmental protection and energy saving, which results in the limited resources allocated to conduct systematic and comprehensive analysis when conducting planning and design of a green port.

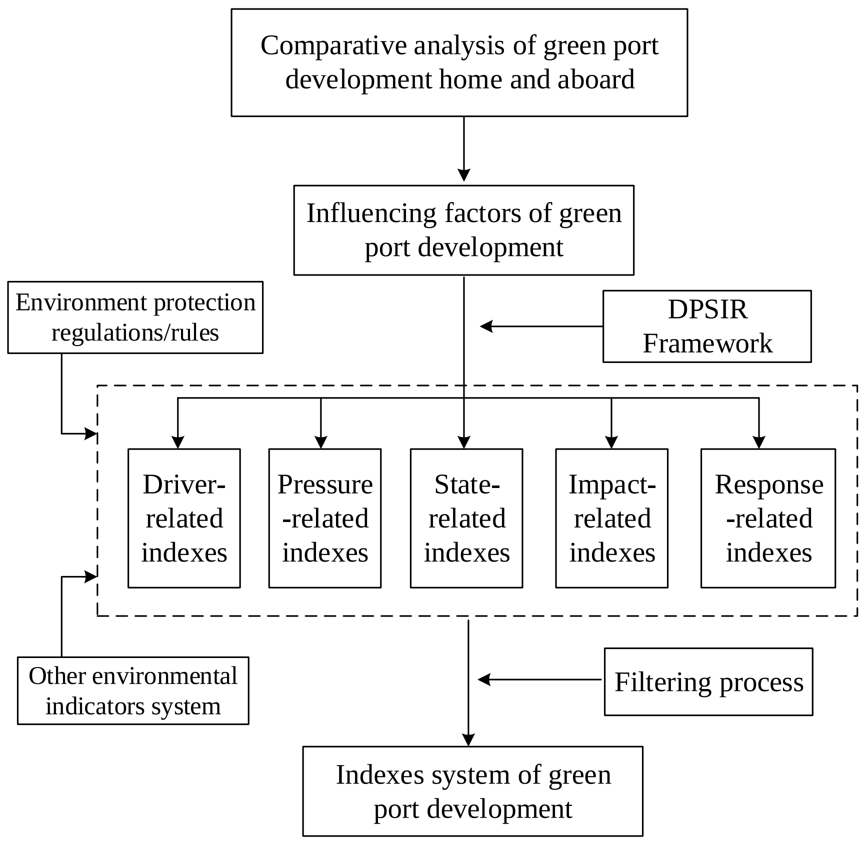
c) The incompleteness of important evaluation criteria for development of green port which causes certain blindness in the green port development and seriously affects the sustainable development of port resources, environment and economy.

As a result, it leads to a significant research gap to be fulfilled, wanting an appropriate green port evaluation model developed. This paper aims to establish a novel model for the comprehensive evaluation of green port development and propose supporting methods for realizing the quantitative measurement. To achieve the aim, the rest of the paper is organized as follows. The evaluation model is developed on the basis of the Drivers, Pressures, States, Impacts and Responses (DPSIR) framework in the following section. In the Section 3, background information on the methods used in this paper is introduced. The Analytic Hierarchy Process (AHP) method is applied to determine the weight of individual criterion at each level of the model and the estimations are aggregated to obtain the overall development status of green port using the Evidential Reasoning (ER) approach. Furthermore, this paper analyzes assessment grades for each criterion and converts both quantitative and qualitative criteria to the same utility space by employing a series of fuzzy membership functions. A case study on investigation of the green port development of five major ports in China is conducted in Section 4 to demonstrate the applicability of the proposed assessment model. The results from the five ports can also be used to benchmark their performance improvement individually as well as to compare their performance collectively. Section 5 concludes this paper with the relevant contributions and limitations being presented.

2. Modeling of green port development

Green port assessment requires a complex model involving many indexes including various concerns. These indexes should be comprehensive, quantitative or qualitative. They should also reflect the real-time changes, capable of adapting to the needs of social development, while maintaining a relative stability for the evaluation of green port in certain periods. The process of developing an assessment model (or an indexes system) for the evaluation of green port development is depicted as Figure 1, and the selection of indexes are further descried in the ensuing section.

Figure 1 –Flowchart of constructing an evaluation indexes system of green port



The assessment model developed in this paper consists of three levels. The top level reflects the goal of the model, which is to assess the development level of green port. The second level (Criteria Level) is constructed according to the DPSIR framework which was introduced in the late 1990s and then applied in the evaluation of sustainable development (Carr, *et al*., 2007). This framework enables the integration of different types of perspectives concerning environmental, social and economic issues, which have been successfully implemented in the evaluation of modernization of the inland port and shipping management (Wen and Chen, 2013). Thus, the idea of DPSIR framework is utilized in this research and the perspectives in Criteria Level are set to be Drivers (B1), Pressures (B2), States (B3), Impacts (B4) and Responses (B5). The indexes in the bottom level (Index Level) are chosen in terms of their associated counterparts in the upper level.

"Drivers" is primarily used to describe the indexes facilitating regional economic activities and industrial development, which may lead to environmental problems if over demanded. The throughput of port and its growth rate are important quantitative indexes in the evaluation of the production and business activities of a port. They also indicate the economic performance (e.g. gross regional domestic product) of the port. "Pressures" indicates the stress on sustainable development of resources, environment and the ecological systems inflicted by port daily operations. Among various factors influencing the port environment, dust pollution, water pollution, solid waste pollution and noise pollution are revealed as primary ones by recent studies (Maragkogianni and Papaefthimiou, 2015; Jiang, 2014; Berechman and Tseng, 2012; Chin and Low, 2010). "States" contains indexes that reflect the current condition of port environment. Indexes in the "Impacts" are selected in this study being able to address not only the operational efficiency but also the safety degree of ports, since these two significant aspects in the development of green port have been widely studied (Dong *et al*., 2011; Knapp and van de Velden, 2011). "Responses" focuses on the actions taken by port authorities to achieve a sustainable development of ports (Wang, 2014). After a study of the important characteristics of the green port development and an extensive examination of the literature, some of the most important indexes with respect to different perspectives of the DPSIR framework are identified. In the filtering process, all identified indexes are further verified through extensive discussions with domain experts. The detail information of the experts is shown as follows.

- Expert No.1: An experienced port manager with more than 8 years' experience in safety management of port operations in China.

- Expert No.2: A professor engaged in port performance research for more than 10 years with particular reference to environmental effects. He is also a senior consultant for the development of a major port in China.

- Expert No.3: A senior officer in charge of environmental protection from a leading port operator.

Finally, 16 indexes that make up the Index Level are selected due to their significant importance. They are categorized into qualitative and quantitative groups based on the availability of the associated data in collection. Interpretations of these indexes are provided in Table 1.

Table 1 – Interpretations of each index in the Index Level

Indexes	Interpretations	Reference
Drivers		
C1. Gross Domestic Product (GDP) per capita	GDP/ total population of the port city	(Goh, 2010) (Wang, 2014);
C2. GDP Growth Rate (GDPGR)	It reflects the economy development speed of a port city.	
C3. Port Throughput (PT)	It reflects a port's size and its final result of activities of production.	
C4. Port Throughput Growth Rate (PTGR)	It shows the development trend of a port's service capability.	
Pressures		
C5. Volume of Waste Water Discharged per Throughput (VWWDT)	It reflects the amount of waste water (whether treated or not) produced during the daily operation in a port.	(Chin and Low, 2010); (Berechman and Tseng, 2012); (Jiang, 2014); (Maragkogianni and Papaefthimiou, 2015)
C6. Volume of Waste Gas Emission per Throughput (VWGET)	Waste gas means the atmospheric pollutant mainly composed of sulfur dioxide, nitrogen oxides and inhalable particles.	
C7. Amount of Waste Residue Produced per Throughput (AWRPT)	Waste residue refers to solid or semi-solid waste materials during the production, consumption and other activities in a port.	
C8. Average Noise Level of Port (ANLP)	It reflects the quality of acoustic environment of a port.	
States		
C9. Ambient Air Quality Fine Rate (AAQFR)	The ratio is obtained through weather report statistics.	(Wang, 2014)
C10. Coverage Rate of Low-Noise Area (CRLNA)	It reflects the radio of area with good acoustic environment.	
Impacts		
C11. GDP per Throughput (GDPT)	It reflects the operational efficiency and professional ability of a port.	(Dong et al., 2011); (Knapp and van de Velden, 2011)
C12. Accident Frequency of Port (AFP)	Accidents here refer to those that have caused death or severe pollution in port area.	
Responses		
C13. Rate of Recycled Waste Water (RRWW)	It reflects the capacity of a port in dealing with wastewater.	(Goulielmos, 2000); (Stojanovic et al., 2006); (Karim and Susan, 2007)
C14. Rate of Comprehensive Utilization of Waste Residue (RCUWR)	It reflects the capacity of a port in dealing with solid wastes.	
C15. Emergency Response Capacity of Climate Change (ERCCC)	It refers to the ability of a port in emergency response to flooding, storm surge, sea level rising and other extreme negative effects caused by climate change.	

C16. Perfection Degree of Environmental Management System (PDEMS)	The establishment of the organization of environmental management, rules and regulations as well as rewarding and punishment measures are included in this index.	

3. Methodology

The following steps are developed in order to carry out the estimation of green port development (Zhang et al, 2015).

Step 1: Carry out the pairwise comparisons in each level of the hierarchical structure in terms of the relative importance of the identified parameters to the development of green port and calculate the weighting vectors of the indexes in the corresponding level.

Step 2: Develop a set of evaluation grades with respect to various criteria and fuzzy membership functions to transform quantitative criteria into qualitative ones using an information transformation technique.

Step 3: The ER algorithm is used to carry out the assessment for synthesizing the estimates of bottom level criteria in the hierarchical structure.

Step 4: The results are prioritized and compared by using utility values to obtain the development levels of the investigated green port(s).

Step 5: The proposed model is illustrated through a case study of some leading ports in China, and it is validated via a comparison analysis with the results obtained from an expert survey which reflects the green status of the investigated ports from an alternative perspective.

3.1 Analytical Hierarchy Process

AHP was developed by Satty (1980) and it was designed to solve complex multi-criteria decision making (MCDM) problems. AHP requires the decision makers to supply judgments about the relative importance of each criterion and then specify a preference for each decision alternative against each criterion. AHP is especially appropriate for complex decisions which involve the comparison of decision criteria that are difficult to quantify (Pillay and Wang, 2003). It is based on the assumption that when dealing with a complex decision the natural human reaction is to cluster the decision criteria according to their common characteristics. Since AHP was introduced three decades ago, many useful applications have been seen in the literatures, including but not limited to, assessment of environmental pollution (Abbaspour et al., 2015), industrial engineering application (Yang *et al*., 2003), and evaluation of green port (Maritz, 2014). This is because AHP has several useful characteristics (Anderson et al., 2003):

a) AHP can handle situations in which the unique subjective judgments of the individual decision maker constitute an important part of the decision making process.

b) Relative ease with which it handles multiple criteria.

c) AHP is easier to understand and it can effectively handle both qualitative and quantitative data.

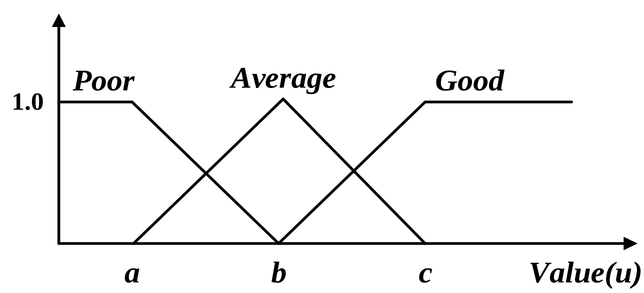
3.2 Membership Degree of evaluation indexes

As both the quantitative and qualitative indexes are included in the evaluation system, they should be transformed and presented in uniformed grades respectively.

3.2.1 Membership degree of quantitative indexes

This study defines the development of green port using three grades, namely, Good, Average and Poor. Membership degrees of quantitative indexes can be obtained through the graph of function shown in Figure 2, which is composed of fuzzy triangular and trapezoidal distributions.

Figure 2 – Graph of membership degree function



Here, *a* refers to the most possible value of Poor while *c* is the most possible value of Good, and b represents the most possible value of Average. Supposing the value of an index is *u*,

a) When $u \geq c$, the grading will be 100% Good;

b) When $u \leq a$, the grading will be 100% Poor;

c) When $a < u < b$, the grading will be $(b- u)/(b- a)$ Poor and $(u- a)/(b- a)$ Average;

d) When $b \leq u < c$, the grading will be $(c- u)/(c- b)$ Average and $(u- b)/(c- b)$ Good.

In this study, the standards of grading for quantitative indexes are obtained from a recent study (Wang, 2014) and in-depth discussions with the experts described in Section 2. They are shown in Table 2.

Table 2 – Grading for quantitative indexes

Quantitative index	*a*	*b*	*c*
C1 GDP (CNY/ person)	80000	100000	120000
C2 GDPGR (%)	5	7.5	10

C3 PT (10^4 ton)	30000	50000	70000
C4 PTGR (%)	5	7.5	10
C5 VWWDT (ton/10^4 ton)	1000	700	400
C6 VWGET (ton/10^4 ton)	1.5	1	0.5
C7 AWRPT (ton/10^4 ton)	1	0.6	0.2
C8 ANLP (db)	75	65	55
C9 AAQFR (%)	40	60	80
C10 CRLNA (%)	75	85	95
C11 GDPT (CNY/ ton)	1500	2500	3500
C12 AFP (accident number/ year)	2	1	0
C13 RRWW (%)	40	50	60
C14 RCUWR (%)	90	94	98

3.2.2 Membership degree of qualitative indexes

The grades of qualitative indexes are also described using Good, Average and Poor. Definitions of each grade for qualitative indexes (China Water Transportation Construction Association, 2013) are shown in Table 3.

Table 3 – Definition of each grade for qualitative indexes

Qualitative indexes	Definition of each grade		
	Good	Average	Poor
C15 Emergency Response Capacity of Climate Change	Complete emergency response plans	Partial complete emergency response plans	No emergency response plans
C16 Perfection Degree of Environmental Management System	Mature rules and regulations for management	Newly-built rules and regulations for management	Lack of rules and regulations for management

3.3 Evidential reasoning and utility value

ER was developed in the 1990s to deal with MCDM problems under uncertainty. The ER algorithm is based on the decision theory and the D-S (Dempster–Shafer) theory of evidence, which is well suited to handling incomplete assessment of uncertainty (Yang, 2001). The algorithm can be used to aggregate criteria of a multilevel structure. ER is widely used in many applications such as system safety, risk assessment, organizational self-assessment and supplier assessment (Chin *et al*., 2009; Liu *et al.*, 2008; Ren *et al.*, 2008).

The set $S(E) = \{(H_n, \beta_n), n = 1, \ldots, N\}$ represents a criterion E which is assessed to grade H_n with degree of belief β_n, $n = 1, \ldots, N$. Let $m_{n,i}$ be a basic probability mass representing the degree to which the ith basic criterion e_i supports the hypothesis that the criterion y is assessed to the nth grade H_n.

To obtain the combined degrees of belief of all the basic criteria, $E_{I(i)}$ is firstly defined as the subset of the first i basic criteria as follows:

$$E_{I(i)} = \{e_1, e_2, \ldots, e_i\} \quad (1)$$

Let $m_{n,I(i)}$ be a probability mass defined as the degree to which all the i criteria in $E_{I(i)}$ support the hypothesis that E is assessed to the grade H_n and let $m_{H,I(i)}$ be the remaining probability mass unassigned to individual grades after all the basic criteria in $E_{I(i)}$ have been assessed. Eq. (2) and Eq. (3) are obviously correct when $i = 1$.

$$m_{n,I(1)} = m_{n,1},\ n = 1, 2, \ldots\ldots, N \quad (2)$$

$$m_{H,I(1)} = m_{H,1} \quad (3)$$

By using Eq. (2) and Eq. (3), Eq. (4) can be constructed for $i = 1, 2, \ldots, L$-1 to obtain the coefficients $m_{n,I(L)}$, $\bar{m}_{H,I(L)}$ and $\tilde{m}_{H,I(L)}$ (Yang and Xu, 2002):

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \neq t}}^{N} m_{t,I(i)} m_{j,i+1}\right]^{-1} \quad (4)$$

$K_{I(i+1)}$ is a normalizing factor.

$\{H_n\}$:

$$m_{n,I(i+1)} = K_{I(i+1)}[m_{n,I(i)} m_{n,i+1} + m_{H,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1}]\ \ n = 1, 2, \ldots, N \quad (5)$$

$$\tilde{m}_{H,I(i+1)} = K_{I(i+1)}[\tilde{m}_{H,I(i)} \tilde{m}_{H,i+1} + \bar{m}_{H,I(i)} \tilde{m}_{H,i+1} + \tilde{m}_{H,I(i)} \bar{m}_{H,i+1}] \quad (6)$$

$$\bar{m}_{H,I(i+1)} = K_{I(i+1)} \bar{m}_{H,I(i)} \bar{m}_{H,i+1} \quad (7)$$

$\{H\}$:

$$m_{H,I(i)} = \tilde{m}_{H,I(i)} + \bar{m}_{H,I(i)},\ i = 1, 2, \ldots, L - 1 \quad (8)$$

The combined degrees of belief of all the basic criteria for the assessment to criterion E are calculated by:

$$\{H_n\}: \beta_n = \frac{m_{n,I(L)}}{1 - \bar{m}_{H,I(L)}},\ n = 1, 2, \ldots, N \quad (9)$$

$$\{H\}: \beta_H = \frac{\tilde{m}_{H,I(L)}}{1-\bar{m}_{H,I(L)}} \tag{10}$$

However, it is difficult to rank the development levels of green port by using belief degrees associated with linguistic terms (i.e. Good, Average, Poor) because they are not sufficient to show the difference between the results. Numerical values (crisp values) are therefore generated from the obtained distributed results. The concept of expected utility is used to obtain a crisp value for each alternative in order to rank them in terms of green port development levels.

Suppose the utility of an evaluation grade H_n is denoted by $u(H_n)$ and $u(H_{n+1}) > u(H_n)$ if H_{n+1} is more preferable than H_n (Yang, 2001). Therefore, the utility of the general criterion can be calculated using a linear distribution as Eq. (11) and Eq. (12):

$$u(H_n) = \frac{n-1}{N-1},\ n = 1, 2, \ldots, N \tag{11}$$

where, N denotes the number of the linguist terms.

$$u(E) = \sum_{n=1}^{N} \beta_n u(H_n) \tag{12}$$

In this way, a crisp value can be calculated based on the distribution generated via the ER technique and a comparison between alternatives can therefore be carried out.

4. Case study

In this paper, five major ports in China (Port A, B, C, D and E) are selected and investigated to analyzes their green performance. These five ports have carried out a series of pioneering research projects on the technologies of energy saving and emission reduction of port, so they hold relative leading positions in the green port development in China. Besides, in 2013, they are among the ten biggest ports in the world in terms of their throughputs (360 documents, 2014). Data of their performance in 2013 has been collected through official statistics, questionnaires and field investigation.

4.1 Calculation of the weights of evaluation indexes

Pairwise comparisons are made by three domain experts mentioned in Section 2 through in-depth interviews and the weights of each index in the assessment model are obtained using the AHP method. Since the knowledge and experience of all three experts involved are considered as equivalent, the normalized relative weight of every expert is equally assigned while combining their judgments. Similar process can be implemented to each level and the weighting vectors of all pairwise comparison matrixes can be obtained, to represent the local importance degree of each index. The weights of all the indexes are shown in Table 4.

Table 4 – Weights of each index of the assessment model

Goal Level	Criteria Level	Index Level	Local Weights	Global Weights
Development of Green Port	Drivers 0.317	C1	0.334	0.107
		C2	0.181	0.057
		C3	0.323	0.102
		C4	0.162	0.051
	Pressures 0.174	C5	0.274	0.048
		C6	0.233	0.041
		C7	0.215	0.037
		C8	0.278	0.048
	States 0.120	C9	0.5	0.060
		C10	0.5	0.060
	Impacts 0.072	C11	0.333	0.024
		C12	0.667	0.048
	Responses 0.317	C13	0.237	0.075
		C14	0.264	0.084
		C15	0.208	0.066
		C16	0.291	0.092

4.2 Evaluation results of the investigated ports

Historical objective data used in the evaluation of quantitative indexes were collected from official statistics from the cities in which the five investigated ports are located, news, statistical yearbooks (Economic BBS by Renmin University of China, 2014) and recent research literature (Wang, 2014; Gao, 2013). They are shown in Table 5.

Table 5 – Values of quantitative indexes of five ports

Qualitative indexes	Value				
	Port A	Port B	Port C	Port D	Port E
C1 GDP (CNY/ person)	90092	99607	103493	185269	129356
C2 GDPGR (%)	5.5	6.9	9.6	13.8	9.3
C3 PT (10^4 ton)	77574	50063	45783	47199	33373
C4 PTGR (%)	5.5	5	10.6	4.8	10.1
C5 VWWDT (ton/10^4 ton)	803	458	361	964	603
C6 VWGE T(ton/10^4 ton)	0.8	1.4	0.6	0.4	1.1
C7 AWRP T(ton/10^4 ton)	0.7	0.8	0.5	0.3	0.4
C8 ANLP (db)	67.9	67.6	68.9	67.6	68.9
C9 AAQFR (%)	66.0	64.3	72.9	71.2	79.5
C10 CRLNA (%)	85	81	88	98	93
C11 GDPT (CNY/ ton)	2784	2839	1748	3281	2290

C12 AFP (accident number/ year)	0	0	1	1	0
C13 RRWW (%)	45	50	60	45	50
C14 RCUWR (%)	97.1	98.9	96.0	95.7	97.9

Evaluation results of each quantitative index can be calculated and expresses by Good, Average and Poor according to the membership functions and standards in Table 2, while those of qualitative indexes are determined according to experts judgments by use of standards in Table 3. Judgments from the three experts described in Section 2 are merged together with equal weights. Taking the Port A as an example, its GPDGR is 5.5%, locating between "a" (5) and "b" (7.5). As a result, 5.5% belongs to "7.5" (Average) with 20% degree of belief and "5" (Poor) with 80% degree of belief. The evaluation results (grades) are shown in Table 6.

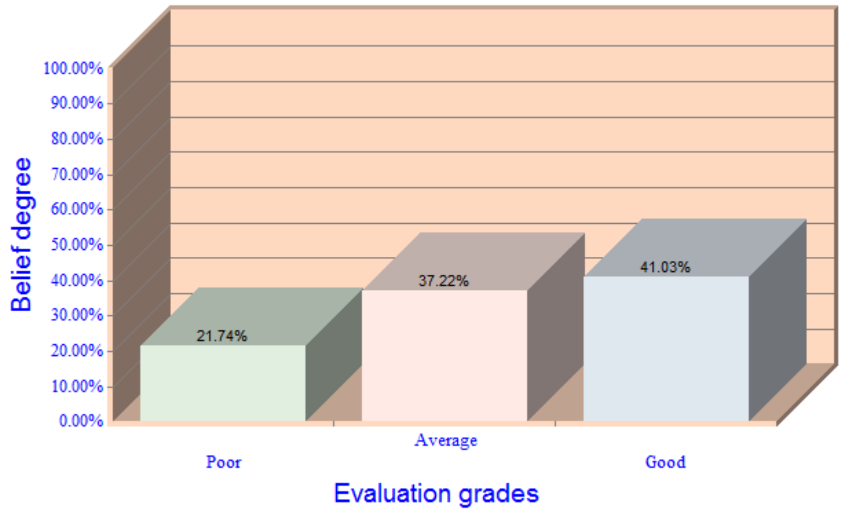
Table 6 – Evaluation of each index of Port A in 2013

Criteria Level	Index Level	Grade		
		Good	Average	Poor
Drivers	C1 GDP		0.5	0.5
	C2 GDPGR		0.2	0.8
	C3 PT	1		
	C4 PTGR		0.2	0.8
Pressures	C5 VWWDT		0.66	0.34
	C6 VWGET	0.4	0.6	
	C7 AWRPT		0.75	0.25
	C8 ANLP		0.71	0.29
States	C9 AAQFR	0.3	0.7	
	C10 CRLNA	0.4	0.6	
Impacts	C11 GDPT	0.28	0.72	
	C12 AFP	1		
Responses	C13 RRWW		0.5	0.5
	C14 RCUWR	0.78	0.22	
	C15 ERCCC	0.7	0.3	
	C16 PDEMS	0.7	0.3	

4.3 Evaluation of development of green port

In this section, the IDS software (Xu & Yang, 2005) was used to compute the development of Port A, employing the ER algorithm for synthesis of the criteria in the hierarchical structure. All the inputs with weightings of the relevant lowest level criteria are combined to determine the estimation of their corresponding higher level criteria. Based on the results in Table 6, the green performance of Port A can be calculated and shown in Figure 3.

Figure 3 –Green performance of Port A

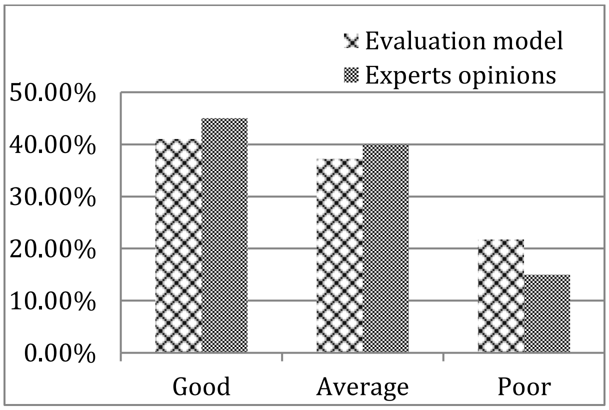


It can be seen from Figure 2 that the green performance of Port A in 2013 is evaluated as 21.74% poor, 37.22% average and 41.03% good. Thus, utility value of Port A development can be calculated as 0.5964 using Eq. (11) and Eq. (12). Similarly, the utility values of all ports can be calculated and ranked as *u* (Port A) =0.5964 ＜*u* (Port B) =0.6120＜ *u* (Port D) =0.7190＜ *u* (Port C) =0.7332 ＜*u* (Port E) =0.7595. Meantime, the crispy values associated with each investigated port can be used as a benchmark to measure their green performance improvement in a longitude study (e.g. Zhang et al, 2015).

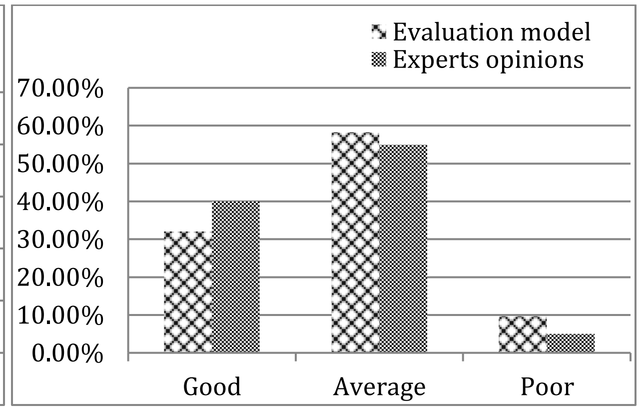
4.4 Validation

In order to validate the evaluation results from the proposed model, another 20 experts involved in port operation and management are interviewed to give their opinions on the green performance of these five ports in 2013. All the statistical data are given to them before making their decisions. Considering the similar working experiences in terms of sustainable development of port, all these experts are treated equally when emerging their opinions. The green performance of the five ports from experts' judgments can be obtained in the following way. Supposing there are five experts believing that the green performance of Port A is "Good" , while the other fifteen experts think that it should be "Average", then the probability given to "Good" is 5/20 = 0.25, and that given to "Average" is 15/20 = 0.75. The results obtained from the proposed evaluation model and that from experts opinions are presented and compared, as shown in Figure 4.

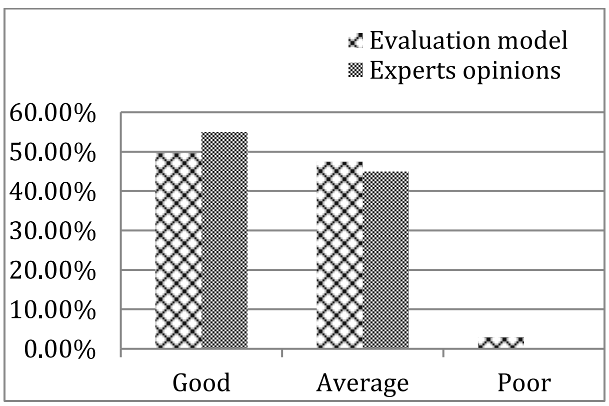
Figure 4 –Comparison of green performance evaluation of each port



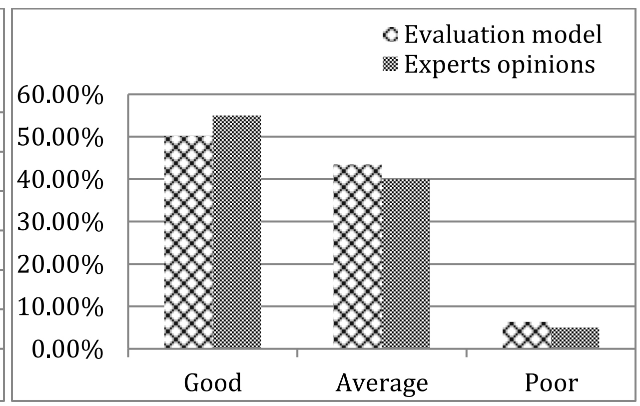
(1) Port A



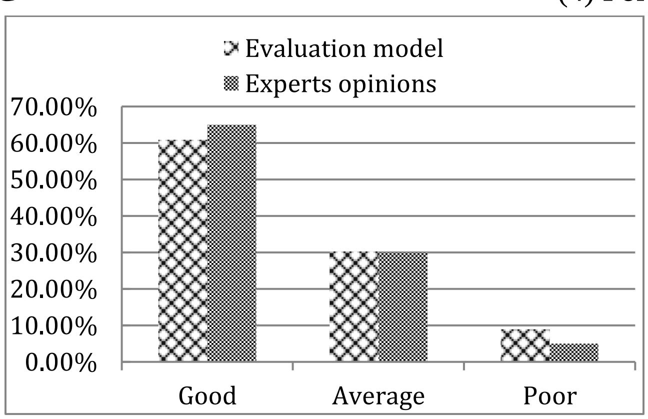
(2) Port B



(3) Port C



(4) Port D



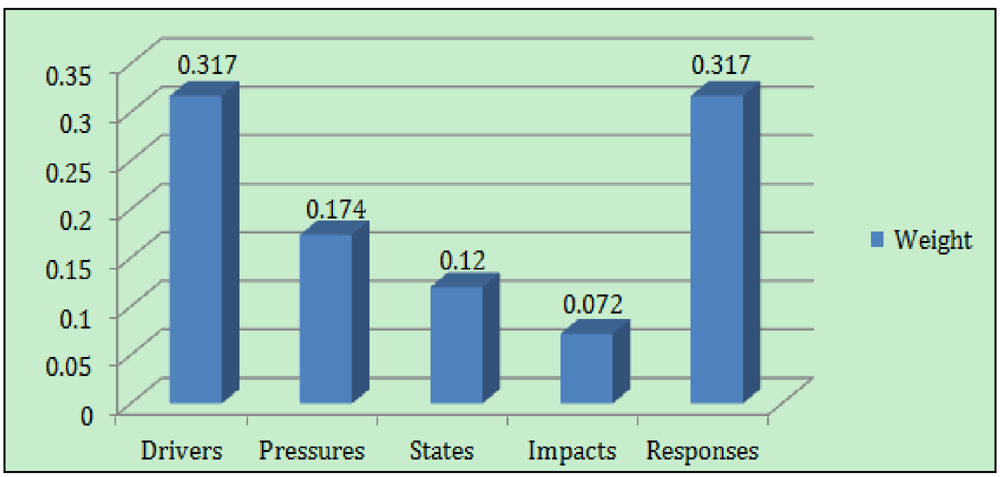
(5) Port E

The figures above show that the results from the evaluation model are in harmony with expert judgments, which demonstrates the feasibility of the proposed model. After that, the same functions (Eq. (11) and (12)) are used to calculate the utility values of each port. They are ranked as *score* (Port A) =0.65 < *score* (Port B) =0.675 <*score* (Port D) =0.75 <*score* (Port C) =0.775 <*score* (Port E) =0.8. The ranking obtained from experts' judgments shows a consistency with that obtained from the evaluation model and historical data, further reflecting the validity and reliability of the proposed model. However, the proposed model has superiority in terms of tackling uncertainty in data, and providing a tool for performance benchmark.

4.5 Discussion

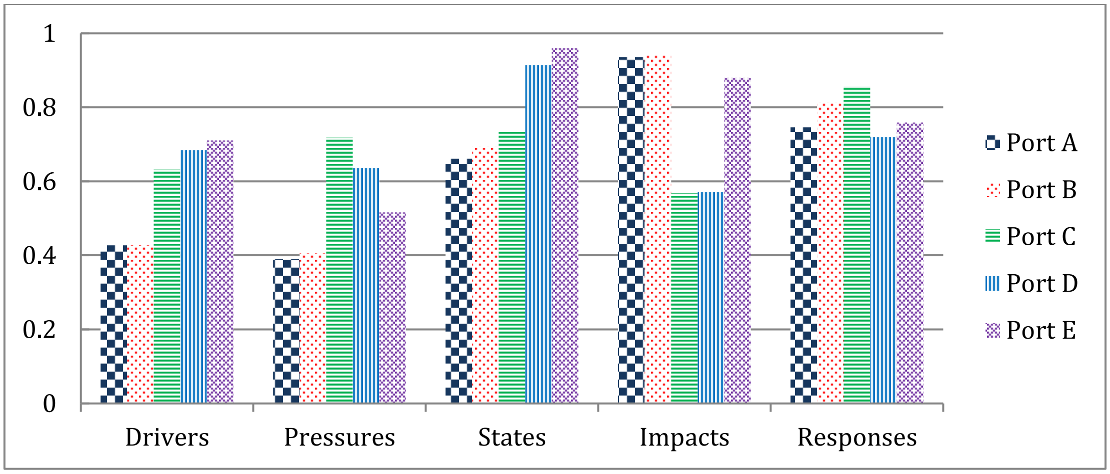
Shown as Figure 5, the indexes "Drivers" and "Responses", sharing the same weight of 0.317, take the highest importance in criteria level than others. Within the "Drivers", "GDP per capita" (C1) is the most important index with a weight of 0.334, while "Perfection Degree of Environmental Management System" (C16) is the most important indexes in the "Responses".

Figure 5 – Weights of each index in criteria level



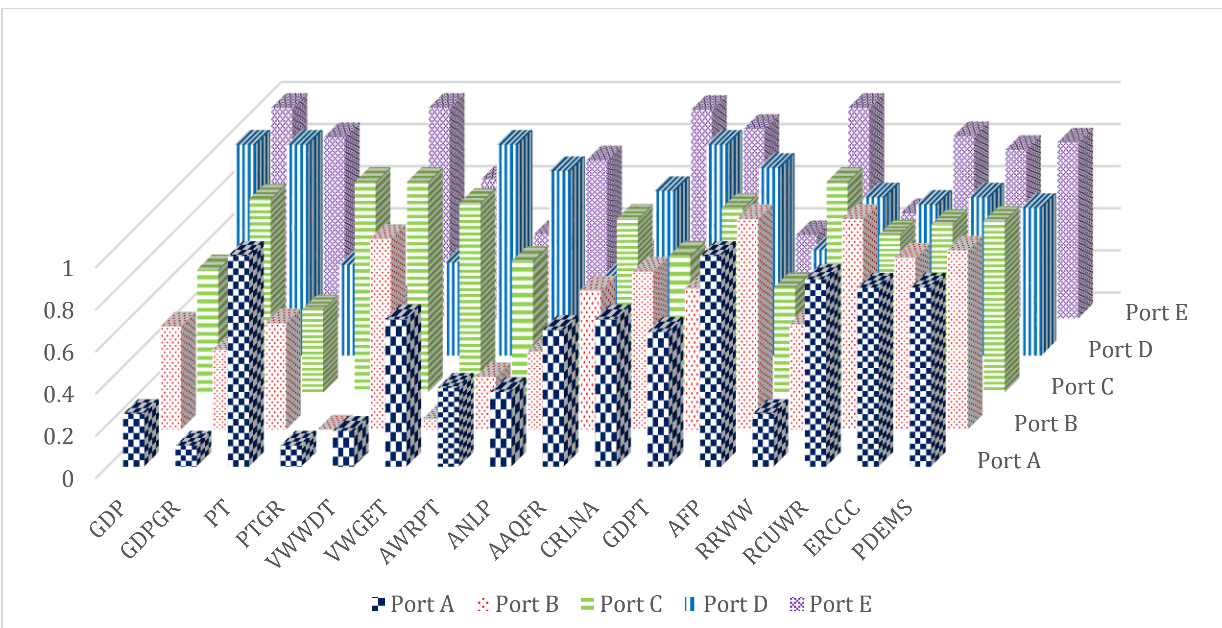
The variation trends of values of Criteria Level are virtually presented in Figure 6.

Figure 6 – Utility values of indexes in Criteria Level of different ports



The rankings of Port E remain first in Figure 5 against “Drivers” and “States”. While, Port A having the lowest values against “Drivers”, “Pressures” and “States”, shows less performance in green port development evaluation.

Figure 7 – Utility values of indexes in Index Level of different ports



The utility value of each index at the bottom level is shown in Figure 7. Taking Port A as a simple illustration, it is clear that Port A performs well in terms of Port Throughput (PT), ranking the first (nearly 776 million tons in 2013) compared to other ports. While, its growth rate is relatively low, which reflects a trend of slow development of its service capability in recent years. Thus, from the perspective of stakeholders, more effort such as deepening cooperation with shipping companies, updating equipment, and improving port service level are needed in order to facilitate the development of its throughput. The Volume of Waste Water Discharged per Throughput (VWWDT) is a negative index, which means that the more waste water a port discharges, the lower the utility value it holds. Port A discharged 8.03 million tons waste water per throughput in 2013 (referring to the historical data in Table 5), which is twice more than the amount of Port C, resulting in its lowest ranking. Also, its performance is not satisfactory in terms of the discharge of waste residues (see index AWRPT). Thus, from the results of the above two indexes, Port A is highly recommended to make more efforts on controlling the pollutant emission on both waste water and residues in future. The Accident Frequency of Port (AFP) indicates the safety status of a port, from which it can be seen that Port A had been keeping a high level of safe operations during 2013 without any fatality caused by accidents or severe pollution in the port area. The relative high utility values of index ERCCC and PDEMS reflect good performance of Port A to response to negative effects caused by climate change, as well as to manage the port environment in a standardized way. By conducting similar analysis on other ports, the advantages and disadvantages of development of green port can be identified and analyzed as well. Therefore, the assessment model developed in this paper can be applied not only in the evaluation of current situation of green port development, but also as a tool to provide port managers with certain insights on improving daily operations.

5. Conclusion

In this study, a novel model for the quantitative evaluation of green port development has been established, composing of 16 indexes which are generated and classified according to the DPSIR framework. The AHP and ER methods are integrated into the hierarchical model to calculate the relative importance of indexes within each level and deal with the estimate synthesis in order to achieve the evaluation of the top level. The proposed model is further demonstrated in a real case study through comparative analysis of the development level of five major ports in China. The limitation of this study lies on the ignorance of possible relationships among the indexes in the developed model. Thus, advanced models capable of addressing the interdependencies among the indexes should be generated in the future work.

This paper contributes to the existing literature of green port development considering both developing and developed countries. It also serves as an exploratory study to apply the idea of DPSIR framework in the field of green port, and to develop a set of suitable indexes system for the quantitative evaluation of its development. This work will promote the development of sustainable and green theory in the port industry. Furthermore, the evaluation results generated from the empirical study of port cases in China reveal their advantages and deficiencies in terms of the green port development. Thus, the novel model and flexible methods presented in this paper will not only be applicable for evaluating the development level of green ports, but also capable of providing useful insights and guide for port authorities and the stakeholders to formulate management measures and ensure their green port development.

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