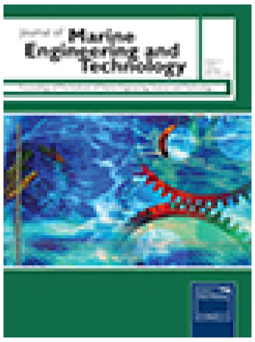

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Evaluating navigation safety for harbours in Taiwan: An empirical study

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The purpose of this study is to develop a model to evaluate navigation safety for vessels sailing to Taiwanese commercial harbours, based on a dataset of marine casualties. In order to devise the practical model, linear programming and Data Envelopment Analysis (DEA) are applied to develop a DEA model algorithm. Firsly, a simplified DEA model structure is constructed with one input variable, eleven output variables and four decision-making units (DMUs). Then, a dataset of marine casualties are employed to obtain all variables, as well as to appraise the superiorities of all DMUs. Finally, utilising a DEA solver, the highest navigation safety for the DMUs can be evaluated. Furthermore, an empirical survey of navigation safety in Taiwanese commercial harbours is performed to appraise the systematic approach, ie, the DEA model. The results of this study show that: (1) Keelung and Kaohsiung are the most dangerous harbours; (2) Taiwan's safest commercial harbour is Haulien, followed in ranking by Taichung, Kaohsiung and Keelung; (3) Based on the algorithm of the proposed DEA model, the results can reflect reality.

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INTRODUCTION

The main and most important type of human activity at sea is shipping. While shipping is perhaps the most international of all the world's great industries it is one of the most dangerous. Ships encounter enormously increasing risks and uncertainties.[1] Navigation safety, security and marine casualties affect not only the safety of life and property at sea but also the safety of the marine environment.[2] Improving navigation safety has been pursued zealously by all shipping-related organisations, especially the International Maritime Organization, IMO. Also, policies, training and strategies are enforced on the shipping industry, so shipowners and seafarers have to make greater efforts to maintain navigation safety to preserve the marine environment and avoid marine casualties.

Four commercial harbours in Taiwan – Keelung, Taichung, Kaohsiung and Haulien – have been playing their part in assuming responsibility for the safety of cargoes and preserving port safety, while the harbour bureaus have been considering sea-area safety as an important criterion to preserve navigation safety. Furthermore, the safe and efficient navigation of a ship depends on various factors, such as the navigational features of the ship, the ship's geographical environment, the ship's navigation process, and the maritime navigation safety and efficiency system.[2] It is obvious that, by promoting navigation safety for seafarers and vessels, marine casualties can be avoided, the safety of people and property at sea can be advanced, and the marine environment can be protected from pollution by ships. Thus, the safety of Taiwan's commercial harbours has become an important issue of discussing how to avoid marine casualties and how to maintain high navigation safety for vessels.

There are increasing scopes of automation, particularly with regard to navigation systems in vessels, that impact on the human element.[3,4] New technological aids have been derived from efforts to increase the safety of marine navigation, including the Electronic Chart Display and Information System (ECDIS), Automatic Identification System (AIS), Global Positioning System (GPS), Automatic Radar Plotting Aid (ARPA) and Integrated Bridge System (IBS).[2,4,5,6,7,8] Therefore, evaluating the level of navigation safety within commercial harbours is beneficial to seafarers. However, experience has shown that the evaluating process is a multi-criteria problem. It involves a multitude of complex considerations and a decision-making tool is crucial.

Data Envelopment Analysis (DEA) has been widely applied to address various decision analysis problems due to its usefulness in evaluating multi-criterion systems and providing improvement targets.[9,10] An important feature of DEA is that it can provide efficiency scores, while taking account of both multiple inputs and multiple outputs.[10,11] The benefits of DEA are detailed in the next section.

This paper describes the development of a practical model for navigation safety application, the research methodologies, the construction of a DEA structure, and the empirical study. Finally, some conclusions are detailed in the last section.

RESEARCH METHODOLOGIES

Data Envelopment Analysis (DEA), developed by Charnes, Cooper and Rhodes (the CCR model),[12] provides a nonparametric methodology for evaluating the efficiency of each set of comparable decision-making units (DMUs).[13] In the original model,[12] efficiency is represented by the ratio of weighted outputs to weighted inputs. An important feature of DEA is that it can provide efficiency scores, while taking account of both multiple inputs and multiple outputs.[11]

DEA has been widely applied to address various decision analysis problems due to its usefulness in evaluating multi-criterion systems and providing improvement targets for such systems.[9] It can transform multiple resources into multiple problems. Efficiency has been calculated using variable returns to scale the input oriented model of the DEA methodology.

Data envelopment analysis

DEA is a linear programming technique initially developed to evaluate the efficiency of public sector non-profit organisations.[12] Consider n units, each is called a DMU, that convert i inputs into j outputs, where i can be larger than, equal to or smaller than j. To measure the efficiency of this converting process for a DMU, the use of the maximum of a ratio of weighted outputs to weighted inputs for that unit is proposed, subject to the condition that the similar ratios for all other DMUs are less than or equal to one. The fractional form of a DEA mathematical programming model is given as follows:[11]

$$
\begin{aligned}
& Max \quad h_k = \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}} \\
& s.t \quad \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \le 1, \qquad j = 1,2,\dots,n \qquad (1) \\
& u_r \ge 0, \qquad r = 1,2,\dots,s \\
& v_i \ge 0, \qquad i = 1,2,\dots,m
\end{aligned}
$$

where:
u_r = the weight for output r;
v_i = the weight for input i;
y_{ij} = the amount of output r of DMU_j;
x_{ij} = the amount of input i of DMU_j;
S = the number of outputs;
m = the number of inputs and;
n = the number of $DMUs$.

The dual model of DEA

DEA measures the relative efficiency of each DMU in comparison to other DMUs. An efficiency score of a DMU is generally defined as the weighted sum of outputs divided by the weighted sum of inputs, while weights need to be assigned. There is a potential difficulty in assigning weights that give the highest possible relative efficiency score to a DMU while keeping the efficiency scores of all DMUs less than or equal to 1 under the same set of weights. [9,11,12,13]

The function (1) seeks to maximise the efficiency score of a *DMUj* by choosing a set of weights for all inputs and outputs. A *DMUj* is considered efficient if the objective function of associated function (1) problem results in an efficiency score of 1, otherwise it is considered inefficient.[9,13]

By moving the denominator in the first constraint set in function (1) to the right-hand side and setting the denominator in the objective function to 1, function (1) can be converted into a linear programming problem as function (2):[12,13]

$$
\begin{aligned}
& Max \quad h_k = \sum_{r=1}^{s} u_r y_{rk} \\
& s.t \quad \sum_{i=1}^{m} v_i x_{ik} = 1 \\
& \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0, \qquad j = 1,2,\dots,n \qquad (2) \\
& u_r \ge 0, \qquad r = 1,2,\dots,s \\
& v_i \ge 0, \qquad i = 1,2,\dots,m
\end{aligned}
$$

The dual model of function (2) can be given as follow:

$$
\begin{aligned}
&Min \quad h_k = \theta \\
&s.t \quad \theta x_{ik} = \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- \\
&\qquad y_{rk} = \sum_{j=1}^{n} \lambda_j y_{rj} - s_j^+ \\
&\lambda_j \geq 0, \qquad j = 1,2,\ldots,n \\
&i = 1,2,\ldots,m, \quad r = 1,2,\ldots,s
\end{aligned} \tag{3}
$$

where θ, λ_j, S_i^-, S_j^+ are the dual variables.

Base on function (3), a DMU_j is efficient if and only if, in the dual optimal solution, $\theta = 1$, and $S_i^{-*} = S_j^{+*} = 0$ for all i and j, where an asterisk denotes a solution. In this case, the optimal objective function value of function (3) is 1, and the corresponding primal problem of function (2) also has an optimal objective value of 1. For an inefficient DMU, appropriate adjustments to the inputs and outputs can be applied in order to improve its performance to become efficient.[9,13]

DEVELOPMENT OF DEA STRUCTURE

A DEA structure which can be utilised to study the benefits among DMUs is the framework of system structure. It can help harbour bureaus to explore the impact of different variables against the evaluated system. In this paper, a DEA structure with one input variable, eleven output variables and four DMUs is constructed, as shown in Fig 1.

'Maritime casualty' is defined in International Maritime Organization (IMO) Resolution A.849 (20), Code for the Investigation of Marine Casualties and Incidents (IMO, 1997). The Code was accepted and passed on 27 November 1997.[14] In the Code, marine casualty means an event that has resulted in any of the following:

- the death of, or serious injury to, a person;
- the loss of a person from a ship;
- the loss, presumed loss or abandonment of a ship;
- material damage to a ship;
- the stranding or disabling of a ship, or the involvement of a ship in a collision;
- material damage to marine infrastructure external to a ship, that could seriously endanger the safety of the ship, another ship or an individual;

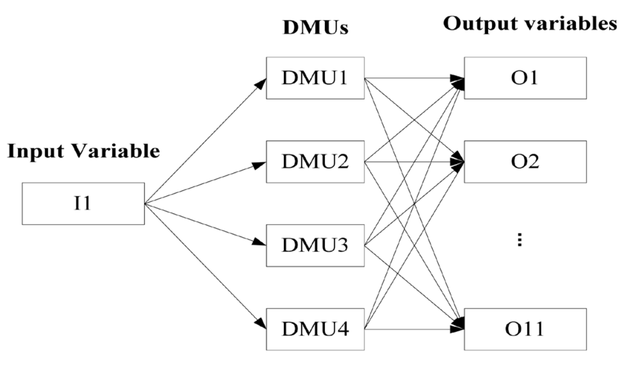

Fig 1: DEA structure

- severe damage to the environment, or the potential for severe damage to the environment, brought about by the damage of a ship or ships.

Marine casualties can be caused by a variety of means – collision or contact, capsize, foundering, sinking, breaking-up, grounding, stranding, fire or explosion, breakdown of the ship underway, or bad weather conditions.[15] Casualties that resulted in deaths include causes such as weather, machinery, foundering, stranding, collision, capsizing, fire and explosion, ship missing and other casualty.[16,17] Previous research[18] found an advantage in distinguishing between five different causes of death at sea: death through maritime disasters, occupational accidents, illnesses, crewing personnel missing at sea and suicides, homicides and unexplained causes. Port safety can be evaluated by GRA*, which be applied to accident sites where marine casualties occurred, and be categorised by six casualty types related to navigation safety, including collision, stranding or grounding, contact, fire or explosion, machinery parts damage and list or capsize.[8]

Numerous variables need to be considered in a multiple input, multiple output evaluation problem. In this paper, the variables[15,19] are eleven key multiple outputs to show the navigation safety variables. These key multiple outputs are collision, stranding, leaking, fire, listing, structural failure, machinery failure, inter-twisting, heavy weather damage, missing vessel, and others. According to certain viewpoints,[15] any harbour bureau should concentrate on reducing marine casualties and any seafarers should concentrate on maintaining the seaworthiness of vessels. On the other hand, the multiple input, based on the port statistics data, are derived from port publications, official Taiwan sources and literature review.[15,19] Eleven output variables and one input variable are suggested and their codes are shown below in parentheses.

1) Input variable (I). This variable is a multiple input, berth (I1) – the number of berths of each Taiwanese commercial harbour, ie, a ship's allotted place at a wharf or dock. With this variable, the production capacity invested by the port can be gained.

* GRA is Grey Relational Analysis, and in Grey System Theory is a famous technique that has been used in the last three decades. Grey System Theory, initiated by J-L Deng, is a useful method that is applicable to uncertain problems with too little data or information. It is mainly utilised to discuss uncertainties in system models, analyse relations between systems, establish models, and make forecasts and decisions.

GRA is one of the more important methods in the Grey System. Recently, the GRA has been become very popular in a number of domains such as supply chain model, customer satisfaction, e-learning system. In Grey System Theory, GRA is essentially believed to have captured the similarity measurement or relations in a system. GRA can also be used as a measure of the absolute point-to-point distance between sequences. In other words, GRA can be viewed as a measure of similarity for finite sequences.

2) Output variable (O).This variable includes eleven multiple outputs: collision (O1), stranding (O2), leaking (O3), fire (O4), listing (O5), structural failure (O6), machinery failure (O7), inter-twisting (O8), heavy weather damage (O9), missing vessel (O10), others (O11). Output variable means a variety of marine casualties were occurred at sea by ships.
3) Decision-making Unit (DMU). This variable includes the four Taiwanese commercial harbours: Keelung (DMU1), Taichung (DMU2), Kaohsiung (DMU3), and Haulien (DMU4).

EMPIRICAL STUDY

In this section, an empirical study evaluating navigation safety for the four commercial harbours is utilised to demonstrate the computational process of the DEA model, described above. The process of the algorithm is empirically implemented as follows.

In this navigation safety DEA structure, the number of berths in Taiwanese commercial harbours is the input variable. It represents not only the production capacity but also the maximum service volume invested by the port. The number of berths in Taiwanese commercial harbours is shown in Table 1.

Harbours	Berths
Keelung	56
Kaohsiung	118
Taichung	50
Hualien	25

Table 1: The number of berths in Taiwanese commercial harbours

The data of marine casualties in Taiwanese commercial harbours from 1992 to 2003 are displayed in Table 2, and Fig 2

DEA model design and data collection

In this step, one input variable, eleven output variables and four commercial harbours were used to design the DEA model, which comprises the navigation safe evaluating system. A harbour is normally able to approximately predict its number of berths, at least for the port capacity introduction. It can also attempt to predict its longer-term marine casualty statistics by historic dataset. In this case, the data are mainly taken from the marine casualty database of each of the four Taiwanese harbours. The latest data available on port marine casualties[19] was for 1992–2003, and this was chosen as the basis for the analysis

From 1992–2003, there were 3248 marine casualties nearby Taiwanese commercial harbours. The annual average event is 271. Table 3 shows the aggregated data from 1992–2003 for the input and output variables mentioned above. Table 4 shows the statistics of a variety of ship marine casualties incurred at Taiwanese commercial harbours.

Empirical results

The following steps were taken to compute the navigation safety ratings for the four harbours. According to the method presented in function (1), the data of 3248 marine casualties is used to seek to maximise the efficiency score of a DMU by choosing a set of

Harbours	Collision	Stranding	Leaking	Fire	Listing	Structural	Machinery	Inter-twisting	Heavy weather damage	Missing vessel	Other
Keelung	341	84	63	69	8	86	268	47	122	4	200
Kaohsiung	262	114	62	190	26	25	642	26	89	10	127
Taichung	92	27	5	18	11	0	5	3	4	1	39
Hualien	63	13	10	2	0	9	14	6	14	1	46
Total	758	238	140	279	45	120	929	82	229	16	412

Table 2: Statistical data of marine casualties in Taiwanese commercial harbours

DMU	Input variable	Output variables										
	I1	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11
Keelung harbour	56	341	84	63	69	8	86	268	47	122	4	200
Kaohsiung harbour	118	262	114	62	190	26	25	642	26	89	10	127
Taichung harbour	50	92	27	5	18	11	0	5	3	4	1	39
Hualien harbour	25	63	13	10	2	0	9	14	6	14	1	46

Note: Input variable (I).This variable is a multiple input, berth (I1).
Output variable (O).This variable includes eleven multiple outputs: collision (O1), stranding (O2), leaking (O3), fire (O4), listing (O5), structural failure (O6), machinery failure (O7), inter-twisting (O8), heavy weather damage (O9), missing vessel (O10), others (O11).

Table 3: The DAE collecting value of all input variable and output variables

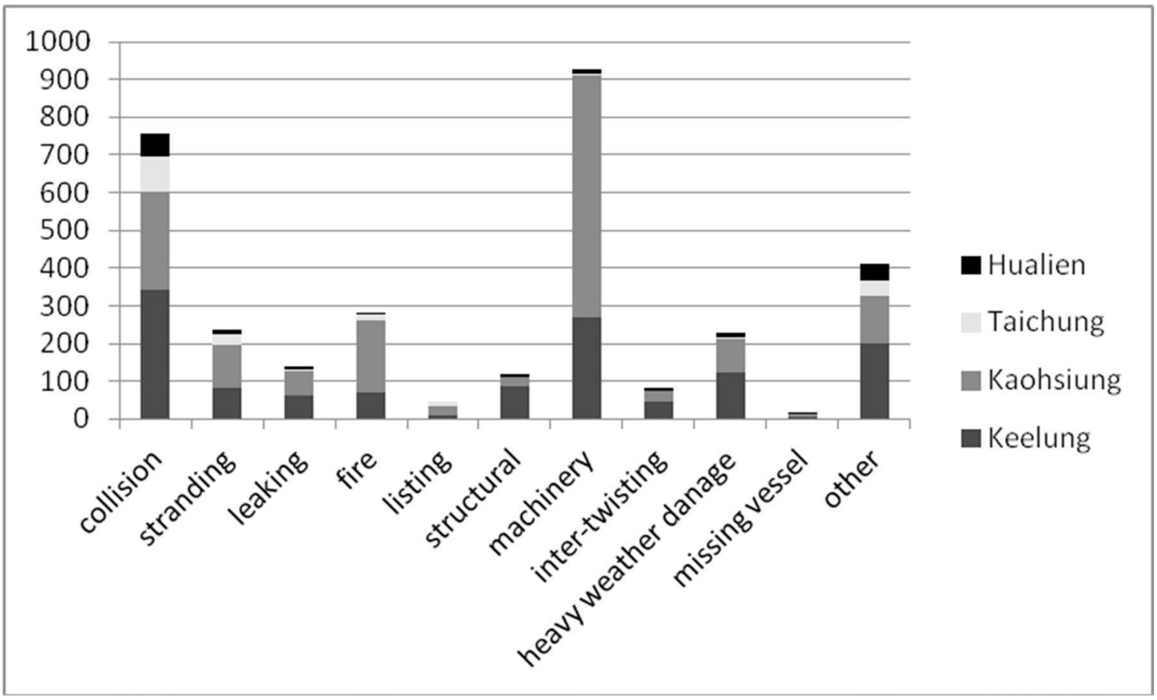

Fig 2: Distribution of marine casualties in Taiwanese commercial harbours

	Input variable	Output variables										
	I1	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11
Max	118	341	114	63	190	26	86	642	47	122	10	200
Min	25	63	13	5	2	0	0	5	3	4	1	39
Average	62.25	189.5	59.5	35	69.75	11.25	30	232.25	20.5	57.25	4	103
SD	34.223	115.89	41.20	27.56	73.70	9.42	33.55	259.07	17.68	49.77	3.67	65.82

Table 4: The statistics on all input and output variables

weights for all input and output variables. Before DEA analysis, a correlation analysis is conducted between all input and output variables, shown in Table 5. As a result, it has a positive correlation between all variables in this DEA model.

Furthermore, Table 6 shows the weight of all input and output variables, which were calculated with the DEA-Solver Pro5.0/ CCR-I model.[12] They are also shown as v_i and u_r in equation (2). In the most beneficial circumstances of Keelung harbour, the weight value of collision (u_1) is 0.0179 and berth (v_1) is 0.0029 between all variables.

By multiplying each input weight v_i with each input variable, and multiplying each output weight value u_r with each output variable, the weighted data value of all input variable and output variables is obtained. Dividing the total output value by the total input value we get the relative efficiency score θ of each DMUs. Table 7 shows the input variable values and output variable values after multiplication. In the most beneficial circumstances of Keelung harbour, the weighted value of collision (O1) is 1.0000, and berth (I1) is 1.0000 between all variables.

The resulting efficiency score and the peer group of each commercial harbour are obtained from the computation. Table 8 gives the DEA results for the four commercial harbours in a hydraulic group, as an example. In the most beneficial circumstances of Keelung harbour, the relative efficiency score θ is 1.0000 between the four harbours. For the other harbours, the relative efficiency score θ of Kaohsiung harbour is 1, Taichung harbour is 0.9986, and Hualien harbour is 0.5506.

From the results in Table 8, it can be seen that Hualien, over the 12 years' casualty database, is the safest commercial harbour within the Taiwan sea-area. It is apparent, based on the score proposed in the DEA-Solver Pro5.0/ CCR-I model, that Keelung and Kaohsiung are the most dangerous of the four harbours.

The outcome of the empirical study in Table 8 is as follows:

1) Keelung and Kaohsiung harbours, ranking 1, are the most dangerous of Taiwanese commercial harbours based on the DEA algorithms.
2) Taiwan's safest commercial harbour is Haulien, followed in ranking by Taichung, Kaohsiung, and Keelung.
3) Based on the algorithm of the proposed DEA model, the results can reflect reality.

CONCLUSIONS

This paper presents the methodology of applying DEA to evaluate navigation safety and demonstrates this application

	I1	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11
I1	1.0000	0.5674	0.8893	0.6969	0.9779	0.9811	0.1134	0.9456	0.3702	0.5327	0.9603	0.4039
O1	0.5674	1.0000	0.8752	0.9618	0.6504	0.4638	0.8812	0.7069	0.9711	0.9873	0.6500	0.9795
O2	0.8893	0.8752	1.0000	0.9457	0.9359	0.8090	0.5519	0.9543	0.7528	0.8607	0.9315	0.7758
O3	0.6969	0.9618	0.9457	1.0000	0.7966	0.5741	0.7728	0.8522	0.9128	0.9750	0.8073	0.9246
O4	0.9779	0.6504	0.9359	0.7966	1.0000	0.9189	0.2358	0.9924	0.4856	0.6445	0.9970	0.5147
O5	0.9811	0.4638	0.8090	0.5741	0.9189	1.0000	–0.0095	0.8648	0.2441	0.4042	0.8887	0.2807
O6	0.1134	0.8812	0.5519	0.7728	0.2358	–0.0095	1.0000	0.3266	0.9640	0.8944	0.2495	0.9543
O7	0.9456	0.7069	0.9543	0.8522	0.9924	0.8648	0.3266	1.0000	0.5648	0.7149	0.9967	0.5906
O8	0.3702	0.9711	0.7528	0.9128	0.4856	0.2441	0.9640	0.5648	1.0000	0.9806	0.4967	0.9993
O9	0.5327	0.9873	0.8607	0.9750	0.6445	0.4042	0.8944	0.7149	0.9806	1.0000	0.6563	0.9857
O10	0.9603	0.6500	0.9315	0.8073	0.9970	0.8887	0.2495	0.9967	0.4967	0.6563	1.0000	0.5241
O11	0.4039	0.9795	0.7758	0.9246	0.5147	0.2807	0.9543	0.5906	0.9993	0.9857	0.5241	1.0000

Table 5: The correlation value of all input variable and output variables

DMU	Input variable	Output variables										
	I1	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11
Keelung harbour	0.0179	0.0029	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Kaohsiung harbour	0.0085	0.0000	0.0026	0.0000	0.0037	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Taichung harbour	0.0200	0.0000	0.0000	0.0000	0.0000	0.0909	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hualien harbour	0.0727	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8029	0.0043

Table 6: The weight of all input variable and output variables

DMU	Input variable	Output variables										
	I1	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11
Keelung harbour	1	1	0	0	0	0	0	0	0	0	0	0
Kaohsiung harbour	1	0	0.2981	0	0.7019	0	0	0	0	0	0	0
Taichung harbour	1.0015	0	0	0	0	1	0	0	0	0	0	0
Hualien harbour	1.8163	0	0	0	0	0	0	0	0	0	0.8029	0.1971

Table 7: The weighted data value of all input variable and output variables

through an empirical study of Taiwanese commercial harbours. The objective of this DEA application is to apply a systematic analysis to aid decision making and to provide improved navigation safety in the harbours. While the input and output variables used in the DEA model vary in different navigation safety scenarios, a simplified model was proposed to demonstrate the use of DEA for the overall performance evaluation of the harbours. In this simplified model, the output variables include collision, stranding, leaking, fire, listing, structural, machinery, inter-twisting, heavy weather damage, missing vessel, and others. To demonstrate the use of the simplified DEA model, commercial harbours of each peer group were compared.

The 21st century shipping industry faces new challenges. Today technological advances have contributed to decrease manning, in some case to just 16 seafarers on a containership. Improvements in ship design and navigation aids have reduced the frequency and severity of marine casualties. As a result, commercial harbours, the shipping industry and seafarers are striving for great effects to improve navigation safety and the safety of people and property at sea, while the harbour bureaus have been considering harbour safety as an important criterion in providing services. Thus, navigation safety among commercial harbours has gradually become an important

DMU	Score	Rank	Peer group
Keelung	1	1	Keelung
Kaohsiung	1	1	Kaohsiung
Taichung	0.9986	3	Kaohsiung
Hualien	0.5506	4	Keelung

Table 8: DEA results of Taiwanese commercial harbours

issue. Hence, the main purpose of this study is to develop a DEA model to evaluate navigation safety in the four Taiwanese commercial harbours, based on the marine casualty database.

In order to facilitate the evaluation, the DEA algorithm is constructed to apply some concepts and methods. One input variable, eleven output variables and four commercial harbours were used to design the DEA model for evaluating navigation safety. This is done by using the DEA methodology to represent the performance of DMUs.

Subsequently, the empirical study is utilised to demonstrate the computational process of the systematic approach, ie, the DEA algorithm. For matching this evaluation process, a DEA structure of evaluating navigation safety is constructed with one input variable, eleven output variables and four DMUs. According to available data,[19] from 1992–2003 there were 3248 marine casualties around the four harbours – an annual average event of 271.

Finally, the results of the empirical study are as follows:

1) The max value of berth for input variable is 118, which is at Kaohsiung.
2) The top five output variables influencing the navigation safety are (1) machinery failure; (2) collision; (3) fire; (4) stranding; (5) heavy weather damage. At Keelung harbour, the major marine casualties are collision; machinery failure and others. On other hand, at Kaohsiung harbour, the major marine casualties are machinery failure; collision and fire.
3) Among the four commercial harbours Keelung and Kaohsiung are determined as the most dangerous based on the results of the proposed DEA algorithm.
4) According to the DEA structure and algorithm, Taiwan's safest commercial harbour is Haulien, followed in ranking by Taichung, Kaohsiung and Keelung.
5) Based on the algorithm of the proposed DEA model, the results can reflect reality.

Furthermore, this paper with its methodologies can be employed as a practical tool for navigation safety applications. The proposed model facilitates its implementation as a computer-based decision support system for evaluating navigation safety. With this simplified DEA model, harbour bureaus and seafarers can not only improve but also reduce the number of marine casualties and protect the safety of people and property at sea.

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