

Seakeeping analysis of dead ship condition in fishing ships based on Artificial Neural Networks

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Abstract

In the operation of ships, assessing seakeeping performance is crucial. Historically, this has been done through experimentation in towing tank basins or numerical computations. However, with the rise of Artificial Intelligence (AI) and increased computational resources, there are many opportunities to use AI in predicting seakeeping performance. This research will utilize a pre-trained Artificial Neural Network (ANN) to evaluate the behaviour of fishing vessels in various operational scenarios. One of the key advantages of using these algorithms is the ability to predict a large number of scenarios quickly, compared to traditional methods. By analysing millions of variations in the principal dimensions of a fishing ship and different sea states, the study aims to identify the optimal seakeeping performance in challenging conditions, ultimately improving ship safety by examining principal form coefficients and dimensions. The research will also determine significant conclusions.

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1. Introduction

Dead ship condition (DSC) is known as the condition of a ship when subject to the waves without neither propulsive nor steering capabilities. This condition is one of the most dangerous ones in terms of safety at sea, and the danger increase as the seastate becomes more energetic. Based on the Spanish Commission for Maritime Accidents (*Comisión de Accidentes e Incidentes Marítimos del Gobierno Español*, CIAIM), the number of maritime accidents between 2010 and 2019 has increased [1], and a large percentage of this accidents happened in DSC. And most of the accidents under DSC had severe consequences (Table 1).

Table 1. Number of maritime accidents between 2010 and 2019 [1]

Year	N*	DS*	VS*	S*	M*	I*
2010	91	2	-	-	-	-
2011	101	3	-	-	-	-
2012	60	5	2	1	0	2
2013	123	7	1	1	3	2
2014	97	16	4	3	4	5
2015	204	87	1	50	4	32
2016	316	209	0	202	6	1
2017	298	181	0	177	2	2
2018	274	178	0	176	2	0
2019	283	208	1	196	6	5

(* N = Number of accidents; DS= *Dead Ship*; VS= *Very severe*; S= *Severe*; M= *Moderate*; I= *Incident*.)

Early 2020, after a long and demanding process, the second generation of intact ship stability criteria (SGISc) of the International Maritime Organization (IMO) were ultimate. [2]. And within the framework of the SGISc measure that provide

orientation and limitations during navigation have been implemented to contribute to the design of safer ships [3]. A number of works regarding the implementation of the SGISc can be found in the literature. Among them we find Mata- Álvarez-Santullanol and Pérez-Rojas [4], where a set of 10 small fishing ships are analysed in terms of stability under DSC. In this work it is concluded that the SGISc provides orientation towards selecting among different options during the ship design stage. In Choi et al. [5] the probability of capsizing in DSC under the action of waves and wind is analysed. This analysis is also combined with a first order method to evaluate the fidelity when defining the potential scenarios leading to capsizing. Kubo et al. [6] developed a numerical model with coupled sway, heave, roll and pitch motions and validated it against model testing under artificial conditions of irregular waves and unsteady wind.

Gu et al. [7] remark that within the SGISc the IMO has included some method for directly evaluating the stability under DSC. The authors presented model testing and computational results to validate the latest concluding that more accurate numerical models need to be developed to evaluate stability in DSC, including the effects of drift and sway on roll motion. Shin and Chung [8] recently analysed thousands of tanker ships to transport oil derived chemical products under the SGISc concluding that the SGISc can provide clues to predict in advance the stability in DSC in the event of a ship engine failure. And Hu et al. [9] analysed the seakeeping response of a damaged ship (DTMB 5415) under beam waves in DSC using the method of volume of fluids. It was found that the roll motion amplitude of the damaged ship is smaller than that of the intact

ship. Given the coupling motion of the wave excitation and the heeling moment produced by flooding water, various differences are observed in the value of the roll amplitude, and the flooding water effect turns into the damping of ship rolling.

The irruption of Artificial Intelligence in the last years is opening up new possibilities to cope with the seakeeping problem. Several works can be already found in the literature using machine learning techniques to predict the seakeeping performance of ships. Liu et al. [10] developed a Reservoir Computing capable of predicting the movements of the six degrees of freedom for the KVLCC2 ship under irregular seawaves. Taghva et al. [11] predicted heave roll and pitch response amplitude operators (RAOs) and added resistance in waves obtained by the strip theory for the S175 hull using artificial neural networks (ANNs). In [12,13] Cepowski continued that line of research applied to ferries and passenger ships. And in [14] Cepowski trained ANNs to predict the added resistance in waves using basic ship form factors. The ship database contained 14 different ships.

The operational requirements of ships have been traditionally assessed either by seakeeping computational models or by experimental tests. Both methods are time consuming and require the exact geometry and mass particulars of the ship, so they are not applicable in early design stages where only few form coefficients are known.

One of the most recent works in this line of research has been published by the authors of the present work [15]. In [15], Romero-Tello et al. trained ANNs to predict the seakeeping hydrodynamic loads. A large number of different ships were used for an extensive training, resulting on a dataset of more than 20.000 ships under different wave frequencies and directions. As a result, obtained an ANN capable of predicting the seakeeping hydrodynamic loads for any type of conventional displacement monohull ship.

2. Objectives

It would be desirable to be able to assess the safety of ships in the early design stages to analyse, for instance, DSCs, and try to minimize the effects on the crew, passage, and avoid capsizing. And the main objective of this work is to provide an answer based on AI techniques.

In this work, the operational parameters of an existing fishing ship (*Ciudad de Cartagena*, see Figure 1 and Figure 2) will be optimized using the DSC under different seastates. The ANNs developed in [15] will be used to predict the seakeeping loads based on the form coefficients of the new hulls obtained by parametric transformation of the original ship. Since the ANNs can predict thousand of ships per second, the optimization process can be carried out through an extensive analysis of the parametric space.

The objective is to find the ship with the best response to the DSC subject to predefined wave scenarios. This search will be carried out across millions of parametric transformations of the original ship. And the selection of the best ship will be based on the following key performance indicators (KPI): motion sickness incidence (MSI); vertical and horizontal root mean square (RMS) accelerations; and maximum roll and pitch angles (MRA and MPA).

This work is organized as follows: the case study is presented in section 3. Section 4 introduces the optimization methodology. Section 5 shows the results obtained from the optimization, as well as the ship selected as the best. Section 6 provides the conclusions of this work.

3. Case study

Figure 1 shows the original ship (*Ciudad de Cartagena*) to be used as case study. This is a fishing ship currently used as a school ship by the *Universidad Politécnica de Cartagena (UPCT)*. Table 2 provides the main particulars under fully loaded conditions and Figure 2 provides the body plan.



Figure 1. Ciudad de Cartagena general view

Table 2. Ciudad de Cartagena main particulars under loaded condition

Overall length (m)	24.000
Waterline length (m)	21.650
Breadth (m)	6.661
Draft (m)	2.980
Block coefficient C_B	0.472
Waterlines area coefficient C_F	0.852
Midship area coefficient C_M	0.750
Prismatic coefficient C_p	0.630
Longitudinal position buoyancy centre XB (m)	10.975
Vertical position buoyancy centre KB (m)	1.969

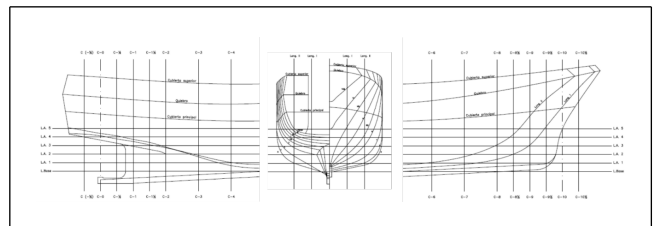


Figure 2. Ciudad de Cartagena body plan

During its operational life as a fishing ship, the fishing campaigns took place in the areas of the Mediterranean Sea and South Atlantic. And for this analysis, a period of one operational year will be used to determine the wave conditions in the areas. Table 3 shows the significant wave height (H_s), peak period (T_p) and wave spectrum ($S_{\xi\xi}(\omega)$) selected based on [16].

Table 3. Significant wave height, peak period, and wave spectrum ($S_{\xi\xi}(\omega)$)

Zona	H_s (m)	T_p (s)	Wave spectrum
Mediterranean Sea	2.347	6.0	JONSWAP
South Atlantic	3.570	8.8	JONSWAP

4. Optimization methodology

4.1. Pre-trained ANNs

In this work, the ANN developed by Romero-Tello et al. [15] will be used to predict the seakeeping loads of convectional monohull ships. By seakeeping loads we refer to the wave radiation loads (added mass and damping), as well as the excitation loads (Froude-Krylov and diffraction wave loads), in the frequency domain. The ANN developed in Romero-Tello et al. [15] can predict these loads based only on the hull form coefficients, with no need of the exact hull geometry (Figure 3). And the average error when compared to traditional 3D frequency-domain seakeeping codes based on potential flow and the boundary element method (BEM) is below 5%. The dataset of ships used for training this ANN was composed of 2.0×10^4 different hulls. This dataset was built out of 50 different conventional monohull ships (bulkcarriers, cruise ships, crude carriers, fishing ships, etc.), and then augmented by carrying out 20×20 parametric transformations of L/B and B/T for each. The main advantage of using the ANN developed in Romero-Tello et al. [15] is the computational speed, which allows to compute the KPIs of two cases per second while keeping a good precision.

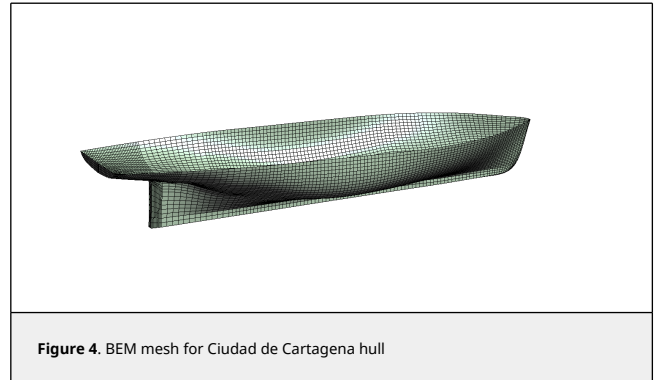


Figure 4. BEM mesh for Ciudad de Cartagena hull

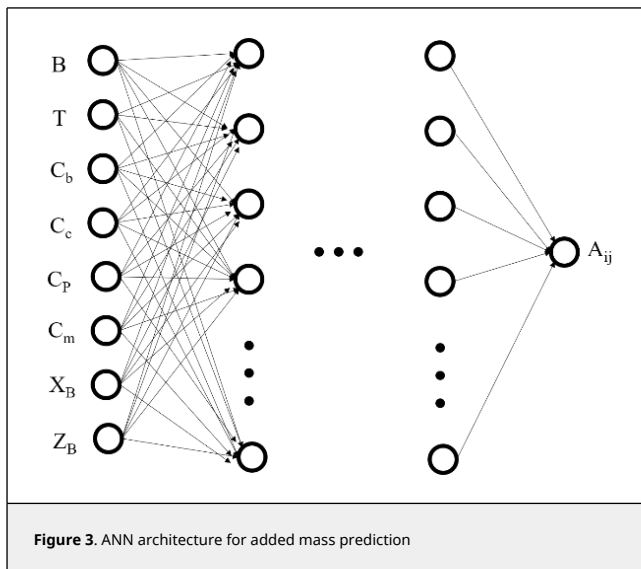
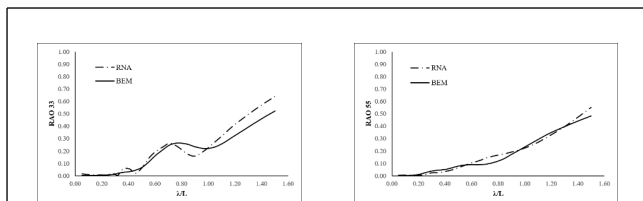
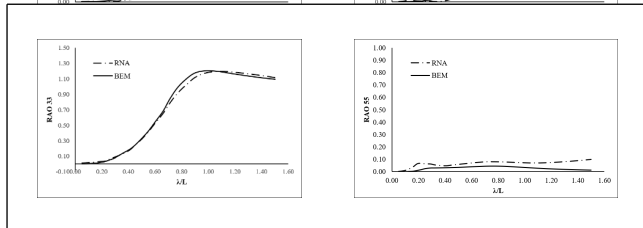
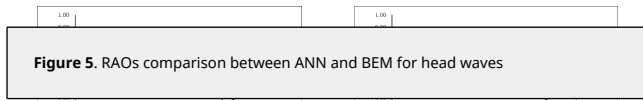


Figure 3. ANN architecture for added mass prediction

To assess the viability of the ANN, a comparison of the ANN and a BEM developed in Delhommeau [16] results for the original ship of the case study is carried out. It has to be said that the Ciudad de Cartagena was not used in the training of the ANN, so that the results are inferred from the results from other ships. Heave and pitch RAOs under head, following and beam seas are compared.

For the BEM computations, a mesh of 6400 elements has been generated for the Ciudad de Cartagena ship (Figure 4). Figures 5, 6 and 7 show a comparison between RAOs obtained by ANN and BEM computations for head waves, beam waves and following waves respectively. Heave (RAO₃₃) and pitch (RAO₅₅) response amplitude operator curves define the vessel response, for one particular degree of freedom, to one particular wave direction, amplitude and period.



Heavy manual work (RMS)	0.15 g	0.07 g	4.0 deg
Intellectual work (RMS)	0.05 g	0.05 g	3.0 deg
Passengers (RMS)	0.05 g	0.04 g	2.5 deg
Cruise line (RMS)	0.02 g	0.03 g	2.0 deg

Table 6. USCG [19]

Criterion	Threshold	Location
Vertical acceleration	0.4 g	Bow
Vertical acceleration	0.2 g	Bridge
Horizontal acceleration	0.2 g	Bridge
Motion Sickness Incidence (MSI)	5% under 30 min. exposition	Any
Motion Induced Interruption (MII)	2.1 stops per minute	Any
Roll angle	8.0 °	-
Pitch angle	3.0 °	-

In this work for the optimization analysis considering DSC, the NORDFORSK 1987 criteria for heavy manual work (recommended for fishing ships) have been adopted because those are the most demanding. Along with the NORDFORSK criteria, we have included the STANAG maximum RMS pitch angle in order to also reduce the pitch movement. The KPIs are then computed at three different locations: point 1, bow; point 2, stern-starboard; and point 3, navigation bridge (Figure 8). Table 7 shows the dimensionless coordinates of the three locations to be analysed.



Figure 8. 3D view of the locations to compute the KPIs on the Ciudad de Cartagena

4.2. Key performance indicators (KPIs)

Seakeeping stability criteria limit the maximum roll and pitch angles, as well as the maximum horizontal and vertical root mean square (RMS) accelerations. There exist a number of works investigating those criteria such as Rumawas et al. [17], Pattison and Sheridan [18], Ghaemi and Olszewski [19], and Stevens and Parsons [20]. They analyzed the seakeeping criteria provided by the North Atlantic Treat Organization (NATO) STANAG 4154, the NORDFORSK (Nordic Council of Ministers that provides funding for and facilitates Nordic cooperation on research and research infrastructure), and the USCG (United States Coast Guards, Cutters certification plan), which are provided in Tables 4, 5, and 6.

Table 4. NATO STANAG 4154 [21]

Recommended criterium	Threshold	Location
Motion Sickness Incidence (MSI)	20%	Any
Motion Induced Interruption (MII)	1/m	Any
Roll	4°	-
Pitch	1.5°	-
Vertical acceleration (RMS)	0.2 g	Bridge
Horizontal acceleration (RMS)	0.1 g	Bridge

Table 5. NORDFORSK 1987 [22]

General criteria for ship operability	Merchant	Naval	Fast ship
Vertical acceleration RMS at bow	0.275 g ($L \leq 100$ m)	0.275 g	0.65 g
	0.050 g ($L \leq 330$ m)		
Vertical acceleration RMS at bridge	0.15 g	0.20 g	0.275 g
Horizontal acceleration RMS in bridge	0.12 g	0.10 g	0.10 g
Roll	6.0 deg	4.0 deg	4.0 deg
Slamming probability	0.03 ($L \leq 100$ m)	0.03	0.03
	0.01 ($L \leq 330$ m)		
Greenwater probability	0.05	0.05	0.05
Acceleration and roll angle criteria	Vertical acceleration	Horizontal acceleration	Roll angle
Light manual work (RMS)	0.20 g	0.10 g	6.0 deg

Table 7. Dimensionless coordinates of analysis points

	X/L _W	Y/B	Z/T
Bow	0.923	0.000	2.769
Stern-board	0.024	0.460	2.469
Navigation bridge	0.701	0.000	2.783

Next the KPI are described. The MSI KPI measures the percentage of sickness after two hours navigation. This is evaluated as:

$$MSI (\%) = 100 \times \Phi \left\{ \frac{\log \left| \frac{\dot{\eta}_{33}}{g} \right| - \mu_{MSI}}{0.4} \right\}, \quad (1)$$

where:

- Φ is the cumulative normal distribution,
- $\dot{\eta}_{33}$ is the heave acceleration obtained from $0.784 \sqrt{m_4}$,
- m_i is the i -th spectral moment,
- g is the gravity acceleration,

- $\mu_{MSI} = 0.654 + 3.697 (\log(f_e) + 2.32 (\log(f_e))^2)$ is a factor given by O'Hanlon and McCauley in 1974 [24] and depends on:

- $f_e = \omega_e / (2\pi)$,
- $\omega_e = \sqrt{\frac{m_4}{m_2}}$.

The vertical and horizontal RMS accelerations are given by:

$$a_v^{RMS} = \sqrt{m_{433}}, \quad (2)$$

$$a_h^{RMS} = \sqrt{m_{422}}, \quad (3)$$

And maximum and significant roll and pitch angles are given by Eqs. (4) and (5), respectively

$$X_{max} = \sqrt{2 \ln(N)} \sqrt{m_0}, \quad (4)$$

$$X_S = 2\sqrt{m_0}, \quad (5)$$

$$N = \frac{t}{2\pi \sqrt{\frac{m_0}{m_2}}}, \quad (6)$$

where m_0 , m_2 , and m_4 are the zero, second, and fourth spectral moments.

4.3. Analysis

Before optimizing the operational parameters, it will be verified whether the selected criteria are fulfilled by the Ciudad de Cartagena. Then, geometrical transformation of the original hull will be performed to improve the seakeeping performance. Table 8 provide the ranges of variation of the form coefficients for the geometrical transformations ($\pm 10\%$, of initial values), where L is the ship length, B is the breadth, T is the draft, Vol is the displacement, A_F is the flotation area, A_M is the midship area, A_C is the amidship area, and X_b and Z_b are the horizontal and vertical position of the buoyancy centre respectively. Z_b is measured from free surface.

For each resulting combination, dimensionless form coefficients will be obtained, discarding unrealistic combinations such as those with block coefficient larger than one. These dimensionless hull form coefficients are the inputs for the ANN developed in Romero-Tello et al. [15]. Longitudinal and transversal distance from the gravity centre to the metacentric centre (GM_L and GM_T) are assumed to remain unchanged respect to the Ciudad de Cartagena.

Table 8. Ranges for geometric transformations

	L (m)	B (m)	T (m)	Vol (m ³)	A _F (m ²)	A _M (m ²)	A _C (m ²)	X _B (m)	Z _B (m)
Initial value	21.650	6.661	2.980	203.024	122.922	14.879	56.239	10.975	-1.011
Minimum value	19.485	5.995	2.682	182.722	110.630	13.391	50.615	9.878	-0.910
Maximum value	23.815	7.327	3.278	223.326	135.215	16.367	61.862	12.073	-1.112

For each geometrical factors, equidistant values are obtained within the range of variation. And for each of them the KPI is obtained. Then the KPI evaluation process consists of the following steps:

- Step 1: Generate analysis cases within the range of parameter variations given in Table 8.
- Step 2: Obtain RAOs using the ANNs developed in Romero-Tello et al. [15].

- Step 3: Obtain spectral movements for each new ship: got the operational areas defined in Table 3, and for 7 wave directions covering from following to head waves.

- Step 4: Obtain the maximum value of each KPI evaluated at each analysis point given in Table 7, considering the two operational areas and wave directions every 30 degrees (Eqs. (7)-(11)). Where *Med* . and *Atl* . refer to the Mediterranean Sea and the South Atlantic, respectively, and *pt* . refers to each of the three analysis points on the vessel

$$MSI_{max} = \max \{ (MSI_{pt1}, MSI_{pt2}, MSI_{pt3})_{Med}, (MSI_{pt1}, MSI_{pt2}, MSI_{pt3})_{Atl} \}, \quad (7)$$

$$a_v^{RMS}_{max} = \max \{ (a_v^{RMS}_{pt1}, a_v^{RMS}_{pt2}, a_v^{RMS}_{pt3})_{Med}, (a_v^{RMS}_{pt1}, a_v^{RMS}_{pt2}, a_v^{RMS}_{pt3})_{Atl} \}, \quad (8)$$

$$a_h^{RMS}_{max} = \max \{ (a_h^{RMS}_{pt1}, a_h^{RMS}_{pt2}, a_h^{RMS}_{pt3})_{Med}, (a_h^{RMS}_{pt1}, a_h^{RMS}_{pt2}, a_h^{RMS}_{pt3})_{Atl} \}, \quad (9)$$

$$Roll_{max} = \max \{ (Roll_{pt1}, Roll_{pt2}, Roll_{pt3})_{Med}, (Roll_{pt1}, Roll_{pt2}, Roll_{pt3})_{Atl} \}, \quad (10)$$

$$Pitch_{max} = \max \{ (Pitch_{pt1}, Pitch_{pt2}, Pitch_{pt3})_{Med}, (Pitch_{pt1}, Pitch_{pt2}, Pitch_{pt3})_{Atl} \}, \quad (11)$$

The optimal geometry is obtained after a ship selection process. This is as follows:

1. Select all ships fulfilling all established criteria.
2. In case there is none, select all ships improving the maximum value of each KPI compared to the initial vessel.
3. If none, select all ships improving the higher number of KPIs respect to the initial ship.
4. After the previous process, all selected ships will be ranked based on each KPI, from lowest to highest.
5. For each ship, the worst ranked position out of all KPI ranks will be taken, the candidate ships are ordered based on their position in the previously selected ranking.
6. Finally, the ship with the lowest rank is selected.

5. Results

First, it has been verified the fulfilment of the NORDFORSK criteria for the original ship under the wave conditions provided in Table 3. Table 9 provides the maximum values at the three analysis points of the ship. It is observed how the initial ship does not fulfil the selected requirements.

Table 9. Maximum KPIs for Ciudad de Cartagena

	Max.			Max.
	Bow	Stern-board	Nav. bridge	
MSI	34.863	28.146	25.981	34.863
Max. Horizontal acceleration (m/s ²)	7.419	5.740	7.243	7.419
Max. Vertical acceleration (m/s ²)	1.433	1.121	1.134	1.433
Max. Roll angle (°)	54.768			
Max. Pitch angle (°)	15.288			

5.1. KPI evaluation and ship selection process

For each geometrical factors, four equidistant values are obtained within the range of variation. Then, 262,144 geometrical variations are considered. After discarding unrealistic combinations, the resulting dataset to be analysed is reduced to 190,080 combinations. Then the KPI are evaluated at

the three locations, and for the seastates and wave directions defined for the operational areas. This results in 1,140,480 case scenarios simulated.

After obtaining all the KPIs for the 190,080 candidates, none of them fulfil all the four selected requirements. Then, it is found that 3,858 ships improved all maximum KPIs respect to the initial ship. Following the ranking method described for the ship selection process, it is found the best ship. [Table 10](#) compares the geometrical particulars of the selected ship respect to the *Ciudad de Cartagena*. [Table 11](#) provides the KPIs for the selected ship.

Table 10. Initial and best ships particulars

	Ciudad de Cartagena	Best ship
LW (m)	21.650	20.928
B (m)	6.661	5.995
T (m)	2.980	3.079
Displacement (t)	208	229
CB	0.472	0.578
CF	0.852	0.947
CM	0.750	0.725
CP	0.630	0.797
XB / LW	0.507	0.507
KB / T	0.661	0.639

Table 11. KPI values for selected best ship

	Max.			Max.
	Bow	Stern-board	Nav. bridge	
MSI	29.464	28.987	22.164	29.464
Max. Horizontal acceleration (m/s^2)	3.902	3.469	3.915	3.915
Max. Vertical acceleration (m/s^2)	1.198	1.141	1.005	1.198
Max. Roll angle (°)	28.352			
Max. Pitch angle (°)	14.901			

5.2. Discussion of results

[Table 12](#) compares the maximum KPI values for the *Ciudad de Cartagena* and the best selected ship. It is observed that a considerable improvement of the seakeeping performance is achieved.

Table 12. KPI values comparison for selected best ship and the *Ciudad de Cartagena*

	Ciudad de Cartagena	Best ship
MSI	34.863	29.464
Max. Horizontal acceleration (m/s^2)	7.419	3.915
Max. Vertical acceleration (m/s^2)	1.433	1.198
Max. Roll angle (°)	54.768	28.352
Max. Pitch angle (°)	15.288	14.901

The selected recommendations are appropriate to assess seakeeping performance since they established thresholds based on the work to be carried out on board. In the case study of this work, a fishing ship, those of heavy manual work are taken as appropriated.

6. Conclusions

A wise selection of the form coefficients in the early design stage of ships is key to ensure the seakeeping performance and safety of the ship, for instance, in dead ship conditions. In this context, the ANN developed in [15] can be used for fast evaluation of KPIs and hull form optimization, providing ship designer with a powerful tool to this end.

It has been shown how the ANN from Romero-Tello et al. [15] provides the capability of testing a very large number of hulls in a negligible time. In this work, approximately 200,000 ships have been evaluated under two operative conditions and three points of analyses (1.14×10^6 cases) in 172 hours.

Out of the analyses carried out, it is observed that the most critical KPIs are the maximum roll angle and RMS horizontal acceleration. And the ship selected out of the optimization process improved the KPIs respect to the initial ship.

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