Multicriteria Analysis Method for Evaluation of Vessel Simulation Models in Open Waters

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Modern ship simulators enable simulations of reality using available environment and ship models. When choosing a specific vessel from a catalogue, however, it is not always immediately apparent as to how true a simulation is to the original vessel. Its makers are required only to have software certificates, which does not ensure the exact modelling of a ship in the simulation. This paper presents research in continuation of previous work presenting a general methodology for the evaluation of the degree of accuracy of a simulated ship model compared to its real-world counterpart. In this paper, the results are shown of a comparative analysis based on actual measurements with the use of one of the methods of multi-criteria analysis. Furthermore, the methodology for the construction of ship models is presented. The paper concludes with a test verifying the accuracy of the assumptions.

1. INTRODUCTION.   Organisations that build marine simulation centres for the purposes of research and training must base the simulation on software which meets the requirements of the Standard of Training and Certification of Watchkeepers (STCW) Convention (International Maritime Organization (IMO), 1995). Section A-I/II of this Convention imposes standards regulating the use of simulators and their detailed configuration. In the paragraph specifying the minimum software requirements in terms of a ship's behaviour, only the phenomena and forces that must be allowed for by their mathematical models are detailed. From a scientific point of view, however, the credibility of the behaviour of a virtual vessel is crucial, especially when a real navigational situation is to undergo analysis within the simulation environment. This can occur when, for example, the behaviour of a ship's crew is evaluated during incidents at sea (Mimito et al., 2014). When a digital model is to be used as a copy of the physical ship for this purpose, establishing

to what degree they are similar is essential. Presently, there is no legal requirement that imposes any obligation on software developers and research teams to have their models certified for correspondence with their real-world counterparts. Currently, simulators must have relevant certificates issued by companies providing classification services only with respect to the simulation software and vessel models themselves require no specific certification. For example, one such company, Det Nort Veritas (DNV), provides classification procedures, describing software requirements with regard to the realistic behaviour of simulation models (DNV, 2011. Section C2). It describes the specific requirements with respect to the simulation of a ship's motion within six degrees of freedom as well as the characteristics of the necessary hydrodynamic forces allowed for by a vessel's mathematical model. However, as in the convention's documents, it gives no information on how individual vessels can be verified for their correspondence to the reference ship. Upon analysis of the most important documents from the perspective of the operation of centres fitted with navigational and manoeuvring simulators, it may be stated that there is a legal gap which affects the use of simulation models in research projects. This is of particular importance when a faithful copy of a real vessel is essential. It is reasonable, therefore, to ask whether we can evaluate the credibility of a simulation that uses a non-verified model. An increasing number of research teams throughout the world are advocating for a change in approach to the evaluation of simulation models (US Coast Guard, 1998; Fang et al., 2012). Berg and Ringen (2011) and Elot et al. (2015) raised the point that the methods for validating numerical models used in manoeuvring simulators need to be improved.

This paper presents the results of the authors' work on their own method for the evaluation of vessel simulation models based on a real-world study. It constitutes a continuation of the research, whose first-stage conclusions were presented in Czaplewski and Zwolan (2016). In the earlier paper, the methodology described concerned the process of taking actual measurements that involved building a special measurement platform. Actual measurements allow for the generation of research material that is necessary to evaluate the degree of adequacy of a simulation model with a real vessel. In this paper, the following stages of this methodology are described pertaining to the construction of ship simulation models and the comparative analysis with the evaluation of a degree of similarity of a virtual model and its reference. In simulation studies, the authors used the Transas navigational and manoeuvring simulator (Transas, 2011a; 2011b), available at their place of work.

2. CONSTRUCTION OF A VESSEL SIMULATION MODEL. In order to perform a comparative analysis of a simulation model with a real vessel, it is necessary first to devise an adequate simulation model.

2.1. *Construction of a vessel simulation model.* The construction of the vessel simulation model was aided by the Model Wizard – Virtual Shipyard software by Transas and auxiliary applications designed for the generation of Three-Dimensional (3D) models. For the needs of this article, the authors built a virtual model of the training ship, *ORP Wodnik*, property of the Polish Navy. The process of creation of a virtual model of the vessel was completed in the following stages.

2.1.1. *Construction of a 3D model of a vessel.* The process of generation of a three-dimensional model of a ship and in particular of its outline is relevant when it comes to the simulation of a mooring manoeuvre and when accounting for its geometry for the effects of
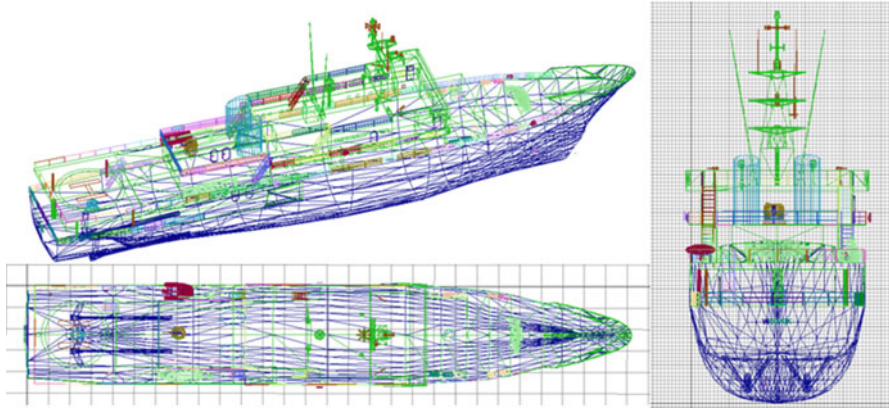
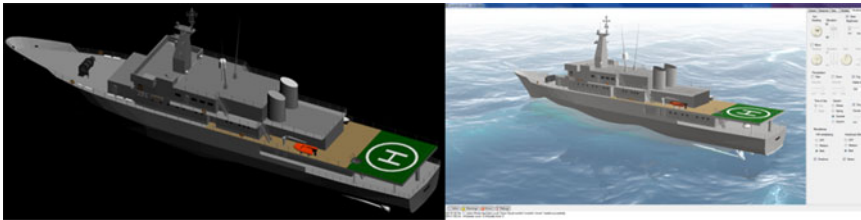Figure 1.   Construction grid of a three-dimensional model of a vessel.

Figure 2.   Model of a vessel after rendering.

ship-ship and ship-wharf interactions, etc. The first stage of the 3D model generation (for example, "3D Studio Max") is the creation of the model construction grid (Figure 1). The sketches from the ship's technical documentation proved to be useful here.

The next step is the overlaying of textures based on photographs, followed by rendering, which allows for a visualisation of the virtual model. The complete model is transformed to a format compatible with the simulator's environment (Figure 2).

2.1.2. *Creation of the ship's motion.*   This involves the development of a simulation vessel based on input data with the use of the Virtual Shipyard application. This is the most important stage in the whole process of producing a virtual model of a ship. The process requires the introduction of a range of data and coefficients conditioning the model's credibility of behaviour in specific hydro-meteorological conditions. Generally, the process can be presented as shown in Figure 3.

It is possible to devise simulation models using the data from the simulator's database, the technical documentation of a ship or the actual records. Therefore, for the purposes of the comparative analysis, two versions of the simulation model of *ORP Wodnik* were created:

(a) an "extended version" – based on detailed data from the ship's technical documentation;
(b) a "corrected version" – a corrected "extended version" based on the real manoeuvring data of the reference ship.
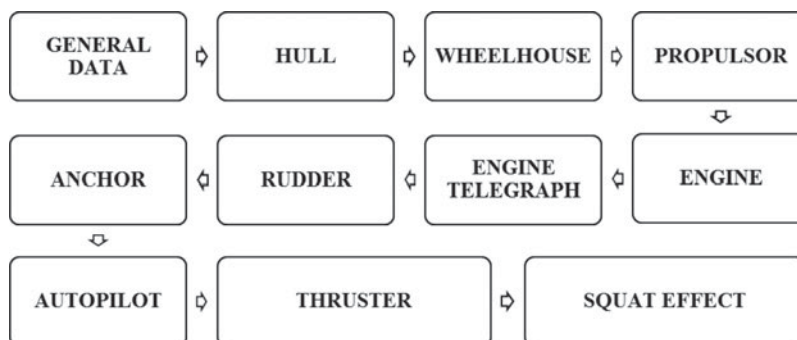
Figure 3. Creating the model of a vessel's motion.

Each of the models mentioned above is characterised by a different degree of adequacy with comparison to the real-world model. Their limitations were confirmed by the method created for model assessment allowing for a determination of their suitability to various purposes. The results of this comparative analysis of both models in comparison with their reference ships are presented further in this article.

2.1.3. *Basic manoeuvring tests.* These allow for verification of the model's behaviour under specific weather conditions, or the performance of manoeuvres in accordance with IMO guidelines. During this process, the application shows all forces and coefficients available in the mathematical model of the simulation.

2.1.4. *Creation of the ship's manoeuvring documentation.* Alongside the creation of an object to be imported to the simulator's software, the ship's manoeuvring documentation in the form of three conventional documents is created: a pilot card, a wheelhouse poster, and a manoeuvring booklet.

2.1.5. *Generation of the installation file.* The process of creation of a simulation model ends with the generation of an output file that should be installed as a new object in the simulator environment. The algorithm of the construction process of a vessel's simulation model is presented in Figure 4.

3. VESSEL SIMULATION MODEL - THE EVALUATION PROCESS. We decided to apply a multi-criteria analysis method to this problem. These methods are being used more and more frequently in various disciplines of science. Looking for a mathematical apparatus, we decided that the main goal must be the ability to apply a reference value, which will be the result of manoeuvring tests carried out on a real ship. Therefore, a multi-criteria evaluation method was chosen, as it utilises a reference of quality described among others in Jajuga and Walesiak (2000), Cox and Cox (2000), Byun and Lee (2005) and Kläs et al. (2010).

The proposed method combines tools of various fields of knowledge such as: multi-criteria optimisation, multi-criteria decision support and statistical comparative analysis. The aim of the adopted method is to define the degree of correspondence of the selected vessel simulation model parameters with their real-world counterparts. This degree will be called "distance" $\left(d_{U_j}\right)$ and be defined as the difference of values of the parameters under study. In addition, the multi-criteria evaluation method enables several models to be analysed at the same time and their level of correspondence to be determined.
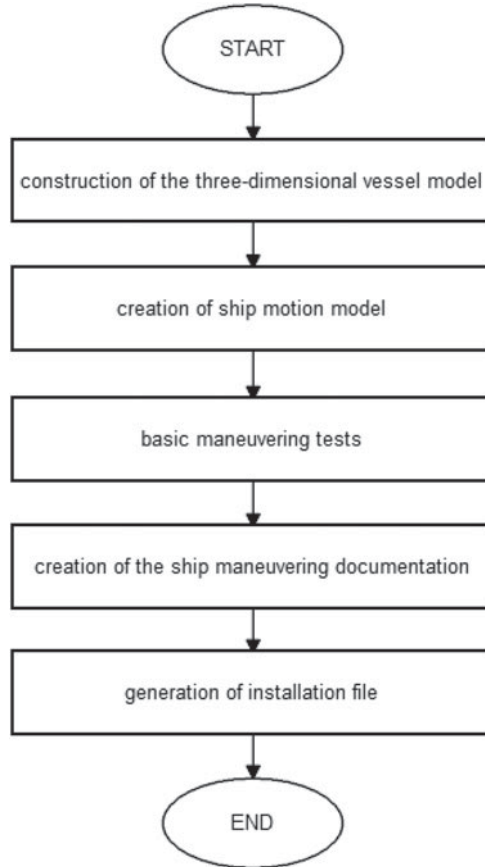
Figure 4.   Construction of a vessel's simulation model.

3.1. *Defining the analysis goal and observation matrix of technical parameters.*
Owing to the significant number of technical parameters of a simulation model that can
be tested, the goal of the comparative process must first be established. Depending on the
goal, an adequate set of diagnostic parameters can be chosen, which will be subject to
verification. The verification of a simulation model may be present only within a specific
functional scope. It is possible, therefore, to select several research scenarios in which it is
necessary to verify the individual parameters of the virtual model. Defining these scenar-
ios will make it easier to choose an adequate set of technical parameters and, if necessary,
apply weights to them, depending on their importance. In Table 1, the most frequently used
sets of technical parameters suited to the research goal are shown.

It may therefore be stated that for each of the simulation models studied, creating the
set $\mathbf{M} = \{M_i, i = 1, \ldots, n\}$, may be defined by technical parameters (U_j) for $j = 1, \ldots, k$.
The technical parameters included by the authors are: drift speed, course over ground, drift
angle, roll, pitch, etc. The distance of technical parameters of the simulation model from
the real vessel affects the scope of its use in a scientific process. If the number of technical
parameters $k > 1$, the evaluation of a model will be of a multi-criteria nature. Then, a set

Table 1. Example research scenarios and technical parameter features.

	Research scenario goal	Essential features	Additional features
1	Defining ship's manoeuvring elements in accordance with IMO guidelines	− diameter of circulation in shallow waters − diameter of circulation in deep waters − stopping characteristic − acceleration of a ship − squat effect − zig zag manoeuvre	
2	Manoeuvring in a port	− course over ground − drift speed − drift angle − crash-stop − acceleration of a ship	− coasting − diameter of circulation in shallow waters − diameter of circulation in deep waters − canal effect
3	Analysing the effect of wind and waves on the behaviour of a drifting vessel	− drift speed − course over ground − drift angle − roll − pitch	
4	Analysing sea accidents caused by hydro-meteorological conditions	Selection of parameters depending on the emergency situation analysed	Selection of parameters depending on the emergency situation analysed

of technical parameters will be formed which will characterise the simulation model:

$$U = \{U_1, U_2, \ldots, U_k\} \tag{1}$$

where U_j is the j th technical parameter describing the simulation model ($j = 1, \ldots, k$) and k is the number of distinguished features.

After inserting the assumption Equation (1) into the function of the set of simulation models (M), a matrix of observations of technical parameters of individual models can be created:

$$\mathbf{U_M} = \begin{bmatrix} U_1(M_1) & U_1(M_2) & \cdots & U_1(M_i) \\ U_2(M_1) & U_2(M_2) & \cdots & U_2(M_i) \\ \vdots & \vdots & \vdots & \vdots \\ U_j(M_1) & U_j(M_2) & \cdots & U_j(M_i) \end{bmatrix} \tag{2}$$

Likewise, a matrix of observations of technical parameters for the real vessel is created:

$$\mathbf{U_W} = \begin{bmatrix} U_1(W) \\ U_2(W) \\ \vdots \\ U_j(W) \end{bmatrix} \tag{3}$$

During the measurements of technical parameters in comparable hydro-meteorological conditions, different values for individual parameters are obtained. Their number depends on the quantity of measurements made in real conditions. The larger the amount of data gathered in similar conditions, the more accurate the comparative analysis will be. Then, the elements of matrices $\mathbf{U_M}$, $\mathbf{U_W}$ will be just arithmetic means of individual technical parameters from individual measurements.

3.2. *Determination of the distance between the studied parameters and the real vessel.* The distance between the individual technical parameters of the simulation model and the real vessel can be calculated using the formula:

$$d_{U_j} = \sqrt{\sum_{j=1}^{k} w_{U_j} \left[U_j \left(M_i \right) - U_j \left(W \right) \right]^2} \tag{4}$$

where w_{U_j} is the weight for the jth technical parameter, $U_j \left(M_i \right)$ is the normalised value of the jth technical parameter for the ith simulation model and $U_j \left(W \right)$ is the normalised value of the technical parameter for the real vessel.

In this research problem, the most favourable situation is when distance (understood as the difference) between the individual technical parameters of the simulation model and the real vessel is as small as possible and is within the specified range:

$$d_{U_j} = \begin{cases} d_{U_j}^0 & \text{for} \quad d_{U_j} \in \langle a, b \rangle \\ d_{U_j} & \text{for} \quad \text{other values} \end{cases} \tag{5}$$

The values from the range $\langle a, b \rangle$ are the adopted limits of acceptability of the adequacy of the simulation model and are determined before each evaluation of the simulation models.

Depending on the type of research task defined in Table 1 with respect to which model M_i is to be used, the effect of the individual technical parameters on the degree of correspondence can be determined. For this purpose, the weight of an individual U_j should be determined in the studied model M_i. Weight may take values from the range $w_{U_j} \in \langle 0, 1 \rangle$.

In comparative practice, a quick assessment of the quality of determinations is related to the need to present the non-correspondence of a model with the real vessel as a percentage, therefore presenting the distance d_{U_j} as a percentage seems reasonable. Then, the values obtained from Equation (4) can be specified as follows.

If $U_j \left(M_i \right) > U_j \left(W \right)$ then:

$$d_{U_j}(\%) = \frac{U_j \left(M_i \right) - U_j \left(W \right)}{U_j \left(M_i \right)} \cdot 100\% \tag{6}$$

If $U_j \left(M_i \right) < U_j \left(W \right)$ then:

$$d_{U_j}(\%) = \frac{U_j \left(M_i \right) - U_j \left(W \right)}{U_j \left(W \right)} \cdot 100\% \tag{7}$$

3.3. *The use of the method of evaluation for a chosen research scenario.* In order to verify the correctness of the assumptions, the authors adapted the assumed evaluation model to a research scenario: "The analysis of the effect of wind and waves on the behaviour of a drifting vessel" (Table 1). To this end, the technical parameters of the model subjected to assessment for accuracy were specified. A set of technical parameters takes the following form:

$$U = \{U_1, U_2, U_3, U_4, U_5\}$$

where U_1 is the drift angle (difference of a change of a true course in the analysed time range) [°], U_2 is the drift speed (average drift speed in the analysed time range) [kn], U_3 is the course over ground (average value in the analysed time range) [°], U_4 is the pitch (maximal pitch values) [°] and U_5 is the roll (maximal roll values) [°].

Two versions of a simulation model of a ship were built, therefore, the set of simulation models will take the following form:

$$M = \{M_1, M_2\}$$

where M_1 is the "extended" model and M_2 is the "corrected" model.

According to Equation (2), a matrix of technical parameters in the function of models ($\mathbf{U_M}$) was created, and according to Equation (3), a matrix of technical parameters of the reference ($\mathbf{U_W}$) was built:

$$\mathbf{U_M} = \begin{bmatrix} U_1(M_1) & U_1(M_2) \\ U_2(M_1) & U_2(M_2) \\ U_3(M_1) & U_3(M_2) \\ U_4(M_1) & U_4(M_2) \\ U_5(M_1) & U_5(M_2) \end{bmatrix} \quad \mathbf{U_W} = \begin{bmatrix} U_1(W) \\ U_2(W) \\ U_3(W) \\ U_4(W) \\ U_5(W) \end{bmatrix}$$

Next, using Equations (4), (6) and (7), the distances for individual technical parameters were specified. In the research scenario, only the basic technical parameters are analysed, therefore, a constant value of weights $w_{U_j} = 1$ is assumed. Then, according to Equation (5), a correction of coefficients will follow. For the purpose of this article, we specified acceptability limits for the simulation model's adequacy as $d_{U_j} \in \langle -15\%, +15\% \rangle$. A practical realisation of the method is presented next.

4. NUMERICAL TEST. A numerical test was performed with the use of a navigation and manoeuvring simulator located in the Polish Navy Academy in Gdynia. It was divided into two stages. The first consisted in verification of the level of correspondence of the "extended" model generated based on real construction parameters. The second stage involved checking the "corrected" model against the function of coefficients. A drifting vessel was subject to analysis (Table 1, scenario 3). Table 2 shows the actual records taken during the measurement session conducted on board *ORP Wodnik* (Czaplewski and Zwolan, 2016). These records provided the basis for the comparative analysis.

Table 3 presents the results of a simulation test of the "extended" model. The test was performed under simulated hydro-meteorological conditions corresponding to the real-world studies. Graphic results of comparative analysis of the "extended" model with the real vessel are presented in Figures 5–9.

Table 2.   Results of measurements for the vessel based on real-world studies.

Time (s)	φ (°)	λ (°)	TC (°)	COG (°)	SOG (kn)	TWD[1] (°)	TWS[2] (kn)	Pitch (°)	Roll (°)
00	54·92473300	14·20990000	77·5	30·5	0·6	192	8	0·0213	0·0478
10	54·92475000	14·20991700	77·3	32	0·6	183·2	8·9	0·0248	−0·0491
20	54·92478300	14·20995000	77·2	18	0·7	177·4	11·2	0·0245	0·0482
30	54·92480000	14·20996700	77·1	20·7	0·6	186·2	8·2	0·0245	−0·0478
40	54·92481700	14·20998300	76·9	20·5	0·6	181·2	10·1	0·0266	0·0462
50	54·92483300	14·21000000	76·8	21·2	0·6	184	9·3	0·0251	−0·0488
60	54·92486700	14·21001700	76·7	25·1	0·6	189·7	9·5	0·0256	0·048
70	54·92488300	14·21003300	76·7	27·3	0·6	187·7	8·9	0·0226	0·0462
80	54·92490000	14·21005000	76·6	25·8	0·7	182·4	9·7	0·0265	−0·0518
90	54·92493300	14·21006700	76·7	21·9	0·6	184·8	10·3	0·0256	0·0499
100	54·92495000	14·21008300	76·7	21·3	0·6	185·8	8·9	0·0243	−0·0485
110	54·92498300	14·21010000	76·7	13·3	0·6	184·3	9·5	0·0209	−0·0489
120	54·92500000	14·21011700	76·7	28·5	0·6	183	10·7	0·0221	0·0491

[1] True Wind Direction
[2] True Wind Speed

Table 3.   Results of the simulation test for the "extended" model.

| Time (s)	φ (°)	λ (°)	TC (°)	COG (°)	SOG (kn)	TWD (°)	TWS (kn)	Pitch (°)	Roll (°)
00	54·92473	14·20987	77·5	352·9	0·5	192	8	0·002	0
10	54·92473	14·20987	76·7	352·2	0·5	183·2	8·9	0	−0·019
20	54·92474	14·20987	75·8	351·6	0·6	177·4	11·2	0	−0·078
30	54·92474	14·20986	74·9	351·3	0·5	186·2	8·2	0	−0·048
40	54·92475	14·20986	74·1	351·0	0·6	181·2	10·1	0	−0·077
50	54·92476	14·20986	73·4	350·6	0·5	184	9·3	0	−0·071
60	54·92477	14·20986	72·8	350·7	0·5	189·7	9·5	0	−0·075
70	54·92478	14·20985	72·2	350·5	0·5	187·7	8·9	0	−0·073
80	54·92479	14·20985	71·8	350·2	0·5	182·4	9·7	0	−0·086
90	54·92480	14·20985	71·4	349·9	0·6	184·8	10·3	0	−0·097
100	54·92482	14·20984	71·2	349·7	0·5	185·8	8·9	0	−0·083
110	54·92483	14·20984	71·1	349·5	0·5	184·3	9·5	0	−0·092
120	54·92484	14·20983	71·0	349·3	0·6	183	10·7	0	−0·112
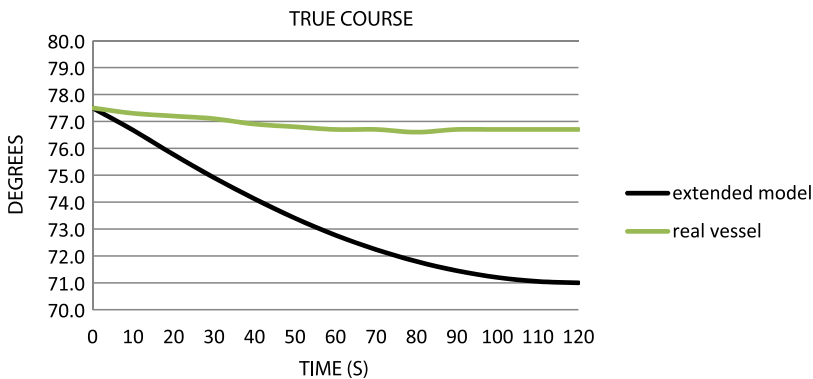
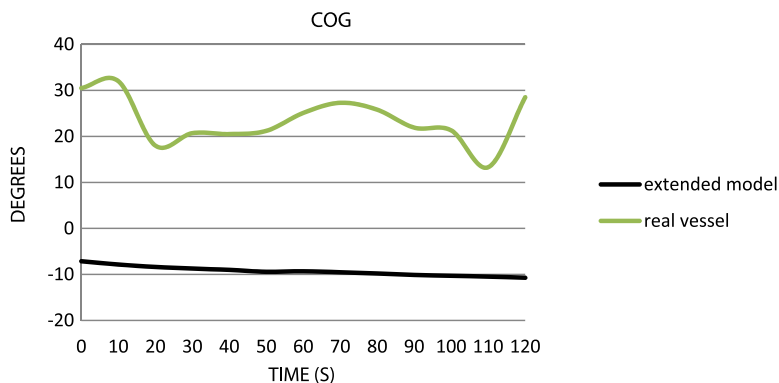Figure 5.   Comparison of the true courses.

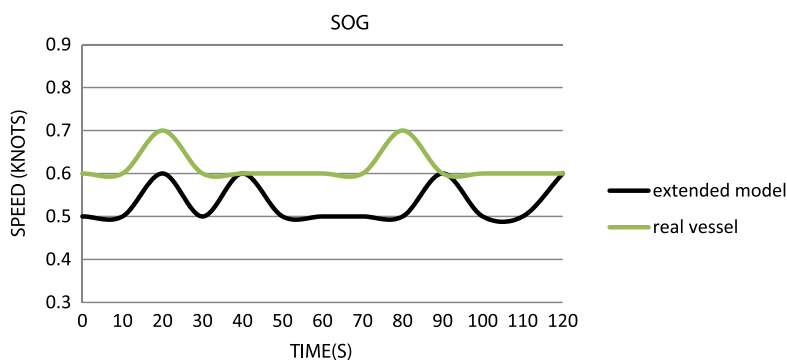Figure 6.   Comparison of the courses over ground.

Figure 7.   Comparison of the speeds over ground.

As shown in Figure 5, the "extended" model changes its True Course (TC) under the influence of wind much more quickly. There is, however, a full compliance when it comes to the direction of the movement of the bow and stern.

The analysis of the track describing the Course Over Ground (COG) indicates significant differences between the two vessels; the difference is about 40° (Figure 6). This illustrates a problem that despite the correct introduction of data pertaining to the lateral wind exposed area, the curves responsible for the drift angle need revising.

When comparing the drift speed data (Speed Over Ground, SOG) (Figure 7), it can be seen that the introduction to the model of detailed data concerning wind exposed areas or the underwater part of the hull does not give satisfactory results, and the simulation drifts more slowly than the real vessel.

For pitch and roll data, it is clear that the "extended" model is not correctly calibrated with the reference. Pitch is close to 0° (Figure 8), which is caused by waves at transverse angles. The roll of the "extended" model is too small with respect to the reference (Figure 9), so the model also needs calibration in this respect.

According to the methodology of the model assessment described in this paper, the values of the technical parameters were specified for the real vessel, "extended" model (Table 4) and the "corrected model" (Table 7).
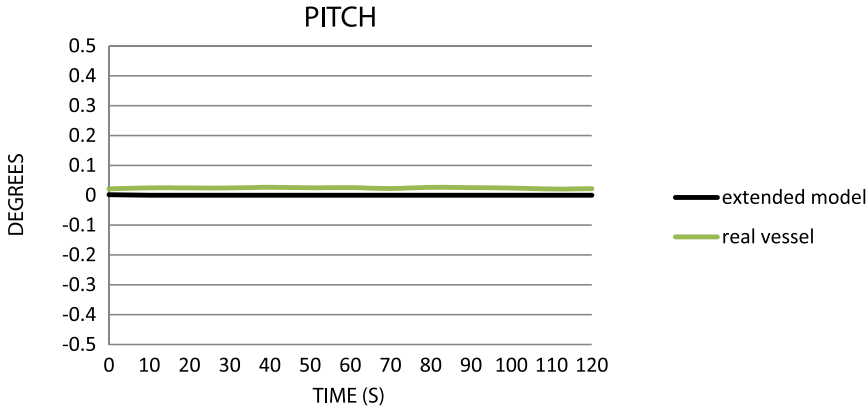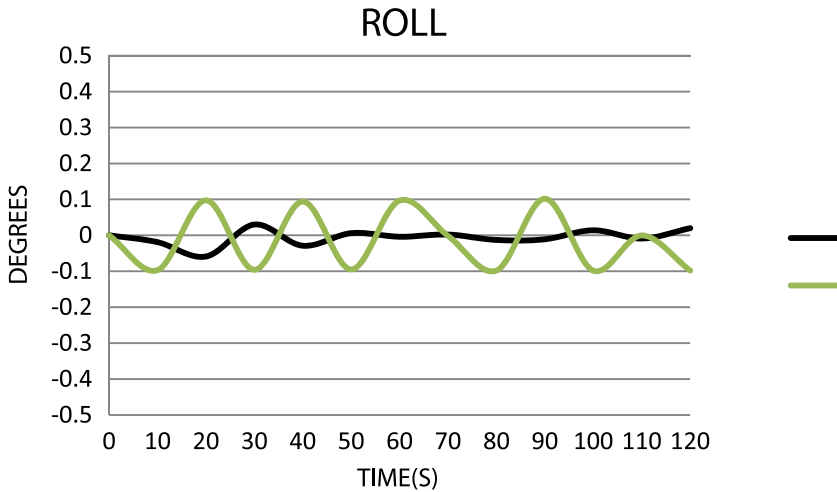
Figure 8.   Comparison of the pitch values.

Figure 9.   Comparison of the roll values.

Table 4.   Technical parameters of the extended model and the real vessel.

	(U_1)	(U_2)	(U_3)	(U_4)	(U_5)
M_W	−0·8	0·62	23·5	0·007	0·200
M_1	−6·5	0·53	−9·8	0·002	0·089

For the parameters presented in Table 4, a matrix of the "real vessel" technical parameters is constructed:

$$\mathbf{U_W} = \begin{bmatrix} U_1\,(W) \\ U_2\,(W) \\ U_3\,(W) \\ U_4\,(W) \\ U_5\,(W) \end{bmatrix} = \begin{bmatrix} -0{\cdot}800 \\ 0{\cdot}620 \\ 23{\cdot}500 \\ 0{\cdot}007 \\ 0{\cdot}200 \end{bmatrix}$$

Table 5.   Percentage values of non-correspondence of distances for individual technical parameters of the "extended" model with respect to the real vessel.

	d_{U_1}	d_{U_2}	d_{U_3}	d_{U_4}	d_{U_5}
"Extended" model	−88 %	−15 %	−58 %	−71 %	−56 %

Also constructed is the matrix of the "extended" model's technical parameters:

$$\mathbf{U_M} = \begin{bmatrix} U_1\,(M_1) \\ U_2\,(M_1) \\ U_3\,(M_1) \\ U_4\,(M_1) \\ U_5\,(M_1) \end{bmatrix} = \begin{bmatrix} -6{\cdot}500 \\ 0{\cdot}530 \\ 9{\cdot}800 \\ 0{\cdot}002 \\ 0{\cdot}089 \end{bmatrix}$$

The matrix of distances of the technical parameters **du** calculated based on Equation (4) takes the following form:

$$\mathbf{du} = \begin{bmatrix} d_{U_1}\,(M_1) \\ d_{U_2}\,(M_1) \\ d_{U_3}\,(M_1) \\ d_{U_4}\,(M_1) \\ d_{U_5}\,(M_1) \end{bmatrix} = \begin{bmatrix} 5{\cdot}700 \\ 0{\cdot}090 \\ 0{\cdot}110 \\ 0{\cdot}005 \\ 0{\cdot}111 \end{bmatrix}$$

The calculated percentage values of non-correspondence of distances $\left(d_{U_j}\right)$ for the specific technical parameters of the "extended" model with respect to the reference are shown in Table 5.

Based on the analysis of the data included in the table it may be stated that the model created based on the real vessel's construction data did not meet the condition of the percentage tolerance for correspondence. Therefore, the coefficients of the "extended" model need to be corrected. Table 6 shows the results of the simulation tests in the "corrected" model. Graphic results of comparative analysis of the "corrected" model with the real vessel are presented in Figures 10–14.

It may be concluded from the above figure that differences of TC reach 0·1°–0·2° after 2 minutes (Figure 10). A noticeable difference, however, is a steadier movement of the simulation model.

The difference when comparing the mean values of the COG (Figure 11) of both vessels and the angle between the starting and the final position resulting from the adjustment of the model's coefficients is less than 1°.

The comparative charts showing the values of SOG (Figure 12) indicate that accuracy with the real vessel occurs for the average speed. However, what is noticeable is a different reaction of the real vessel's hull from that of the simulation model with regard to the time ranges of differences in drift speeds. Most importantly, however, the average drift speed is fully correspondent with the ship.

The pitches (Figure 13) are close to 0°, which is induced by waves at transverse angles. The roll (Figure 14) for a drifting vessel, with a sea state one, does not exceed 0·2°. A remarkable improvement can be seen in the case of the model's behaviour in this aspect as compared with the "extended" model. The chart shows only maximum roll in the selected

Table 6.   Results of simulation test for the "corrected" model.

| Time (s)	φ (°)	λ (°)	TC (°)	COG (°)	SOG (kn)	TWD (°)	TWS (kn)	Pitch (°)	Roll (°)
00	54·924732	14·209904	77·5	26·6	0·6	192	8	−0·012	0
10	54·924743	14·209911	77·4	25·9	0·7	183·2	8·9	−0·013	−0·141
20	54·924759	14·209922	77·3	25·1	0·7	177·4	11·2	−0·016	−0·182
30	54·924780	14·209935	77·2	24·3	0·6	186·2	8·2	−0·015	−0·083
40	54·924803	14·209950	77·1	23·6	0·7	181·2	10·1	−0·013	−0·01
50	54·924829	14·209968	77·0	23·0	0·7	184	9·3	−0·017	−0·026
60	54·924856	14·209986	76·9	22·1	0·6	189·7	9·5	−0·014	−0·104
70	54·924883	14·210006	76·8	21·6	0·6	187·7	8·9	−0·015	−0·142
80	54·924910	14·210027	76·8	21·3	0·7	182·4	9·7	−0·015	−0·135
90	54·924939	14·210048	76·7	20·8	0·7	184·8	10·3	−0·018	−0·106
100	54·924968	14·210072	76·7	20·8	0·6	185·8	8·9	−0·016	−0·078
110	54·924997	14·210096	76·6	20·5	0·6	184·3	9·5	−0·015	−0·1
120	54·925026	14·210121	76·6	20·3	0·7	183	10·7	−0·017	−0·135
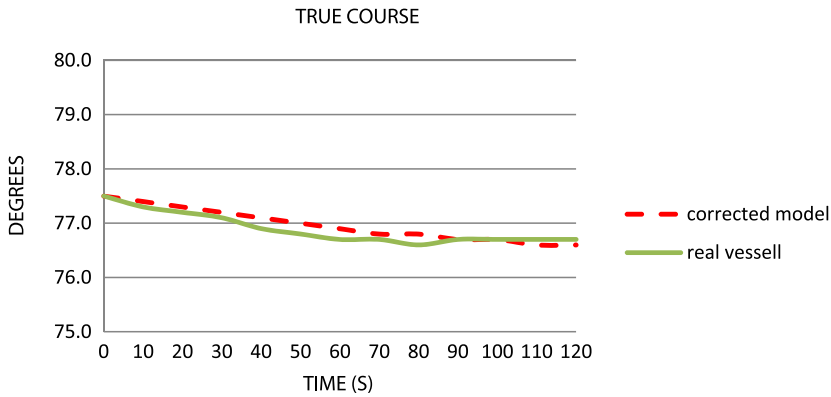
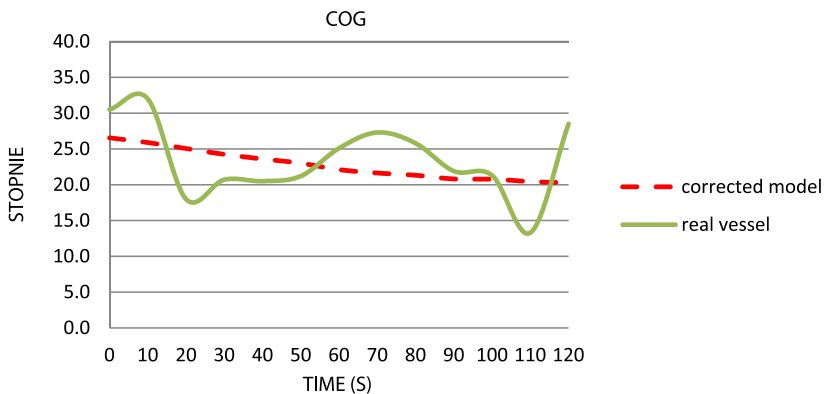Figure 10.   Comparison of the true courses.

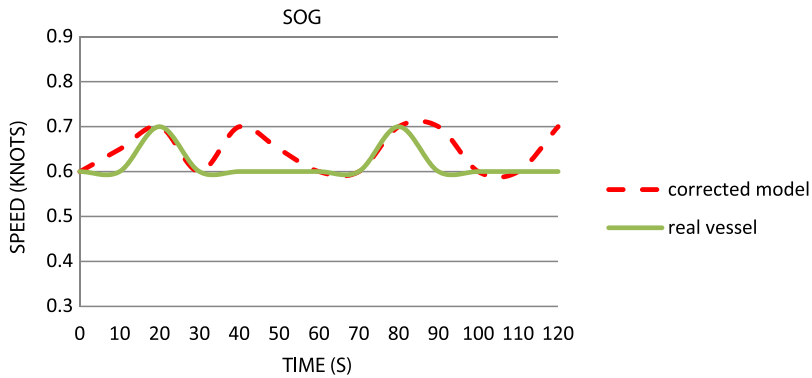Figure 11.   Comparison of the courses over ground.

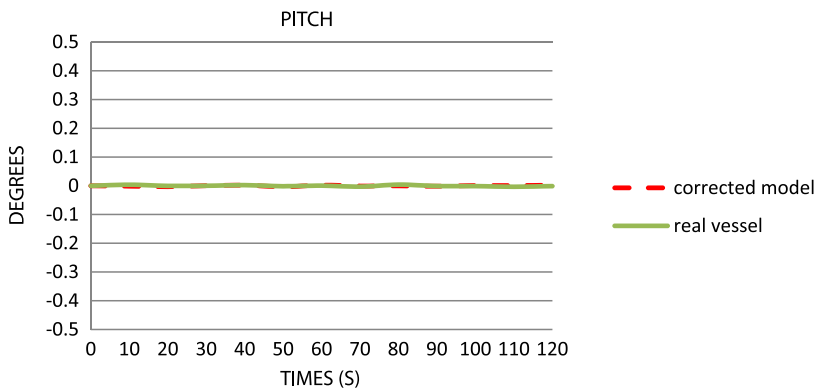Figure 12.   Comparison of the speeds over ground.

Figure 13.   Comparison of the pitch values.

time ranges. To obtain a more precise analysis of roll, the time ranges must be much smaller.

The matrix of observations of technical parameters for the real vessel is the same as it was during the analysis of the "extended" model. The matrix of the observations of technical parameters for the "corrected" model, however, takes the following form:

$$\mathbf{U_M} = \begin{bmatrix} U_1\,(M_2) \\ U_2\,(M_2) \\ U_3\,(M_2) \\ U_4\,(M_2) \\ U_5\,(M_2) \end{bmatrix} = \begin{bmatrix} -0{\cdot}900 \\ 0{\cdot}650 \\ 22{\cdot}700 \\ 0{\cdot}006 \\ 0{\cdot}238 \end{bmatrix}$$

The matrix of distances of technical parameters **du** is as follows:

$$\mathbf{du} = \begin{bmatrix} d_{U_1}\,(M_1) \\ d_{U_2}\,(M_1) \\ d_{U_3}\,(M_1) \\ d_{U_4}\,(M_1) \\ d_{U_5}\,(M_1) \end{bmatrix} = \begin{bmatrix} 0{\cdot}100 \\ 0{\cdot}030 \\ 0{\cdot}800 \\ 0{\cdot}001 \\ 0{\cdot}038 \end{bmatrix}$$
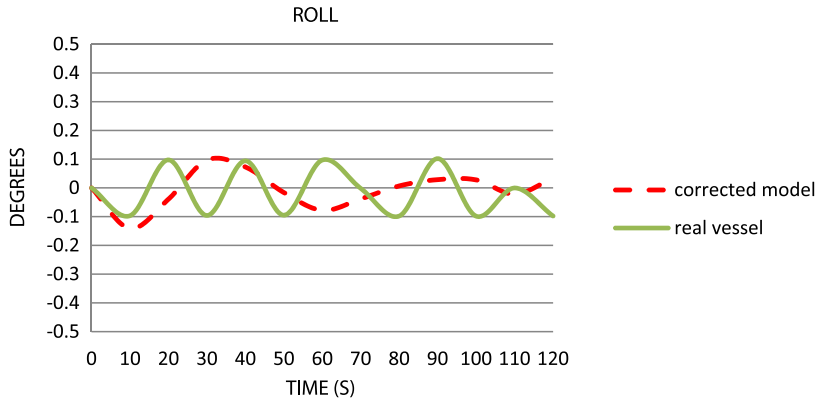
Figure 14.   Comparison of the roll values.

Table 7.   Values of technical parameters of the "corrected" model and the real vessel.

	U_1	U_2	U_3	U_4	U_5
M_W	−0·8	0·62	23·5	0·007	0·200
M_2	−0·9	0·65	22·7	0·006	0·238

Table 8.   Percentage values of distance non-correspondence of the "corrected model's" individual technical parameters with respect to the real vessel.

	d_{U_1}	d_{U_2}	d_{U_3}	d_{U_4}	d_{U_5}
"Corrected" model	−11 %	5 %	−3 %	−14 %	19 %

Having analysed the data contained in Table 8 concerning the final comparative analysis, it may be asserted that the non-correspondence values of the "corrected" model's technical parameters with respect to the real vessel, for four out of five parameters under study, is contained within a specific percentage range. Only the heel values exceed the assumed acceptability limits. This is because the angle values of heels are minute as the analysis is performed at sea states equal to one and two. Therefore, the differences equal to decimal numbers of an angle translate into significant percentage differences. Final results show that the model created based on construction data grossly deviates from the real vessel. Its application in a research process and the given scenario would result in significant errors in the interpretation of the studies. However, the adjustment of the model's coefficients significantly improves the degree of the models' correspondence with the real vessel.

5.   CONCLUSIONS.   This article presents a method for evaluation of the degree of correspondence between a simulated vessel and its real-world counterpart based on a multi-criteria analysis method for the test scenario developed. The method may also be used for any scenario once the goal of the research and the vessel's technical parameters have been defined and relevant weights assigned.

The limitation of the method proposed is the need to provide detailed information on local wind-driven waves. For this reason, a drifting ship and sea state one were the subject of examination presented in this paper. The assumed direction of waves was identical to the direction of the wind. In order, however, to examine manoeuvring elements of a ship at higher sea states, a method for evaluation of sea waves should be devised for the cases where no such information is available from other sources. This area of modelling was not the subject of this research. Such a method may be based on, for example, analysis of pictures taken during studies with elements allowing evaluation of scale and dimensioning.

By analysing the final results of the method presented, it was found that the corrected model was 90% correspondent with the real vessel. This evaluation is heavily undermined by the correspondence of the ship's heeling, but due to very small angles of heel of the reference, the real-world angle values are contained in decimal fractions of a degree. When only drift elements in the form of angles and speeds are considered, the corrected model's accuracy reaches 94%. Thus, the results show that it is plausible to adjust the coefficients of the simulation model in such a manner as to truthfully reflect the behaviour of a real vessel in specific hydro-meteorological conditions.

The feasibility of the methodology proposed depends to a large extent on a relevant database of real records. A rich collection of records registered in various hydro-meteorological conditions will enable the parameters of the model to be edited to an even greater extent than as described in this paper.

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