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A DECISION-MAKING SYSTEM SUPPORTING SELECTION OF COMMANDED OUTPUTS FOR A SHIP'S PROPULSION SYSTEM WITH A CONTROLLABLE PITCH PROPELLER

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Abstract:

The ship's operators have to make decisions regarding the values of commanded outputs (commanded engine speed and pitch ratio) which ensure maximum vessel speed and minimum fuel consumption. Obviously, the presented decision problems are opposed. Therefore, there is a need for a compromise solution that enables more flexible vessel voyage planning. This paper deals with development of a computer-aided system supporting selection of commanded outputs (commanded engine speed and pitch ratio) for a ship's propulsion system with a controllable pitch propeller. The main component of this system is the decision-making system. In particular, development of both the functional models using ANN techniques, and the two-objective optimization model of the mentioned decision-making system are presented.

Keywords: ship propulsion, commanded outputs, decision-making system, optimization

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1. Introduction

Operators of all types of ships are interested in decreasing their operational costs associated with consumption of material resources, e.g., fuel consumption by ship propulsion, and operational losses, e.g., excessive travel time to the destination. Therefore, there is a need to manage these resources effectively.

In the case of a ship equipped with a controllable pitch propeller (CPP), its propulsion system can produce the desired thrust or achieve the desired ship speed at many combinations of the outputs: commanded torque and pitch ratio. Most commercial vessels use a shaft speed/pitch ratio controller. In this controller, the commanded torque is controlled to maintain a certain shaft speed.

However, there are vessels that are not equipped with such controllers and in which combinations of the outputs are selected manually. In such cases, due to diverse conditions at sea, selecting output values is extremely difficult because of the uncertainty of meteorological conditions on the waters where navigation takes place. For this reason, it would be useful to support such decision-making with a decision-making support system. This, in turn, requires acquisition of the appropriate data, which could be obtained by carrying out sea trials, preferably aboard a ship, for which the following are true:

– the output combinations often change, and
– their changes significantly affect the efficiency of navigation.

Moreover, the conduct of sea trials should not contribute to substantial operational losses for ship owners.

Sailing vessels comply with the presented requirements when they are powered by the engine and are not using sails. Their navigation could be characterized by the following distinctive factors:

– sensitivity to changes in weather conditions, and

– relatively low engine power from their propulsion system.

The first factor is a result of the increased air resistance of high masts and the hull shape sensitivity to the direction, steepness, and height of the waves. The second factor decreases ship maneuverability and controllability, particularly in the case of an upwind course. The operators of such sailing vessels have to make decisions regarding the values of the mentioned combination of the outputs (commanded engine speed and pitch ratio) which ensure maximum vessel speed and minimum fuel consumption. Obviously, the presented decision problems are opposed. Therefore, there is a need for a compromise solution that enables more flexible vessel voyage planning.

As a rule, vessel operators (skippers or watch officers) select the appropriate settings for the ship propulsion system (hereafter called the commanded outputs) using their own experiences and rules of conduct for certain weather conditions. In general, such procedures have no theoretical justification and are based only on intuition. Therefore, the operators have to analyze all available information independently. Based on the information obtained, they make decisions which can sometimes be irrational or inappropriate. To avoid such situations, a computer-aided system supporting selection of these commanded outputs for sailing vessels equipped with engine powered propulsion systems with a CPP has been developed. The main component of this system is the decision-making system; a set of interrelated elements and their functions to process the received data using computer techniques.

2. Literature review

The problem of selecting the commanded torque and pitch ratio is connected to both the ship's resistance and the efficiency of the engine powered propulsion system. Therefore, the literature review should answer the following questions:

– what is the current state of knowledge about the considered problem?

– what empirical methods were used to solve similar research problems?

– what relations exist between the main elements of the considered issue?

The literature survey has shown that there are possibilities to influence ship propulsion performance in two essential stages of a ship's life cycle, namely the design and operational use phases.

In the first phase, the main role of design is to achieve the best combination of low ship resistance and high efficiency of the propulsion system.

Ship resistance is defined as the force required to tow the ship in calm water at a constant velocity. This issue is well recognized and widely presented in subject literature. The "father" of the method to evaluate ship resistance is William Froude, a British engineer who was the first to formulate the laws governing the resistance experienced by ships sailing on water. In 1868, he performed a detailed examination of ship resistance, the results of which were published by Froude (1872). Froude realized that the ship resistance issue should be broken into two different parts: residuary resistance (primarily wave-making resistance) and frictional resistance. The resistance with which water counteracts the motion of the ship immersed in it is composed of a number of partial resistances. Detailed descriptions of particular partial resistances are presented by Molland et al., (2011), Lewis (1988) and, Dudziak (2008).

Evaluation of ship resistance for the various hull shapes during the initial design phase is essential to develop both a fuel-efficient hull form and a propulsion system. There are many methods for estimating ship resistance. They can be divided into the following groups (without taking air resistance into account):

– scale-model experiments,
– semi-empirical methods,
– analytical methods, and
– numerical methods.

The traditional means of measuring such characteristics is the appropriate scale-model experiment (Molland at al. 2011). The existence of scale effect between a model and a ship has to be proved on theoretical grounds. As a general rule, they are carried out in special research centers; so-called ship model basins. They are organized worldwide in the ITTC (International Towing Tank Conference) to standardize their model test procedures. This approach is reliable, but it also consumes extensive time and cost. It remains the most accurate and reliable method but it may only be used to obtain the ship's resistance within certain limits or when comparative data exists to forecast the resistance of a ship class.

There are a number of semi-empirical methods for rough estimation of ship resistance. Generally, these methods do the following:

– use regression equations, for which coefficients are determined based on a series of measurements carried out on a towing basin using reduced-scale ship models,
– allow only one of parameters to change while the other parameters have fixed values during the measurement, and
– select the shapes of the ship's hull in an arbitrary manner.

In addition, these methods are based on time- and work-consuming computations. They require calculating a large number of factors and carrying out their subsequent corrections. As a rule, the accuracy of the results is generally unsatisfactory.

Due to the complicated nature of flow around the ship's hull, satisfactory analytical methods relating speed and power requirements to a hull form has not yet been developed. However, to determine the drive propulsion characteristics of high-speed craft, the 'Slender Body Method' is used. It based on the results of research presented by Tuck and Luzauskas (1998) and Couser et al. (1998) to determine the wave resistance of a symmetrical ship hull. In addition, it is confined to determining the resistance elements for different wave patterns.

Prediction of the ship's resistance can also be obtained by means of numerical methods. Their essence is to determine the resistance by a set of equations adequately describing the phenomenon of flow around a ship's hull. CFD software packages for analysis of the ship and propeller flow produce the desired results. An example of the application of numerical methods to determine the drive propulsion characteristics is presented by (Molland at al. 2011).

Regarding air resistance, forces and moments caused by the interaction of both the wind and the ship's structure above water are only a negligible fraction of the total ship's resistance. However, under some circumstances such as towing, mooring and dynamic positioning of vessels, air resistance plays an important role. Tests carried out on reduced-scale ship models in wind tunnels are the most accurate means to estimate the impact of wind forces on air resistance. Because they are very expensive tests, alternative methods have been developed. They are presented by Isherwood (1972), Gould 1982), Blendermann (1994), OCIMF (1994) and, compared by Blendermann (1995).

During the evaluation of a ship's resistance it is crucial to select the propeller and the entire propulsion system. In the considered case, the propulsion system is a means of creating a force leading to ship motion and it consists of a source of mechanical power (engine), and a means of using this power to generate force, such as a controllable pitch propeller. The propulsion system's efficiency can be characterized by a set of drive propulsion characteristics. Generally, they are depicted as a set of empirical curves obtained by connecting the observed values of propulsion power, thrust, efficiency and torque at the propeller cone, fuel consumption, ship speed, etc. and the given ship resistance characteristic.

In the operational use phase of the ship's life cycle, knowledge of the propulsion characteristics allows for rational selection of the commanded outputs of the drive propulsion parameters (the engine rotational speed and the propeller pitch) for variable weather conditions. It also predicts the operational parameters of the ship (e.g., vessel speed, fuel consumption) as the sea state changes.

Issues relating to selection of the appropriate commanded outputs of the drive propulsion parameters of the propulsion system equipped with a CPP are presented in many publications, including Chachulski (1988), Pedersen and Larsen (2009).

Methods for selecting optimal drive propulsion parameters are presented by Chachulski (1988). The proposed method is based on controlling the ship propulsion system to maximize its efficiency. The efficiency of an engine is a function of engine load and speed based on data provided by the manufacturer, whereas the efficiency of a propeller is determined by means of its hydrodynamic characteristics or based on results obtained from the scale-model experiments. The maximum efficiency curve of the propeller and its pitch coefficients (throughout its rev range) is a plot of the engine effective power vs. the propeller rotational speed for the given conditions of navigation.

Another method for determining the optimal range of a ship's propulsion system is presented in Technical Report (1991). This method is based on the minimum fuel consumption criterion for a given ship speed, propeller pitch and engine RPM changes. It uses the characteristics of engine fuel consumption provided by the manufacturer and the results of scale-model hull tests carried out for a particular type of vessel.

A practical method of determining propulsion characteristics is proposed by Gorski and Cwilewicz (2002). This method is based solely on the results of the energy measurements performed onboard the ship. Therefore, results of ship hull model tests and engine bed tests are unnecessary. Planning the experiment using standard values of input parameters makes it possible to considerably lower the number of measurement points, thereby reducing the time and cost of the measurements. Nevertheless, the time and cost of such an experiment, the need to bring the measurement team aboard, and the deed to install specialized devices generally discourages the implementation of such an approach.

The literature analysis showed that models based on polynomial or regression equations are used to select the drive parameters of a ship's CPP-equipped propulsion system.

As a rule, algorithms for solving systems of equations in both models are too complex. For this reason (among others), the following assumptions are used:

– propeller torque force is approximated as a quadric function of engine rotational speed,
– power required to turn the propeller is approximated as a cubic function of engine rotational speed, and
– ship speed is proportional to the rotational speed of a controllable pitch propeller.

Pedersen and Larsen (2009) noted the difficulties of traditional ship performance analysis techniques requiring the estimation of a number of unknown friction-related coefficients, often from limited model test or empirical full-scale trials data. As an alternative to resistance modeling, the presented research outlines a method using artificial neural networks to predict propulsive power from the same theoretical variables influencing ship resistance, such as ship speed, relative wind speed and direction, air temperature, and sea water temperature. This method does not require a priori assumptions of the formula of the modelled function. Using actual ship datasets segmented by draft and trim conditions, they report propulsion power prediction accuracy of greater than 2,7%, compared to a range of 18 to 28% using traditional resistance techniques.

A review of the methods of selecting the commanded outputs indicates that the most important issue is the determination of the drive propulsion characteristics of the ship. All of the methods used correctly reproduce design and operational characteristics of ships with CPP. However, there is a problem with their use during ship operation. It is known that, due to changing sea conditions, the working parameters of the ship's propulsion system are subject to change as well. The disadvantages of these methods are the difficulties with estimating sea conditions. Nonetheless, knowledge of these conditions is essential to selecting the appropriate propeller pitches and engine rotational speeds. In this research, 'sea condition' are situations that influence efficiency of navigation at sea, such as meteorological (wind speed and direction), nautical (sea current speed and direction), and operational (biofouling, quality of sails folding) conditions.

3. Development of a decision-making system supporting selection of commanded outputs for engine ship propulsion with a CPP

3.1. Modeling approach

From the viewpoint of physics, the vessel is a solid object partly submerged in water and air fluids. When such a vessel is propelled by an engine – the water, the air, and the ship itself are affected by its relative motion. These enumerated elements set up the arrangement shown in Figure 1.

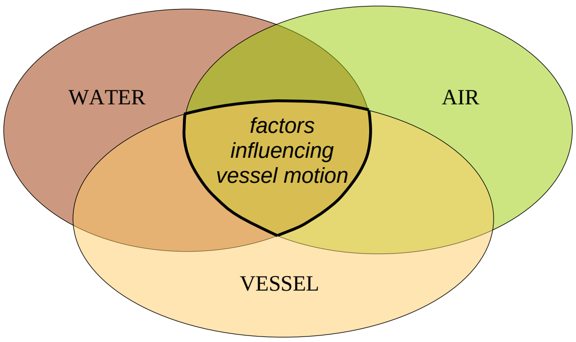

Figure 1. Factors affecting the motion of a vessel

Based on the presented elements and the relationships between them, groups of specific factors influencing vessel motion can be distinguished, such as in the following cases:

– the vessel: the type and structure of its propulsion system; the type of its hull form; displacement; hull roughness; the type of propeller and rudder; aerodynamic shape of superstructure, etc.,
– the water: temperature, density, tides, sea currents, etc.,
– the air: wind, temperature, etc.,
– the vessel - water relationship: waves generated by moving a vessel, etc.,
– the vessel - wind relationship: trim; list, etc., and
– the air - water relationship: wind, waves, etc.

The impact of these factors on the vessel motion depends on the accepted design solutions, the vessel operational time, the conditions at sea, etc. For the purpose of model development, they have been divided into the following groups of factors:

– factors that cannot be measured directly and controlled,
– factors that can be measured but cannot be controlled,
– factors that can be measured and controlled, and
– informative factors.

Factors that cannot be measured directly and controlled are the determined and imposed parameters whose values are relatively steady. This group may contain:

– ship design parameters that result from ensuring other more important ship properties such as power, speed, etc., and
– ship operational parameters that result from the vessel's operational state, seawater characteristics, etc.

The first group includes the hull sizes and hydrodynamic forms; the number and the hydrodynamic shape of the propeller blades; the size and hydrodynamic shape of the rudder; and the size and aerodynamic shape of the ship superstructure including sailing vessel rigging, etc. The second group includes the ship's displacement when it is floating (depending on the loading condition of the ship and the salinity and temperature of the seawater); changes in the shape and surface roughness of the underwater section of the hull (biofouling); the quality of sails folding, etc.

Factors that can be measured but cannot be controlled are the determined parameters whose values can change during ship motion and be measured. This group includes: the sea current's speed and direction; the temperature and salinity of the seawater; the wind direction and speed; the air temperature; the height, duration, and shape of wind waves; etc.

Factors that can be measured and controlled are parameters that provide the desired sailing vessel motion while under engine powered propulsion. They include the commanded outputs of the drive propulsion parameters.

Informative factors are parameters that support effective decision making regarding the working parameters of the drive propulsion.

The problem can be condensed down to a decision-making model presented in the form of a 'black box' subject to the factors listed above (Fig. 2).

In this model, the decision-making variables X_{Di} are factors that can be controlled to produce the desired sailing vessel motion under engine powered propulsion, namely: rotational speed and pitch of the propeller.

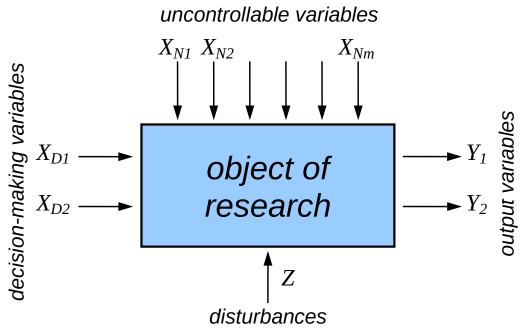

Figure 2. Decision-making model in a 'black box'

The uncontrollable variables X_{Nj} include factors affecting the vessel motion that cannot be controlled but can be measured. Their values may change as the result of variations of the conditions at sea. These factors can counteract the ship's motion (e.g., headwind) or be conducive to the ship's motion (e.g., sea current in the direction of the vessel's motion).

In the developed decision-making model, the decision-making X_{Dn} and the uncontrollable X_{Nm} variables set up the input variables X_i.

Other factors affecting the vessel's motion that cannot be controlled or impacted are considered the disturbances Z. They include, primarily, the ship's design and operational parameters.

The output variables Y_k include factors characterizing efficiency of ship motion such as engine fuel consumption and the ship's speed.

Taking these factors into consideration, the decision-making model can be expressed as follows:

$$Y_k = f(X_{Dn}, X_{Nm}, Z) \tag{1}$$

where:

Y_k – output variables,

X_{Dn} – decision-making variables,

X_{Nm} – uncontrollable variables, and

Z – disturbances.

Then, the considered problem can be formulated as follows: *what should the values of the decision-making variables X_{Dn} be for the given values of the uncontrollable variables X_{Nm} to provide the desired values of the output variables Y_k.*

The considered output variables Y_k are engine fuel consumption and the ship's speed, which are in a contradictory relationship. To find a compromise solution, we developed the computer-aided system supporting selection of these commanded outputs of the sailing vessel equipped with the engine powered propulsion system with the CPP.

Development of the computer-aided system supporting selection of the commanded outputs of a ship's propulsion system requires the following:

- selection of a vessel for obtaining the data needed to develop the decision-making system,
- selection of a set of significant model parameters used to develop necessary input and output variables,
- collection of the data (input and output variable values) needed to build the necessary models,
- development of the functional model (models) combining input and output variables, and
- development of the optimization model that allows selection of the values of the decision-making variables to achieve the optimal commanded outputs of the ship's propulsion system.

3.2. Subject of experiment

It is obvious that development of the proposed computer-aided system requires the collection of the appropriate data. As already mentioned, the most representative vessel for obtaining such data seems to be a sailing ship which navigates on different water regions with changing sea conditions. These criteria are met by the prototype tall ship "Pogoria" launched in 1980. She is equipped with a Volvo-Penta auxiliary propulsion engine producing 228 kW of nominal power to drive a two-blade controllable pitch propeller via a reduction gear with a gearbox ratio equal to 1:4,5. The nominal rotational speed of the propeller is 356 rpm. According to the technical data of the propulsion engine, the standardized fuel consumption is 212 g/kWh for the rotational speed of 1800 rpm. Its gross tonnage is 290 GT, overall length 47.29 m, width 8 m, and draught 3.5 m. More information regarding this tall ship is presented by Kozak and Tarelko (2011).

The following are the characteristic features concerning its navigation:

- low main engine power in relation to the size of the ship,
- defined proportion of motoring (approximately 50% of navigation during a one-week voyage),
- voyages over very different water regions (Baltic Sea, North Sea, Mediterranean Sea, and Atlantic Ocean) with different sea conditions, and
- relatively long times between successive dockings.

To collect all data needed for building the necessary models, the preliminary and basic experiments have been conducted.

In the first case, 20 parameters were preselected and used to develop the necessary input and output model variables. Their values were obtained from 800 observations made during preliminary sea trials. They were then used to develop the functional model in the form of multiple regressions. The obtained results show the following (Rudzki, 2014):

- the regression methodology has a weak ability to extrapolate and generalize, which can be traced to inherent limitations of the data,
- the regression methodology requires a determination of the forms of regression functions a priori,
- a majority of the observed parameters turned out to be statistically insignificant, for example: engine inlet fuel and air temperatures, engine oil temperature, and seawater temperature of the engine cooling system, and

– the effect of ship hull biofouling should be taken into account during the next sea trails.

Nevertheless, there are modeling tools that will not require the determination of the function forms a priori and that are capable of extrapolation and generalization, such as Artificial Neural Networks (ANN). Therefore, ANN have been applied to build the desired functional models.

3.3. Selection of model variables

To select the model input and output variables, we have accounted for the following assumptions in the next stage of the experiment:

– the decision variables X_{Dn} should include the commanded outputs of the ship propulsion system, and

– the uncontrollable input variables X_{Nm} should include parameters that have a wide range of possible values and can be measured by measurement devices normally installed or additionally developed and mounted onboard the ship.

Based on these assumptions and the results of the preliminary sea trials, both the input variables X_i and the output variables Y_k necessary to develop the functional model (models) have been selected (Table 1).

Values for the selected parameters were obtained from 315 observations made during basic sea trials. Their results have been collected and published as a PhD thesis (Rudzki, 2014).

Table 1. Input and output variables

variable name	variable identifier	unit
rotational speed of the engine	X_1	[rpm]
pitch of the propeller	X_2	[pitch scale]
angle of wind direction in relation to the longitudinal axis of the ship	X_3	[^{o}]
speed of the wind	X_4	[knot]
state of the sea	X_5	[degree]
angle of tidal current direction in relation to the longitudinal axis of the ship	X_6	[^{o}]

speed of the tidal current	X_7	[knot]
time since the last docking of the ship	X_8	[months]
hourly fuel consumption rate	Y_1	[dm^3/h]
instantaneous speed over the ground	Y_2	[knot]

Commanded outputs for the rotational speed of the engine, (and, consequently, the shaft speed) and for the controllable propeller pitch were selected using two command levers situated on the navigation bridge (Fig. 3).

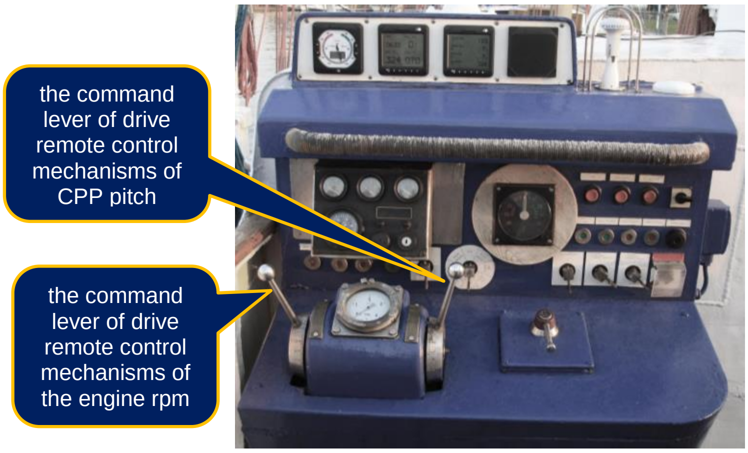

Figure 3. Command levers of the navigation bridge

These levers remotely control the engine injector pumps and the controllable pitch propeller. Values of the variable X_1 'rotational speed of the engine' were read as indications of the RPM indicator (with 50 rpm accuracy) as standard equipment of the propulsion engine system. The minimum idle rotational speed of the propulsion engine is approximately 530 rpm, while the maximum rotational speed is 2000 rpm. However, there is no direct relation between the position of the command lever and the engine rotational speed, as setting the rotational speed may correspond to different positions of the control rod of the inline injector pumps depending on the current load.

Values of the variable X_2 'pitch of the propeller' were read as successive positions of the command lever of the drive remote control mechanism assuring repeatable positioning and propeller pitch adjustment. The propeller pitches were read as the lever position with respect to the disc engraved scale marked from -25 to +25 marks (negative values mean vessel motion backward).

In practice, the available ranges of the commanded outputs are limited by sea conditions, and vary between 1100 and 1900 rpm for the engine rotational speed and up to 18 marks for the propeller pitch, respectively. Exceeding these limits generates unacceptably high temperatures in the gearbox of the engine propulsion system. The selected model variables X_1 and X_2 belong to the set of decision-making variables X_{Dn} (Fig. 2).

The next two input variables X_3 'angle of wind direction in relation to the longitudinal axis of the ship' and X_4 'speed of the wind' are closely related and were measured using the ultrasonic anemometer mounted on top of the vessel superstructure. In our approach, we assumed that a range of apparent wind angles varies from -90° to 90° in relation to the longitudinal axis of the ship, wherein the -90° angle referred to the wind blowing from the bow of the ship, and the 90° angle from the stern of the ship. This approach reflects the fact that the apparent wind blowing from the bow increases resistance of the ship motion maximally, whereas wind from the stern supports the ship motion maximally. Values of wind direction angles were estimated as values of the angle of the apparent wind direction reduced by -90°, regardless of which side of the board the wind blows from.

Values of the input variable X_5 'state of the sea' were estimated by means of the Douglas Scale. Values of the next two input variables, X_6 'sea angle of tidal current direction in relation to the longitudinal axis of the ship', and X_7 'speed of the tidal current', were calculated for given waters based on nautical charts and tide and tidal current tables. Similar to X_3, values of the sea angle of tidal current direction were estimated as the difference between the actual tidal current direction and the ship course calculated by the GPS satellite navigation system.

The last input variable X_8 ‘time since the last docking of the ship’ is related to the effect of ship hull biofouling. To determine the impact of this effect on the ship’s propulsion system efficiency, a two-year experiment was carried out. Based on the obtained results, the conclusion is that biofouling considerably affects the parameters which characterize the efficiency of the ship propulsion system. The build-up of the biofilm layer can lead to a remarkable decrease in vessel speed. A detailed description of this experiment and its results are presented by Tarelko (2014).

The input variables from X_3 to X_8 constitute the set of uncontrollable variables X_{Dn} (Fig. 2).

Values of the output variable Y_1 ‘hourly fuel consumption rate’ were measured using a specially developed measuring device. The operating concept consists of connecting a volume calculator tank to the main engine fuel installation. A schematic of this installation is shown in Fig. 4. The three-way T-type valves, marked z1 and z2, cut off the measuring tank once the measurements are completed and return to the normal situation in which the main engine is supplied from the day fuel tank.

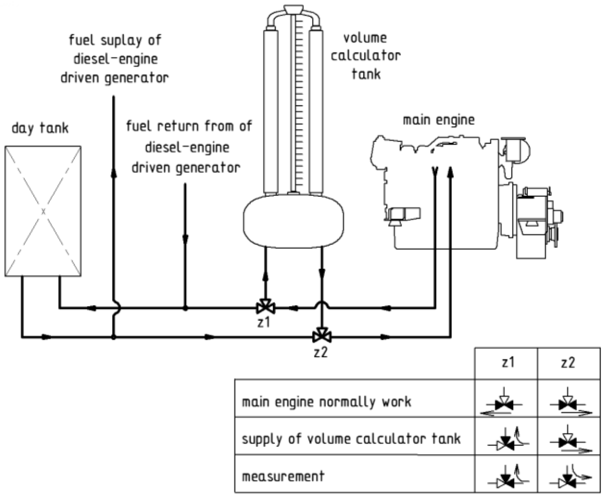

Figure 4. Schematic diagram of a volume calculator tank

The values of the output variable Y_2 'instantaneous speed over the ground' were read from a universal receiver of a satellite navigation system (GPS).

Obviously, parameters which characterize efficiency of the ship's propulsion system are subject to changes in sea conditions. During sea trials, conditions such as the ship's course, the force and direction of the wind, the speed and direction of the current, and the sea state (height and direction of waves) were considered temporarily constant during the measurement period, which never exceeded 15 minutes.

4. Functional models developed using ANN

The data obtained during the basic sea trials were used to build the ANN functional models. They were organized into input and output variables according to Table 1.

In the first step, the quality of the collected data was assessed using the STATISTICA software module. To analyze the correctness of the factor space structure, the central agglomerative procedure and six combinatorial methods were used. The dendrograms obtained from these methods had similar structures. The data are practically separated by method and metric in a similar procedure - with the exception of specific numeral values of similarity. Based on the correct clustering, it was agreed that the choices of the model variables were appropriate for the collected data.

In the next steps, the MATLAB software neural network toolbox was applied to develop the desired ANN models.

To extrapolate the data beyond the observed range, a linear normalization with 10% overlap rate was used across the range of 0.1 to 0.9 for positive values of the variables (X_1, X_2, X_4, X_5, X_7, X_8, Y_1, Y_2), and across the range of -0.9 to 0.9 for positive and negative values of the variables (X_3, X_6). Next, the cross-validation of the ANN training procedure was performed to ensure accuracy of the results. The MATLAB function using random indices divided the input data into three sets whereby 70%, 20% and 10% of them are used for training, validation and testing of ANN, respectively.

The preliminary experiment (Rudzki, 2014) shows that the considered decision-making problem is non-linear. Therefore, to build a functional model, the non-linear neural network was selected. The outputs of such a model could be received by means of one common or two detached networks. We decided to develop two separate networks based on a suggeestion presented by Tadeusiewicz (2007). As a result, two functional models using ANN techniques have been obtained.

In the subsequent stages of ANN development, the appropriate network architecture was selected. In particular, the number of hidden layers, neurons in these layers, and the type of the activation function were determined. To describe the network structure, 'feedforward' neural networks were chosen.

Based on the MATLAB neural network toolbox and its functions, all activities necessary to develop the required ANNs were performed. In particular, the number of epochs, the type of activation function for the neurons, the fit quality of ANN, the ANN training step was completed, and the appropriate MATLAB codes were prepared.

Extensive computational experiments produced two separate ANNs for both output variables, Y_1 'hourly fuel consumption rate' and Y_2 'instantaneous speed over the ground'. In both cases, the Multi Layer Perceptron (MLP) network of the following structure was used:

- eight neurons in the input layer representing the input variables for both functional models,
- two hidden layers with different numbers of neurons, and
- one neuron in the output layer representing the output variables separately for each of the functional models.

Both networks differ only in the number of neurons in the hidden layers. The basic architecture of the developed ANNs is presented in Fig. 5, and MATLAB custom network diagrams with functions of the selected neural network toolbox for both functional models are shown in Fig. 6.

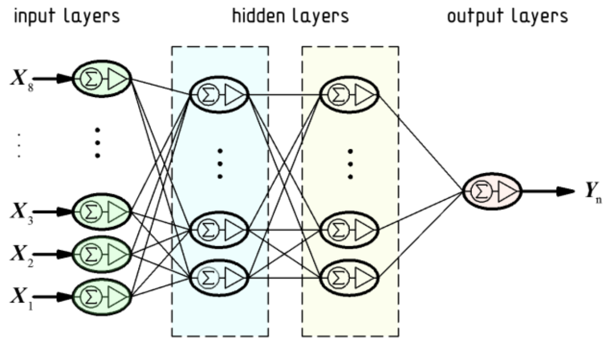

Figure 5. The basic architecture of the developed ANNs

a) b)

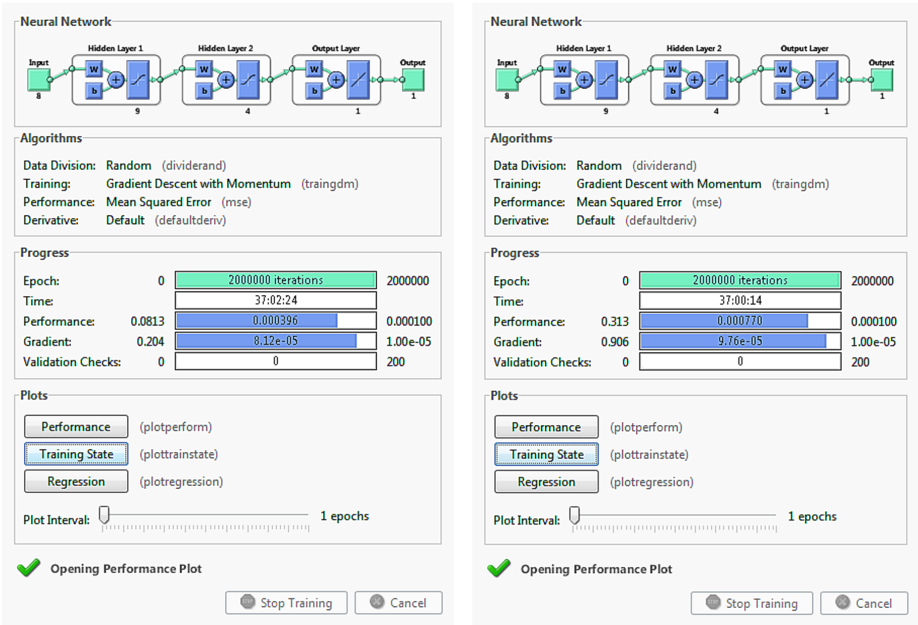

Figure 6. MATLAB custom network diagrams for the functional models: a) hourly fuel consumption rate; b) instantaneous speed over the ground

To verify the correctness of the presented approach, additional sea trials were conducted after development of the computer-aided system. The representative values of the input variables (observations) are shown in Table 2.

Table 2. The representative values of the model variables obtained during additional sea trials

variable identifier	value of observation	unit
X_1	from 1100 to 1900 with steps of 50	[rpm]
X_2	from 2 to 18 with steps of 1	[pitch scale]
X_3	-90	[^{o}]
X_4	5	[knot]
X_5	1	[degree]
X_6	15	[^{o}]

X_7	0,6	[knot]
X_8	10	[months]

Examples of the relationships between the output variable Y_1 'hourly fuel consumption rate', the output variable Y_2 'instantaneous speed over the ground', and the decision-making variables X_1 'rotational speed of the engine' and X_2 'pitch of the propeller', for the representative values of the uncontrollable variables X_3 to X_8 (Table 2) are shown in the form of 2-D MATLAB graphs in Fig. 7 and Fig. 8, respectively.

Usunięte: ¶

a) b)

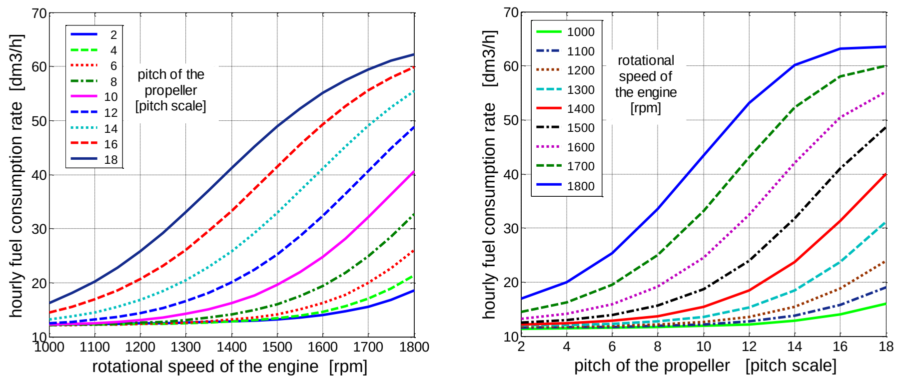

Figure 7. The relationships between 'hourly fuel consumption rate' and: a) 'rotational speed of the engine'; b) 'pitch of the propeller'

a) b)

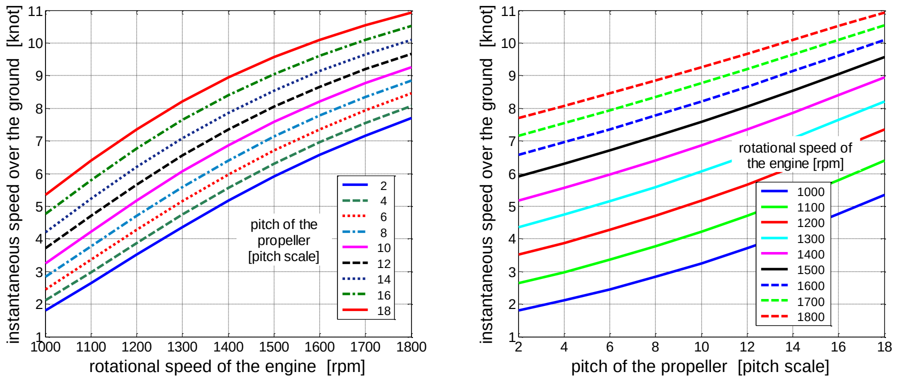

Figure 8. The relationships between 'instantaneous speed over the ground' and: a) 'rotational speed of the engine'; b) 'pitch of the propeller'

Curves of all of the generated graphs are smooth, which means that these ANN models produced a good fit of the experimental data. Thus, they can be used to develop the optimization model.

5. Two-objective optimization model for selection of commanded outputs of the ship propulsion system using ANN

The development of the computer-aided system supporting selection of commanded outputs of the ship's propulsion system also requires the optimization model to set the values of the decision-making variables (rotational speed of the engine and pitch of the propeller) to achieve the system objectives. Both objectives, minimum fuel consumption rate and maximum speed, constitute two criteria of a multi-objective optimization. Therefore, this issue reduces to a two-objective optimization problem.

Such a problem is often solved by combining its two objectives into one single-objective scalar function. This approach is known as the weighted-sum method. The weighted-sum method minimizes a positively weighted convex sum of these objectives:

$$Z = w_{q1} \cdot Y_1 - \left(1 - w_{q1}\right) \cdot Y_2 \;\rightarrow\; MIN \tag{2}$$

and

$$w_{q1} + w_{q2} = 1 \tag{3}$$

where:

Z – the substitute objective function of a two-objective optimization problem,

Y_1 – the hourly fuel consumption rate (criterion 1),

Y_2 – the instantaneous speed over the ground (criterion 2),

w_{q1} – the weight factor of the criterion Y_1,

w_{q2} – the weight factor of the criterion Y_2.

Equation (2) represents a new optimization problem with the unique objective function Z. To illustrate this approach, three different navigational options are considered:

a) navigation with rational fuel consumption and sufficient speed is desired; in this case the ship operator assigns equal weight values to the two criteria,

b) navigation with the lowest fuel consumption is needed, while time to reach the destination is not important; in such a case the ship operator assigns the maximum weight value to the first criterion of the hourly fuel consumption rate (the minimum maneuvering speed should be assured),

c) navigation with the highest possible speed is required (e.g., in the case of a dangerous situation); in this case the ship operator assigns the maximum weight value to the second criterion of instantaneous speed over the ground (the fuel consumption is not taken into account).

It is clear that the ship operator can determine other combinations of the weight values, but in all cases should fulfill condition (3).

An important stage of optimization model development is the determination of the set of admissible solutions. This set is determined by constraints imposed on the solutions' values.

In this optimization problem, constraints on the values of the decision-making variables have been imposed. They set up two inequality constraints of the optimization model that result directly from the operation of the drive remote control mechanisms of commanded outputs, the engine rotational speed and the propeller pitch. In practice, the available ranges of these commanded outputs are limited by sea conditions. They range between 1100 and 1900 rpm for the engine rotational speed and up to 18 marks of the disc engraved scale for the controllable propeller pitch. Exceeding these limits can produce unacceptable conditions in the propulsion system such as high temperatures in the propulsion system gearbox.

To verify the appropriate selection of the commanded outputs of the ship propulsion system within the permissible range of loads, measuring the torque M on the propeller shaft was introduced. Its values were measured using a wireless tensometric torque meter specifically installed on the propeller shaft. The torque meter transmits the signal using magnetic induction. Read-outs of the torque values were performed by a deflection gauge as a percentage of the calculated nominal torque. To determine the relationships between the torque *M* and the input variables X_{Dn}, a separate model was built using ANN. To develop this ANN model, the same approach and observations were used as those used to develop the ANN functional models.

Figure 9 presents two-dimensional graphs calculated by the developed ANN model for the decision-making variables X_1 'rotational speed of the engine' and X_2 'pitch of the propeller', respectively, and for the representative values of the model variables obtained during additional sea trials (Table 2).

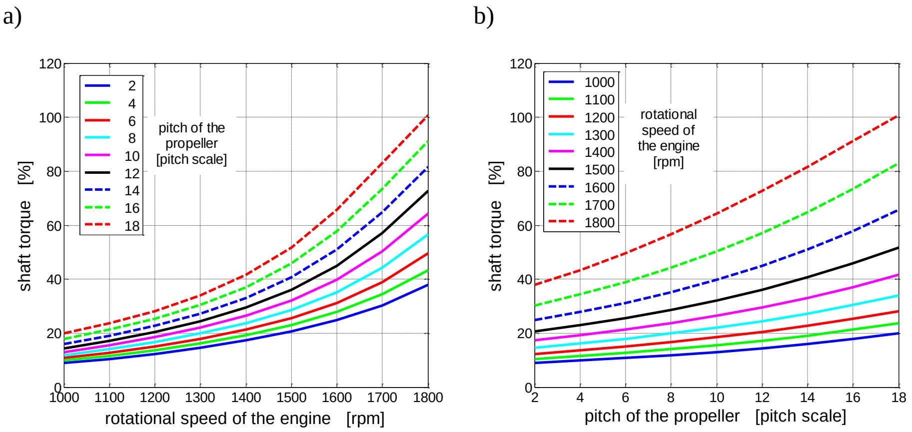

Figure 9. The relationships between shaft **torque *M* and: a) 'rotational speed of the engine'; b) 'pitch of the propeller'**

The permissible values of the propeller shaft torque *M* constitute the third of the inequality constraints of the considered optimization model.

Another significant constraint included in the optimization model was the minimum ship maneuvering speed. Based on the years of experience of the *Pogoria* skippers, it was agreed that this constraint should not exceed 2 knots.

To determine the optimal commanded outputs of the ship's propulsion system, the brute force method was used. This method attempts to calculate all possible solutions and decides afterwards on the best solution. Based on the developed ANN functional models, the minimum of the substitute objective function was determined for each combination of commanded outputs. Because the graph curves of the ANN functional models have consistent slopes (Fig. 7 a, b and Fig. 8 a, b), the substitute objective function Z of the considered optimization problem was modified by introducing a new output variable Y_{ls} representing the loss of speed of a vessel:

$$Y_{ls} = Y_{2max} - Y_2 \tag{4}$$

where:

Y_{ls} – the output variable representing loss of speed,

Y_{2max} – the maximal instantaneous speed over the ground.

Then, equation (2) has the following form:

$$Z = w_{q1} \cdot (1 - Y_2) + \left(1 - w_{q1}\right) \cdot Y_1 \rightarrow MIN \tag{5}$$

This is a purely technical approach that does not alter the optimization results.

Based on the selected optimization criteria, their mathematical descriptions, and the determined constraints, an algorithm of the two-objective optimization was designed. All necessary calculations were performed using codes developed from the MATLAB optimization toolbox.

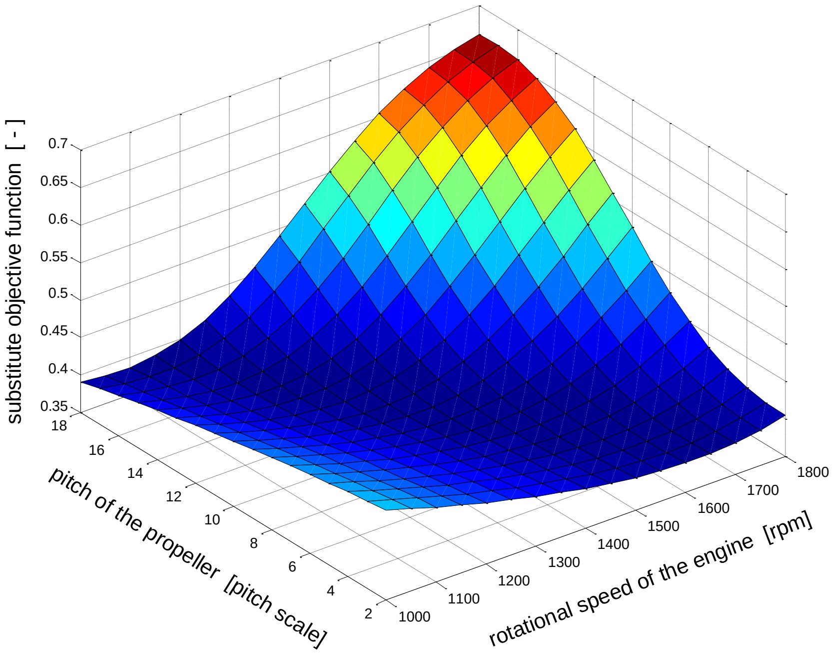

Figure 10. The value of the substitute objective function in relation to decision-making variables substitute objective function'

Analysis of the substitute objective function was performed before the optimization calculations. Figure 10 shows a three-dimensional surface plot of this function for all ranges of the decision-making variables X_{Dn} and the representative values of the uncontrollable variables X_{Nm} (Table 2) for the weight factors w_{q1}=w_{q2}=0,5. This surface has a 'cavity', where the minimum of the substitute objective function can be determined.

a) b)

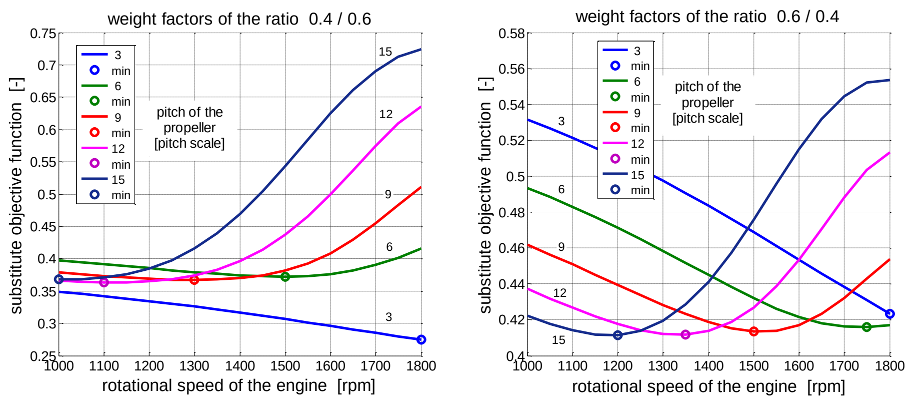

Figure 11. Graphs of the substitute objective function of the two-criterion optimization for the relationship of the weight factors of the ratio 0.4/0.6 and various commanded outputs: a) rotational speed of the engine [rpm]; b) pitch of the propeller [pitch scale]

Two-dimensional graphs presenting the curves of the substitute objective function *Z* obtained from equation (5) are presented in Figure 11. These curves have marked points representing the minimum values of the considered function. In some cases, these minimum values lie on an edge of the graph due to reaching an established constraint.

In our opinion, occurrences of the minimum values of the substitute objective function confirm the correctness of the designated approach.

6. Computer-aided system supporting selection of the commanded outputs of the ship's propulsion system

The computer-aided system supporting selection of the commanded outputs of the ship's propulsion system consists of the following components (Fig. 12):

- data acquisition module that records and converts information acquired from actual observation of sea conditions, where the following are true:
  - inputs are values of uncontrollable variables X_{Nm},
  - the output is the vector of normalized ANN data **X**,
- identification module that builds ANN functional models, where:

- inputs are the vector of normalized ANN data and two vectors of all values of decision-making variables X_{Dn} (ranges of the commanded outputs of the ship's propulsion system),
- the output is a matrix **M** representing ANN internal representation of data,

– optimization module that allows the selection of the optimal commanded outputs of the ship's propulsion system, where the following are true:
  - inputs are the matrix representing ANN internal representation of data and the vector of weight factors W of the two-objective optimization model,
  - outputs are the optimal values of the commanded outputs (the engine rotational speed – X_{D1} and the propeller pitch – X_{D2}).

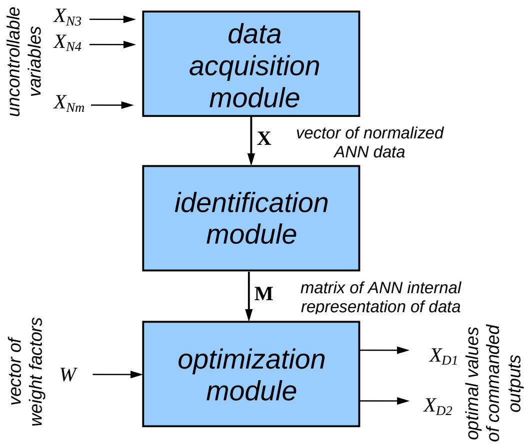

Figure 12. The block diagrams representing the relationships between the main components of the computer-aided system supporting selection of the commanded outputs of the ship's propulsion system

To verify the functioning of the developed system, all calculations used codes prepared by the MATLAB neural network and its optimization toolboxes. Based on outcomes of the sea trials (Table 2), the optimal values of the commanded outputs (the engine rotational speed and the propeller pitch) have been calculated (Table 3) for weight factor values varied from 0 to 1 with a step of 0,1. The predicted values of the output variables (fuel consumption rate and speed) have been estimated.

Table 3. The output variable values predicted by the two-criterion optimization model

Weight factor	Optimal setting of the engine rotational speed	Optimal setting of the propeller pitch	The estimated speed of the vessel achieved at the optimal commanded outputs	The estimated fuel consumption at the optimal commanded outputs
w [-]	X_1 [rpm]	X_2 [marks]	Y_1 [knot]	Y_2 [dm^3/h]
0.0	1000	3	2.1	11.6
0.1	1050	8	3.6	12.06
0.2	1100	10	4.3	12.62
0.3	1100	11	4.6	12.99
0.4	1150	12	5.1	13.95
0.5	1200	13	5.6	15.54
0.6	1300	13	6.1	17.98
0.7	1800	7	7.2	25.48
0.8	1800	15	9.8	57.42
0.9	1800	15	9.8	57.42
1.0	1800	15	9.8	57.42

The two-objective optimization model's substitute objective function calculates the minima for different values of the weight factors. This, in turn, determines the optimal values of the commanded outputs of the ship's propulsion system for the preferred navigational options. When weight factors are close to their boundary values, the minimum of the substitute objective function occurs on the established constraints. When the weight factor value equals 0 or 1, the decision-making problem of selection of the commanded outputs for the ship's propulsion system comes down to a single-objective optimization.

7. Conclusions

The developed decision-making system can be summarized as follows:

- It supports selection of commanded outputs for the ship's propulsion system with a CPP that ensure arrival within the established time to reach a destination with a reasonable fuel consumption.
- It enables the selection of these commanded outputs in the dialogue between the ship operator and the computer, where the computer processes the acquired data and provides a proposal for the commanded outputs, and the operator makes appropriate decisions.
- It ensures cooperation with other systems used during ship navigation, e.g., systems collecting current meteorological data.
- It provides multiple uses, including the ability to select new commanded outputs as weather conditions change.
- It enables continuous updating of the decision-making system as new data are acquired.

This methodology can be used on other types of vessels with a similar ship propulsion system. It requires the conduct of a new experiment and acquisition of new data specific to the vessel.

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