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Dependence of Ships Turning at Port Turning Basins on Clearance under the Ship's Keel

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Abstract: Turning ships in port turning basins is an important and responsible operation, mainly involving the ship itself and the port tugboats. Such operations involve many maneuvers that consume a lot of energy (fuel) and emit a lot of emissions. Turning basins in harbors and quay approaches are, in most cases, relatively shallow. This paper examines the turning of ships in port turning basins using harbor tugboats, the effect of shallow depth on ship turning, energy (fuel) consumption and the generation of emissions during such maneuvers of harbor tugboats. This paper presents the developed theoretical models, and the experimental results on theoretical models that were verified on real ships and using calibrated simulators. Discussions and conclusions were prepared on the basis of the research results. The use of the developed methodology makes it possible to increase shipping safety, optimize maneuvers and reduce energy (fuel) consumption when turning ships in the port and, at the same time, reduce the amount of fuel consumed by port tugboats and reduce the number of emissions of tugboats during such operations.

Keywords: sustainability; ships turning basins in ports; ships maneuvers; tugs operation in ports; emissions from ships; maritime safety; energy efficiency



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1. Introduction

Ships in ports are usually turned around in ship turning basins or other harbor areas. These port operations are very important and responsible for ship crews, especially masters, as well as for port pilots and harbor tugboats masters. Turning operations are made even more special by the fact that ports are trying to attract larger ships with minimal infrastructure development, including the parameters of ship turning basins [1–3]. Large ships often do not have their own additional propulsion devices (thrusters), and in this case, the harbor tugboats basically perform the turning of the ships. Port depths are often limited, including turning basins or other areas where large ships are turned, i.e., ship turning operations are carried out at low clearance, i.e., the water gap between the hull of the ship and bottom of the ship turning basins [4,5].

Due to the relatively small parameters of the turning basins in some ports, the ratio of the turning basin diameter to the length of the ship is close to 1.10–1.15 [6,7], which means that a very precise performance of the ship's turning operation is necessary. At the same time, imprecise ship turning planning often requires additional maneuvers of the ship itself and port tugboats, which consume additional energy (fuel) and generate additional emissions [8,9].

The accurate planning and assessment of ship turning maneuvers in basins, including the optimal use of port tugboats and accurate information about the ship's maneuverability at low clearance, allows to optimize the maneuvers of the ship and port tugboats performing the ship turning [10]. Good planning and execution of ship maneuvers allow to reduce the number of maneuvers of the ship and the tugboats performing ship turns and, at the same time, reduce energy (fuel) consumption and reduce the number and quantity of emissions [11,12].

The indicated ship turning operations in ports require precise knowledge of the ship's handling, the precise actions of the port tugboats, if they are used, and of course, this depends primarily on the knowledge and experience of the ship's masters and harbor pilots (if their services are used) [10]. About 80% of ship accidents and emergency situations occur in port approaches and ports, and the majority of them are caused by human errors, which are incorrect actions by ship captains and port pilots and, in some cases, also by port tugboat captains [13,14].

The main objective of this paper is to present a developed methodology to determine the optimal ship turning in port ship turning basins in low clearance conditions, during which the ship is still well controlled by port tugboats, with minimum fuel consumption and minimum generated emissions, which are very important for the development of "green" ports [15,16]. The novelty of this article is based on development of the methodology that allows calculation of the optimal port tugboats, using minimum fuel consumption and generating minimum emissions, depending on the size of the clearance (in the case of low clearance).

The research methodology is based on the evaluation of the external and internal forces and moments acting on the ship when it is turning in the turning basins and water areas in harbor, in the presence of low clearance, while the ship is still well controlled by the tugs. Optimizing the bollard pull forces and the number of maneuvers of the tugboats turning the ship minimizes the fuel consumption of the tugboats and the number and quantity of generated emissions.

This article presents a method for calculating the optimal tugboats number and main engine power, which are important for many ports, using the minimum fuel consumption and its application in specific conditions, which allows guaranteeing navigation safety in ports during ships turning, optimize fuel consumption, reduce emissions from port tugboats and research results [17]. This article consists of the research analysis of the existing situation, the principles of creating a mathematical model and the mathematical model itself. The application of the developed mathematical model in specific conditions and the results of experiments performed on real ships using port tugboats for the ships turning and using a calibrated visual simulator are presented [18,19]. It also presents the discussion and conclusions of the calculated and experimentally verified results on the optimal number of port tugboats and its main engines powers using minimal fuel consumption.

This research introduces a novel methodology for determining the optimal number of tugboats required for ships maneuvering within port basins or other water areas, aiming to minimize fuel consumption and the environmental impact.

2. Ships Turning in Port Situations and Literature Analysis

As the parameters of individual types of ships (tankers, container, bulk carriers, etc.) increase, ports try to accommodate larger ships with minimal development of the existing infrastructure due to geographical limitations (urban areas, islands, etc.) and economic conditions (development of the port infrastructure requires a lot of investment) [4]. Port ship turning basins in ports are one of the very important infrastructure elements of the port, and increasing their parameters also requires space and large investments [4,10,20].

Many researchers have studied the navigation of ships in harbor waters, including ship turning in turning basins and other harbor waters [21,22]. At the same time, researchers have paid very little attention to the turning of ships with low clearance at the turning points (port ship turning basins or other port water places), which is typical for many ports, using harbor tugboats, evaluating their energy (fuel) consumption and generated emissions [9,16,23,24]. The turning process of ships in ports seems quite simple, but under the influence of external forces and low clearance, the processes of turning ships in ports become very complicated and require deep knowledge of such processes and good preparation of the ship and all persons involved [4,15,25–27]. A significant number of ship accidents in ports are related specifically to ships turning when the process is not properly prepared [5,13,20,22,28,29].

The parameters of the turning basins of ships in ports are usually selected using various recommendations, for example, PIANC [30], ROM [31], etc. The turning basins of ships in ports usually have smaller depths than the internal shipping channels of the port, so it is very important to accurately calculate their required depths in advance, assessing the possible tilting angles of ships due to external impact forces and especially due to the effect of harbor tugs when ships are turned around with their help [3,4,17].

In some ports, the parameters of the turning basins are small compared to the length of the turning vessels, for example, in the inner port of Gdansk, the diameter of the turning basin is about 310 m [6], but within it, vessels are turned with a length of up to 295 m (PANAMAX-type container ships) (Figure 1), and in Ventspils inner harbor, there is a relatively small turning basin with a diameter of 280 m [7], and the lengths of turning vessels can be 240 m. (Figure 2). Turning basins are relatively shallow in many ports, with ship draft to depth ratios of up to 0.9 and higher.

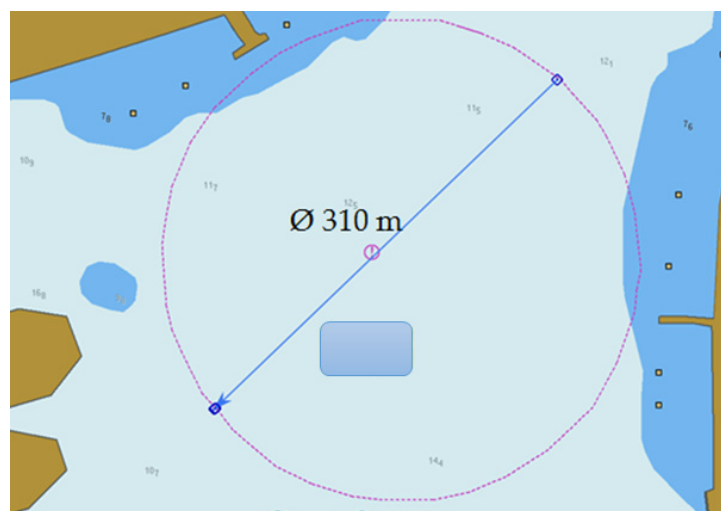
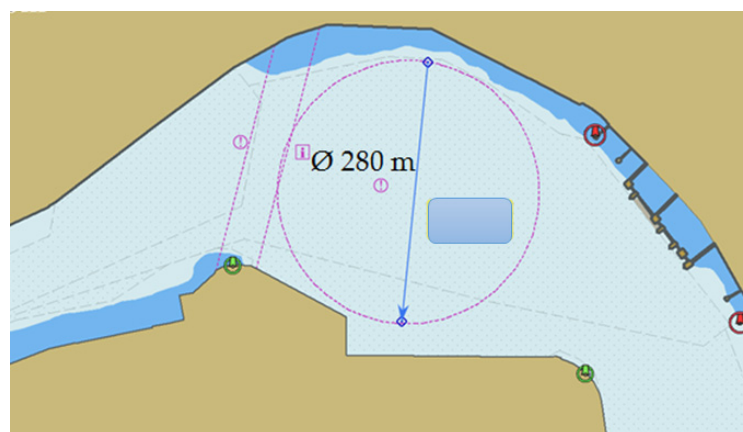


Figure 1. Gdansk inside a port ship turning basin (diameter 310 m) [32,33].



Many researchers have studied these problems, but at the same time, there are few studies on the effect of low clearance on the increase of ship draft due to momentary heeling and differential [1,4,21,25,35]. In some ports, where there is soft ground in the turning basins, in some cases, almost zero clearance is acceptable [25], and this does not significantly affect the safety (damage) of the ship's hull, but this situation greatly affects the handling of ships, i.e., energy (fuel) consumption and emissions of the ship itself and port tugboats, if they are used to turn the ship [11,36,37].

Tugboats are auxiliary vessels that help to carry out separate operations of ships in the port, and their construction has been studied in terms of their functions [10,12,18]. At the same time, complex studies have rarely been encountered, but they are very important, and this article focuses on complex aspects, i.e., the safety of shipping when turning ships in port ship turning basins, using tugboats, the optimal number of tugboats and their necessary optimal power and the minimization of emissions generated by tugboats.

When the ship is moving straight and clearance is close to zero, this does not have a significant effect, except for the increase in the resistance of the transverse movement of the ship's hull, but when turning the ship in a port turning basin, their resistance increases significantly [38]. With a very low clearance, navigational safety is very important, but at the same time, tugboats consume more energy (fuel) compared to similar operations with a higher clearance, i.e., when the T/H is lower than 0.5–0.7. There has been insufficient study of such operations, not only from the point of view of energy (fuel) consumption and generated emissions but also from the point of view of the total cost of the ship itself. If only the main ship control devices (ship rudders and propellers) and additional ship control devices such as thrusters are used with the port tugboats [39,40], it does not allow optimizing the process of turning ships in ports.

The turning of ships in port turning basins with small clearances is very important from the point of view of shipping safety and environmental impact [40,41]. The analysis of the literature showed that there is a relatively small amount of research on these problems, and in many cases, there is not enough clarity on how to estimate or what the optimal traction force of port tugboats should be, especially in the case of low clearance. The potential minimal or optimal energy (fuel) consumption of port tugboats for such operations in the case of low clearance and, at the same time, the possibility of minimizing emissions have been little studied. The low level research on the mentioned problems does not allow a clear assessment of the methods and ways of reducing their impact on the environment, i.e., correctly deciding what is more beneficial, whether to use more and more powerful tugs or to perform additional maneuvers of the ship. The optimal solution of these problems is very important from the point of view of shipping safety and environmental impact.

In this way, the main goal of this article is to study ship turns in port ship turning basins using port tugboats, creating a practically acceptable methodology for solving the specified problems and optimizing maneuvers.

3. Theoretical Justification of Turning Ships in Port Turning Basins with Low Clearance

The theoretical justification of this article is primarily based on the characteristics of shipping safety, i.e., to turn a ship safely in a turning basin independently (using the ship's thrusters) or with the help of port tugs. In the case of a safe possible navigational operation, the focus is on the minimum energy (fuel) demand and the minimum emissions generated by the ship itself (self-rotating) or tugboats.

3.1. Steps of the Research Methodology

The following research methodology steps were used to conduct the study: Ship turning basins in ports analysis, literature review and data collection, mathematical model development, conducting calculations using the developed mathematical model, carrying out experiments on real ships, performing simulations using the calibrated simulator and writing the discussions and conclusions (Figure 3). A mathematical model was created

after a literature review and an analysis of turning basins of ships in ports and actual ship turning in ports.

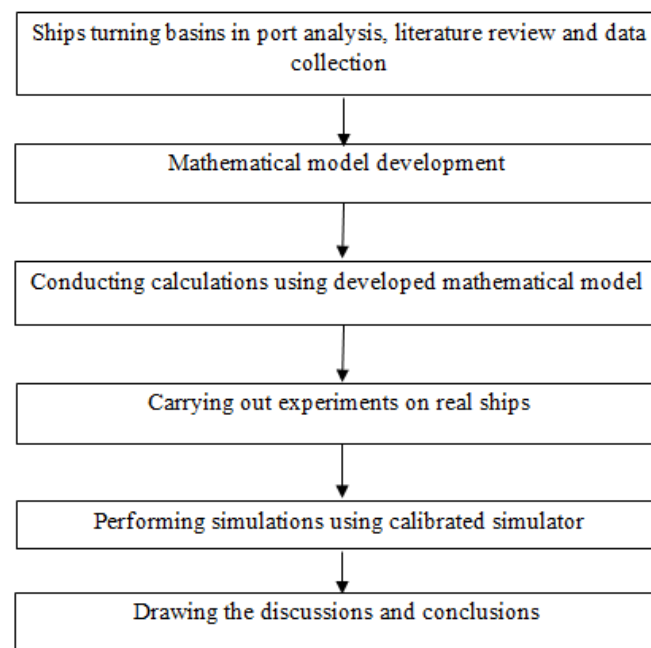


Figure 3. The algorithm of the ships turning basins in the first step research methodology.

Based on the presented principal methodology (Figure 3), a theoretical model of ship turning with the help of ship pushers or tugboats was created, and experiments were carried out with real ships and with the help of a calibrated simulator; finally, the theoretical model was improved on the basis of real ships and calibrated simulator experiment results [42,43]. After determining the possible optimal operations of turning ships in the turning basins, in the case of low clearance, the estimated possible minimum energy (fuel) consumption and minimum generated emissions during the turning of a ship under various hydrological and hydrometeorological conditions were calculated [44,45].

The resistance of the ship's hull during ship turning is mostly related to the lateral resistance of the ship's hull in the water, especially at low clearance, i.e., for a T/H ratio close to unity [27,46]. Since the turning of the ship in the port turning basin is performed either with the help of the ship's propulsion mechanisms (thrusters, if there are such equipped) or with help of tugboats, it is necessary to create forces and moments that overcome the lateral resistance of the ship from external forces [40,46,47]. In order to evaluate the controllability of the ship using tugboats or ship steering devices (thrusters), the methods of calculating the turning elements and the trajectory of the ship in shallow depth were used [35,48]. When calculating the ship's energy (fuel) consumption, the power of the tugboat engines or the ship's propulsion mechanisms was calculated, depending on the traction force created by the tugboats or ship's propulsion devices, and the number of emissions, according to the amount and quality of the fuel used (diesel or LNG), the actual ship's propulsion or the power and working time of the tugboat engine when turning the ship [39,49]. To evaluate the accuracy of the calculations and experimental results, the maximum distribution method was used using data obtained from experiments on simulators and real ships [50]. The maximum distribution method can be applied if at least five measurements are taken.

In order to verify the accuracy of the theoretical calculations and the practical application of the developed methodology, experiments were performed on the calibrated simulator and on real ships. The simulation was carried out using the full-mission simulator SimFlex Navigator (a product of Force Technology) [33], calibrated according to the results of real experiments on similar ships, with the help of which, similar maneuvers of real

ships were tested and analyzed, taking into account external forces, turning real ships in a turning basin [51]. In order to calibrate the simulator, tests of real ships (POST PANAMAX container carriers with a container capacity of about 9000 TEU) were performed in the ship turning basin of the port using tugboats. POST PANAMAX container ships, for example, arrive at the port of Klaipeda every week. The length of these ships is about 335 m, width about 43 m and draft from 12.0 to 13.8 m.

A similar POST PANAMAX container ship was also selected in the simulator. After entering in the simulator analogous conditions to real ships (wind, current, depth and traction forces of tugboats), differences between the results obtained using real ships and in the simulator were determined. On the basis of the received real ships and simulator data, we obtained the calibration coefficients, for example, the angular speed of the ship under specific conditions, the ship's turning time and other parameters. The real ship's "tables of maneuvering elements" on the ship's bridge and the ship's "information about the ship's maneuvering elements" were also used. Measurements of the fuel consumption of tugboats when turning ships in the ship turning basin were also made and compared to the results obtained in the simulator of similar tugboats under the same conditions, and the calibration coefficients were determined. With the help of the calibrated simulator, more than 50 experiments related to the turning of ships in harbor turning basins were carried out. In many cases, one or two data points of a specific parameter of the real ship were sufficient for the evaluation of specific parameters for the simulator calibration. Container ships of various sizes were used for the experiments as well. Tugs of 300 kN and 500 kN bollard pull power were used to turn the ships.

Then, the results were analyzed, discussions were initiated, conclusions were drawn and suggestions for further research were presented.

3.2. Mathematical Model

The literature review, general equations of ship motion forces and moments and simulator and real ship test results, where different clearances between the ship hull, channel bottom and turning basins of harbor ships were used, were used to develop mathematical models of shipping navigation safety, energy (fuel) consumption and emissions from ships turning in port turning basins [3,24,35,38,52]. When conducting research and creating mathematical models, it was assumed that ships in port ship turning basins safely maneuver independently using thrusters or using port tugboats assistance, and the controllability of the ship is ensured by the ship's own steering equipment, thrusters or/and port tugboats. In ship turning basins, ships turn with the help of their control equipment (propulsion complex), and if necessary, they can use the help of ship steering devices (thrusters) and tugboats [40,47]. It is also assumed that, when ships turn due to the effect of low depth, the lateral and longitudinal resistance of the ship changes, and resistance of the ship's lateral and longitudinal movement additionally appears [40,47].

The safe depth of the port turning basin, so that the largest ship (with the largest draft) does not touch the bottom of the basin with its hull, accepting the main potential impacts, can be calculated according to the following formula [17,40]:

$$H_{min} = T + \Delta T_v + \Delta T_\theta + \Delta T_\psi + \Delta H_m + \Delta H_{VL} + \Delta H_{\Delta VL} + \Delta H_n, \quad (1)$$

where T is the maximum draft of the calculated vessel, and ΔT_v is the increase in draft due to settlement (speed) [3,17,40]. The ship's speed during the ship's turning process is very low or close to 0, and this factor could be excluded. ΔT_θ is the increase in draft due to heeling as an act of the tugs [40] (large ships can reach up to 1.5–2.0 degrees in port conditions); ΔT_ψ is the increase in draft due to the effect of pitch (change in the different) [40] (in port conditions and in the absence of waves, large ships during maneuvers do not exceed 0.03–0.05 m); ΔH_m is the accuracy of the depth measurement [3] (modern depth measurement equipment allows to achieve measurement accuracy of up to 0.05 m); ΔH_{VL} is the level of the water in a particular port (the accuracy of the water level measurement depends on the density of the water level measurement points in the port, and in many ports, it is between 0.01

and 0.05 m); $\Delta H_{\Delta VL}$ is the accuracy of the measurement of the water level [40] (depends on the water level measuring equipment used, the accuracy of the visual equipment (ruler) is about 0.01–0.02 m, and the accuracy of the laser water level measuring equipment currently used in many ports is about 0.003–0.005 m); ΔH_n is the navigational margin, which can be decomposed into a direct navigational margin, which is assumed to be about 2–3% of the ship's draft, by means of accurate bottom depth measurements (using modern depth measurement techniques) and a layer of sediment, which has to be periodically removed (maintenance dredging). The above elements of Formula (1) can be calculated using the methodology presented in [30].

It is very important to maintain a safe clearance (ΔH) or use a simulator (ΔH_k) when turning the ship, i.e., the gap between the ship's hull and the bottom of the turning basin.

External forces and moments acting on ship sailing or turning by port navigational channels and port waters or port ship turning basins shall be compensated by forces and moments created by the ship's rudder or if the ship uses tugboats assistance, created by additional tugboats forces and moments. A ship's motion mathematically is mostly described by D'Alembert or vector methods. Thus, the calculation of the forces and moments can be conducted using the following mathematical model based on the D'Alembert principle [40]:

$$X_{in} + X_k + X_\beta + X_P + X_N + X_a + X_c + X_b + X_{sh} + X_T + X_{tug} + \dots = 0 \quad (2)$$

$$Y_{in} + Y_k + Y_\beta + Y_P + Y_N + Y_a + Y_c + Y_b + Y_{sh} + Y_T + Y_{tug} + \dots = 0 \quad (3)$$

$$M_{in} + M_k + M_\beta + M_P + M_N + M_a + M_c + M_b + M_{sh} + M_T + M_{tug} + \dots = 0 \quad (4)$$

where X_{in} , Y_{in} and M_{in} are the inertia forces and the moment; X_k , Y_k and M_k are the forces and moment created by the ship's hull, which can be calculated by using the methodology stated in [40]; X_β , Y_β and M_β are the ship's hull as the acting "wing"-related forces and the moment, which can be calculated using the methodology stated in [27]; X_P , Y_P and M_P are the forces and the moment created by the ship's rudder or other steering equipment [40]; X_N , Y_N and M_N are forces and the moments created by thrusters [40]; X_a , Y_a and M_a are aerodynamic forces and the moment, which can be calculated using the methodology stated in [40]; X_c , Y_c and M_c are forces and the moment created by the current, which can be calculated using the methodology stated in [40]; X_b , Y_b and M_b are the forces and the moment created by waves, which can be calculated using the methodology stated in [40] (in port conditions this parameter is insignificant and often not applicable); X_{sh} , Y_{sh} and M_{sh} are the forces and the moment created by the shallow water effect [39,40] (in port conditions, this parameter is very important, especially when the ratio of the ship's draft to the depth of the turning basin is greater than 0.9); X_T , Y_T and M_T are the forces and the moment created by ship's propeller (propellers), which can be calculated using the methodology stated in [38,40] and X_{tug} , Y_{tug} and M_{tug} are the forces and moment created by tugs. Additional forces and moments can be created by anchor or mooring ropes or other factors.

Large ships in ports are usually turned with the help of harbor tugboats, especially if the ship does not have its own propulsion devices (thrusters). In many ports, the turning basins for ships are very limited. At the same time, there are no waves at the place of turning basins in ports, the current changes little while the ship is turning (due to a relatively small time interval) and the ship has a minimum longitudinal speed. The equation of the ship's turning moments can be written as follows:

$$M_{in} + M_k + M_a + M_{sh} + M_{tug} + \dots = 0, \quad (5)$$

The inertia moment, under the baseline conditions of turning the ship in the port ship turning basin, can be expressed as follows [40]:

$$M_{in} = (I_z + \lambda_{66}) \frac{d\omega}{dt} \quad (6)$$

where I_z is the moment of inertia of the ship; λ_{66} is the added moment of inertia of the ship turning in water; $\frac{d\omega}{dt}$ is the acceleration of the ship's rotational angular velocity.

The inertia moment of the ship can be calculated as [53,54]

$$I_z = \rho V L^2 / 12 \quad (7)$$

where ρ is water density, $\frac{t}{m^3}$; V the ship's displacement, m^3 ; L is the ship's length, m .

The inertia moment together with the added inertia moment of the ship can be calculated as follows [40,53,54]:

$$\lambda_{66} = k_{66} I_z \quad (8)$$

where k_{66} is the added moment coefficient, which, for the analyzed situation (ship turning in the port turning basin in the case of $(T/H = 0.90-0.95)$), is equal to 3 [40,47]. Finally, the inertia moment with the added inertia moment can be calculated as follows:

$$\sum I_{in} = (1 + k_{66}) \rho V L^2 / 12 \quad (9)$$

In this way, M_{in} can be written as follows:

$$M_{in} = ((1 + k_{66}) \rho V L^2 / 12) \left(\frac{d\omega}{dt} (\exp(-3t/T_{in})) \right) \quad (10)$$

where T_{in} is the ship's inertia period, which can be taken as $T_{in} \approx L/3$ (Figure 4) (experiments on real ships results).

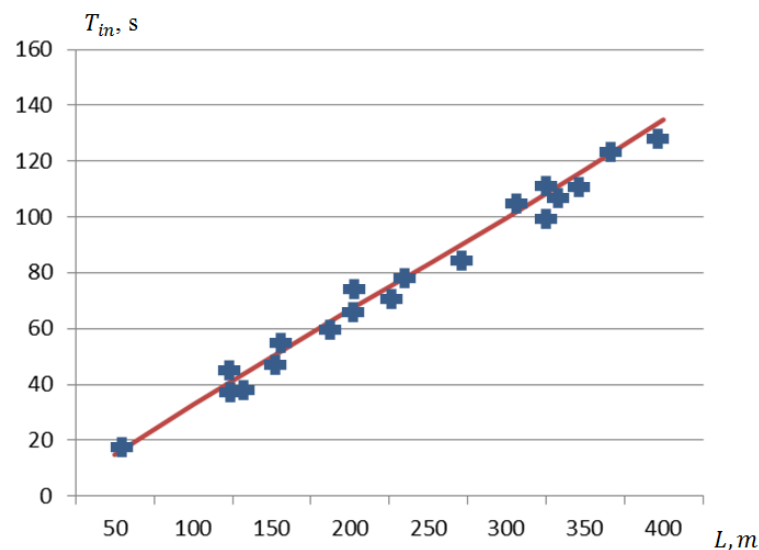


Figure 4. Dependence of the period of the moment of the inertia of the ships, obtained by experiments on real ships, on the length of the ships.

The ship's hull moment (M_k) can be calculated as the resistance of the ship's hull to lateral movement at a large drift angle (about 90 degrees) [38,40]:

$$M_k = (k_{22} \rho V L \frac{dv_y}{dt} (1 - \exp(-\frac{3t}{T_{in}}))) (1 + 4.95(T/H)^2) \quad (11)$$

where k_{22} is the coefficient of the added water mass when the ship moves in the transverse direction; v_y is the speed of the ship's movement in the transverse direction; T is the average draft of the ship; H is the depth of the port ship turning basin.

The aerodynamic moment when the ship is turning can be calculated as follows [38,40]:

$$M_a = C_a \frac{\rho_1}{2} \sqrt{S_x^2 + S_y^2} v_a^2 x_a \sin q_a \int_0^t \omega dt \quad (12)$$

where C_a is the aerodynamic coefficient of the above water part of the ship; ρ_1 is the air density, and 1.25 kg/m^3 can be accepted for calculations; S_x and S_y are the areas of the projections of the above water part of the ship to the middle and transverse planes; v_a is the wind speed; x_a is the abscissa of the aerodynamic force addition point with respect to the middle plane of the ship; q_a is the wind heading angle at the start of the maneuver.

The ship will start turning when the moment created by the tugboats is greater than the moments of inertia and other external forces, i.e.,

$$M_{tug} > M_{in} + M_k + M_a \quad (13)$$

When multiple tugboats are used, the total moment generated by the tugboats can be calculated as follows [12]:

$$\sum M_{tug} = F_{tug1} l_1 \sin q_{tug1} + F_{tug2} l_2 \sin q_{tug2} + F_{tug3} l_3 \sin q_{tug3} + \dots \quad (14)$$

where F_{tug1} , F_{tug2} and F_{tug3} are tugs 1, 2 and 3 tugboats' bollard pull; q_{tug1} , q_{tug2} and q_{tug3} are the traction angles of tugboats to the middle plane of the ship; l_1 , l_2 and l_3 are the distances from the middle plane of the ship of the towing ropes of the tugboats' fixed places on the ship or the tugboats' pulling points to the ship's hull.

In this way, the part of the moment created by the tugboats, which will act to turn the ship, will be [18]

$$\Delta M_{tug} = \sum M_{tug} - M_{in} + M_k + M_a \quad (15)$$

Finally, the obtained part of the moment created by the tugboats can be written as follows:

$$\Delta M_{tug} = R l' = C_R \frac{\rho}{2} F_d v_y^2 l' \quad (16)$$

where R is the total rolling resistance of the ship; l' is the relative length of the point of attachment of the tugboats from the middle plane of the ship; C_R is the total resistance of the ship's hull to the rotation of the ship coefficient; ρ is the density of the water; F_d is the area of the projection of the underwater part of the ship to the middle plane of the ship; v_y is the speed of the ship's lateral movement at the point l' away from the center plane.

F_d is the area of the projection of the underwater part of the ship onto the middle plane of the ship, which can be calculated as follows [3,40]:

$$F_d = \zeta L T \quad (17)$$

where ζ is the fullness coefficient of the projection of the ship's underwater area to the middle plane, and T is the average draft of the ship.

l' , the distance of the point from the midline, can be calculated as follows:

$$l' = \frac{l_1 \sin q_{tug1} + l_2 \sin q_{tug2} + l_3 \sin q_{tug3} + \dots}{n_{tug}} \quad (18)$$

where n_{tug} is the number of tugs.

The speed v_y of the lateral movement of the ship at the point far from the middle plane l' can be calculated as follows:

$$v_y = \sqrt{\frac{2 \Delta M_{tug}}{C_R \rho F_d l'}} \quad (19)$$

The angular velocity (ω') of the ship can then be calculated as follows:

$$\omega' = \frac{v_y}{l'} \quad (20)$$

The turning of the ship in the turning basin course angle (φ) can be calculated as follows:

$$\varphi = \int_0^t \omega' dt \quad (21)$$

In this way, the methodology developed for turning ships in port turning basins at shallow depths allows to evaluate the possibilities of turning ships in various conditions and to select the optimal number of tugboats, the power they use and, at the same time, to reduce the number of emissions during such operations. In some ports, it happens that the technical standing of tugboats in the port is insufficient, so it is recommended to accept no more than 75–80 percent of the nominal power of the tugboat's main engine in the calculations.

A tugboat's engine power (N) and the amount of fuel consumed (q_f) over a given period of tugboats working, during which ship is turning, time (t), e.g., an hour, and the relative fuel consumption (q'_f) link as [9,52,55]:

$$N = q_f / (q'_f t) \quad (22)$$

The amount of fuel consumed by tugboats when turning a ship in a port's turning pull can be calculated as

$$q_f = \int_0^t q'_f N_{av} dt \quad (23)$$

where N_{av} is the average engine's power of the tugboats during the turning of the ship.

Emissions from tugboats during a ship's turning in a port ship turning basin directly depend on the quantity and quality of the fuel used, engine power and engine running time [11,24,41,56–58]. The main emissions from tugboats constitute carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur oxides (SO_x) and particulate matter (PM) [41]. Thus, the carbon dioxide emissions are calculated according to the formula [24,41,52]

$$CO_2 = k_{CO_2} q_f \quad (24)$$

where k_{CO_2} is the carbon dioxide coefficient for petroleum products (diesel and fuel oil), which is between 3.0 and 3.5, for LNG between 2.5 and 2.9.

The sulfur oxide content can be calculated using the formula

$$SO_x = k_{SO_x} q_f \quad (25)$$

where k_{SO_x} is the sulfur oxide coefficient, which depends on the type of fuel: for petroleum products, it ranges from 0.001 to 0.035, and for LNG, it is around zero.

The carbon monoxide content can be calculated using the formula

$$CO = \int_0^t N_{av} k_{CO} dt \quad (26)$$

where k_{CO} is the carbon monoxide coefficient, which depends on the type of engine.

The amount of nitrogen oxides generated is calculated using the formula

$$NO_x = \int_0^t N_{av} k_{NO_x} dt \quad (27)$$

where k_{NO_x} is the nitrogen oxide coefficient, depending on the engine type.

The particulate matter generation is calculated using the formula

$$PM = \int_0^t N_{av} k_{PM} dt \quad (28)$$

where k_{PM} is the particulate matter coefficient, which depends on the type of engine and the type of fuel: up to 10 g/kWh for petroleum products and close to zero for LNG fuels [52].

Harbor tugboats have powerful main engines, which means that they consume a lot of fuel and emit large amounts of emissions when using high power. By reducing the power of the tugboats' main engines, guaranteeing the navigational safety of the ongoing operation, it is possible to significantly reduce the fuel consumption of the tugboats' main engines and, at the same time, reduce the amount of generated emissions.

4. Case Study of the Ship Turning in a Port Ship Turning Basin

As a case study was the Klaipeda port south ship turning basin (Figure 5) [32] and a real POST PANAMAX container vessel, which has a length of 330.0 m, width of 42.8 m and draft of 13.2 m and was turned by two tugboats with a bollard pull of 500 kN and had 3500 kW main engines. Additionally, there was, on the basis of the real ship (POST PANAMAX container vessel), an experimental data SimFlex Navigator simulator [33], which was used for a lot of experiments. The simulator calibration was based on obtaining the calibration correction coefficients by comparing the analog parameters of the simulator with the parameters of the real ships and, later, with the help of the obtained calibration coefficients, correcting the parameters obtained with the help of the simulator. The obtained simulation results were compared to the real experimental data of similar ships. The arrival of similar ships in the port of Klaipeda happens every week, and part of the experimental data was obtained with the help of the AIS (automatic identification system) [51] and pilot navigation devices. This made it possible to sufficiently reliably check the correctness of the developed methodology.

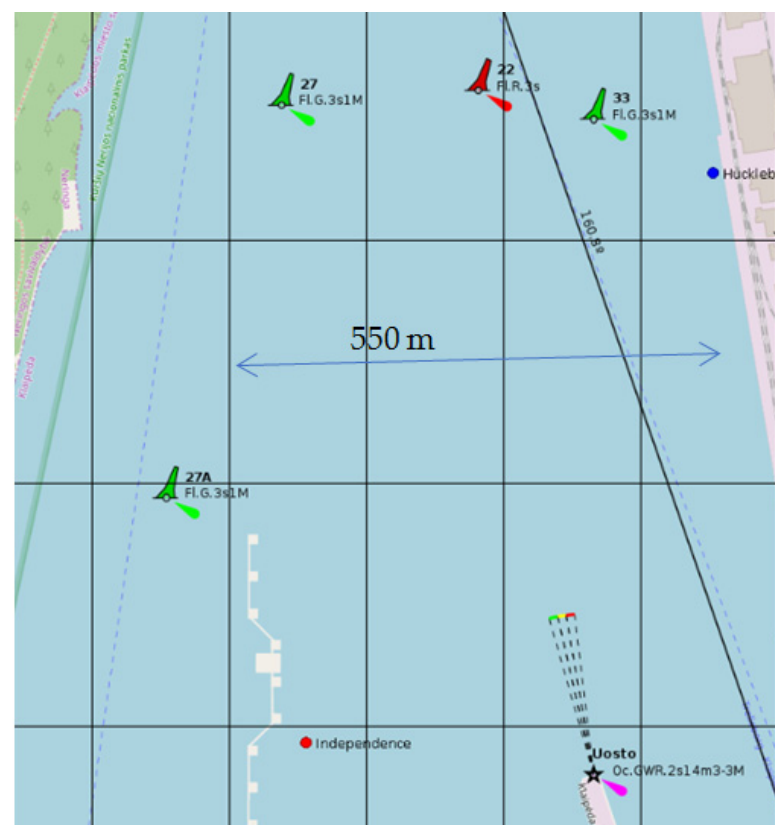


Figure 5. Klaipeda port south ship turning basin (diameter 550 m).

The selected vessels (in green) were usually turned in the port ship turning basin using two 500 kN tugboats. The turning of the real ship and the turning trajectory (red line) of the POST PANAMAX container ship were obtained from the real ship (Figure 6).



Figure 6. Trajectory of the POST PANAMAX container vessel during turning in the port ship turning basin (T/H about 0.95) received by the calibrated simulator and on the real ship.

The turning trajectory of the POST PANAMAX container ship in the port turning basin (restricted by green and red buoys) used two 500 kN tugs (on Figure 7 red color, 50 T (500 kN) bollard pull). A wind speed of up to 10 m/s and a current of 0.3 knots and a ship draft to a depth (T/H) ratio of about 0.93 were obtained using the calibrated simulator (Figure 7).

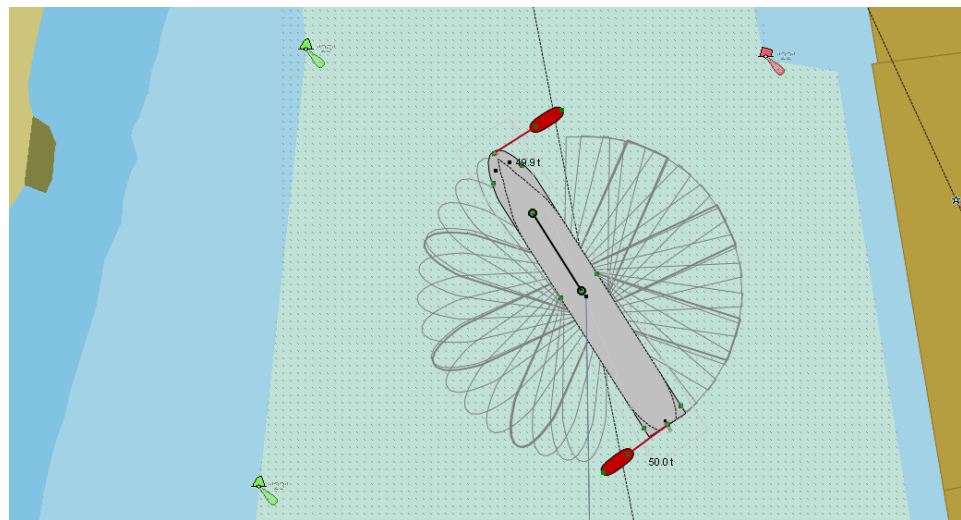


Figure 7. POST PANAMAX container ship turning trajectory using two tugs (50 T or 500 kN each) received by the calibrated simulator.

In similar conditions (wind up to 10 m/s, current 0.3 knots and the ship's draft and depth ratio about 0.93), the turning parameters of the POST PANAMAX container ship were calculated and experimentally obtained: turning time, tugs bollard pull, angular turning speed and clearance (Figure 8).

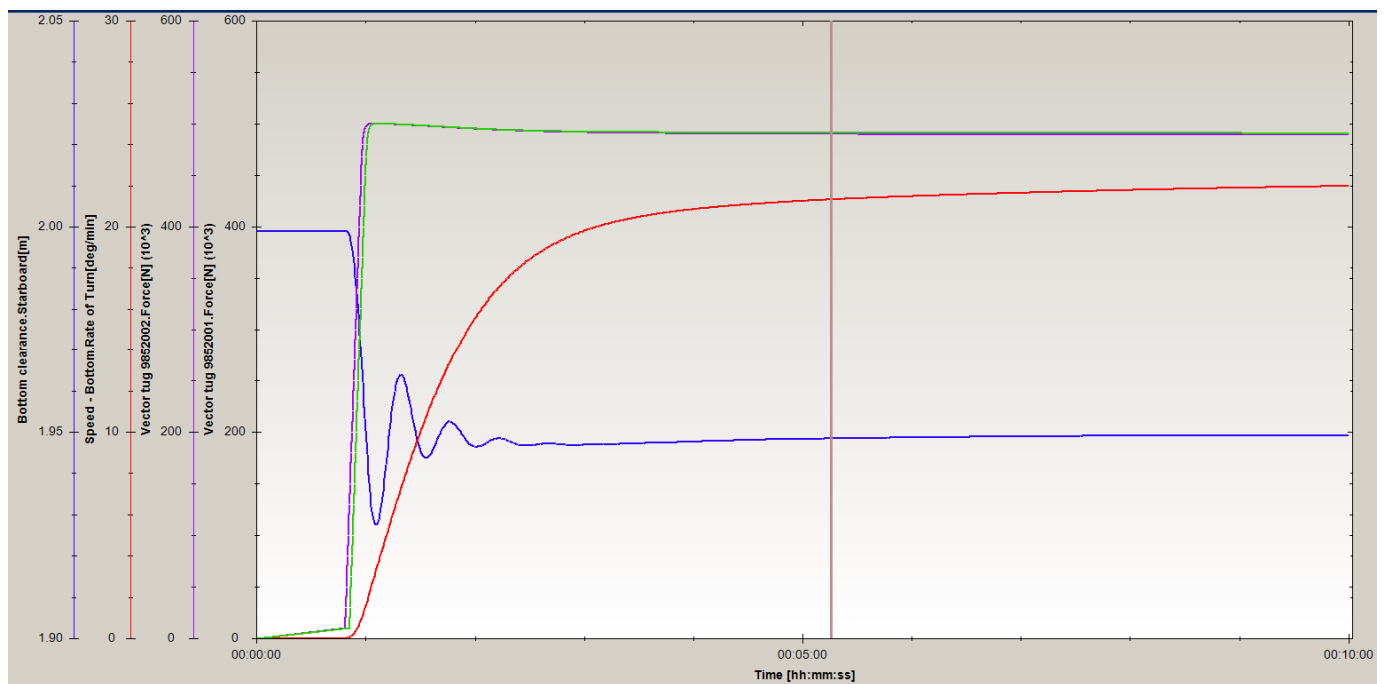


Figure 8. POST PANAMAX container ship's turning parameters: turning time; tugboats' bollard pulls (F_{tug1} and F_{tug2} —green and purple lines); angular speed of turning (ω' —red line) and clearance (ΔH_k —blue line).

The obtained results of the experiments with real ships were used to calibrate the SimFlex Navigator simulator, and about 50 experiments were carried out with the help of the calibrated simulator. The obtained results confirmed the correctness of the developed methodology for turning ships using tugboats or the own ship's thrusters in the presence of low clearance. The maximum distribution method [50] and the Kalman filter [59] were used to process the obtained experimental results (with the help of real ships and a simulator). The turning time of the POST PANAMAX container ship was obtained by the developed theoretical method and experimentally (real ship and using a calibrated simulator) ($\blacktriangle$ experiments on real ships results and by calibrated simulator), depending on the clearance, using two 500 kN tugs, and is presented in Figure 9.

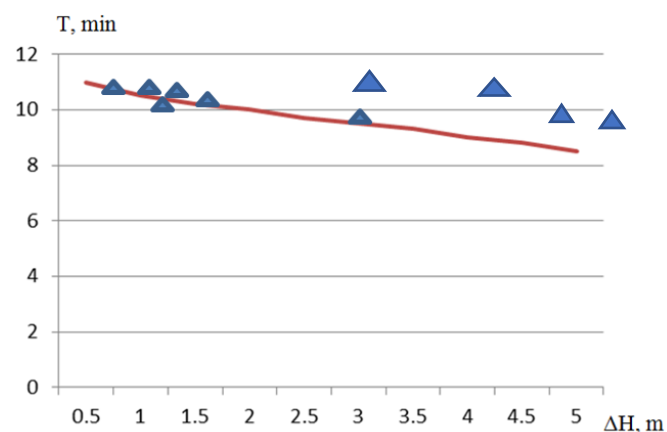


Figure 9. POST PANAMAX container vessel turning time use 2 tugboats (500 kN bollard pull) depends of the clearance between ship's hull and the ship turning basin bottom.

In ports, it is not always possible to use tugboats with extremely high pulling forces, and the use of lower engine power in tugboats offers the opportunity to reduce the environmental impact by reducing fuel consumption and emissions. Conducted studies using

lower engine powers of port tugboats, i.e., reducing the power of the main tugboat engine by about 40–50 percent, have shown that the turning time of ships in a port ship turning basin increases only by about 15–18 percent, but at the same time, the number of emissions decreases by about 25–35 percent, which positively affects the development of “green” ports without the use of large investments (● experiments on real ships results) (Figure 10).

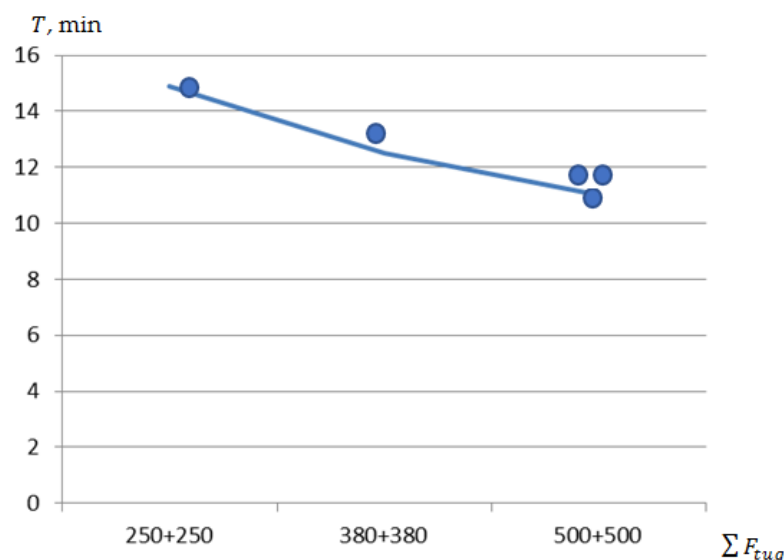


Figure 10. POST PANAMAX turning time depends on the bollard pull of the tugboats (clearance between the ship’s hull and ship turning basin bottom is about 0.7 m).

The angular rotation speed of the ships when turning the ships in the port turning basin of the ships is important, but when turning large ships, i.e., PANAMAX and larger ships, from the point of view of navigation safety, it is not recommended for the big ships to exceed the angular rotation speed of the ship 15–18 degrees per minute, so it is often possible to use smaller tugs (which are not very acceptable for navigation from the point of view of safety in emergency situations). However, with the use of more powerful tugboats, it is possible to reduce the power of their main engines up to 25–50% and, at the same time, reduce fuel consumption and the number of emissions generated during such operations and have a reserve of the main engines (and, at the same time, bollard pull) of port tugs (◆ experiments on real ships results) (Figure 11).

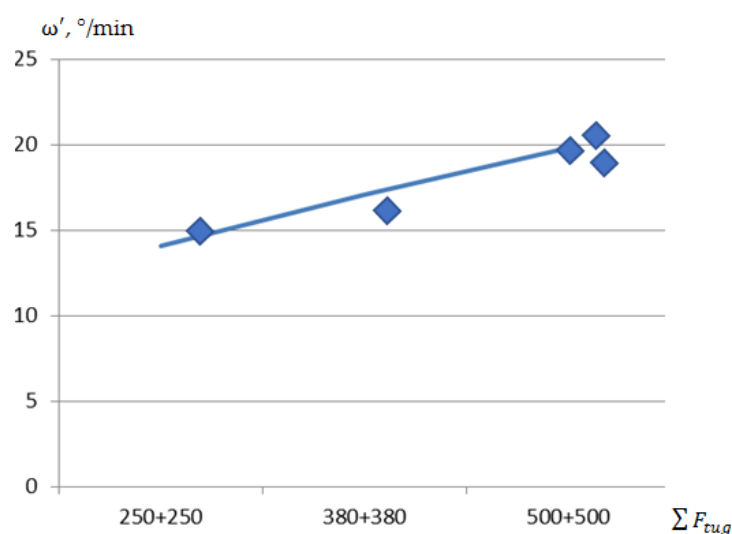


Figure 11. Angular speed of POST PANAMAX container ship turning, depending on the bollard pulls of tugs (clearance is about 0.7 m).

The clearance has a significant influence on the lateral resistance of the ship and, at the same time, on the angular speed of the ship when turning the ship using tugs. Conducted research with real ships and using a calibrated simulator has made it possible to verify the correctness of the developed methodology and, at the same time, to find the optimal bollard pull of the tugboats, depending on the size of the clearance, minimizing the possible power of the tugboat engines and, at the same time, the fuel consumption during the turning of the ships and the possible minimum generated emissions. The obtained maximum angular speeds of the POST PANAMAX container ship using two tugboats with a pulling force of 500 kN, depending on the clearance, are presented in Figure 12 (✕ experiments on real ships results).

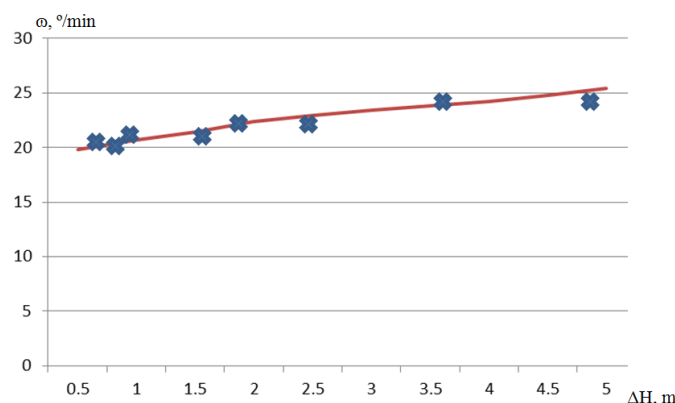


Figure 12. POST PANAMAX container ship's maximum angular rotation speed depending on the clearance (2 bollard pull tugs of 500 kN are used).

It is necessary to note that the angular speed of rotation of large ships should not exceed 15 degrees/min; therefore, using the developed methodology, it is possible to plan in advance the necessary bollard pull of tugboats and, at the same time, estimate the possible powers of the tugboats' main engines and, also, fuel consumption and the number of generated emissions.

Conducted experiments with real ships have shown that the methodology developed and presented in this article for ship turning in port ship turning basins with small clearances allows not only to optimize ship turning in ports but also to minimize the impact on the environment.

Theoretical calculations and experimental studies of turning ships in ports and environmental impact assessments using the developed methodology, using tugboats with a bollard pull from 250 kN to 500 kN, depending on the size of the clearance, showed that it is very important to find the optimal bollard pull to guarantee the safety of shipping during such operations and to have the least impact on the environment.

The theoretical and experimental studies of the emissions of port tugboats when turning POST PANAMAX container ships in the ship turning basin of a port are presented in Figures 13–16.

When the tugboats use different fuels during the turning of the ship, i.e., diesel or LNG, depending on the draft and depth ratio of the POST PANAMAX container ship, turning the ship 180 degrees, the results of calculating the fuel consumption and emission generation using the methodology presented in the article and experimentally are presented in Figure 13 (▲ experimental results of real tugboats using diesel fuel and LNG fuel quantities obtained by calculations).

The number of emissions generated by CO_2 and SO_x directly depends on the amount and quality of fuel used (diesel, LNG, ammonia, etc.). Calculations of the amounts of emissions generated by CO_2 and SO_x were performed and obtained during the experiment when turning the POST PANAMAX container ship (a CO_2 measurement station was installed on one of the tugboats), depending on the draft and depth ratio of the turning

ship, and the results are presented in Figure 14 (● experiments on real ships results; in the case of LNG fuel, using CO_2 quantities obtained by calculations).

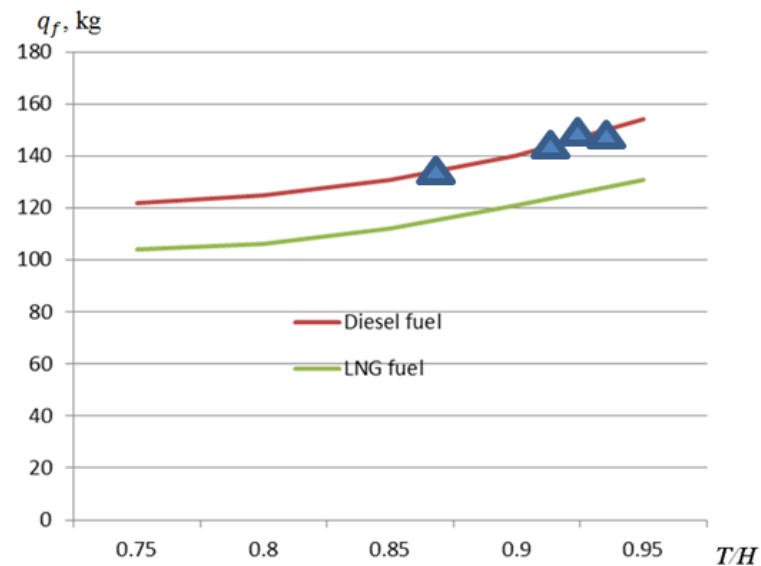


Figure 13. Two tugboats' (500 kN each) fuel consumption (diesel and LNG) when turning the POST PANAMAX container ship 180 degrees depending on the ship's draft and depth ratio (T/H).

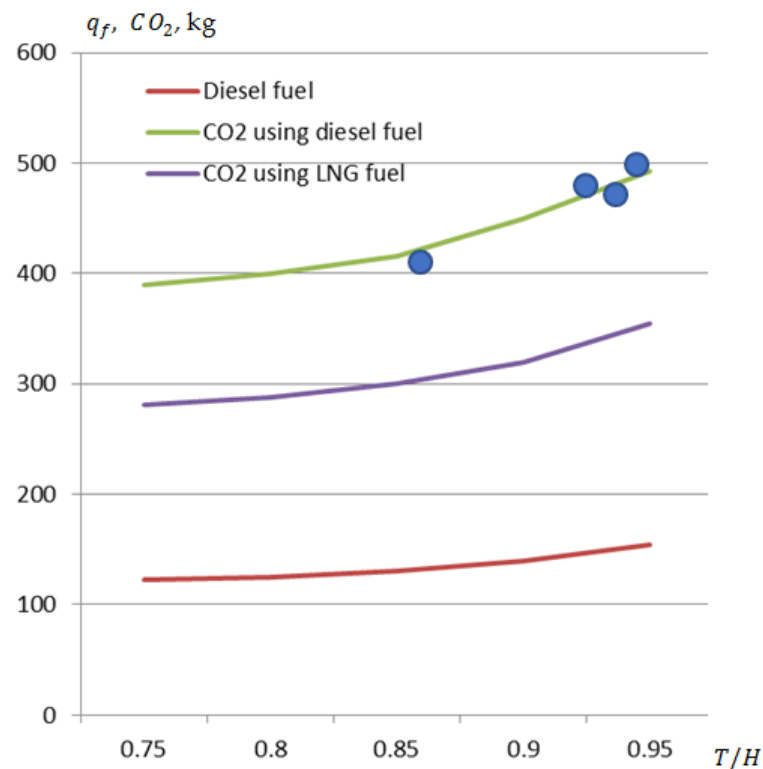


Figure 14. Fuel consumption of tugboats (500 kN each) and the amount of CO_2 (labeled CO_2 in the figure) emissions generated by turning the POST PANAMAX container ship 180 degrees depending on the ship's draft and depth ratio (T/H) (red line explains the diesel fuel quantities presented in Figure 13).

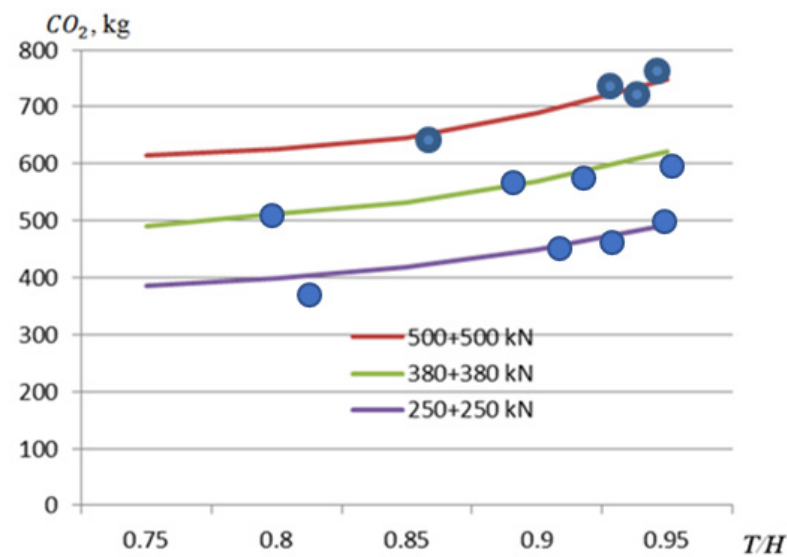


Figure 15. The amount of CO_2 emissions generated by the tugboats when turning the POST PANAMAX container ship 180 degrees, depending on the draft and depth ratio (T/H) of the ship and the traction forces of the 2 tugboats.

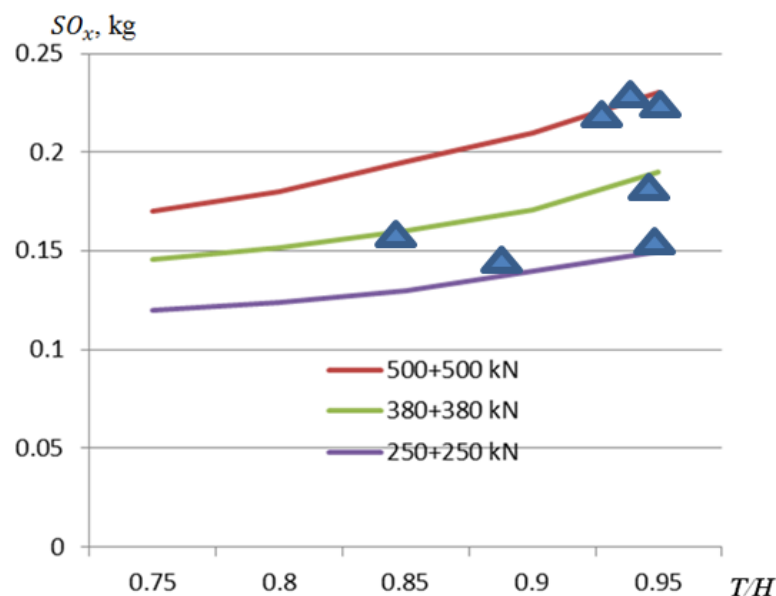


Figure 16. Amount of SO_x emissions generated by tugboats when turning the POST PANAMAX container ship 180 degrees, depending on the draft and depth ratio (T/H) of the ship and the traction forces of the 2 tugboats (▲ experiments on real tugboats results).

When turning the POST PANAMAX container ship with help of two tugboats, the amounts of CO_2 and SO_x generated by the tugboats using different powers (bollard pull) of the tugboats, depending on the draft and depth ratio of the turning vessel being turned, are presented in Figures 15 and 16 (● and ▲ are the experiments on real ships results).

The CO , NO_x and PM amounts of the generated emissions depend on the power of the tugboat engines used and the working time when turning the ships. The results of the emissions generated by the tugboats when turning the POST PANAMAX container ship, depending on the bollard pull and the draft and depth ratio of the turning ship, are presented in Figures 17–19.

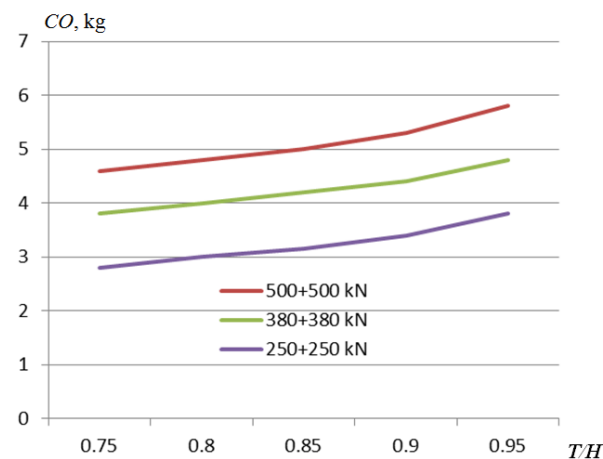


Figure 17. The amount of CO emissions generated by the tugboats when turning the POST PANAMAX container ship 180 degrees, depending on the draft and depth ratio (T/H) of the ship when using the different traction forces of the 2 tugboats.

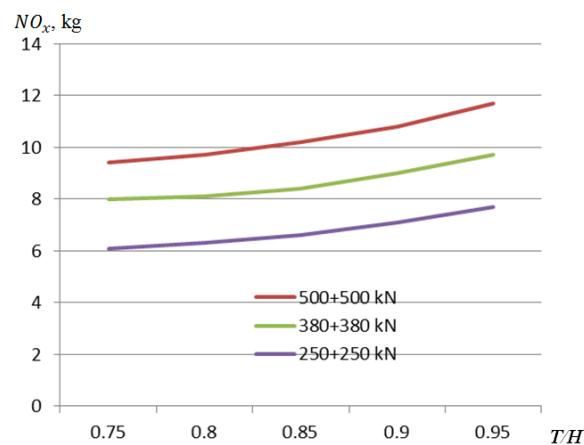


Figure 18. Amount of NO_x emissions generated by the tugboats when turning the POST PANAMAX container ship 180 degrees, depending on the ship's draft and depth ratio (T/H) when using the different traction forces of the 2 tugboats.

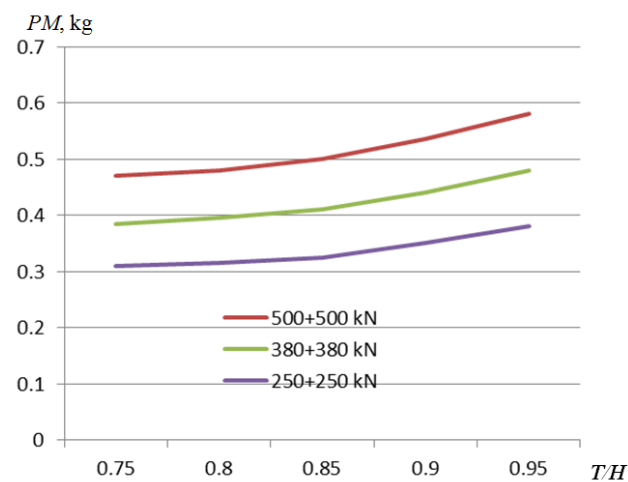


Figure 19. Amount of PM emissions generated by the tugboats when turning the POST PANAMAX container ship 180 degrees, depending on the ship's draft and depth ratio (T/H) when using the different pulling forces of the 2 tugboats.

When turning large ships in ports, it is necessary to maintain an angular rotation speed of not more than 12–15 degrees/min in order to be able to turn the ship safely and adjust to any nonstandard situations in a timely and reliable manner and to not create large angles of inclination of the ship. Using the given case study, it can be seen from Figures 10 and 11 that, assuming a turning angular speed of up to 15 degrees/min and with a ratio of the ship's draft to the depth of the turning basin of about 0.95, two tugboats with a bollard pull of about 300 kN should be used, and each tugboat's main engine uses about 1900 kW. Under the specified conditions, the turnaround time of a POST PANAMAX container ship would be about 12 min, and using diesel fuel for the tugs would consume a total of about 170 kg of diesel fuel and would generate about 540 kg of CO₂, 0.18 kg of SO_x, 4.2 kg of CO, 9.0 kg of NO_x and 0.43 kg of PM.

About 60 POST PANAMAX container ships enter the port of Klaipėda per year, and two tugboats, each with a pulling force of about 500 kN, are used to turn them. Using tugboats optimally, i.e., using about 300 kN of pulling power for each tugboat, it is possible to reduce about 7200 kg of diesel fuel (compared to the full use of the power of the main engines of the tugboats) and generate 16,000 kg less of CO₂ and, accordingly, other types of emissions per year but, at the same time, have a sufficient amount of tugboat traction force reserve.

As can be seen from the given example, by providing the necessary navigational safety, optimizing the turning of ships in ports with the help of tugboats, the fuel consumption of tugs performing ship turning can be reduced by about 20–25% and the number of emissions generated by the same up to 20–30%, which are very important for ports, especially those located near large cities.

5. Discussions and Conclusions

In developing “green” ports, it is essential to reduce the environmental impact of ships and port equipment whenever possible. Ships and port tugboats that serve them have high-powered engines, consume large amounts of fuel and generate a lot of emissions. It is predicted that the analysis of port-operations with ships and other port equipment and the search for optimal solutions that allow reducing the impact on the environment are important. When turning ships in ports, the assistance of tugboats must, first of all, be focused on navigational safety; therefore, scientific research in this area is very important and must include not only navigational safety but also reducing the impact on the environment.

Turning ships in ports requires not only an accurate assessment of the environmental conditions but also a high level of experience and skill and precise interactions of the ship's master, harbor pilot and tugboats masters. At the moment, in many ports, little attention is paid to the interactions between the participants of the indicated ship turning operations; therefore, the performance of additional tugboat and ship maneuvers and, in some cases, even risky actions is observed. Practical training for pilots and tugboat captains is carried out separately in many ports, and ship captains rarely participate in such training, so joint training, at least for pilots and port tugboat captains, would be very useful.

The movement of vessels from harbor turning basins to quays and diversions from quays to harbor turning basins (basins) are also very important and should involve further research. Good theoretical education and practical experience of ship captains and harbor pilots are very important not only from the point of view of navigational safety but also from the point of view of optimal solutions (maneuvers). Research and the use of optimal solutions for navigation and other port operations are important for the development of ports and their parts.

Scientific research linked to the optimization of shipping, without reducing navigational safety, is very important in reducing energy costs and minimizing generated emissions, thereby improving the quality of life in port cities.

Studies carried out with the help of tugboats on the turning of ships in harbor turning basins are important and allow, providing the navigational safety of the ships, to optimize

the maneuvers and the fuel consumption of tugboats and, at the same time, minimize their impact on the environment.

In ports, it is not always possible to use tugboats with extremely high pulling forces, and the possibility of carrying out evaluations of ship turning in ports in advance, especially in difficult hydrometeorological conditions, would not only reduce the risk of navigational errors but also reduce the emissions generated by port tugboats by 20–25 percent.

The developed methodology of turning ships in ports with the help of tugboats can be adapted to any port and, at the same time, be useful in implementing the “green” course in ports and port cities. The developed methodology was tested in real port conditions with real ships, which confirmed the possibility of using the methodology and its novelty and innovativeness.

The developed methodology of turning ships in ports with the help of tugboats can be adapted to any port and any type of ship, as it is only necessary to adapt to the specific conditions of the port.

Further research in optimizing ship maneuvering in ports using tugs and the ship’s own control devices (thrusters) is very important for minimizing the energy consumption of ships maneuvering in ports and minimizing their impact on the environment and improving living conditions in ports cities and access to ports in order to implement a “green” course in ports.

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