APPLICATION OF A MANEUVERING SIMULATION CENTER AND PILOTS EXPERTISE TO THE DESIGN OF NEW PORTS AND TERMINALS AND INFRASTRUCTURE OPTIMIZATION IN BRAZIL

by

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ABSTRACT

In a recent initiative, the Numerical Offshore Tank Laboratory of the University of São Paulo (TPN-USP) established a research partnership with the Brazilian Maritime Pilots Association (CONAPRA) for the development and enhancement of a Maneuvering Simulation Center for port, rivers and offshore operations. The name of the core simulator code is SMH (Portuguese acronym for Maritime and Waterways Simulator) and it is an engineering tool used for the analysis of new operations in the Brazilian ports, to improve their efficiency in the context of the increasing oil and gas production and commercialization as well as the enhancement of international commercial trades. The accuracy of the mathematical model is an important requirement for a maneuvering simulator dedicated to engineering projects. The engineers, pilots and captains must rely on the dynamics of the simulator since it will be used to give answers to questions related to maneuvering analysis. The simulator is a tool to evaluate new channels design, tugboats requirements, environmental window, DP system analyses, or even to define the maximum dimensions of vessels in an approach channel or basin, among others questions. Therefore, the joint work of the simulator development team and the pilots is crucial to obtain such a calibrated and reliable simulator, combining the local expertise of the pilots and their knowledge about ship handling and behavior in confined waters to the technical skills of the researchers. This paper will present the mathematical model adopted in the simulator and the calibration procedure based on results from sea-trials and pilots' feedback. The tugboat operation both in vectorial and manned simulation models will also be detailed. Several applications in Brazilian coast will be described, including ship-to-ship operations, maneuvering analysis of larger containerships in the existing infrastructure, evaluation of new terminals in design stage with unsheltered turning basin among others.

1 INTRODUCTION

Ship maneuvering simulators are used for predicting the navigation safety in restricted areas (ports and channels) and training. The following paragraph, taken from Webster (1992), summarizes the concepts to be studied. "A limited number of simulations using a less-than-perfect simulator, a few select (design) ship types, a few select environmental conditions over extreme ranges characteristic of the local area, and a few pilots with representative local expertise and ship handling proficiency are sufficient to obtain a useful appraisal of waterway design..."

Some points should be stressed in this statement, which illustrate the benefits and proper way of using simulators. The simulators are never perfect, since mathematical models are simplifications of reality. Therefore, they must always be used in conjunction with the knowledge and experience of local conditions. The use of standards and recommendations (such as PIANC, USACE, ROM, etc.) must also accompany the port studies, corroborating and/or discussing the results of the simulations.

In a recent initiative, Transpetro and Petrobras established a research partnership with the Numerical Offshore Tank Laboratory of the University of São Paulo (TPN-USP) for developing a maneuvering simulator for port, rivers and offshore operations, with the technical collaboration of Brazilian Maritime Pilots Association (CONAPRA). The simulator name is SMH (Portuguese acronym for Maritime and Waterways

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Simulator) is an engineering tool used for the analysis of several new operations in the Brazilian ports to improve their efficiency, due to the increasing oil and gas production and commercialization.

The accuracy of the mathematical model is an important requirement for a training simulator, but even more important for an engineering tool. The engineers, pilots and captains must rely on the ship dynamics represented by the simulator, since it will be used to give answers to questions related to maneuvering analysis. The simulator can be used to evaluate new channels design, tugboats requirements, environmental window, DP system analyses, or even to define the maximum dimensions of vessels in an approach channel or basin, among others questions.

This paper presents the mathematical model of SMH, adequate for low-speed maneuvering. The software is based on the TPN (Numerical Offshore Tank) numerical code (Nishimoto et al., 2002) which had several modifications to perform real-time simulations. The present simulator applies a Modular Mathematical Model, gathering a large number of models to represent the complete behavior of a ship during the navigation in restricted waters. Other time-domain maneuvering simulators are presented by Ankudinov et al. (1993), Koh et al. (2008), Fossen and Smodeli (2004), among others.

The simulator was developed using modern software engineering concepts, guaranteeing a flexible architecture, easy communication between different stations and external equipment and modularity, that enables new developments and improvements. The simulator supports different versions of hardware, such as part-task simulators with 3 or 6 visualization, tugboat stations of full-mission simulators using screen or projection technology.

Several Brazilian ports and rivers have already been studied and, in cooperation with pilots and captains, the simulator has been constantly improved. The feedback from the pilots and captains are used to perform a "fine-tuning" of the maneuvering models and environmental conditions in each port. This synergy between the theoretical background and field expertise has proven to be very effective. Some illustrative results of simulations and important results are exposed.

2 SMH MATHEMATICAL MODEL

2.1 General

This section summarizes the mathematical model implemented in the SMH simulator. The description is based on the paper by Hwang, (2004), that tried to define a standard documentation for maneuvering simulator models. Tannuri et al. (2014) and Queiroz Filho et al. (2014) present a more detailed description of the mathematical formulation and physical fundaments of the SMH models. This section also presents the model calibration and validation procedure.

2.2 Outline of the Mathematical Model

The mathematical models represent the motion of a floating vessel at low speed in 6 DOF (degrees of freedom), subjected to the external forces due to the environmental and tugboats and to the control forces provided by the thrusters, propeller and rudder. The 6DOF floating vessel dynamics differential equations (already considering the interaction with the fluid and the external forces acting on the hull) are solved using 4rd order explicit Runge-Kutta integration method. However, as a matter of simplicity, this section will only present the equations of motion for the horizontal plane.

We adopt two different coordinate systems to derive the ship equations of motions, as shown in Figure 1. The system $OXYZ$ is earth-fixed (inertial system) and the system $oxyz$ ship-fixed, with the origin on central point of the keel midship section. The center of gravity G is at the distance x_G ahead from the point o, ox is the longitudinal axis of the vessel directed to the bow, and oy is the transversal axis, pointing to port. The heading of the vessel ψ defines the angle between the ox and OX axes.

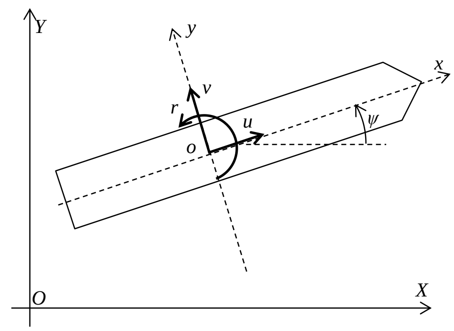


Figure 1 Coordinate system and basic definitions (for the 3 horizontal DOF)

The potential forces due to water-hull interaction are evaluated by means of added-mass and potential damping matrixes. The potential damping for horizontal motions is negligible, and can be simplified if the vessel is symmetrical along ox. Applying Newton's law of the motion, one can obtain the differential equations describing the relationships between the motion equation, given by:

$$\begin{aligned}
&(M + M_{11})\dot{u} - (M + M_{22})vr - (Mx_G + M_{26})r^2 = X_{ext} \\
&(M + M_{22})\dot{v} + (Mx_G + M_{26})\dot{r} + (M + M_{11})ur = Y_{ext} \\
&(I_Z + M_{66})\dot{r} + (Mx_G + M_{26})(\dot{v} + ur) + (M_{22} - M_{11})uv = N_{ext}
\end{aligned} \tag{1}$$

where M is the vessel displacement (mass), I_z is the yaw moment of inertia of the ship, u and v are the surge and sway velocities respectively and r is the yaw angular velocity. The term M_{11} and M_{22} are the ship added masses in the surge and sway directions, M_{66} is the ship added moment of inertia and M_{26} is coupled sway-yaw added inertia. The last term on the right side of the yaw equation is the Munk's moment.

The subscript *ext* represents the external loads, that may be expressed in terms of different factors:

$$X_{ext} = X_h + X_w + X_{wv} + X_p + X_{tug} + X_M \tag{2}$$

where X_h represents the hydrodynamic non-potential forces, including the current and maneuvering forces, X_w , X_{wv} represent the wind and wave forces, respectively X_P represents the thrusters, propeller and rudder forces, X_{tug} represents the external action of the tug boats, either in contact with the hull or connected by a cable and X_M represents the forces due to mooring lines, fenders or anchor lines.

2.3 Modeling Phenomena and Valid Application Range

This section provides information about the physical effects modelled in the simulator, as well as the application and validity range, in a tabular and simplified format.

Modeling Phenomena	Description / Application Range
Steering Gear	• Rudder Angle Velocity is configurable (default value 2.3 deg/s) • Constant rudder angle velocity • Maximum rudder angle is configurable (default value 35 deg)
Main Engine	• Model 1: The balance between hydrodynamic propeller torque and motor torque is calculated at each time step and is applied to the shaft equation (second order system). User must provide the shaft moment of inertia. The motor torque is assumed to be proportional to the telegraph command. This model better represents the behavior of the engine. • Model 2: The machinery model (relation between commanded and effective RPM) is represented by a second order linear dynamics with no speed overshoot. User must provide the time to accelerate the axis from zero to full rpm.
Hull Hydrodynamic Forces	• 6-DOF model with wave motion • Hydrodynamic forces action on the hull are based on the current coefficients obtained by towing tank tests or CFD. Those coefficients must be provided for the complete range of angles (from 0º - stern incidence; to 180º - bow incidence).

Modeling Phenomena	Description / Application Range
	• Sectional integration of the hydrodynamic along the hull (Obokata, 1987). The model can take into account the influence of the yaw rotation and non-uniform current field near a port area.
Propeller Hydrodynamic Forces	• Fixed Pitch Propeller (FPP) or Controllable Pitch Propeller (CPP) • A four quadrant model for the propellers is adopted, including an extra ad-hoc correction for the yaw motion induced by the reverse action of the main propeller (paddle effect). • User must provide the Thrust (KT) and Torque (KQ) coefficients as a function of the advance ratio (J) and Pitch (P/D). Those coefficients must be in tabular or polynomial format. • For CPP propellers, a constant (configurable) pitch variation velocity is assumed. • Wake and thrust deduction factors are input data.
Rudder Hydrodynamic Forces	• - A four quadrant model for the rudder action is adopted, including the interaction between the propeller and the rudder. • - The rudder Lift and Drag curves must be provided. The simulator database includes standard coefficients for all-movable, flapped and Schilling rudders.
Shallow-Water Effects	• The shallow water corrections are applied to the hydrodynamic potential and non-potential forces following two options: • Option 1 (Pre-Calculated): The potential hydrodynamic properties (added masses and potential damping) and forces (first order and drift coefficients) are obtained by potential codes already considering the bottom in the mesh grid, and are provided as input to the simulator. The non-potential forces (represented by the current coefficients) are obtained by towing tank or CFD tests with the bottom already included. The validity of this approach is dependent on the quality of the pre-calculation procedure, and may reach up to h/T=1.05 (h is the water depth; T is the ship draft). • Option 2 (Real-Time Corrections): Ad-hoc corrections to the potential and non-potential forces are performed in order to account for the shallow water effects. Those corrections are valid up to h/T=1.2.
Bank and Passing Ship Effects	• The effects of obstacles, such as banks or passing ships, are evaluated by the real-time calculation of the distance between the vessel hull and the external obstacles. Tabulated suction forces and yaw moments are used in order to provide the adequate physical effect expected by the pilots.
Wind Effects	• The wind effect is simulated by using the aerodynamic force and moment equations which are expressed as functions of aerodynamic force coefficients, above-water projected areas of the ship, the effective wind force and the effective wind direction. Those coefficients are obtained by wind tunnel tests of CFD calculation. • The simulator allows constant or gusty wind. The wind spectra implemented in the code are Harris, Wills, API and NPD, among others.
Wave Forces / Motions	The following wave effects are implemented: • Second order drift forces (Slow and mean drift forces - that induces low frequency wave oscillations and drift) • 6DOF First order forces (that induces the oscillatory vertical motions) • Wave-current (or vessel speed) interaction, that modifies the wave drift forces and the frequency of incidence. • Irregular wave spectrum models (JONSWAP or Pierson-Moskowitz) with directional spreading and bimodality. • The effect of the breakwaters that changes the wave pattern into the sheltered area is considered. A spatial map of wave height and direction may be defined as an input to the simulator. The simulator then calculates an average wave height and direction for the vessel instantaneous midship position, and these wave properties are used for obtaining the forces at that time. • Wave potential coefficients can be imported from different commercial softwares (Wamit, Acqua, Hidrostar).
Bow and Stern Thrusters	• The net thruster forces are dependent on the RPM and is reduced due to the ship longitudinal and lateral speed at the bow or the stern. • The influence of the longitudinal speed is configurable, and the default reduction is zero net-thrust for 6knots. • The influence of the lateral speed at the bow or stern (inlet speed) depends on the thrust coefficient (Kt) as a function of advance ratio (J)
Tugs	Option 1: Simplified Vector Model • No limitation in the number of tugs • Push-pull and Online assisting methods • Correction due to current, wave and vessel speed on the net thrust • Reduction of the efficiency when force astern (configurable)

Modeling Phenomena	Description / Application Range
	• Time to connect the line, to change force and to change direction are configurable. Option 2: Multiplayer simulation • Tugboat is modeled as vessel and is controlled by the part-task simulators. (up to 4 tug boats allowed) • Conventional of Azimuth tugboats • Push-pull, Online and indirect assisting methods
Mooring Lines and Fenders	• No limitation in the mooring line numbers, that are modeled as catenary equation, with linear restoration. • Winches are commanded by the operator interface, with constant (and adjustable) speed. • Fenders are modeled as non-linear restoration elements with contact friction.

2.4 Outline of the Mathematical Model

For each vessel modeled in the simulator, several standard maneuvers are executed and documented in order to check the model. These tests are done in the simulator running in fast time mode, with an automatic procedure for actuating on the rudder and propeller. Those maneuvers include at least:

- Turning Circle
- Stopping Ability (Crash Stop)
- Inertia Test
- Yaw-Checking and Course-Keeping Ability (10/10 And 20/20 Zig/Zag)
- Turning Circles in Shallow Water
- Turning Circles in Wind
- Deceleration Performance
- Pull-In and Spiral Tests
- Accelerating and Coasting Turns
- Low Speed Maneuver - Lateral Thruster Capabilities

The maneuvers must be executed preferable at half-speed, since it is closer to the actual speeds used close to a port area. However, the velocity will depend on the available results from the Sea-Trial report of the actual vessel. The main parameters of each maneuver are calculated and are compared to the results of the real vessel sea-trial. The most important parameters compared are:

- 10/10 And 20/20 Zig/Zag
  - 1^{st} and 2^{nd} overshoot - angle and time
- Turning Circle
  - Tactical Diameter, Advance, Transfer, Speed at heading 90^o, 180^o, 270^o, 360^o
- Stopping Ability (Crash Stop)
  - Head / Side Reach and Travel Distance until stop, Time to stop
- Lateral Thruster Capabilities
  - Time to turn the vessel with bow/stern action with / without speed

If the comparison results a difference larger than 20% in any of those parameters, we do the calibration procedure. Specific vessel parameters are multiplied by a factor from 0.8 - 1.2 to match the model to the actual vessel. The parameters we mostly tune are the sway added mass, rudder lift, current/hydrodynamic forces for bow incidence (that are equivalent to the linear Y_v or N_v hydrodynamic derivatives) and propeller efficiency for astern action. When we change any parameter, all tests must be repeated. An automatic software executes such a process. The vessel parameters allowed to be changed are those estimated/calculated by the laboratory. We do not change the actual vessel parameters (for example, rudder area).

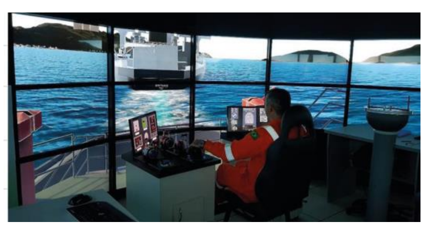
Of course, a comprehensive knowledge of the mathematical maneuvering model is required in this calibration procedure, since the researcher must know, a priori, the effect of any change that is being done. The calibration procedure requires the supervision of the coordinator or the main simulator operator.

In most cases, the vessel documentation provides no sea-trial results for shallow water, and the calibration procedure is only executed for deep-water maneuvers. The hydrodynamic coefficients for shallow water are the applied to the "deep-water calibrated" model, and the results of the vessel in shallow water are compared to those in deep-water. The relation between the deep water and shallow water parameters are compared to results of similar vessel or from literature, in order to verify the model in shallow water. If there are sea-trial results for shallow water maneuver, the calibration procedure is expected to be better since the shallow water maneuvers from the simulator are directly compared to the actual results of the vessel.

After this process, experienced pilots maneuver the vessel in the simulator, performing some typical harbor-like maneuver, such as navigate along a channel, to execute a bend and to stop the vessel. The pilot's expected rudder efficiency, rate of turn, and stopping ability are compared to the simulator and we do some extra adjustments.

3 TPN-USP MANEUVERING SIMULATION CENTER INFRASTRUCTURE

The TPN-USP Maneuvering Simulation Center has 6 simulators, being 3 classified as full-mission (immersive system with more than 270º angle of projection). All simulators can run together in the same run (multiplayer simulation). The following chart presents the main characteristics of each simulator:

General features	• Commands for rudder, fixed or controllable pitch propellers, tunnel and azimuth thrusters • DP System and AutoPilot • GPS, Anemometer, rate of turn, compass, Doppler log, Echo-sounder, Radar, ECDIS, Echo Souder, Speed Log (bottom and water related) • Portable Pilot Unitu (PPU) • Rudder Repeater, Girocompass repeater, Binoculars • RIPEAM interface • Radio communication • Alarms and Anchor, Mooring lines
Full-Mission 1 	• 12m diameter screen, 30 projectors, 270º field of view, Floor Projection • 10 panels for commands and instruments, 4 overhead screens • 2 wings and automatic change of point of view when the pilot is in the wing
Full Mission 2 	• 25 visualization screens, 360º field of view • 7 panels for commands and instruments, 3 overhead screens • Stern bridge for PSV operation 

Full Mission 3

	• 21 4K visualization screens, 360º field of view
	• 2 panels for commands and instruments
	• Customizable simulator, can be used in either mode
	  ○ Tugboat
	  ○ Offshore Crane
	

Simulator 4D 	• 1 large stereo visualization screen • Moving 6DOF platform for complete immersion • 2 panels for commands and instruments • Used for tugboat simulation
Part-Taks Simulators (2 units) 	• 6 visualization screens • 5 panels for commands and instruments

4 APPLICATIONS

The simulator helps in performing various maneuverings in extreme conditions, with different ships and in damaged conditions and/or command failures. The envelope of the ship’s course is obtained in extreme and operating conditions that, in reality, occur seldom during the year. In this way, it is possible to dimension the channels, maneuvering basins and escape routes.

The simulator can also be used to verify the impact of civil works, such as new berths and breakwaters construction. Often, the maneuvering simulation should be associated with a hydraulic and wave diffraction study to predict the alteration of the field of waves and current because of such works.

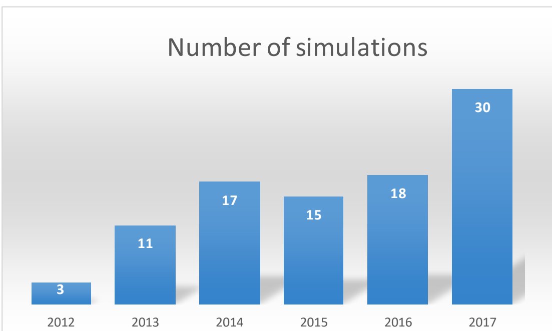
Dredging studies relate to the same context. Deepening a channel does not directly reflect on increasing the draft permitted for navigation. A study should be undertaken with the help of simulators, inasmuch as the maneuverability of the ship with this new draft is altered, as well as other physical phenomena that define the maximum draft, such as squatting, wave motion and current in the channel.

Non-conventional operations, such as ship-to-ship berthing and maneuvering of hulls of future FPSO platforms (without propulsion), can also be examined beforehand using simulation. Moreover, when the dimensions of channels and access bends are very close to or less than obtained by standards or recommendations, it is essential to perform simulations to check the risks associated with extreme operating conditions, and to define environmental windows for operation.

The analysis of the results of simulation can also be used to define the navigation signals and lights design (location and type of buoys) and contingency plans. The number, layout and bollard-pull of tugboats to guarantee the safe positioning of ships can also be appraised using simulators.

4.1 Quantitative evaluation of the simulations executed from 2012-2017

During the period from 2012-2017, TPN-USP executed 94 maneuvering simulation studies, with the participation of over 140 pilots from Different Zones. The Figure 2 shows the number of simulations executed per year and per Brazilian states.



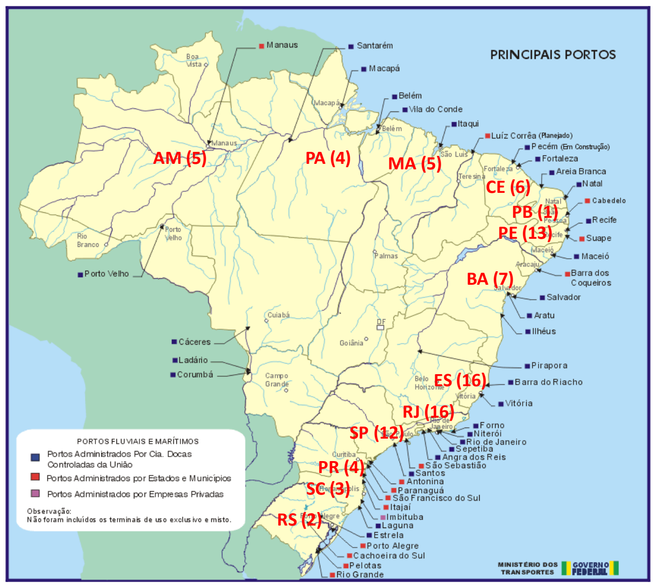


Figure 2 Maneuvering simulations performed at the TPN-USP during 2012-2017: (left) number per year; (left) Distribution by type; (right) Distribution per Brazilian states

The simulations have different levels of complexity and realism and different purposes. The Figure 3 shows the distribution of the simulations among different types and purposes. The classification of the simulation level is:

- Fast-Time Simulation (17% of the total): the simulator operates with algorithms that represent the behavior of the pilot, controlling the ship and tugs. One or more local pilot take part in the initial meeting, defining the maneuvering procedure that the control algorithm must mimic. The maneuvers run in accelerated mode and the execution of a large number of runs is possible. The statistical analysis of the ship tracks can define the optimal layout of the maneuvering area or the limiting conditions.

- Real-Time Single Player (67% of the total): real-time simulation controlled by the local pilot, using a full-mission simulator. The simulator operator uses the so-called vector tug models to control the tugs. Simplified model based on efficiency curves calculates the effective force applied by the tugboat, for different conditions (speed, current, wave and towing angle). To compensate the short comings of using simplified models, sometimes one tug captain attends the simulation campaign and advise the simulator operator on which tug forces or position could applied realistically, on the limitations of the tug, the tow line length, requirement for space, reaction time, etc..

- Real-Time Multi Player (*Interactive tugs* – 16% of the total): the main simulator is the assisted ship, controlled by the pilot, and one or more simulators are the tugs, controlled by tug captains. A 6DOF maneuvering model calculates the tug motion and behavior; in such a way the simulator considers almost all aspects: tug type and characteristics, influence of speed and towing direction, required space, reaction time and pilot-tug captain communication. Since the ship is often assisted by 3 or 4 tugs, it is not practical and very expensive to have such number of interactive tugs during the simulation. Therefore, we use vector tugs combined to interactive tugs. Normally, 1 or 2 most critical tugs are operated in the interactive mode.

The different purposes of the simulations are:

- New Operations (incl. STS): feasibility assessment and definition of environmental window for new operations in an existing port, such as a different type of vessel or ship-to-ship operation alongside the berth.

- New Port and Terminals (Design): evaluation and optimization of the horizontal design of a navigation channel or harbour basin, as suggested by PIANC (2014) in the Detailed Design stage.

- New Port and Terminals (Verification): evaluation of environmental window, operational procedure and pilots' familiarization for a newly built port or terminal or for an existing port that was subjected to dredging or expansion.

- Increase Ship Size: verification if the horizontal dimensions of existing channel and basin are compatible to ships with larger dimensions.

- Increase Draft: the increase in draft is associated with reduction in the maneuvering margin (MM) and increase in the vessel inertia. The maneuvering simulator can be used to verify the impact of those changes in the safety of the maneuver.

- Dredging design: verification of the horizontal dimensions of the area to be dredged, including channels, basins and stopping areas.

- Tugboat specification: verification of the tugboats number, layout, bollard pull and type.

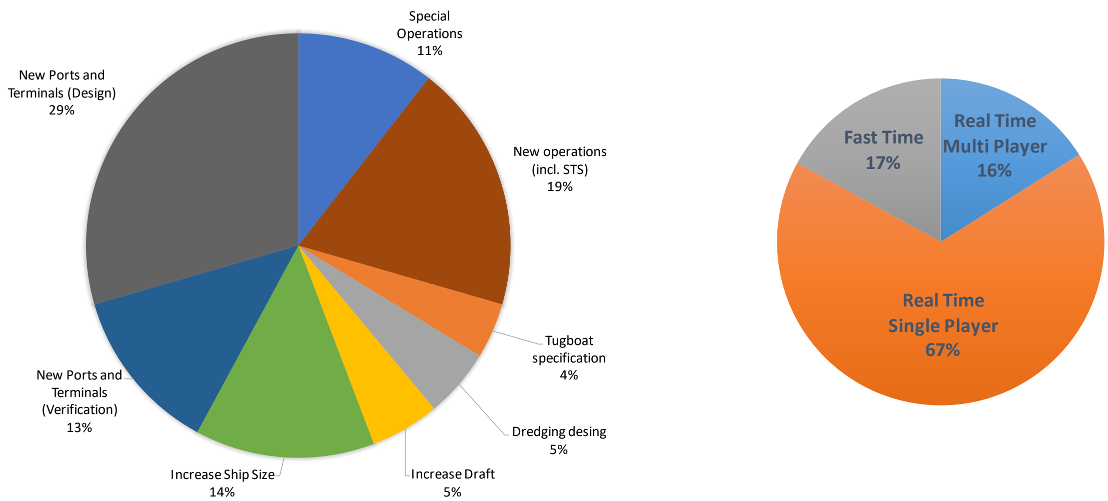


Figure 3 Maneuvering simulations performed at the TPN-USP during 2012-2017: (left) Distribution by type; (right) Distribution by each category

4.2 Case Study 1: Feasibility analysis for larger containerships

The Port of Santos, located in the State of São Paulo - Brazil, is the most important Brazilian port, representing an economic influence greater than 50% of the national gross domestic product. In total, the port counts on 65 berth quays, spread on its both margins, and receives multiple types of ships, including containers, solid and cargo bulk carriers, cruises and Ro-Ro. The nominal access channel water depth is 15 m and the current draft rule in place limits ships with drafts larger than 14.2m, considering 1m of tide.

Despite its local importance, the Port of Santos infrastructure does not enable the traffic of the most recent container vessels in operation by limiting the port access to vessels with maximum lengths of 336m, able to carry around 10.000 TEUS. Notwithstanding, the search of the shipping line companies to achieve economies of scale has given rise to sharply growths of container ship sizes in the last years, increasing the port challenges to improve its capabilities. For comparison, the highest-capacity ship current in operation is able to carry around 19.000 TEUS and is 395m long, 59m wide with a design draft of 14:5m

Based on this scenario, the Port of Santos has been planning to reduce the port restriction and start attending a new class of container ships with maximum length of 366m (13,800 TEU). With this purpose, a series of studies covering different aspects are required to evaluate the manoeuvering feasibility of this novel ship size in the port, such as: suitability of the present horizontal and vertical dimensions of the navigation channel, impacts on the maintenance dredging necessity, dimensioning of new turning basins, ship manoeuvring challenges, new tug bollard pull requirements and impacts induced by its passing speed and distance to moored ships, these last ones being the focus of the present analysis.

Motivated by the studies performed by the Port of Santos, several Brazilian ports executed studies with TPN-USP to evaluate the manoeuvering feasibility of the 366m long containership (Figure 4). They know that if this new class of containerships is allowed to operate in the Port of Santos, they will need to receive those vessels to guarantee their market share. The Figure 4 also shows the number of simulations of containerships carried out by TPN-USP, with a clear tendency of increasing number of vessels with LOA larger than 349m.

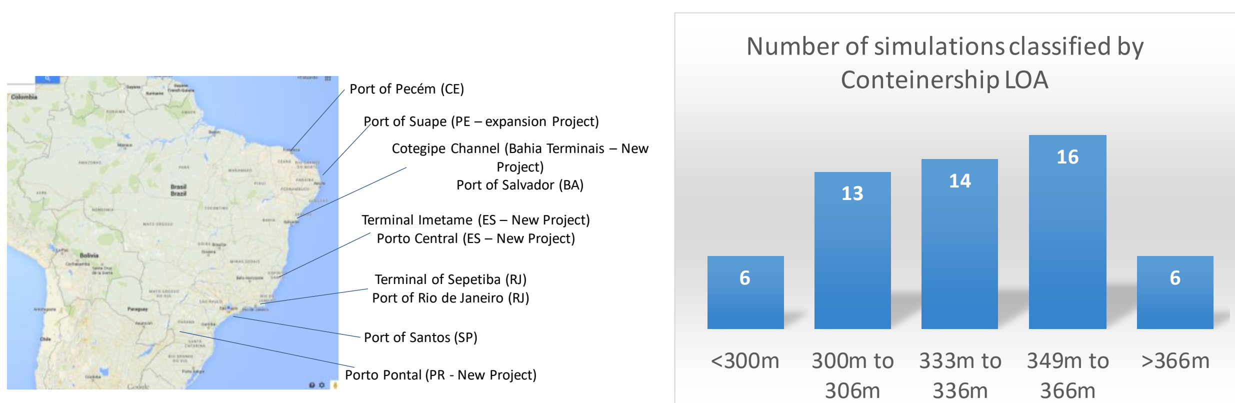


Figure 4 (left) Ports that executed studies with TPN-USP to test the manoeuvering feasibility of the containership with LOA larger than 336m; (right) number of simulations classified by containership LOA

Assessing whether an existing infrastructure can accommodate a larger vessel involves maneuvering simulation. The study should define contingency measures in case of failures, number and types of tugs, environmental limits and operational restrictions.

The Port of Santos is located in an estuarine channel, with berths on both banks and distance between margins of approximately 400m.Today, there are many incidents of mooring lines breaking and fender damaging due to the passing ship problem, caused by the hydrodynamic interaction between the moored ships and the vessel navigating along the channel. The increase in ship size could further aggravate this problem. Therefore, the interaction caused by the 366m long containership was evaluated before to the maneuvering simulations, using a numerical code based on potential flow (Ruggeri et al., 2016). The result was the definition of zones around berths where the vessel should maintain a controlled speed (Figure 5a).

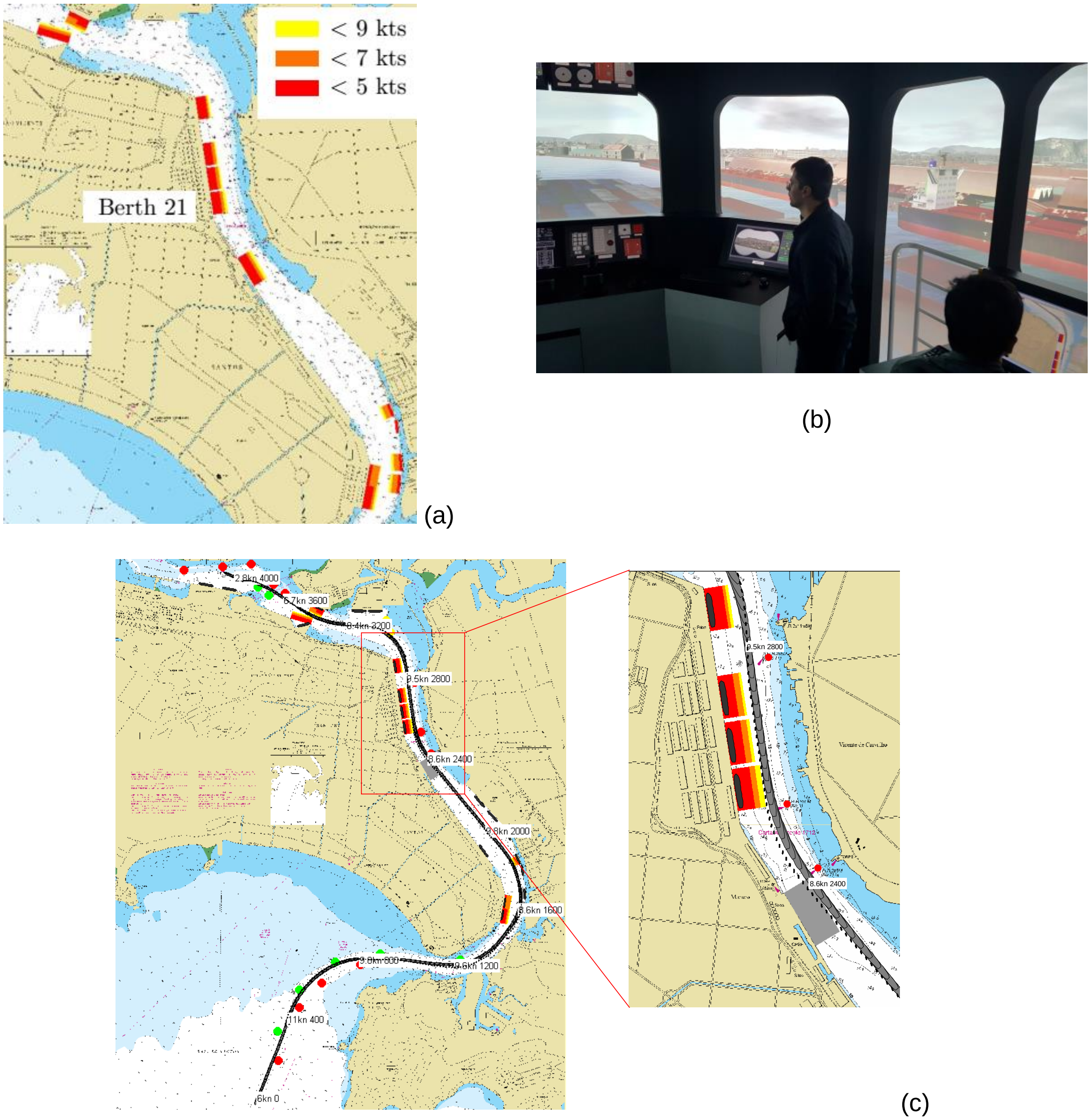


Figure 5 (a) Operational limits for three passing distances printed in nautical chart of Port of Santos; (b) Pilot in the TPN-USP real-time simulator bridge ; (c) Real-time containership trajectory for an inbound maneuver

The next step was to execute of real-time simulations commanded by local and experienced pilots of the Port of Santos (Figure 5b). This is a very important step of the present work since it becomes possible to evaluate whether the ship can be indeed controlled and kept distant enough to the moored ships with relatively low speed. Several manoeuvring simulations were carried out, which comprised combinations of draft, outbound/inbound manoeuvres, flood/ebb tides, wind and wave conditions. In each simulation, the pilot commands aim to avoid the ship to pass under the colored areas above the pre-specified velocities. On the other hand, several factors make this task very difficult to be managed, such as for example the intense traffic of small boats on the navigation channel, wind gusts and also a helmsman delay on complying the pilot command. In many cases, the pilot has to increase the ship speed in order to increase the ship controllability (rudder efficiency), which may expose more the moored ships to the passing ship forces.

The trajectory of the ship in an illustrative inbound maneuver is presented in the Figure 5c. Here, the pilot could keep the vessel in the center of the channel, outside the colored areas.

The final conclusion of the analysis, that combined a potential flow model and a real-time maneuvering simulator is for the feasibility of the 366m long conteinership in Port of Santos, under environmental and operational limits. 4 tugboats with total 270TON must be used in the maneuver, the port authority must interrupt the ferryboat operation and must guarantee no ship crossing the channel during the transit of the larger vessel. The visibility must be larger than 1nm, winds limited to 15knots and the maneuver must occur in the high tide with very low current. It was also recommended to the port authority to strictly control the mooring lines pre-tension in the vessels alongside the critical berths.

Maneuvering simulations can also be used to verify the necessary changes in the existing infrastructure to accommodate a larger vessel. The changes may be the construction of new berths, expansion of existing berths, dredging of the channel or turning basin. As an example, the Port of Sepetiba is going to expand the existing berth, as well as to dredge a new channel with direct access to the new berths. The Figure 6 (left) shows the modifications proposed by the designer. An extensive maneuvering simulation campaign has been carried out, and the new layout was approved by the pilots, with minor modifications in the bifurcation and in the inner berth approaching, as indicated in the Figure 6 (right).

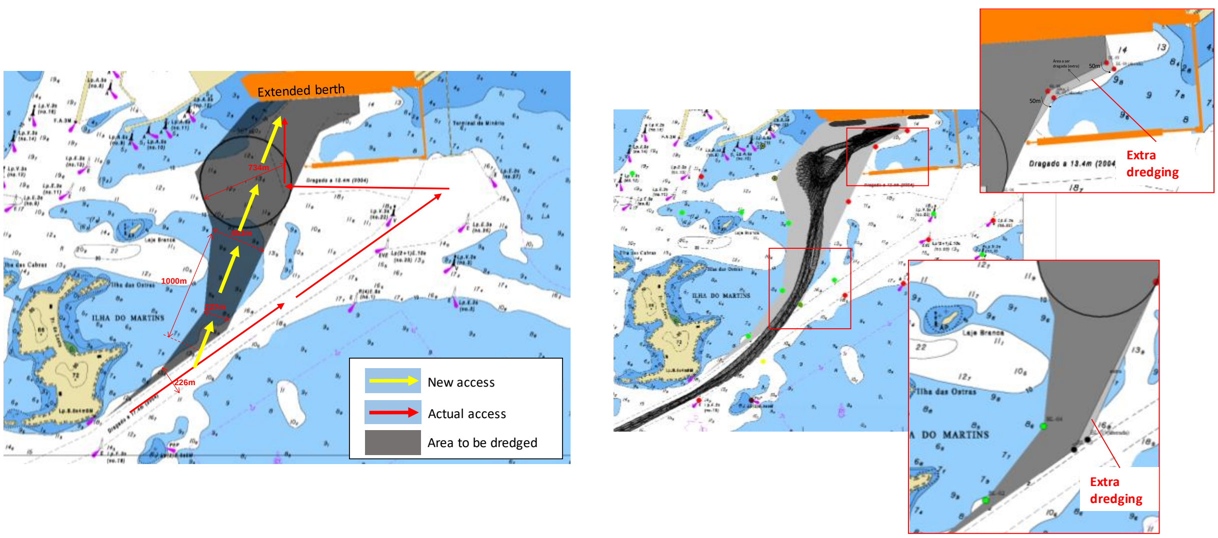


Figure 6 (left) Port of Sepetiba nautical chart showing the new changes; (right) Trajectory of inbound maneuvers of 366m long containership and proposed modifications in the original layout

4.3 Case Study 2: Evaluation of Ship-to-Ship operations

Ship-to-ship (STS) operations have been applied worldwide from military operations to oil/LNG cargo transfer, to improve operational efficiency. In the last years, the increasing oil production in the new pre-salt fields and the lack of available berths/terminals in Brazil has increased transfers in STS. This operation allows the transfer of the oil from the specialized DP shuttle tanker (that brings the oil from the offshore platform) directly to conventional tankers, ready to export, optimizing the occupation of the terminals and on-shore tanks.

The oil companies with operation in Brazil are searching for new areas to perform the STS operation, that can be offshore (STS underway), in sheltered bays (anchored STS) or at berths that can hold the forces generated by two moored vessels (STS alongside the berth). The main challenge is to transfer oil from the Suezmax DP to conventional VLCC tankers.

TPN-USP executed a large number of simulations to verify the manoeuvering feasibility of the STS Operation, as Figure 3 indicated. Figure 7 shows the ports in which the STS feasibility was studied, and the number of tankers simulations carried out by TPN-USP. The largest number of Suezmax tankers reflects that most DP shuttle tankers are Suezmax class vessels.

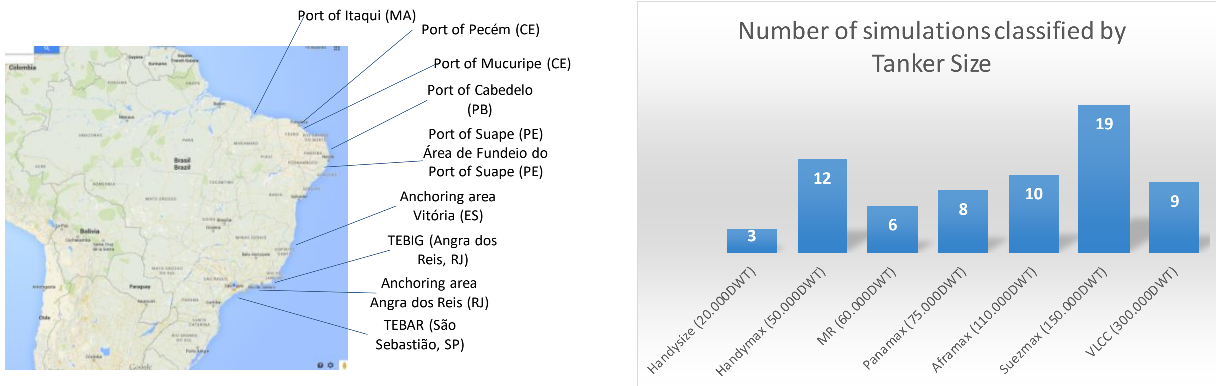


Figure 7 (left) Ports that executed studies with TPN-USP to evaluate the STS feasibility (right) number of simulations classified by tanker size

The analysis and planning of a STS operation require the utilization of state of the art engineering tools. A careful review of different aspects of the operation must be done since it is a new operation in an existing port facility, which was not predicted when the port was originally designed and built. All the procedures are based on the PIANC (2014) detailed design phase. The operations were evaluated in several aspects:

- Calculation of tide, current, wind and waves in the area using in-loco measurements and mathematical models.
- Detailed calculation of the environmental loads acting on the vessels when in ship-to-ship configuration.
- Verification of the as-built layout of the terminal, including the mooring and berthing equipment.
- Mooring analysis; Verification of the loads on the bollards and fenders.
- Berthing and unberthing maneuver and nautical area.
- Bollard pull requirements for tugboats.

A full description of all phases of the analysis for three case-studies may be found in Tannuri et al. (2016a) – Mucuripe Port; Tannuri et al. (2016b) – anchoring area of Vitoria and Ruggeri et al. (2016) – São Sebastião TEBAR Terminal. The maneuverability aspects, which are the target of this paper, should be evaluated through real-time simulation campaigns, with the participation of pilots and tug captains.

Maneuvering simulations should verify, for example, if the approach area to the berth is compatible with the transit of 2 ships. For cases where this area is natural (without dredging), we draw a line delimiting the safe depth in the ECDIS (*Electronic Chart Display and Information System*) or PPU (*Portable Pilot Unit*), and we check the distance along the simulation runs. In cases where the berth approach area is artificial (dredged), it was originally designed for only one ship. Thus, the simulations will allow verifying if with proper use of tugboats and maneuvering techniques it is possible to guarantee the safe approach of the second ship.

As an example of a natural depth approach area, Figure 8 shows the maneuver to the Pier 101 of the Port of Pecém. The STS vessel should turn in the outbound maneuver and may approach "forbidden" area indicated by the black dots. Although the depth is almost constant in the approaching area, waves can penetrate by the SW part of the breakwater, inducing vertical motions on the ship if it moves out of the sheltered region. After several simulations runs, this maneuver was considered safe and feasible. The STS maneuver was also evaluated in the internal berth of the São Sebastião Terminal (PP2). The 16.6m depth line is 106 m from the ship's side. Figure 3 (left) shows one of the simulated maneuvers, and it was found that the ship reaches the border of the demarcated area. Thus, the STS maneuver with Aframax vessel was considered unsafe.

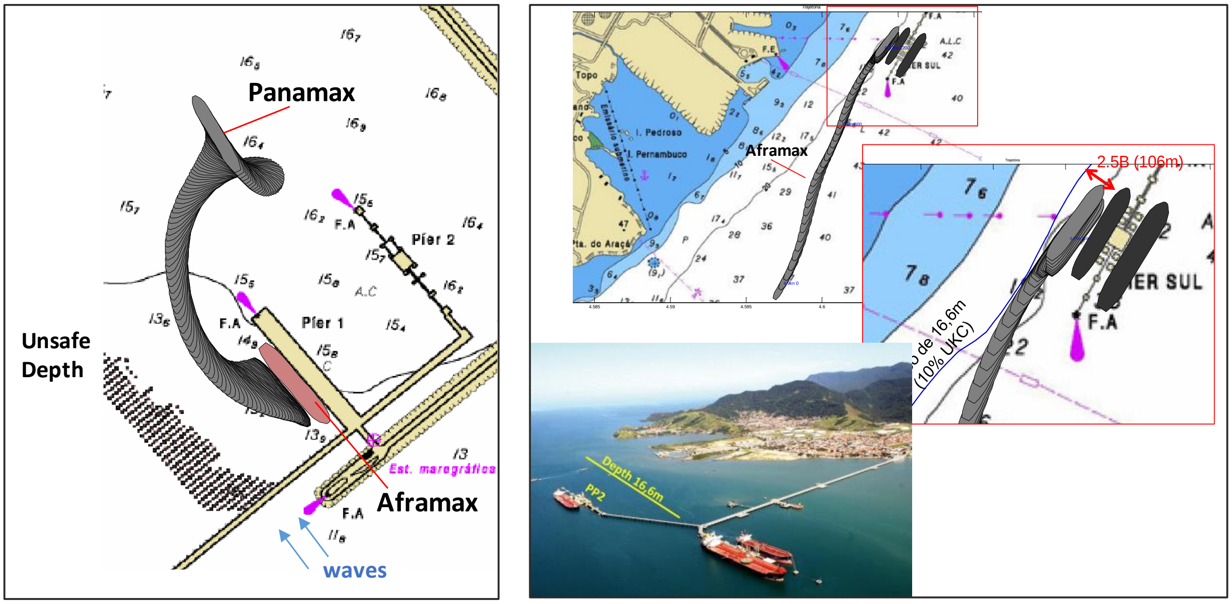


Figure 8 (left) Outbound maneuver at the Pier 101 – Port of Pecém; (right) STS maneuver at the internal berth of the São Sebastião Terminal (PP2).

The Mucuripe Oil Terminal has a dredged access area. The STS operation with Panamax vessels was evaluated by means of maneuver simulations, and it was verified that the STS operation is safe if an extra tug with at least 40TON is used. The distance between the red buoys and the ship in the pier allows approaching or turning safely, even considering the space required for the tugs operation. Figure 9 presents berthing and unberthing maneuvers, which demonstrate this finding.

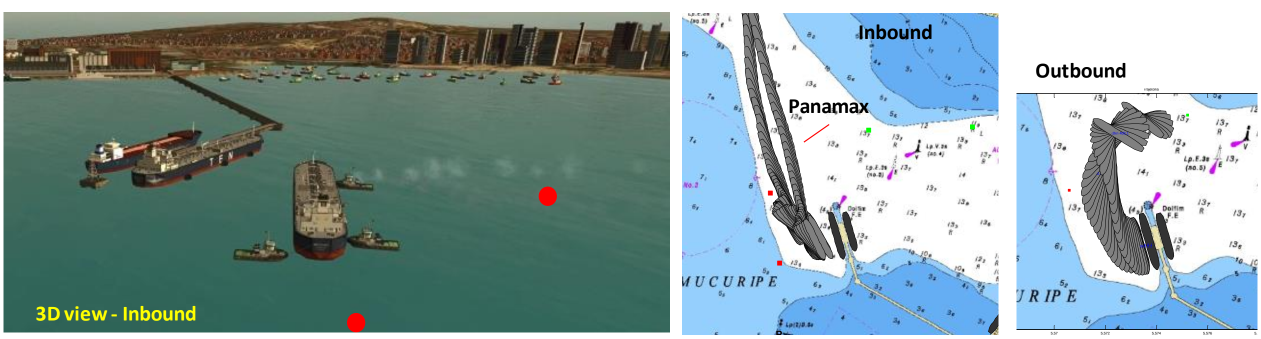


Figure 9 Inbound and outbound STS maneuvers at Mucuripe Oil Terminal

Maneuvering simulation should also verify the influence of the STS operation in neighboring berths. In the Port of Itaqui, for example, it was found that the two vessels alongside berth 106 would reduce the width of the approach channel to the berth 105, that is used by another company, to 175m (Figure 10 – left). Due to the strong currents and tidal variations in this Port, the maneuver to/from the berth 105 was considered unsafe by the pilots if the berth 106 is occupied by two vessels. This information must be used by the authorities to estimate the economic benefits of the operation, as well as to reconcile the interests of the various operators. On the other hand, the STS operation in the Port of Cabedelo does not prevent the maneuver in the neighboring berths, as shown in Figure 10 (right). Although the width of the approach channel reduces to 180m, the fact that ships are smaller and the currents weaker, allowed the inbound/outbound maneuvers to neighboring berths to be considered safe. Therefore, these two examples demonstrate the importance of the participation of the local pilots so that the risk assessment considers all the particularities and previous experience of the area.

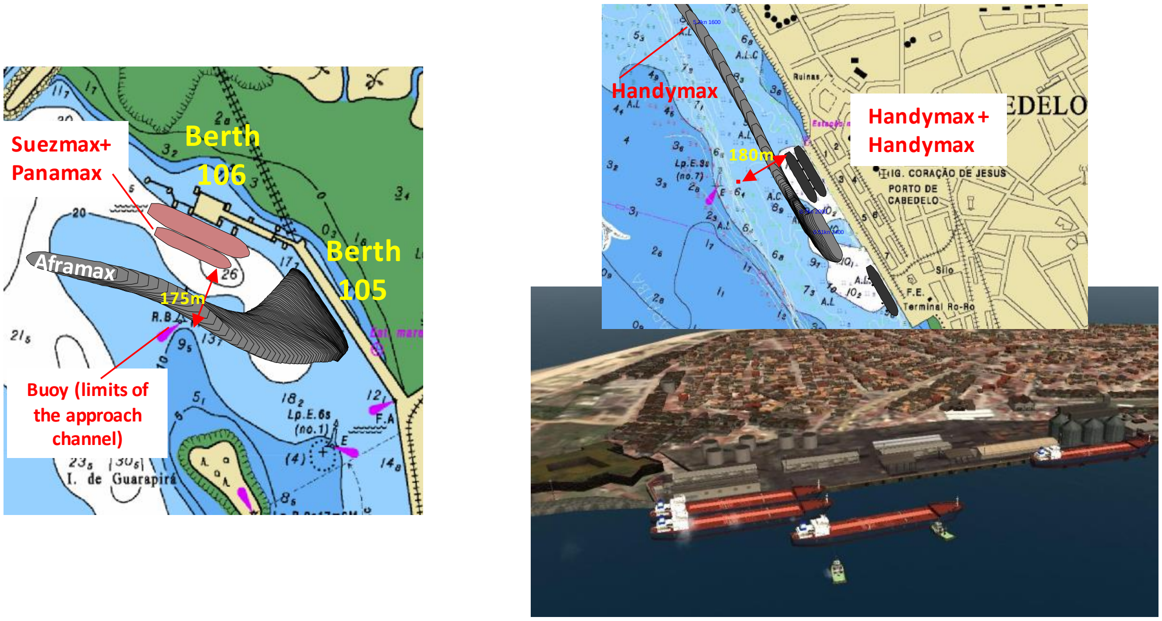


Figure 10 (left) STS operation in the Port of Itaqui; (right) STS operation in the Porto of Cabedelo

The position and heading control of the vessels should also be evaluated in the maneuvering simulation. Particularly in the anchored STS, techniques should be tested to keep the anchored ship stationary when the second ship approaches. Multiplayer simulation campaigns are suggested to test various solutions. Figure 11, for example, presents the actual maneuver executed in the sheltered anchoring area of Angra dos Reis. A tugboat in push-pull mode on the port-quarter of the anchored vessel is used to keep its position. In the case of unsheltered areas, the waves impose restriction on the operation of tugboats on the side. Thus, other solutions of controlling vessel position are being evaluated. One technique under study is the use of an offshore tugboat on a long-line made fast at the stern of the anchored ship, trying to keep its heading during the maneuver. This technique was tested in the simulator and in an experimental operation in the anchoring area of Vitória (Figure 11).

Figure 11 Anchored STS operation in: (left) Angra dos Reis (Sheltered bay); (right) unsheltered anchoring area of Vitória.

4.4 Case Study 3: Evaluation of new port designs

The joint work between the simulator team and pilots with expertise in the area can give important support for engineers during the design of new facilities. The TPN-USP in cooperation with the Brazilian pilots have participated on 30 studies of this category, that can be classified according to the Figure 12.

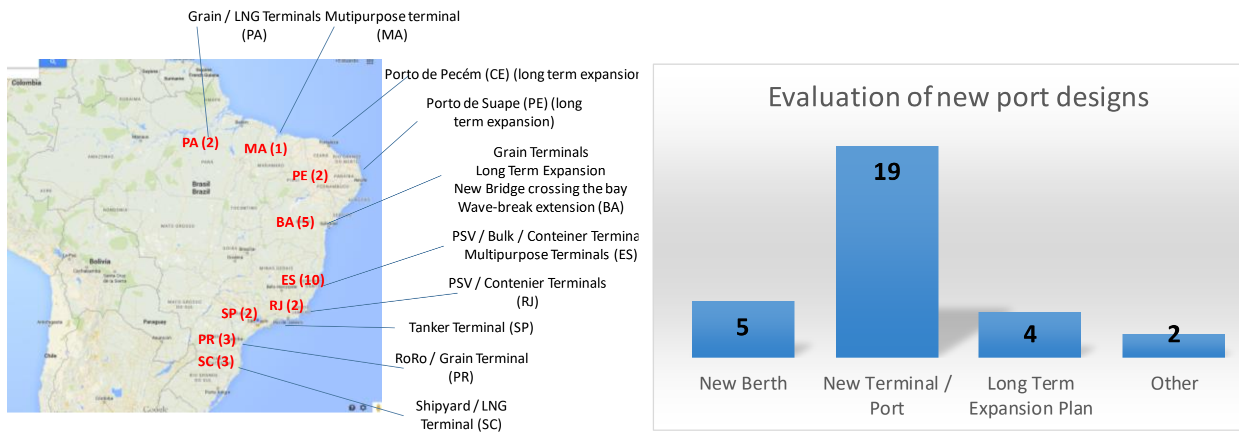


Figure 12 (left) New port facilities that were studied by TPN-USP (right) number of simulations classified by type

As indicated in the PIANC (2014), the maneuvering simulation can be used in the Conceptual Design stage, and is mandatory in the Detailed Design. The following points can be addressed during the simulations of a port in the design stage:

- Dredging optimization of the channel, turning basin and stopping areas
- Verification of localized channel problems for which the recommended width or alignment requirements cannot be satisfied.
- Verification of the influence of the new terminal in the berths or existing ports in the surrounding area
- Assessment of levels of risk during the navigation
- Estimation of the maximum environmental conditions for safe maneuver
- Definition of tug requirements

The long-term expansion plans (up to 30 years) are based on expected port demand, and nautical-port engineering concepts are applied to define the layout for access and position of the berths. The various phases of construction are simulated, and the objective is to evaluate the feasibility of the conceptual proposals, to choose between different proposals, to identify possible design errors and to confirm the defined type ships.

Figure 13 shows two alternatives for expansion of the Port of Suape that were evaluated during maneuver simulations. It is planned to build a new breakwater and new berths for Suezmax tankers. During the simulations, it was verified that Layout 1, even guaranteeing a safe maneuver, would make it impossible to carry out STS operations. Although not originally foreseen by the expansion plan, these operations are carried out frequently by the port in the inner breakwater berths, and the pilots, maritime and port authorities have reached consensus that it would be better to foresee this possibility also for the new cradles. Another advantage point of Layout 2 is that it allows the future construction of new berths, using the structure of the breakwater, as it is already done in the inner berths. So, the Layout 2 was chosen.

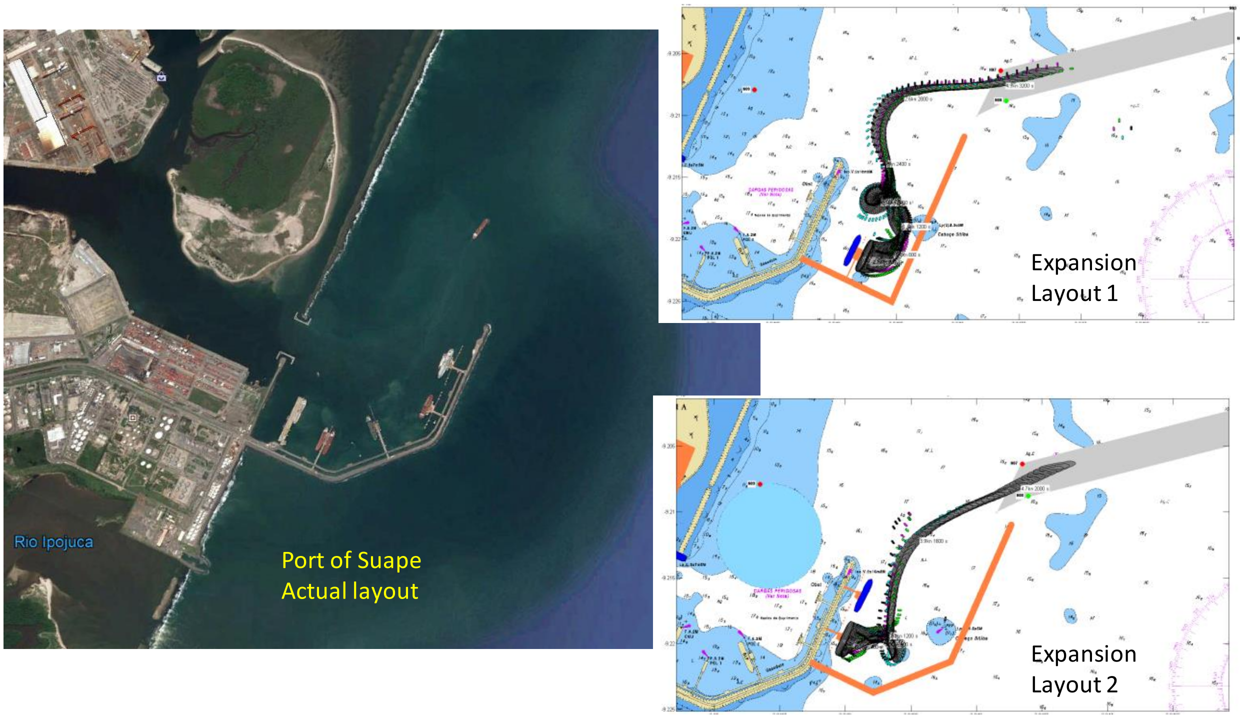


Figure 13 Proposals for the expansion of the Port of Suape

The evaluation of the design of the Porto Central project, a large port facility in the state of Espírito Santo, required several simulation campaigns. The larger ships were simulated in the critical berths, and the maneuver spaces were evaluated, at an initial and final stage of the port construction. Some suggestions for improvement and optimization of the internal arrangement were proposed. A relevant point was the verification of the need for the use of escort tugs for the manoeuvre of the large containerships (LOA greater than 366m), since the unsheltered access channel demands high speed navigation, imposing difficulty for stopping and turning in the sheltered area. With this, it was concluded that tug companies should already be prepared, making the escort tugs available and to start training the tug masters operating in the region.

Figure 14 Porto Central: (left) Maneuvering simulations ; (right) Layout of the port final stage

5 CONCLUSIONS

This paper presented the Maneuvering Simulation Center developed at the University of São Paulo, Brazil, and the benefits arose from a technical partnership established with Brazilian Maritime Pilots Association (CONAPRA) since 2012. We showed, by the description of several case-studies, the importance of the inputs from the experienced pilots since the early phases of the study of a new port or operation and during the maneuvering simulations. It is the only way to ensure that technical ship handling, the important human factors and local particularities are incorporated in the analysis.

6 ACKNOWLEDGMENTS

The authors thank Petrobras for supporting the development of the maneuvering simulation center, and all pilots that participated on the simulation campaigns. The first author thanks the CNPq (process 304784/2017-6) for the research grant and the students and researchers of the TPN-USP Maneuvering Simulation Center.

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