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Maritime Traffic Simulation including Tidal Windows and Squat effect in the Northern Arrival Channel of the Amazon River

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Abstract

Brazil is the world's second largest soybean producer considering the last harvest 2017/2018 with a production of 117 million tons. This increases the grain outflow demand that create a need of larger vessels with greater draft. Navigation on the Amazon River is considered critical due to the presence of fluid mud, which results in restricted depth at 11.7m. However, the current ships can't navigate at full capacity because the risk of running aground or damage to the hull. Considering this problem, this paper reports a case study using a marine traffic simulation program which evaluates the tidal windows of north channel of the Amazon River in order to assess the feasibility of the navigation with greater drafts and, consequently, greater load capacity in this region. The methodology consists of a traffic simulation including tidal prediction and Squat effect to enhance cargo capacity and navigation safety. Preliminary results indicate there is a potential to increase the deadweight of the ships safely. The study proposes to create a model that assists in the decision making of the optimal tide window to navigate which will allow greater cargo transport with less possibility to ground with the bottom.

1. Introduction

The Amazon River has natural characteristics that allows the traffic of vessels with high load capacity in appropriate requirements. Its ports gained prominence in the economy, due to the increase in the Brazilian production of soybean and corn (Ministério da Agricultura, Pecuária e Abastecimento, 2017).

The increase in load capacity is related to the advantage obtained by economies of scale, which occurs when the average cost of production becomes cheaper as the quantity of products produced increases.

Meteorological conditions and waiting time for ships to enter the Amazon river channel are considered uncertain factors, which makes it a complex study environment.

Therefore, the main logistics problem in this region is to be able to reconcile the tide in ideal conditions with the moment the ship enters PC (Figure 1), without it being running aground.

1.1. Context

The Amazon River is the most extensive in the world and has an area of 6.900.000 km². In the region of Brazil, about 20.956 km are of economically navigable routes which corresponds to only 1% of the volume moved in the country (Tokarski, 2014).

The waterway indisputably exerts a catalytic power in the economic development of the regions interested. A study by Antaq (2018) shows that approximately 14.5 million tons were transported by inland waterways in Brazil in the first quarter of 2018, representing a 20.6% increase.

Brazil's exports have grown considerably in the last decade, and many of them make use of seaports to gain access to major importing countries such as China and Western European countries.

1.2. Literature revision

In the literature, regarding the scenery of the channel of the Amazon River, some revealing studies are found. These are arranged below.
Baltazar et al. (2016) presents a study that contributes to the safety of navigation in the Amazon river channel of which predicts water levels and navigable depths through the hydrodynamic modeling operation (Delft 3D) and discrete traffic event simulations. With the results obtained, it was possible to identify the tidal windows taking into account the probabilistic aspects corresponding to the bathymetry measurements. A study made with discrete event traffic simulation combined with the model hydrodynamic (2DH) shows improvement in channel approach performance on Amazon River and the port logistics. According to Moita et al. (2016) for such situations were addressed two aspects

- First, in some approach channels, fluvial currents combined with tidal currents may be too strong at certain stages of the tide to allow some ships to navigate safely;
- Second, depending on transit times and traffic, it may be possible to use tidal windows to bring in deeper drafts ships than would normally be acceptable.

The article cited above shows that the total time of trip is minimized if the ship starts at the end of rising tide and early low tide, in the case of the ship entering by the PC and go to the port of Santana, respectively.

To reproduce one-year scenarios, Arentz (2009) used the numerical experiments with the 2DH hydrodynamic model as the main reason for his research the river flow and astronomical tide. The tool was applied to determination of nautical chart reduction levels and hydrographic data surveys, contributing to improve navigability conditions and safety of the Amazon River estuary region.

The Amazon River estuary is a dynamic coastal environment with a navigation channel particularly sensitive. This is due to the presence of fluid mud which limits the draft of ships at risk of running aground. The referred topic was addressed primarily in oceanographic terms. However, it is worth mentioning the importance of the channel for the navigation of the region, therefore it is appropriate to take a more explained approach in the naval segment to answer the draft limit question.

1.3. Objective

The proposed study consists of a simulation of tidal traffic and SQUAT effect reproducing a model to allow draft increase of ships in the decision-making of the tide window acceptable for navigation of the Amazon River.

2. Scenario Description

2.1. Area delimitation

The study area was delimited according to Baltazar et al. (2016) where 10 stations were analyzed spread over approximately 350 km of the navigation channel of the Amazon River. The locations of these stations are in between the Port of Santana (P1) and PC, and the minimum distance in between two stations is 32.8 km (P9 - PC) and the maximum is 40.3 km (P8 - P9), approximately.

More attention should be given to station P8, due to its limited depth, being an area described as problematic for the navigation and therefore restricting the ships draft traveling through the canal. Figure 1 shows the extensive area of the Amazon and the long course of the Amazon River. Magnified is the station P8, where the fluid mud occurs over an extension of approximately 20 km.

2.2. Transport

The cargo transportation on the Amazon River is composed mainly of bulk carriers. These vessels have cargo holds for transport of grain, cereals, coal and iron ore, besides a robust structure for navigation for long periods of time.
Due to its structural form the amount of cargo transported directly impacts the value of its draft when loaded.

2.3. Tidal study

The northern channel of the Amazon River estuary has a typical feature because it has a critical area for navigation due to the high frequency of sand banks associated with a macro tidal regime. In the Amazon river the converging effect on the incident macro-tide induce an increase of its amplitude, with height above 3 m (Baltazar et al., 2016).

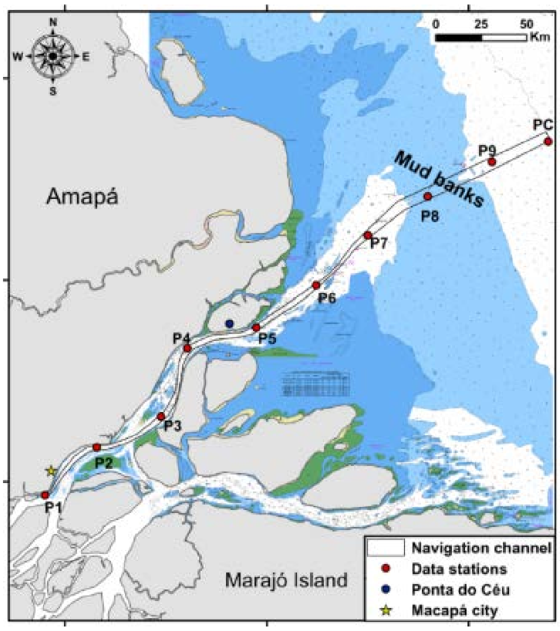

Figure 1 – Localization of data stations along navigation channel (red) and the Ponta do Céu tide station (blue) in Curuá Island (Moita et al., 2016)

2.4. Fluid mud

The fluid mud is formed by high suspended sediment concentrations. Near the bottom, the flow is viscous in a layer approximately 1 m above the bed (Vinzon and Mehta, 2001).

That layer is observed at the mouth of the Amazon River in shallow water areas.

2.5. Load capacity

The period from July to October has a low tidal level thereby reducing the average volume transported to 60% of capacity. During this period, is the harvest of the two most important export goods from the Northern region: corn and soybean (Ministério da Agricultura, Pecuária e Abastecimento, 2017).

According to International Hydrographic Organization (IHO, 2008) the security of maximum capacity cargo transport is directly related to depth of water under the keel, as well as the availability of the water blade for safe navigation. The uncertainties of depth where the under-keel clearance is a critical factor need to be controlled with a greater rigor.

2.6. Draft limit

The depths of the Amazon River channel vary from 30 to 60 meters. Even presenting high depths, the operational draft of the ships sailing in Barra Norte is at maximum 11.5 meters during the daytime and tidal floods so there is no risk of stranding or accident (MTPA, 2017).

The limit of the draft is due to the accumulation of fluid mud which forms a kind of bumper for the ships.

According to Arentz (2009), a way to avoid negative economic effects is improving navigation along the Amazon River through periodic information and updated river basin navigators through the nautical chart.

Barrass (2002) states in his study, when calculating the block draft of ships, the following values (Table 1):

Table 1 – Margin Formatting

$C_B < 0,7$ squat by the bow
$C_B > 0,7$ squat by the stern
$C_B = 0,7$ squat by even keel

2.7. Navigation Safety

Precisely estipulate the depths in the navigation channel of Amazon River together with its hydrographic characteristics shows itself as a solution in ensuring navigation and entry in port more safely. Arentz (2009) defines the need for the most exact depths in order to prevent accident in navigation, or an interruption on traffic of ship with larger draft.

The Diretoria de Hidrografia e Navegação (DHN) adopts the terminology Reduction Level (RL) for the tide dates representing the level of reference both to the depths of the nautical chart as for tide predictions presented by the tables of the tides. For there to be navigation safety it is important to choose the Reduction Level at lower tides, because it is practically guaranteed to the navigator that there will be at least the amount of water indicated in the nautical chart.

Therefore, the relevance of an improved study on navigation safety in the Amazon River is extremely important for reducing the risks of accidents, economic development of the region and environmental conservation.

3. Methodology

Discrete event simulation is a model in which variables discretely change at specific points over time and presents a scenario where systems are necessarily planned (Buffa and Dyer, 1977).

For the creation of the study model, Quest software, created by Dassault Systems, was used, which allows the user to model discrete event simulations both from a graphical interface (GUI) and from its own programming languages.

The model was created with parametric codes and a database, so that in each different case it could be simulated quickly and easily. Because the software has two types of programming languages of its own, BCL and SCL, the agility of the simulation becomes possible.

- BCL (Batch Control Language): a programming language that allows the software user to model the simulation to his desire, including the creation, connection and positioning of elements, and assigning functions to them, among other capabilities;
- SCL (Simulation Control Language): a programming language that allows the user to determine how the simulation should work, that is, how the elements of the simulation should behave and interact with each other.

The model developed for this study simulates the passage of the ship entering and leaving the North canal of the Amazon River. The main expected finding is relating to the tidal window maximizing the ship draft.

3.1. Model description

For the model construction it is important to obtain the database, containing all the necessary information for each case. An already existing database was used (Baltazar et al., 2016), which is related to current and tide in the Amazon River, analyzed during one month. In the study model, the ship passes every 10 minutes and at four different navigation speeds, in order to find the most appropriate tidal window in each scenario.

The model presents a series of elements that creates the simulation and provides the final results. Each element plays a different role in the software and must be properly programmed for the proper functioning of the simulation. Figure 2 shows in a simplified way how the simulation structure of the presented model works.

3.2. SQUAT effect

Ships are designed to travel as efficient as possible from port to port, carrying the maximum amount of load and reducing fuel consumption. However, when entering shallow waters, they start operating in an environment for which they have not been designed and that may cause problems in the handling of ships, increasing the values of the SQUAT effect, reducing under keel clearance (UKC) and also the navigation safety level (Pianc, 2014).

The ship-related components such as the operational draft, sinkage, and trim suffer variations due to water density, vessel speed and calculation uncertainties in regions where the tide is low, which generates a probabilistic factor in the UKC reduction.

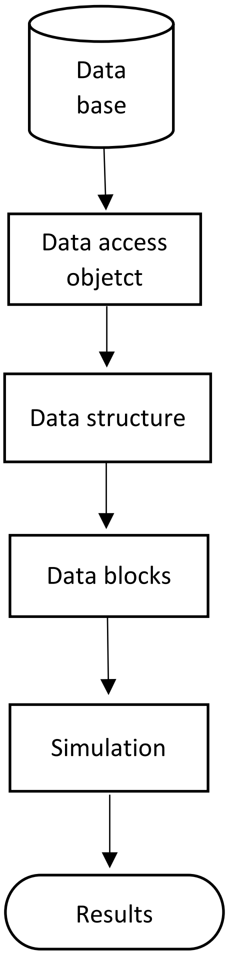

Figure 2 – Simulation model structure

The speed the ship performs has an important role in the process of its operational functioning, once it interacts with the tide limits. Pianc (2014) identifies that the speed over the river floor is important for the tidal window while speed through water is important for maneuverability, squat effect and other factors related to hydrodynamics.

The SQUAT is a downward shift that consists of a translation and rotation due to the moving water flow around the hull. This movement of water induces a relative velocity between the ship and the surrounding water, which causes a water level depression as the ship sinks (Pianc, 2014).

In the length of the Amazon River channel where there is fluid mud, SQUAT effect increases significantly. The velocity field produces a hydrodynamic pressure change along of the ship that is similar to the Bernoulli effect because the kinetic energy and potential must be in balance (Beck, Newman, Tuck, 1975). This phenomenon produces a downward vertical force called sinkage, and a moment about the longitudinal axis, Trim, which may result in values different at the bow and stern, as shown in Figure 3.

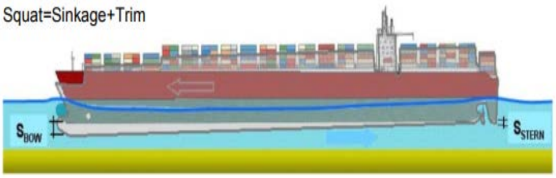

Figure 3 – SQUAT demonstration at the bow of the ship where (Sb) is the maximum squat at the bow, and (Ss) maximum SQUAT at the stern (Pianc, 2014, p. 26)

In this work, the ship water line was considered as being axis origin (zero), that is, the water-mud interface is considered as part of bottom of the ship. This way, the ship's keel will only touch the mud surface, without entering it.

3.3. SQUAT effect assessed with TUCK

To validate the formula, two small-scale experiments were used, one developed by Briggs (Briggs et al., 2010) and the other by K. Elsherbiny et al (Elsherbiny et al., 2019). The data obtained from the experiments were compared with the empirical formula predictions presented in Pianc (Pianc, 2014). Tuck's formula was selected, as it was the most precise one in both cases (Figure 4). In addition, Tuck's formula has no applicability restrictions on ship dimensions, giving the model a greater freedom of use.

Tuck's SQUAT prediction formula was the first one to be developed, in 1966. It considers infinite width shallow waters conditions, commonly described as unrestricted, and its first version had coefficients based on integral, that were not simple to use. A few decades later, on 2002, a simplified version of the formula was reported by Stocks et al. (Stocks et al., 2002). In the Table 2 describes the symbols referring to the equation according to Pianc (Pianc, 2014).

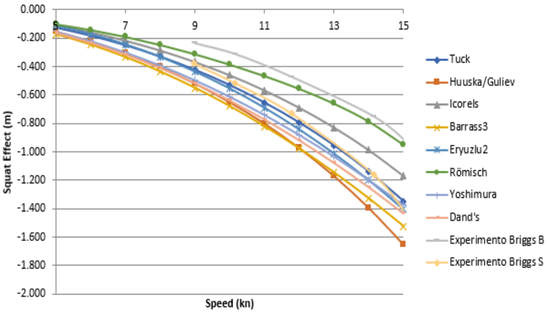

Figure 4 – Graphical presentation of empirical formulas

$$S_{b_T} = 1.46 \frac{\nabla}{{L_{pp}}^2} \frac{{F_{nh}}^2}{\sqrt{1-{F_{nh}}^2}} K_S + 0.5 L_{pp} \sin\left\{ \frac{\nabla}{{L_{pp}}^3} \frac{{F_{nh}}^2}{\sqrt{1-{F_{nh}}^2}} K_S \right\}$$

where:

$$K_S = \begin{cases} 7.45 s_1 + 0.76 & s_1 > 0.03 \\ 1.0 & s_1 \leq 0.03 \end{cases}$$

$$s_1 = \begin{cases} 0.03 & Unrestricted \\ \dfrac{S}{K_1} & Restricted \\ S & Canal \end{cases}$$

$$F_{nh} = \frac{Vs}{\sqrt{gh}}$$

Table 2 – Description of symbols

SYMBOLS		
∇	(m³)	ship's volume displacement
L_{pp}	(m)	ship's length between perpendiculars
K_S	(-)	Huuska/Guliev correction factor for channel width when calculating vessel
F_{nh}	(-)	depth Froude Number
Vs	(m/s)	ship speed (relative to the water)
g	(m/s²)	gravitational acceleration
h	(m)	water depth
s_1	(-)	Huuska/Guliev dimensionless corrected blockage factor for bow squat

4. Results

It was used as a test study the bulk carrier M/V JAG AMAR, that navigates the Barra Norte canal of the Amazon River. Vessel data shown in Table 3 were obtained from MarineTraffic website (MarineTraffic, 2019).

Table 3 – Ship Data M/V JAG AMAR

NAVIO FORTE M/V JAG AMAR		
Vessel data		
IMO:	9723851	
MMSI:	419001016	
Call Sign:	AWLE	
Flag:	India	
Year Built:	2017	
LOA:	229	m
L_{pp}:	225,3	m
T:	14,45	m
B:	32,26	m
DWT:	82084	t
Gross Tonnage:	44127	

The Amazon River Barra Norte canal region has a draft limitation of 11.5 m without the presence of the practical, according to the Santarém River Captaincy Standards and Procedures (Marinha do Brasil, 2015). However, more recent studies in this region show that the dynamic draft can increase to 11.7 m with the presence of the pilot, without presenting any risk to navigation. Thus, for this study's simulation, this 20 cm draft gain was considered.

Four navigation speeds, which are suitable for the studied region, were used over one month. A comparison was made between two scenarios, Entering the Channel and Leaving the Channel, of Barra Norte at the critical point, where there is fluid mud.

- First scenario: The green area on the graph shows the percentage of times the ship sails without grounding, and the red area shows the percentage of times the ship runs aground, as there is contact with the fluid mud (Figure 5).

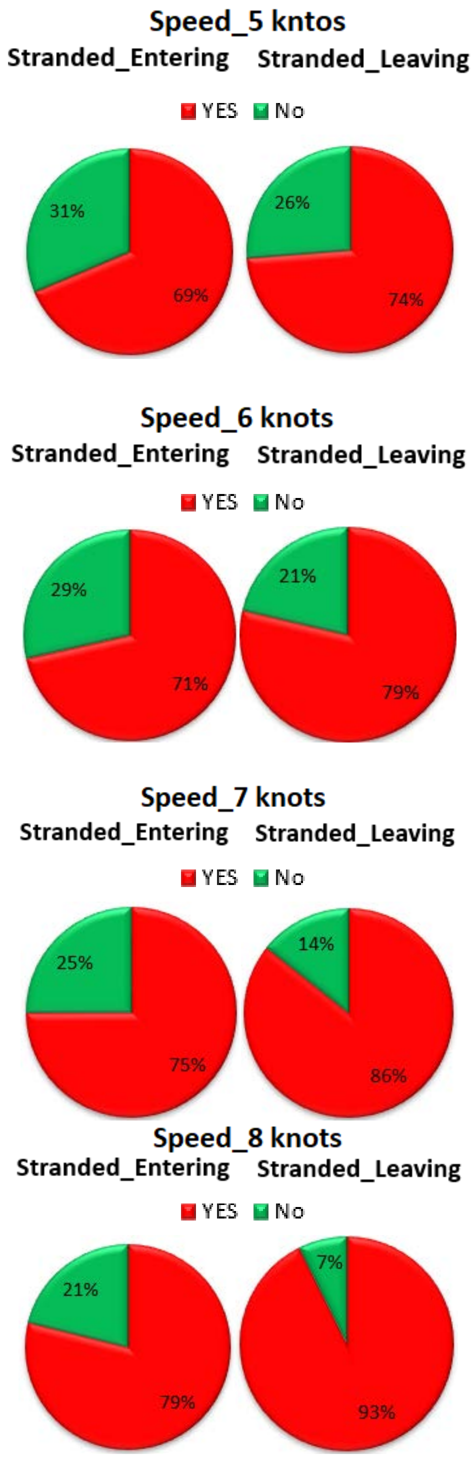

Figure 5 – First scenario graphic (contact with the fluid mud)

- Second scenario: The green area on the graph shows the percentage of times the ship navigates into the mud, up to 0.5 m without running aground, and the red area shows the percentage of times the ship runs aground, as it goes over 0.5 m in the fluid mud (Figure 6).

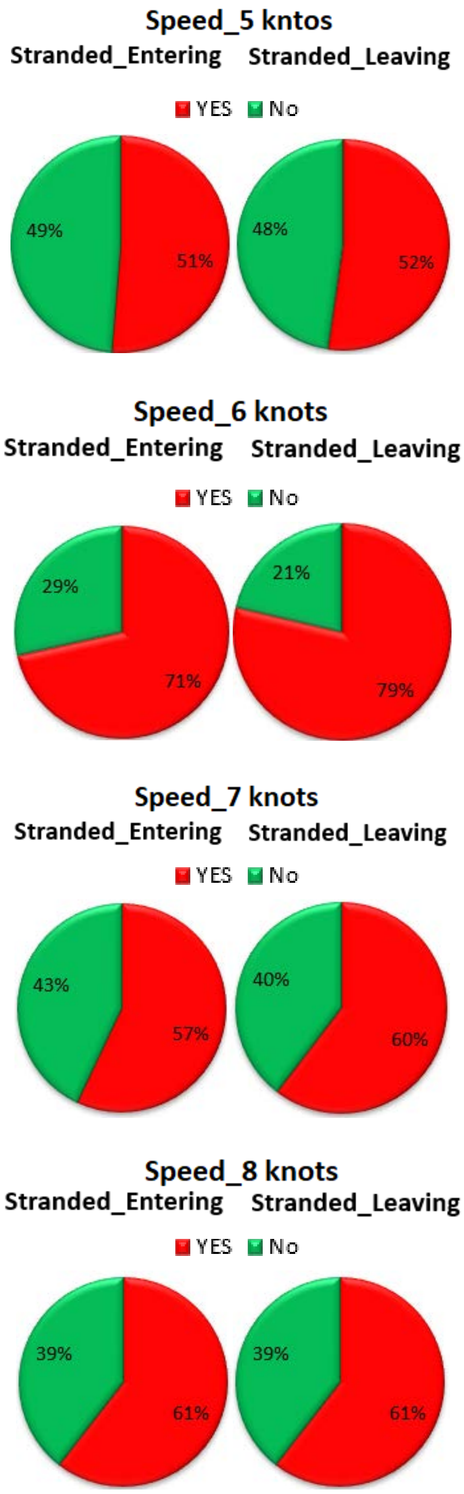

Figure 6 – Second scenario graphic (goes over 0.5 m in the fluid mud)

The critical region, where the fluid mud is located, is about 25 km long. Considering this, in Table 4 presents the sailing time minimum the ship needs to cruise through this region was calculated in relation to the four speeds.

Table 4 – Crossing time minimum

CROSSING_TIME	
Speed_5	02:41:00
Speed_6	02:14:00
Speed_7	01:55:00
Speed_8	01:41:00

From the variables of water height, draft of 11.7 m and the TUCK empirical formula, it was possible to find the possible times windows for each passage of the ship at each speed. The first scenario consider that the ship will ground if the bottom plate of the ship touches the surface of the fluid mud meanwhile the second scenario consider that the ship can enter of 0.5 meter inside the fluid mud before grounding.

Based on time window distributions related to each scenario and speed it was possible to find the average time of the passage of the ship through fluid mud distance (Figure 7).

The Amazon tide is semi-diurnal, that is there are two high tides on each lunar day. Thus, in Figure 8 a comparison was made between the amount of high tides over a month and the total time windows that the ship sailed without running aground in the mud in that same period, and the navigable time window considering the crossing time minimum.

5. Conclusions

This proposed study model suggests an improvement in decision making regarding acceptable time windows for navigation in the Northern Arrival Channel of the Amazon River. It has been shown that the Tuck's empirical formula presented satisfactory results for the Squat effect in fluid mud navigation.

Simulations for the Amazon River has shown that there is a significant influence of ship speed in the two scenarios studied. The probabilistic aspects related to significant gain when the ship navigates through as it goes over 0.5 m in the fluid mud represents an increase in the passage of ships through the region.

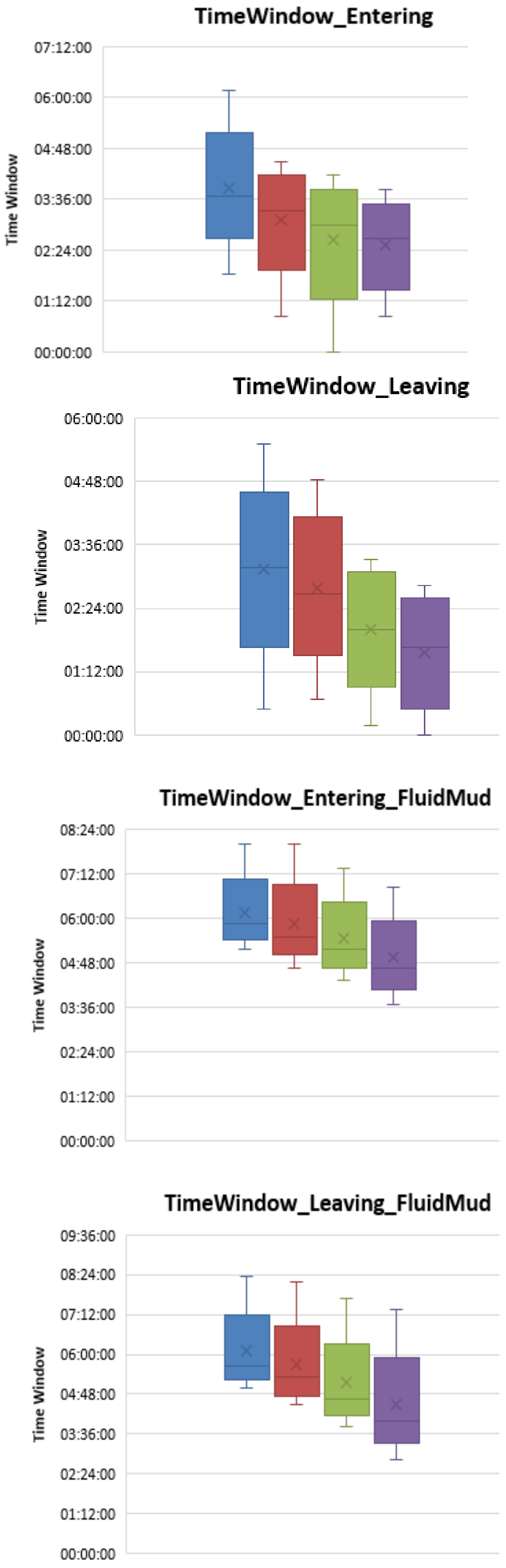

Figure 7 – Mean time window distribution (Subtitle - Blue: Speed_5; Red: Speed_6; Green: Speed_7; Purple: Speed_8)

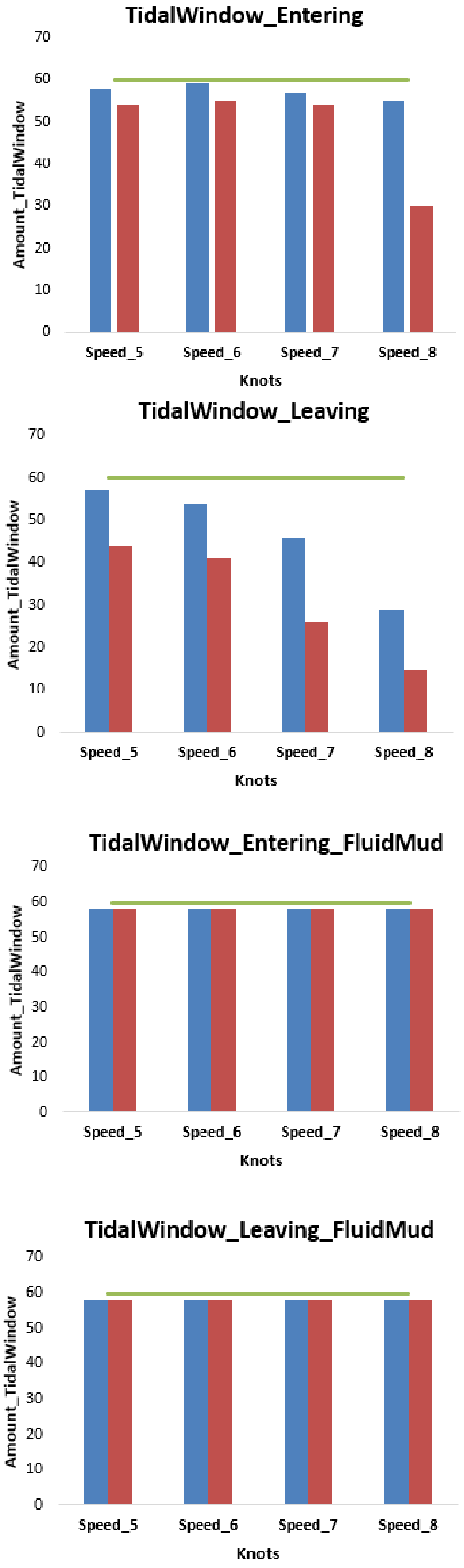

Figure 8 – Total Tidal Window (Subtitle - Blue: TidalWindow; Red: Navigable; Green: Total)

This analysis will lead to better safety and better efficiency for the increase of the ship draft in the navigation of the north channel of the Amazon River. In fact, the methodology allows to calculate the minimum crossing time for each speed and to find the time window related to each scenario for 1 month.

Through the tidal windows it was possible to find the time windows may be used to allow deep draft vessels navigate the region of fluid mud without running aground. Although there is a need to include other effects and parameters in the simulation in order to improve the channel navigation such as wave effects, ocean current effects, ship trim effects, fluid mud navigation effect on Squat, etc.

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