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INTEGRATED METHOD FOR OPTIMAL CHANNEL DREDGING DESIGN

ABSTRACT

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An integrated analytical method was developed and applied to identify the optimal channel layout and dredging depth that allowed for safe navigation; enabled the operation of the required amount of ships per year; and at the same time reduced dredging costs. This method developed by CB&I included an integrated approach combining channel design, hydrodynamic and sedimentation modelling, ship manoeuvring simulations and static and dynamic port operation simulations. The results allowed reducing channel dredging depths up to 3m, causing decreases of capital dredging volumes of about 10 million m³. Based on the outcomes of the dynamic simulation tool, it can be concluded that the proposed integrated approach for channel design provides relevant information for the definition of the business model of the port. This is because it provides easy access to the impacts of changing vessel class or draft in both the cargo trade capacity and CAPEX/ OPEX. This in turn helps to identify the optimal configuration for commercial interests and internal rate of return (IRR) of the terminal.

INTRODUCTION

The logistical constraints in central-southern Brazil and increasing agriculture production in the central-northern areas of the country has given an impetus for the development of new greenfield port terminals in northern Brazil, specifically in the states of Maranhão and Pará. This is due to their strategic locations that allow for cost-effective solutions to export grains and import fertilisers. These greenfield port developments often face design challenges for several reasons – a lack of historical oceanographic and hydrographic data and the macro-tidal regime and associated strong currents observed in this area of the Brazilian coast. The coastal stretch from Maranhão State towards the northern limit of Brazil is characterised by large estuarine bays associated with riverine deltas and a broad and shallow continental shelf.

This configuration of the coastal environment favours the amplification of tidal astronomic constituents inside the bays (tidal ranges up to 7m), generating strong tidal currents (up to 3 m/s) that pose serious hazards to navigation and force migration of seabed sand banks that cause channel shoaling.

MEARIM PORT

Located about 45km inland inside the São Marcos Bay, the Mearim Port is a greenfield port concept that is being studied and designed over the past 8 years (Figure 1). Initial studies of the port considered a 48km long navigation channel for 15m draft vessels, requiring channel depths of 17m. Initially, the channel layout was developed following the deepest areas of the bay with the aim to reduce dredging costs. However, in order to follow the deepest portions of the bay, the channel layout had to cross a short shallower section (about 8m depth), which held much of the capital dredging volume of approximately 17 million m³. This channel crossing was not aligned with ebb and flood currents and experienced strong cross-currents and migrating sand banks. Both characteristics presented severe challenges to the project. The migrating sand banks caused large sedimentation rates of approximately 6 million m³ per year, which required continuous maintenance dredging efforts. The strong
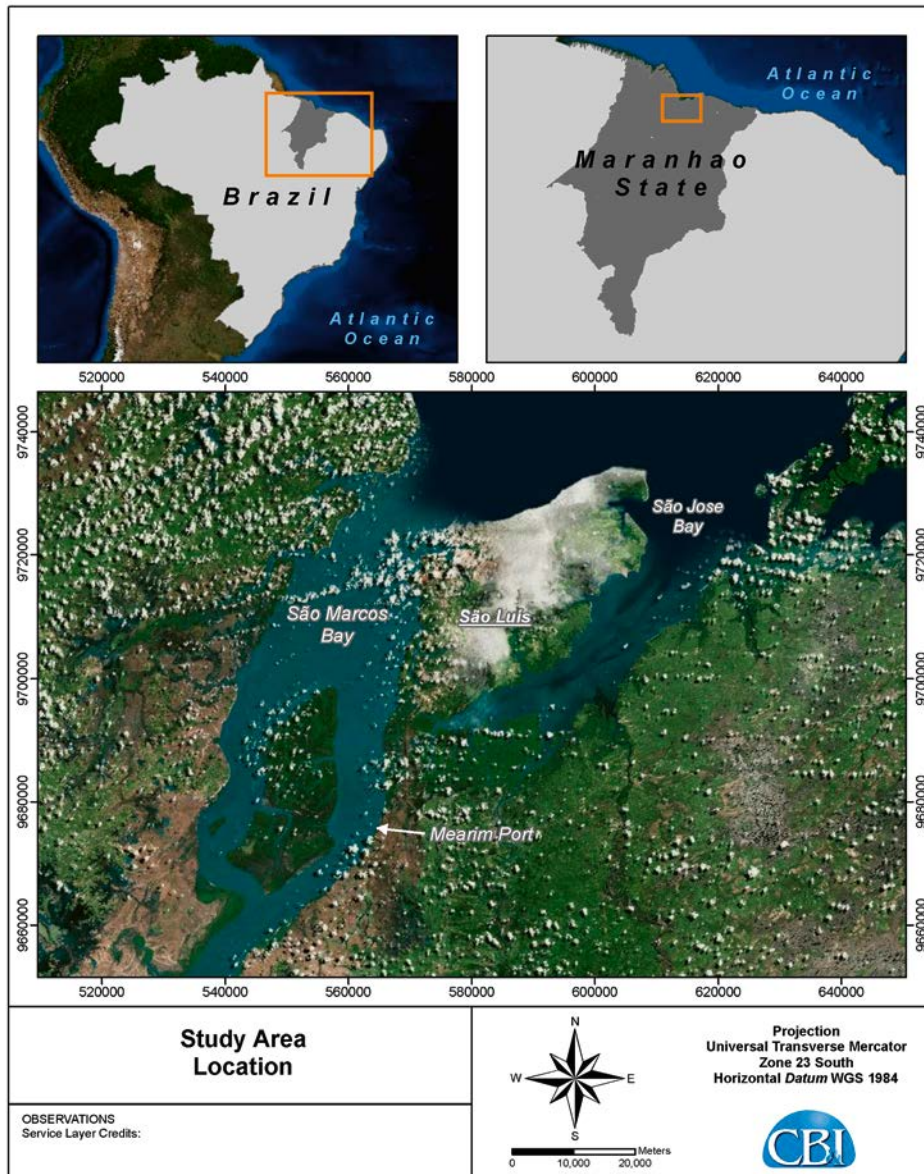

Above: Mearim Port concept is an integrated approach combining channel design, hydrodynamic and sedimentation modelling, ship manoeuvring simulations and static and dynamic port operation simulations.

Figure 1: Study area location map.

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cross-currents caused very difficult navigation conditions. As such, the initial channel layout posed significant economic and technical challenges for the project and had to be revisited. To overcome the challenges, the navigation channel layout and the entire port concept development were re-planned. In this review an integrated analytical method was applied to identify the optimal channel layout that enabled three aspects: safe navigation, the operation of the required amount of ships per year and the reduction of dredging costs. This method developed by CB&I included an integrated approach combining channel design, hydrodynamic and sedimentation modelling, ship manoeuvring simulations and static and dynamic port operation simulations (Figure 2).

METHODOLOGY AND RESULTS
Navigation channel design and dredging CAPEX assessment
Traditionally, the starting point for navigation channel design is the "Design Ship" that is defined based on the cargo matrix, available/future fleets and business strategy. Since the use of this approach, as previously described, led to a port that was too expensive and restrictive, a different approach had to be developed. Instead of starting the analysis

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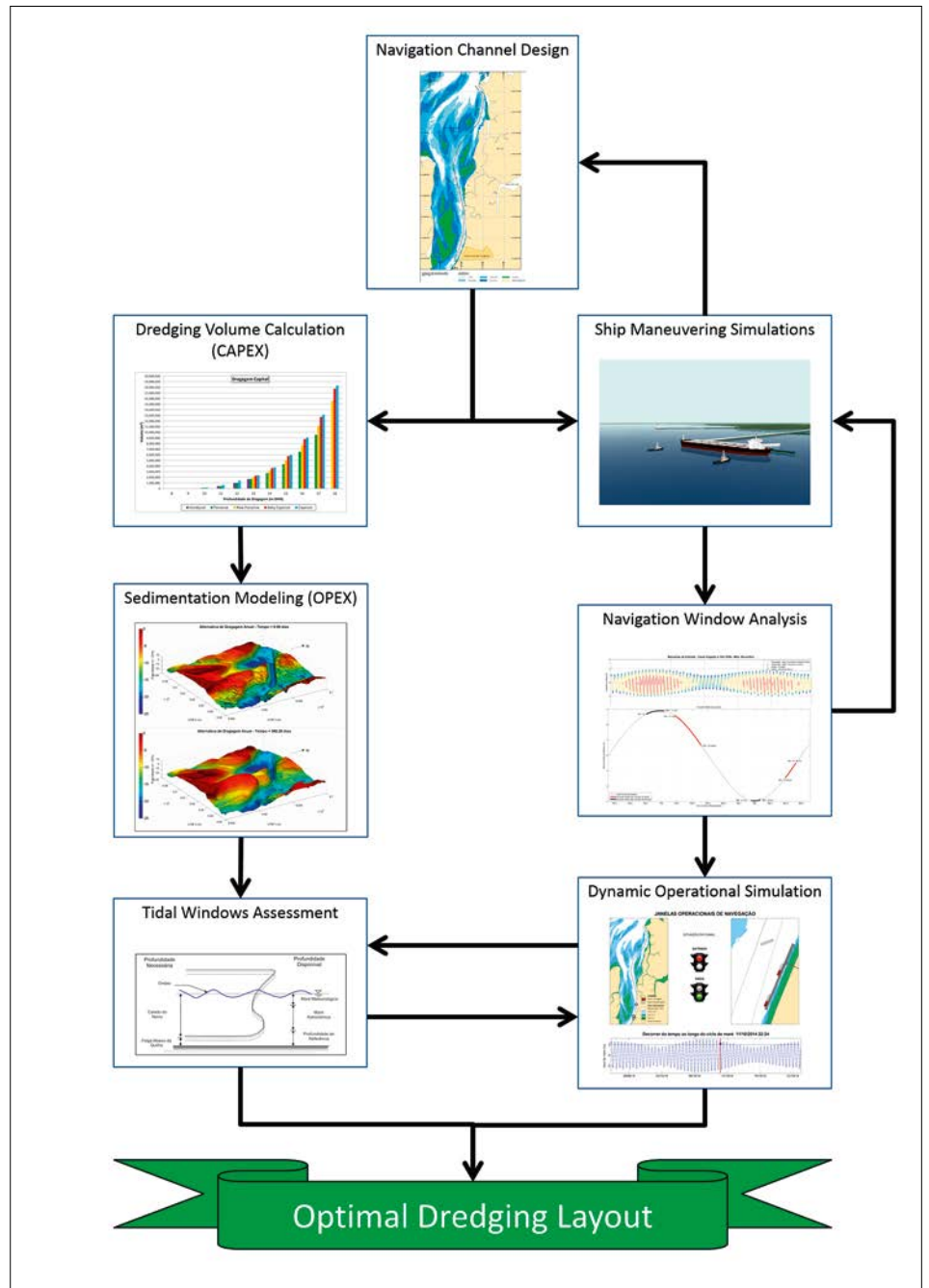
Figure 2: Schematic flow-chart of the method developed to identify the optimal dredging layout.

from a single "Design Vessel", the navigation channel was studied for all bulk carrier ship classes from Handysize to Capesize, with drafts ranging from 10m to 18m (respecting the upper and lower limits for each class). Although some of these vessels or drafts may not be commercially adequate, they were studied with the purpose of determining which vessel types or drafts would be more cost-effective and meet the cargo matrix

requirements.

The channel alignment was modified from the previously studied route, in order to avoid the channel segment that had larger dredging requirements and cross-currents (Figure 3). The channel alignment and curve radius were determined based on the largest vessel (Capesize) and they were kept constant for all vessels. As such, the main changes between the channels would be widths, which is

associated to the ship class dimensions and depths, which is related to the maximum allowable draft for safe navigation (Table 1). The definition of channel dimensions (width at straight and curved sections, curve radius and depths) for each vessel class and draft followed PIANC's "Harbour Approach Channels Design Guidelines" (PIANC, 2014). A total of 33 channel designs were developed and initial dredging volumes were calculated
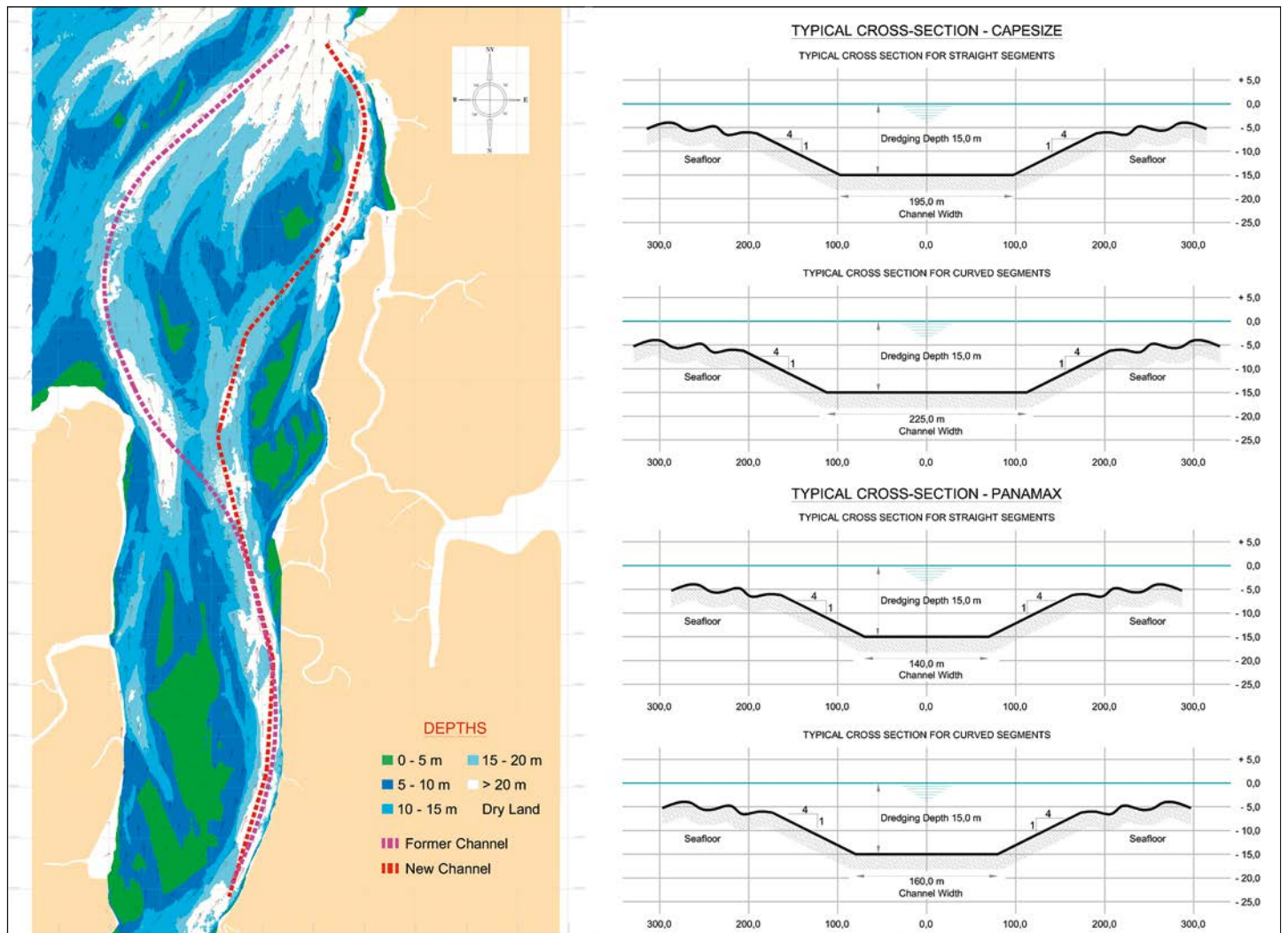
Figure 3: Left: Navigation channel layouts overlaid on bathymetric map and typical ebb current pattern. In magenta, the previous channel layout – that faced strong cross-currents and high sedimentation rates – and in red the new layout, studied for various ship dimensions. Right: Typical channel cross-sections of the new layout are presented for Capesize and Panamax vessels for straight and curved sections of the channel, respectively (from top to bottom).

using AutoCAD® Civli3D, obtaining volumes ranging from 100,000 m³ to 18,000,000 m³ as shown in Figure 4.

Hydrodynamic modelling, ship manoeuvring simulations and navigation windows assessment

In order to evaluate the current and water level patterns along the navigation channel, a numerical hydrodynamic model was developed using Delft3D. The model was calibrated using current measurements at eight stations along São Marcos Bay and water level records from two stations along the bay. The calibration process allowed identifying that the model accurately represents the tidal amplification along the estuary (with maximum tidal range in the vicinity of the terminal reaching 7m) and current velocities up to 6 knots.

The channel layout was validated for navigation purposes using the ship maneuvering simulator PC-Rembrandt, developed by BMT-Argoss (Figure 5). The channel transit was assessed using simulations of Panamax and Capesize vessels over space-varying calibrated Delft3D hydrodynamic fields. Minor adjustments in the channel layout were made based on the simulations, in order to promote the best alignment of the channel with the currents (Figure 6). The simulations were then conducted by a senior captain with ebb and flood currents for various speed classes, in order to identify the

Channel Depth	12 m	13 m	14 m	15 m	16 m	17 m	18 m
Ship Draft	10.0	11.0	11.9	12.8	13.7	14.6	15.5

Table 1: Maximum ship draft for each channel depth, without any tidal benefit; or required depth for safe navigation of each ship draft.

Figure 4: Analysis of channel alignment to the currents along a simulation.

Figure 5: Example of the 3D-view of an unberthing manoeuvre with a Capesize bulk carrier, simulated with PC-Rembrandt.
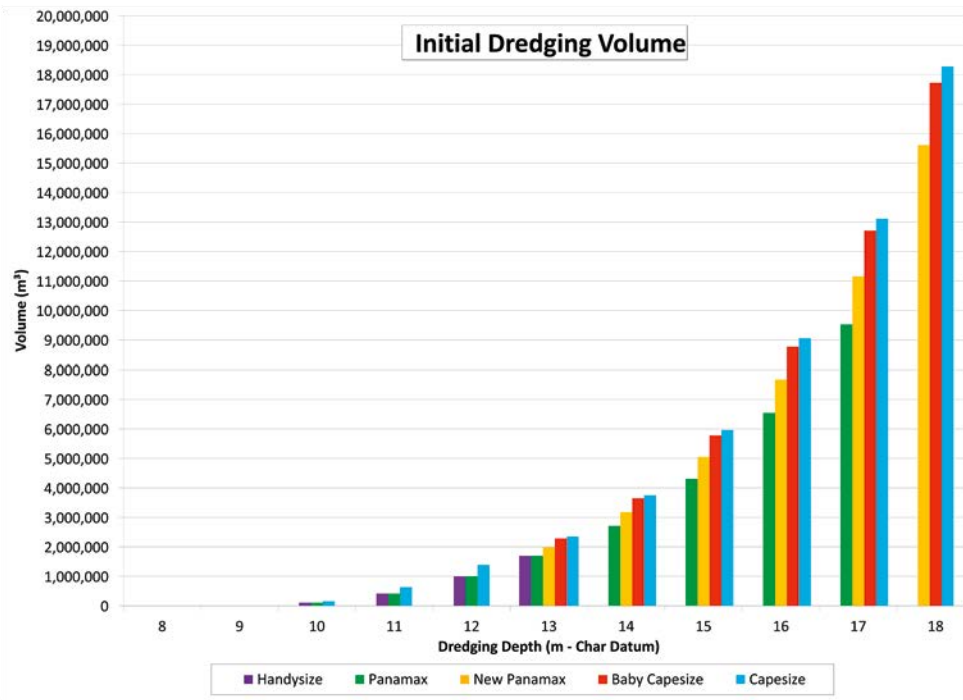

Figure 6: Analysis of channel alignment to the currents along a simulation

channel operational limits. This analysis allowed establishing safe navigation with currents below 4 knots and berth manoeuvres below 2 knots.

After defining the operational limits for safe navigation, a customized Matlab® code was developed in order to identify the safe navigation windows along a typical year. The code used as an input the results of a one year hydrodynamic model simulation,

generating current and water level information along the channel at one minute time-steps. Using that information, the code simulated ship transits starting at every minute of the year. The displacement of the ship assumed a constant telegraph command (10 knots) and took into account the current velocities and relative directions to calculate the speed over ground at every one-minute time-step (Figure 7). Thus, it accounted for the effect of currents on the transit time, i.e.

sailing against the currents would take longer than sailing with stern currents. At every time-step, the current speed, water level and water depth at the ship position were recorded and further analysed, in order to verify if the ship would face currents above the pre-defined operational limits or not.

For the berthing or unberthing manoeuvres, the code would identify if the current velocities were below 2 knots for a period of
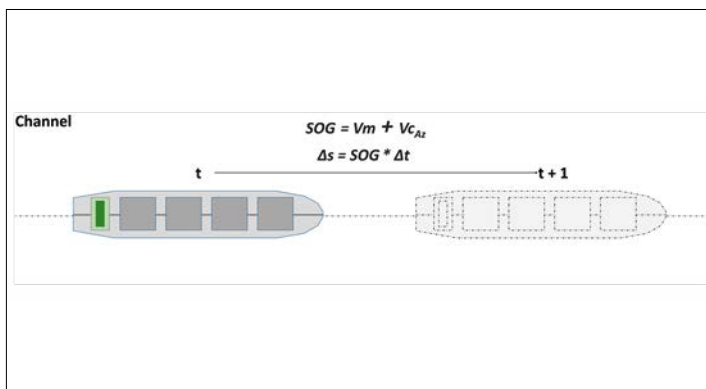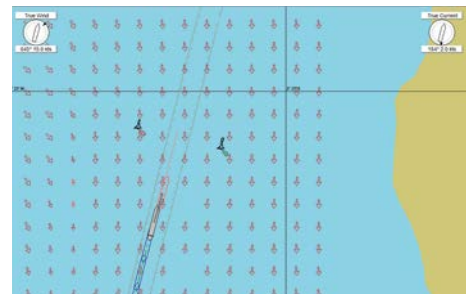

Figure 7: Example of the method used to represent the ship displacement along the channel. SOG is the speed over ground, Vm is the telegraph speed, VCAZ is the current velocity along the ship di splacement direction, Δs is the ship displacement and Δt is the time-step (one minute).
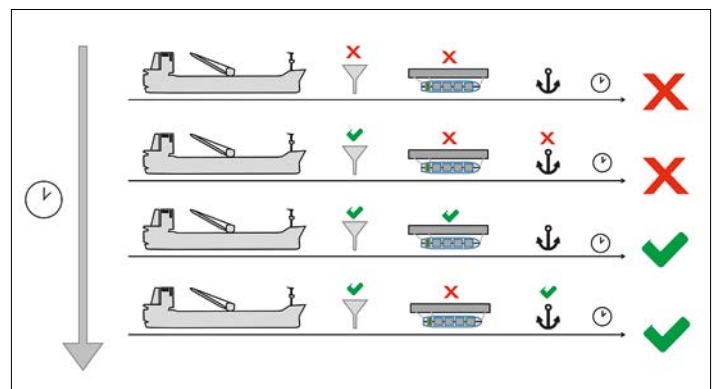

Figure 8: Example of results that could be obtained with the navigation windows code. Top to bottom: Channel and berthing limits are surpassed – manoeuvre is not feasible; channel limits are met but neither berth or anchorage conditions are met – manoeuvre is not valid; channel and berth limits are respected – ship is berthed; channel and anchorage limits are met but berthing limits are not – ship goes to anchorage area.
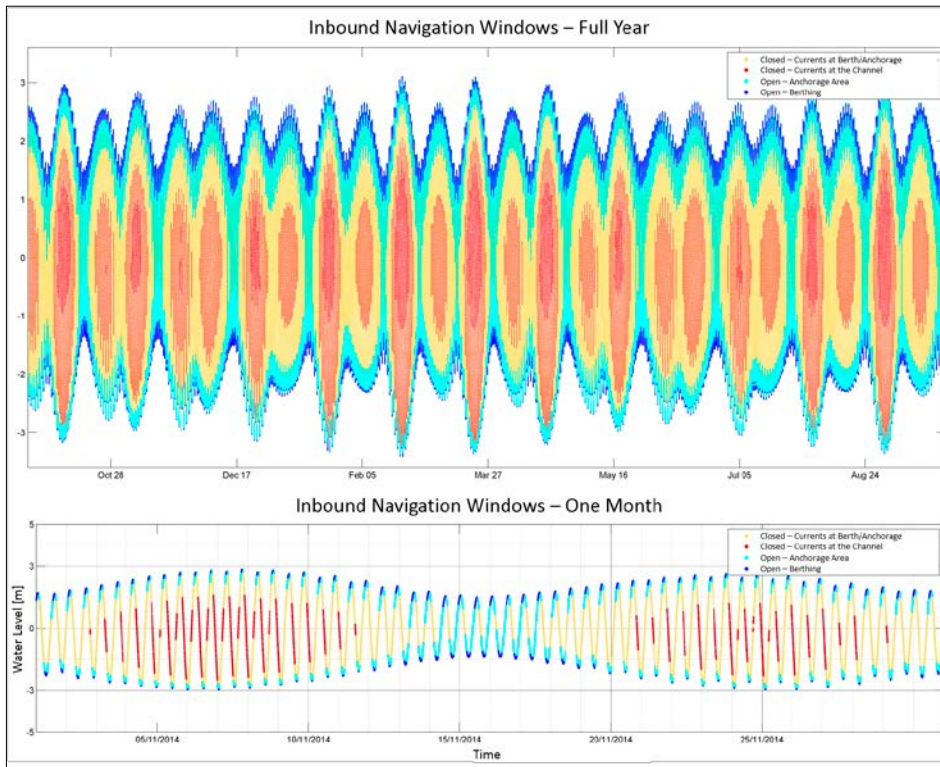
Figure 9: Example of inbound navigation windows plotted over the tidal curve along one year (top panel) and in detail along a month (lower panel). Dark blue dots mark the moments when the channel transit can be started and safely completed to the berth. Light blue dots indicate navigation windows that only allow anchoring the ship in the anchorage area. Yellow dots denote the closed windows due to short time for either berthing or anchoring the ship (although channel transit can be done safely). Red dots indicate moments when the ship would face currents above the operational limit along the channel.
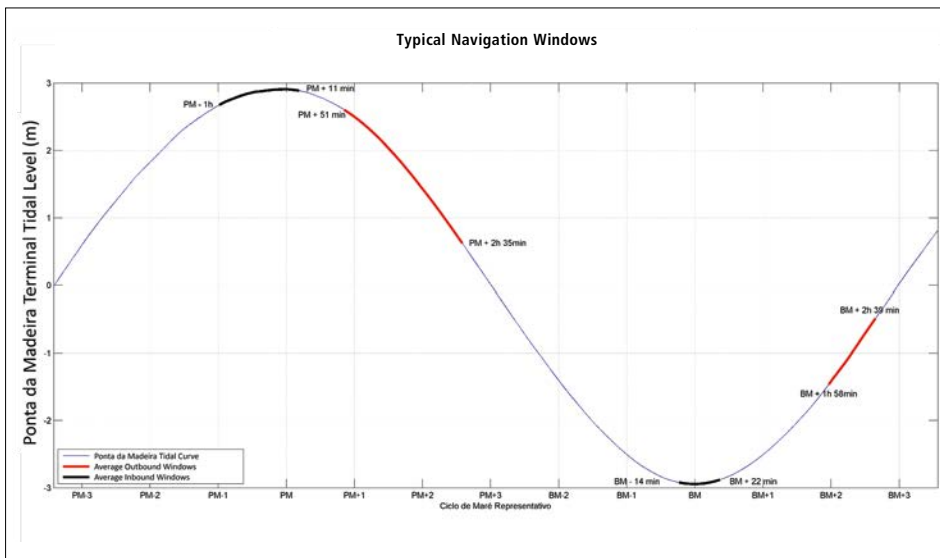

Figure 10: Schematic representation of the navigation windows along a typical tidal cycle. Inbound manoeuvres (black lines) could be started close to the high tide and low tide (referenced to the beginning of the channel) and outbound transits would be performed one hour after high tide or two hours after low tide.

at least 40 minutes in the berthing area. An optional anchorage area in the vicinity of the terminal was also assessed, needing 40 minutes with currents below 3 knots for attaching the ship to a mooring buoy. Therefore, it was possible to define the moments along a typical year when the ship would be able to conduct any kind of manoeuvre (Figure 8). This allowed identifying the safe navigation windows and verifying how they were distributed along the time (Figure 9). The inbound (to the berth) and outbound manoeuvres represent 13% and 21% of the time, respectively. Although the values are apparently low, safe navigating windows occurred every day at high and low tides, with durations of at least 40 min. A typical representation of the navigation windows along the tidal curve is presented on Figure 10.

The identification of the navigating windows and the accuracy of the algorithm were further validated in the ship simulator. A set of 32 scenarios were assessed, with simulations being conducted with space-and-time-varying current conditions for several moments within the predicted navigating windows. It could be observed that despite the assumptions and simplifications adopted in the code, the navigation could be safely performed in all of the scenarios, even in moments that would be slightly off of the predicted windows. As the code used defined threshold of current velocities, minor variations over the threshold (e.g. 0.1 knot) would be cut-off. However, during the simulations it did not have significant impact to the navigation safety. After validating the navigation windows, the assessment of the adequacy of those windows for the operation of the required amount of vessels per year was evaluated in depth in the dynamic operational simulations, described ahead.

Morphodynamic modelling: Channel shoaling and sedimentation rates for OPEX forecast

The calibrated Delft3D hydrodynamic model was used as a base for a morphodynamic simulation. This was done in order to represent the migration of the sandbars within São Marcos Bay and forecast the shoaling and sedimentation rates of each designed channel as a support to the

estimation of dredging OPEX and evaluation of over-dredge requirements. The morphodynamic model was configured with sediment characteristics obtained from over 40 samples collected along the Bay. It was calibrated comparing the simulated volume changes along the navigation channel and the changes measured between two consecutive bathymetries in 2007 and 2009. The simulation used a schematised tide and morphological acceleration techniques as described by Lesser (2009).

After calibrating the morphodynamic model, all of the 33 channel designs were simulated over a five-year period to evaluate channel shoaling and sedimentation rates. The minimum channel depths and associated sedimentation volume over this period were determined for each alternative. Examples of results for 13m and 17m depth channels are presented in Figures 11 and 12. It can be observed that for shallower channels, the channel shoaling rates are more prominent during the first year and tend to stabilise along the time. The same behaviour is observed for the sedimentation volumes for that channel. The deeper channels, however, have very high shoaling rates during the first year (about 1.5-2 m/year), but maintain a relevant shoaling rate of 0.5 m/year on the following years. The sedimentation rates for those channels, however, tend to follow an almost linear behaviour over time, denoting that although some points of the channel may get shallower, sedimentation tends to spread over the entire channel. These results enabled determining the required maintenance dredging interval and volumes, as well as the over-dredge requirements for each ship draft scenario. Furthermore, this information was very relevant to determine the dredging OPEX costs for the economic feasibility analysis of each channel.

Static and Dynamic Operational Simulations

In order to determine the required number of berths, loading/unloading time per vessel and required amount of vessels per year, static operational simulations were conducted. For that purpose, the specifications of mechanical equipment on the berth and the cargo matrix were evaluated on a spreadsheet model. It utilised typical efficiency losses, operational downtime rates and average loading
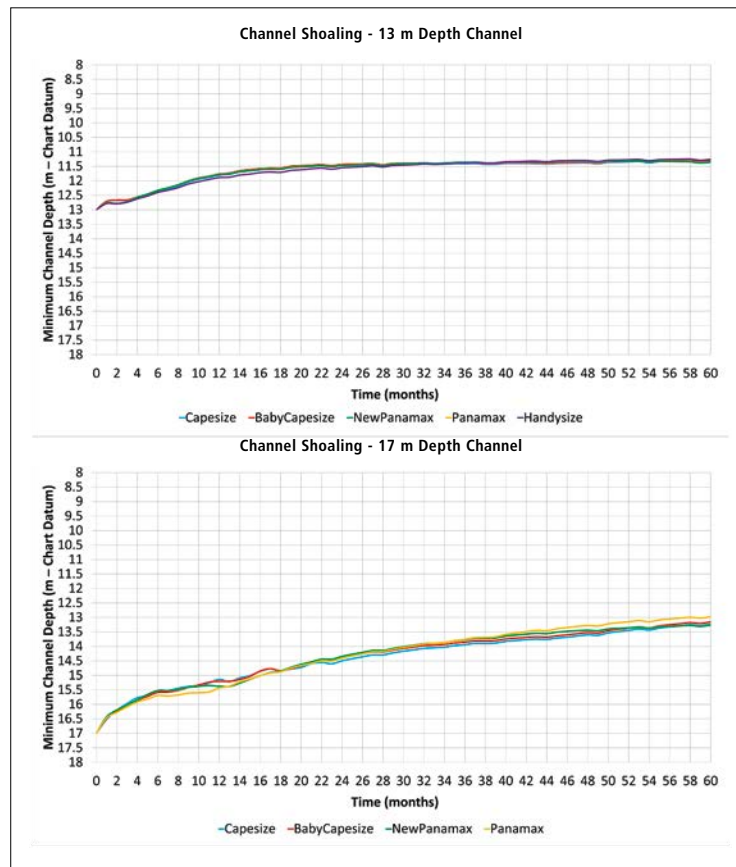
Figure 11: Example of channel shoaling rates (variation of minimum channel depth over time) for 13m and 17m depth channel, for various ship classes.
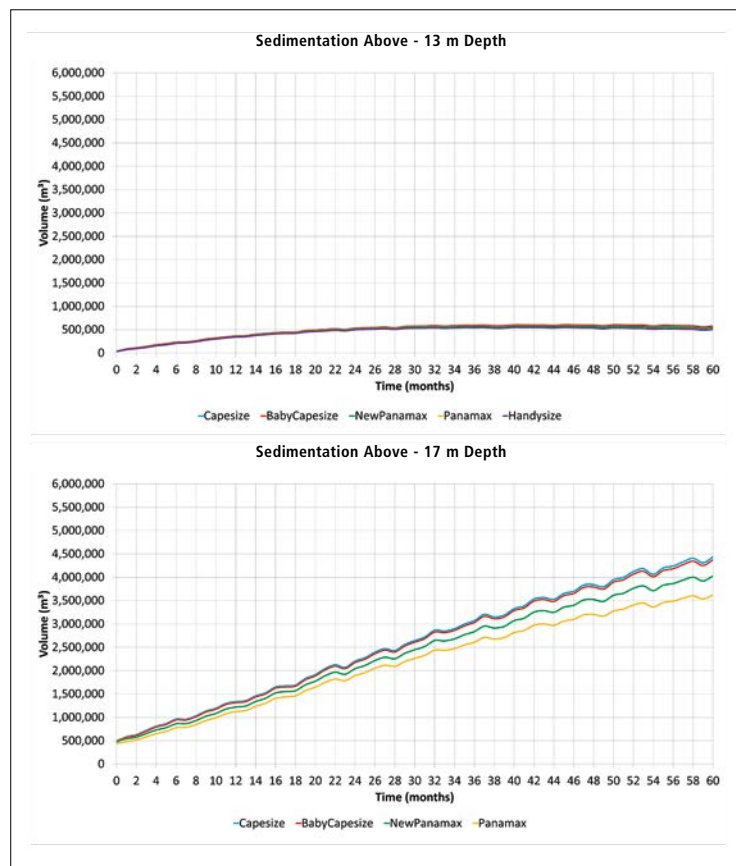
Figure 12: Example of channel sedimentation rates (volumes above original channel dredging depth over time) for 13m and 17m depth channel, for various ship classes.

conditions for grains, fertilisers and general cargo in similar Brazilian ports. This analysis allowed defining that to match the cargo matrix of 10 million tons per year (MTPY) of grains, 3 MTPY of fertilisers and 3 MTPY of general cargo, and 4 berths would be necessary. This is with respect to the design berth utilisation rate of 60%. The average loading times were calculated as 25 hours for grains, 19 hours for fertilisers and 49 hours for general cargo. A total of 357 ships would need to be operated along a year on the terminal to meet the cargo matrix requirements.

A customized dynamic operational simulator developed by CB&I was utilised to integrate the channel design and associated capital expenditure (CAPEX) costs, navigation windows, channel sedimentation rates (OPEX) the loading/unloading operational times. The simulator was also used to determine which vessel types/drafts would meet the commercial requirements of the cargo matrix and be more cost-effective. The dynamic simulation tool, developed in Matlab® environment, enabled the identification of answer for questions such as: How many vessels can be operated within a year, considering the navigation windows, number of berths and operational times? Can the cargo matrix be matched? Is the port 'bottlenecked' by the channel or the number of berths?

The dynamic operational simulator was set using as input the navigation windows, number and classification of berths such as determining type of cargo, loading/unloading times and priority, based on required amount of vessels per year. Also, based on that
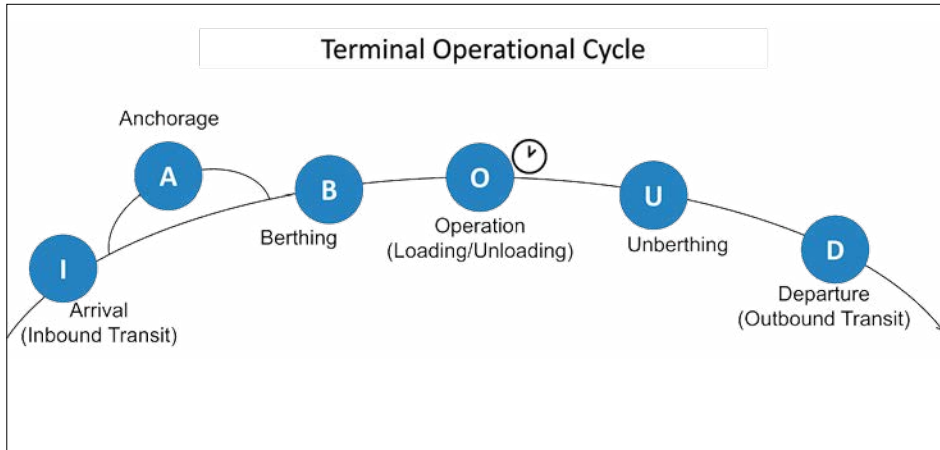

Figure 13: Operational cycle reproduced in the dynamic operational simulator.
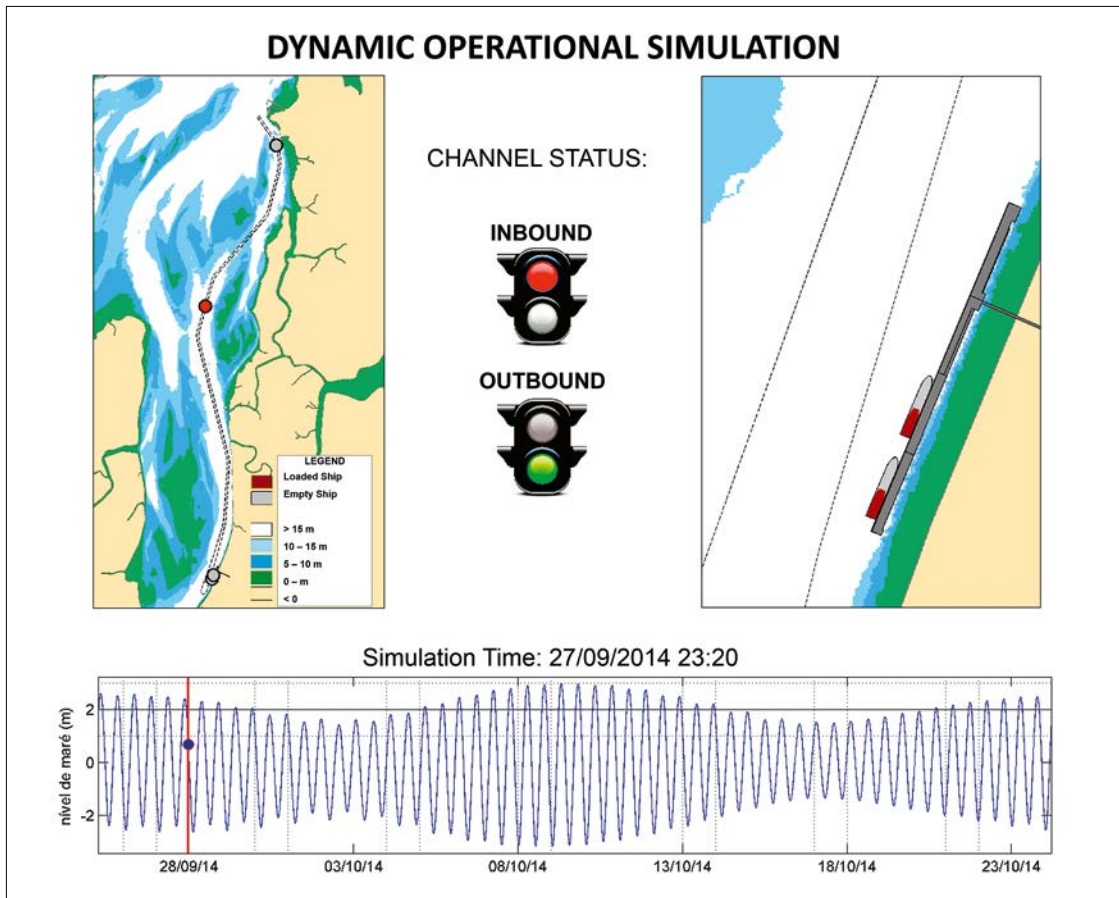

Figure 14: Graphic representation of the dynamic operational simulation: indicates channel status for inbound and outbound transits, two ships leaving the terminal and two ships being loaded. Top left: Overview of the channel; grey circles represent empty vessels and red circles represent loaded vessels. Top right: A close-up of the terminal area. The amount of red filling on each ship represents the amount of cargo loaded until that time. Middle: Traffic lights indicate the status of the channel for inbound or outbound transits. Bottom: Indicates the simulation time along the tidal curve.
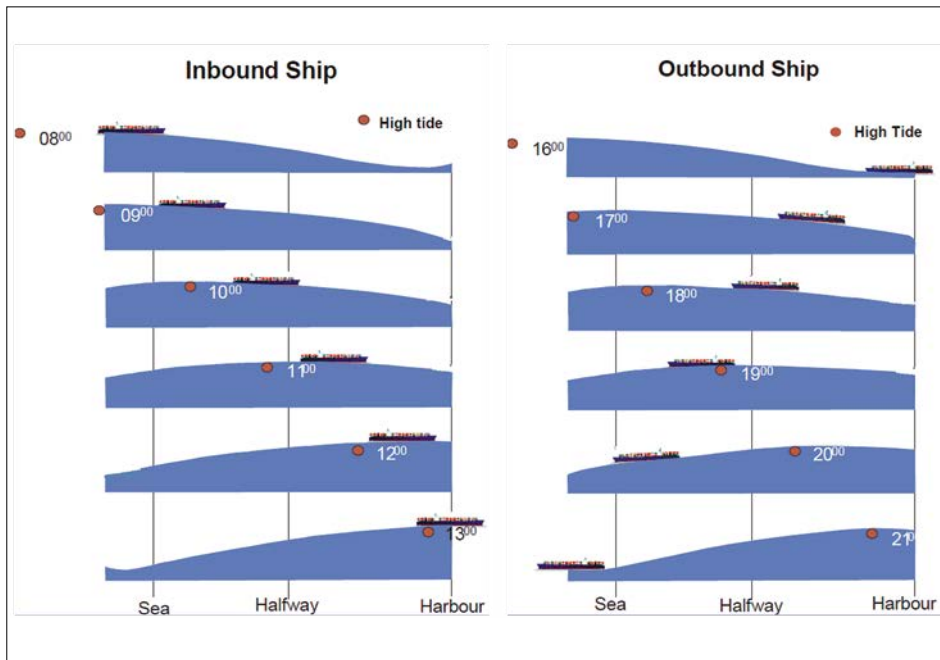
Figure 15: Example of inbound and outbound ship passage using the tide. Extracted from PIANC (2014).
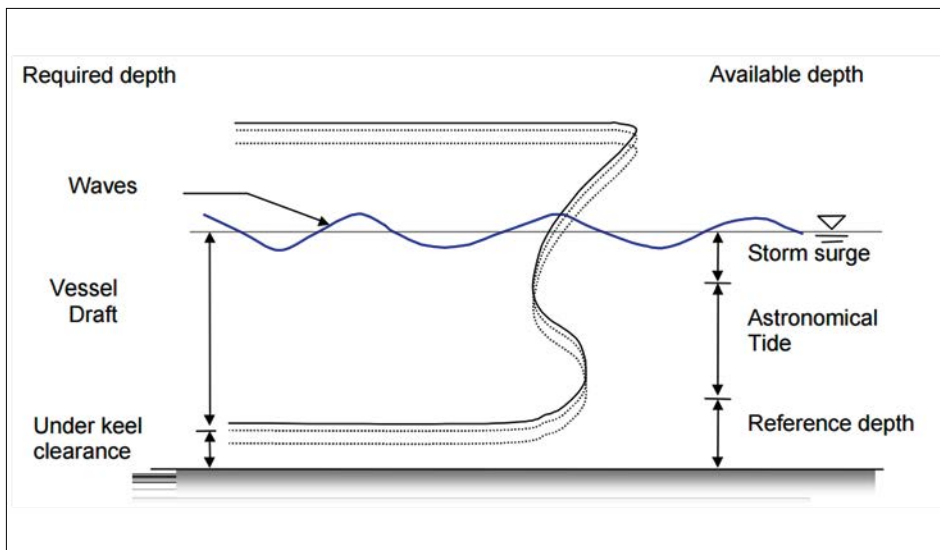

Figure 16: Definition of the concepts of required depth and available depth. If the available depth is equal to or larger than the required depth, the navigation can be performed safely (Lomónaco and Medina, 2005).

information the model simulates the operational cycle for each ship (Figure 13). The simulator is based on several assumptions: whenever the inbound navigation windows are open, there will be vessels available to start the navigation; the port works 24 hours per day; the channel is one-way and the vessel cargo is determined based on the available berth and priority rules. The model runs along one year, calculating every minute the navigation windows status (inbound or outbound), channel and berth usages. It also calculates the status of each vessel along the simulation, such as sailing along the channel, berthing/unberthing, loading/unloading and associated percentage of completion (Figure 14). As output for the dynamic operational simulations, the amount of ships processed per berth along a year – amount of cargo trade – and the berth utilisation rates are provided. If the results indicate berth utilisation rates are higher than what is typically expected (around 60%), there is evidence that the operational restrictions are related to the number of berths. Conversely, output berth utilisation rates that are smaller than 60% denote that the navigation channel is the operational 'bottleneck'.

The results of the dynamic operational simulations indicated that for any evaluated vessel or draft, the navigation windows (considering current-related navigation restrictions only), number of berths and other operational parameters allowed the operation of 732 ships per year. This was more than twice than the required amount of ships. The port operation would also be able to deal with seasonal fluctuations of the cargo. The operational use of the anchorage area to enlarge the navigation windows was proven to be unnecessary. The computed berth utilisation rates were above the design rate of 60%, indicating that the number of berths would be the operational 'bottleneck' if the cargo matrix was to be expanded. As the navigation channel was not responsible for operational restrictions despite the rather short navigation windows, there were opportunities to evaluate dredging cost reduction. In order to achieve this goal, an analysis of tidal windows was conducted, which is described in the following section.

Tidal windows assessment and definition of optimal dredging depths
Based on the successful results of the dynamic operational simulations for the base-case scenario – which considered a channel that would be dredged at a depth that allowed navigation at any tidal level some additional questions were raised. Is it possible to use the 7m tidal range in order to reduce the dredging depth? If the dredging depth is reduced and navigation has to rely on tidal level, can the operation meet the cargo matrix requirements? How much can be saved in dredging costs? How can the channel shoaling rates affect those savings? What is the optimal dredging design, including vessel type and draft, considering costs (CAPEX and OPEX) and commercial aspects?

In order to answer those questions, a tidal window assessment was conducted using the

Amount of Ships Operated per Year		Ship Draft					
		11.0 m	**11.9 m**	**12.8 m**	**13.7 m**	**14.6 m**	**15.5 m**
Channel Dredging Depth (Chart Datum)	**8 m**	563	0	0	0	0	0
	9 m	665	0	0	0	0	0
	10 m	762	654	0	0	0	0
	11 m	764	765	651	0	0	0
	12 m	744	769	765	643	0	0
	13 m	732	742	770	770	507	0
	14 m	728	731	743	766	703	462
	15 m	732	732	732	741	716	619

Table 2: Results of number of ships operated per year from the dynamic operational simulations of each combination of ship draft and channel dredging depth. Green cells indicate valid combinations of dredging depth and draft and red cells denote invalid combinations. Variations in the number of ships operated over 700 are attributed to random definition of ship type on the dynamic simulation as the cargo matrix goal was surpassed.
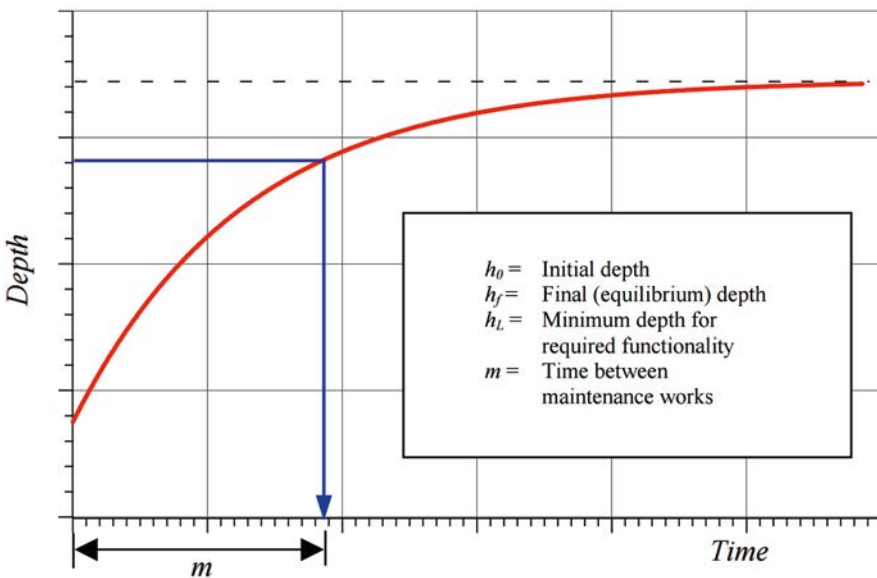

Figure 17: Conceptual definition of the maintenance dredging interval for the navigation channel functionality (Lomónaco and Medina, 2005).
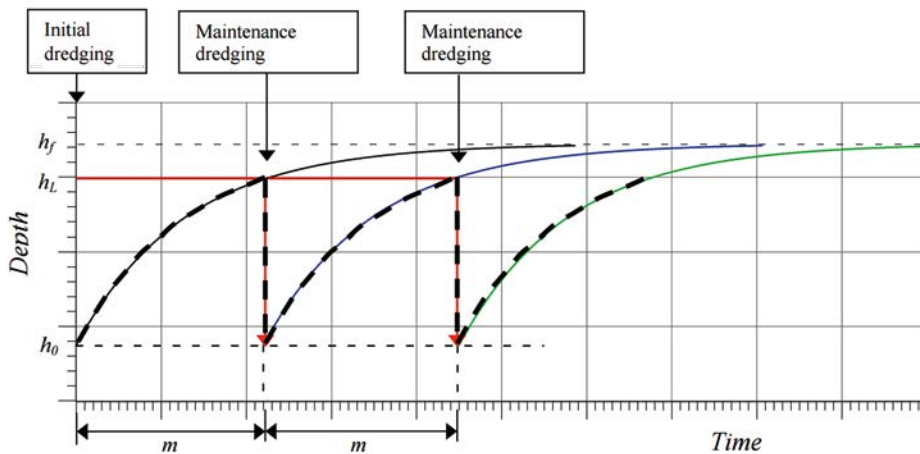

Figure 18: Schematic representation of maintenance dredging events over time to maintain the minimum depth for required functionality (Lomónaco and Medina, 2005).

dynamic operational simulator. The tidal window concept, as defined by PIANC (2014), can be used to allow deep-draught vessels to sail through the channel during high tide, reducing dredging costs, as illustrated on Figure 15. It is important to assure that the vessel speed and its variations due to currents is adequate to follow the tidal windows. Also, the available under keel clearance (UKC) should be high enough so that the available depth along the entire transit is larger than the required depth for safe navigation (Figure 16). Both characteristics were included during the navigation windows assessment, as the currents effect on the ship's speed over ground was considered in the navigation windows code (Figure 7) and the water level and water depth at each time-step of each ship's transit were recorded.

The one-year hydrodynamic model was executed for scenarios with the channel dredged at all depths ranging from 8m (without dredging) to 18m (at 1m steps) and the code to identify the navigation windows was applied for all the situations. After that, an assessment of the effect of changing the channel dredging depth on the distribution of available depths over all possible ship transits could be done.

As the behaviour of the available depths for navigation including tidal effects was known for each dredging depth, an assessment of several ship draft scenarios transiting each dredged channel scenario was performed using the dynamic operational simulator. For that, the same concept of the navigation windows was applied. However, the windows which had minimum available depths inferior

Channel dredged in m	depth shoaling in m	Maintenance Dredging			
		Interval in years		Volume in 1000 m³	
		Panamax	Capesize	Panamax	Capesize
9	8	*Not in 5 years		0 (5 yr)	0 (5 yr)**
10	8	*Not in 5 years		0 (5 yr)	0 (5 yr)**
11	8	*Not in 5 years		80 (5 yr)	108 (5 yr)**
10	9	*Not in 5 years		0 (5 yr)	0 (5 yr)**
11	9	*Not in 5 years		80 (5 yr)	108 (5 yr)**
12	9	*Not in 5 years		270 (5 yr)	316 (5 yr)**
11	10	0.75	0.5	120	109
12	10	*Not in 5 years		270 (5 yr)	316 (5 yr)**
13	10	*Not in 5 years		502 (5 yr)	580 (5 yr)**
12	11	0.5	0.5	148	169,000
13	11	2.4	1.8	528	520,000
13	11	*Not in 5 years		875 (5 yr)	1,021 (5 yr)**
13	12	0.5	0.4	207	200
14	12	1.3	1.3	559	596
15	12	3.1	3.8	1,196	1,543
14	13	0.4	0.3	250	252
15	13	1.2	1.2	674	750
16	13	2.3	2.4	1,441	1,712
*Not reached within the simulated period (5 years) **(5 yr) denotes at year 5					

Table 3: Channel shoaling times for various dredging depths.

than the required depth (Table 1 shows the required depth for each simulated draft scenario) were assumed to be closed. After analysing 48 combinations of ship drafts and dredging depths (6 drafts for 8 depths), the output number of ships operated by the terminal per year was obtained (Table 2). This technique allowed discovering that vessels with drafts up to 11m could operate without any dredging and that reductions in dredging depths up to 4m for larger drafts would be accepted without affecting the port operational requirements or navigation safety. For example, 15.5m draft ships would need an 18m depth dredged channel for transiting

on any tidal level, but using tidal windows would allow safe navigation of 462 ships per year on a 14m depth channel.

The results made clear that there is a clear threshold that delineates a minimum dredging depth for operating each ship draft and that the change from the dredging depth below to the one above the threshold is very abrupt. For example, if the channel was dredged at 10m depth, 654 ships at 11.9m draft could be operated. However, if the channel was dredged at 9m depth, no ship with 11.9m draft would be operated, as the tidal windows would be too restrictive. Due to this abrupt

threshold, care must be taken on the channel shoaling effects and the required interval for maintenance dredging. For that purpose, the analyses of channel shoaling over time (Figure 11) and associated maintenance dredging volumes (Figure 12) were revisited, in order to identify the cost effectiveness of executing over-dredging. Lomónaco and Medina (2005) presented a schematic representation of the channel shoaling effect (Figure 17) indicating that the time interval between maintenance dredging events should be defined as the time-span required for the channel to shoal to a minimum depth for the required channel functionality. If the time interval between maintenance dredging events and sedimentation volume is known, the sequence of dredging events and dredging OPEX costs can be projected (Figure 18). Analysing that information for various dredging depth scenarios allows defining the optimal channel dredging depth.

The results of this analysis are presented on Table 3. It can be noted that, especially for deeper channels, the channel shoaling occurs very quickly, with a reduction in the minimum channel depth of 1m being achieved in less than one year. Therefore, the maintenance dredging interval is very short and the cost of maintaining the channel at that depth would be much greater than dredging a deeper channel. For example, from Table 2 it can be inferred that to operate 14.6m draft ships, a minimum dredging depth of 13m would be necessary. However, on Table 3 it can be observed that the 13m depth channel would shoal to 12m in less than half year, thus crossing the tidal window feasibility threshold. As such, it would be more cost-effective to dredge the channel to 14m, despite the higher initial dredging costs. This is because maintenance dredging would only be necessary 1.3 years later and the accumulated costs over time would be smaller (Figure 19). Based on that approach, the optimal dredging depths for each ship draft scenario could be determined (Table 4).
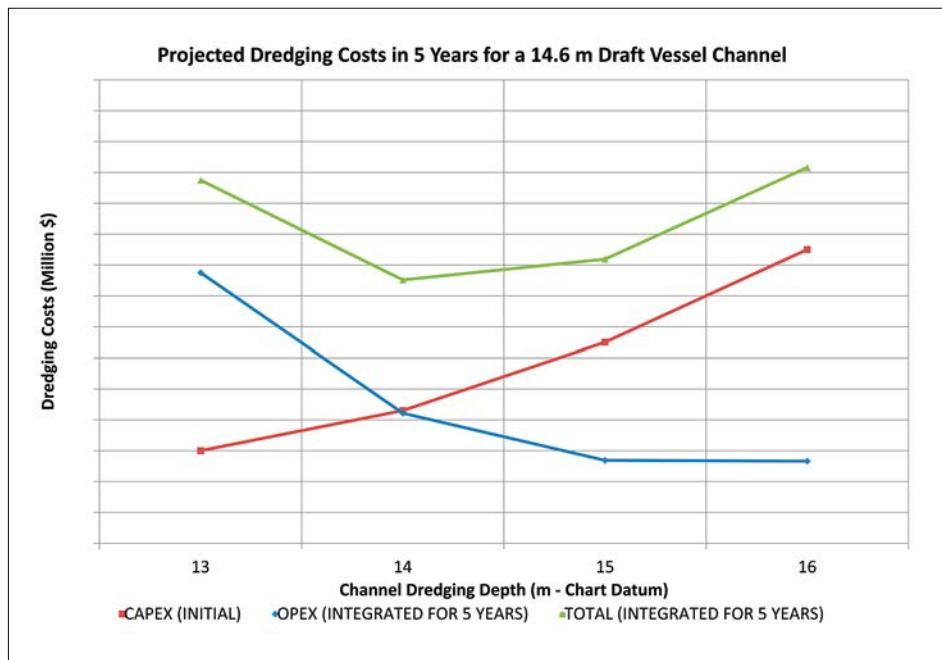
Figure 19: Projection of CAPEX, OPEX and total dredging costs (in US$) accumulated over a five-year period for a 14.6m draft vessel channel. The graph indicates that dredging the channel at 14m depth generates the most cost-effective solution.

Ship Draft	Original Dredging Depth	Optimal Dredging Depth	Initial Dredging Savings (Capesize)	5 Year Cumulative Maintenance Dredging Savings (Capesize)
11.0 m	13 m	8 m	2,000,000 m³	1,900,000 m³
11.9 m	14 m	10 m	3,500,000 m³	2,600,000 m³
12.8 m	15 m	12 m	4,500,000 m³	4,800,000 m³
13.7 m	16 m	13 m	6,700,000 m³	6,400,000 m³
14.6 m	17 m	14 m	10,800,000 m³	12,900,000 m³
15.5 m	18 m	15 m	12,000,000 m³	28,500,000 m³

Table 4: Optimal and original dredging depths for each ship draft scenario and associated savings in initial and maintenance (integrated for five years) dredging volumes for a Capesize vessel channel.

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CONCLUSIONS

An integrated approach was developed and applied in order to determine the optimal channel dredging design for a port in an extreme macro-tidal environment. The approach included engineering designs, ship manoeuvring simulations, hydrodynamic and morphodynamic modelling. It also included the development of customised tools to assess navigation windows, simulate the terminal operation under those windows and verify the feasibility of using tidal windows to reduce dredging requirements. The results obtained allowed reducing channel dredging depths in a way that resulted in a reduction of capital dredging volumes of about 10 million m³ for ships with larger drafts.

Based on the results obtained from the dynamic simulation tool, it can be concluded that the proposed integrated approach for channel design provides relevant information for the definition of the business model of the port. On a technical and economic feasibility analysis, the results provide the impacts of a change on vessel class or draft in both the cargo trade capacity and CAPEX and/or OPEX costs. This information helps to identify the optimal configuration for commercial interests and internal rate of return (IRR) of the project.