Risk and Whole Life Cost -based verification and optimization of harbour approach channel depth

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Abstract

This paper presents the development of a methodology for the verification and optimization of the depth of a harbour approach channel based on the expected total cost over its lifetime. This methodology provides a framework that is general and flexible, which is easily adaptable to medium-sized projects, where it can be applied using the basic and detail design tools given in recommendations PIANC (2014) and ROM (1999), as well as to large projects, where each of the steps involved can be analysed with more complex and accurate numerical and/or physical models. Here the methodology is applied to a case study at the Bay of Cádiz Harbour, Spain.

1. Introduction

PIANC has recently updated its recommendation for the design of harbour approach channels by editing PIANC (2014). This document provides the design engineer with the methodology and tools needed to perform basic and detail design of a harbour approach channel, and also includes some guidelines on how to perform probabilistic verification thereof, particularly in relation to their vertical dimensions (PIANC 2014, Section 2.5). The design process arises, roughly, into three blocks: vertical design, horizontal design and verification of operability and capacity of the channels. However, as mentioned in the recommendation, these aspects are interlinked. Particularly, once that the channel dimensions as well as the operation rules that gives a satisfactory level of safety during passages are defined, the operability and the capacity of the system is determined, so that an iterative process is required to achieve a design that meets both the required operability and safety.

Therefore, PIANC (2014) lays the foundations for progress towards a comprehensive verification and optimization of harbour approach channels, taking into account aspects of safety and operability together. It is believe that the most appropriate method for this is, once basic and detail design stages are finalized, to carry out channel verification and optimization based on the minimization of the total expected cost in its lifetime, including the initial investment costs, the expected maintenance costs and expected costs due to occurrence of failure modes and operational stoppages.

The methodology and the model proposed here are based on the calculation of the expected costs in the lifetime by means of Monte Carlo techniques, simulating a large number of lifetimes and each of the passages that take place during each lifetime. This approach takes into account the interlink between security and operability of the system by estimating the probability of bottom touching during each passages as well as waiting times of each ship, taking into account the uncertainty of each of the involved environmental variables as well. This paper gives directions and references required to implement the methodology and shows an example application to the project of a container terminal of the Cadiz Bay harbour.

2. Objectives

The objective is to establish a methodology to optimize the depth, the operation rules and the maintenance policy of a harbour approach channel by minimizing its whole life costs, while fulfilling the minimum safety and operability criteria pre-established by the recommendations, including in the whole life cost the initial investment for opening or deepening the channel, the maintenance costs and the expected costs associated with the operational downtimes and with the risk of ships touching the bottom.

3. Methodology

The proposed methodology is based on the simulation, by means of Monte Carlo technics, of several lifetimes of the channel, calculating for each lifetime the overall failure probability due to bottom touching and the operability of the channel, as well as the bottom touching probability and the waiting time for each ship transit. From these results the whole life cost of the channel is estimated. The simulation is repeated for different channel depths, operation rules and maintenance policies, in order to find which combination minimizes the expected whole life costs of the channel.

Figure 1 shows an outline of the proposed methodology. It starts from an initial channel design, which is defined by a geometry, a set of operation rules and a maintenance policy (section 3.1).

Multivariate time series of the environmental variables are simulated in an offshore location (section 3.2) and transferred to each channel stretch (section 3.3). Then, knowing the flow in and around each stretch of the channel, the siltation rate is estimated and, taking into account the maintenance policy, the time evolution of the channel depth as well as the number and magnitude of the maintenance dredging are calculated (section 3.4).

On the other hand a time series of ships calling at port is simulated, characterizing ships size and the type and amount of cargo to be loaded and/or unloaded (section 3.5). This information is managed by the traffic control module (Section 3.6), which keeps track of each ship from the moment it calls at port until it leaves. This module also determines the operating condition of the channel depending on its depth and on the value of the environmental variables, and determines when a given transit starts, storing for each transit the waiting time. Each time a ship transits the channel the bottom touching probability is calculated and stored (Section 3.7).

Lastly, the whole life cost of the channel is calculated by adding the initial investment costs to the costs associated with the maintenances, the waiting times and the risk of bottom touching (section 3.8).

Guidelines and references regarding the tools and data required for the implementation of each step of the methodology are given next, on sections 3.1 to 3.8. Details on how to perform the Monte Carlo simulation and on how to calculate failure probabilities for each transit and for the lifetime of the channel are given on section 4.

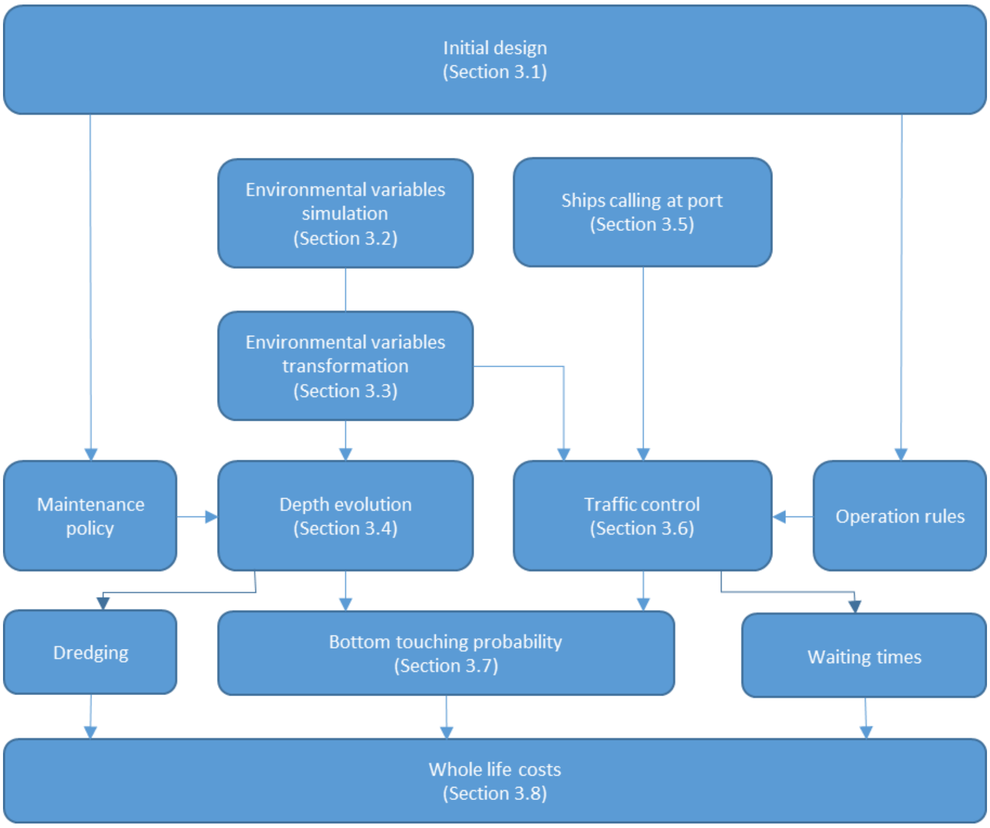

Figure 1 – Outline of the proposed methodology

3.1. Channel initial design

The starting point for the proposed methodology is an initial cannel design that includes its geometry, its operation rules and its maintenance policy. Following PIANC (2014) as well as other recommendations (e.g. ROM 1999) it is possible to obtain preliminary and detail design of the channel.

Regarding the operations rules, it is required to define not only the limiting operation conditions but also the ship transit speed at each channel stretch, the minimum distance between ships, etc.

Limiting operation conditions could be defined by a set of thresholds of the environmental variables (deterministic definition) or by a threshold bottom touching probability (probabilistic definition). The deterministic approach is the most commonly used in practice; however, it is straightforward to include the probabilistic approach on the proposed model (see section 3.7).

For the initial definition of the operation rules the previously given reference could be used as well.

3.2. Time series of environmental variables

The environmental variables module simulates, for one or more offshore locations, the multivariate time series of the meteorological and oceanographic variables that are relevant for the safety and the operability of the channel. Usually this includes, at least, water levels and winds, as well as waves in the case of maritime harbours and river discharges in the case of fluvial or estuarine harbours.

Time series of the environmental variables have several deterministic and stochastic components of different time scales (e.g. astronomic tides and storm surges in the case of water level, mean annual cycle and extreme storm conditions in the case of wind and waves, etc.). Furthermore, the variables have both auto- and cross-correlation.

There are several methodologies for the simulation of multivariate time series of environmental variables that are able to take into account the non-stationarity of the variables as well as their auto- and cross-correlation (see e.g. Monbet et al. 2007). In this work the methodologies described in Solari and Losada (2015) are used.

3.3. Environmental variables transformation

The value of the environmental variables at each channel stretch is calculated using abacus (e.g. Goda's wave diffraction abacus; ROM 1995, etc.), simplified models (e.g. Snell's law for wave refraction) or more sophisticated physic-based numerical models. Nowadays the use of physic-based numerical models for waves, water level and currents is widespread among harbour designers, so no particular reference will be given with regards to this. However, bearing in mind that the proposed methodology for channel depth optimization is based on Monte Carlo simulations, it is recommended that physic-based numerical models are used for generating a data base from which to interpolate the whole series of environmental variables. This could be done by linear interpolation in a hypercube constructed with model results, or resorting to more sophisticate methodologies, as proposed by Camus et al. (2011).

As an alternative to interpolation, the physic-based numerical model results could be used for the calibration (training) of black-box models, whether these are linear (e.g. Autoregressive with exogenous variables) or nonlinear (e.g. Neural Networks).

3.4. Channel depth evolution

By knowing the value of the environmental variables at every stretch of the channel it is possible to estimate the siltation rate in them. For this it is recommended to use PIANC (2008) and references thereof.

The siltation rate, combined with the pre-defined maintenance policy, is used to calculate the time evolution of the channel depth and the number and magnitude of the maintenance dredging carried during the lifetime of the channel.

When a new channel is being optimized there may be not enough information for the calibration and verification of the siltation rate model. As a consequence one would expect this model to give a high level of uncertainty. In such cases it is recommended to verify the model once the channel is in operation and, if required, to perform a new optimization of the maintenance policy incorporating the new information.

3.5. Time series of ship calling at the port

This modules simulates the time series of ships calling at the port, defining for each ship the date and time of calling, its type, dimensions and amount of cargo to be handled.

The definition of the design fleet and its evolution on time are part of the previous studies required for performing an initial design. In case of lacking specific information regarding the probability distribution of ship calls and/or the distribution of the ship dimensions for each type of ship, it is possible to use the values included in ROM (2011).

3.6. Traffic control

The traffic control module determines at what point each transit take place, allowing for the calculation of the waiting time for each transit. For this the module keeps track of the location of every ship that is in the system at every time step and of the waiting queues for using the channel.

Depending on the operation rules and on the value of the environmental variables, this module determines whether the channel is in operation or not, and defines which ship is using the channel at each point.

Figure 2 shows a schematic of the traffic control module. There are two sets of waiting queues, one for entrance transits and one for exit transits. Within each set there may be several queues for different ship types and priority levels, to be defined in the operation rules. In turn two servers are included: the channel and the berths. The latter must be included in order to determine the time at which the ship is ready to leave the harbour. For programming the servers it is required to define the operation rules of the channel (section 3.1) and the service time of the ships at berth, that may depends on the type and amount of cargo of each ship and on the expected throughput of the berths. Information regarding berths throughput and service times is found in ROM (2011).

This module stores the waiting times for each transit, differentiating between those produced by depth limitations and those produced by other causes, such as constraints imposed to avoid exceeding channel way marks, the inability of the pilots to access the ship due to severe environmental conditions, unavailability of berths, etc.

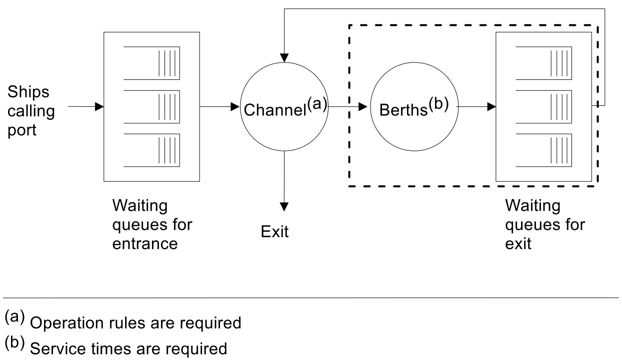

Figure 1 – Outline of the traffic control module

3.7. Probability of touching the bottom during transit

The probability of a ship touching the bottom is calculated for every transit that take place during the lifetime of the channel. To this end each transit is divided into *transit states*, during which the vertical movements of the ship caused by the action of the environmental variables is assumed statistically stationary. Then, the probability of bottom touching during the entire transit is calculated using the probability of bottom touching calculated for each of the transit states that comprise the transit (see section 4 for details).

For calculating the bottom touching probability during a transit state the squat and the dynamic heel (produced by winds, currents and turning) are assumed to be stationary, and the amplitude of the ship oscillations produced by the waves are assumed to follow a Rayleigh distribution, whose parameter may be obtained from PIANC (2014), ROM (1999) or, in the case of larger projects, from specific numerical or physical models (see PIANC 2014). In any case, the parameter will depend on the dimensions of the ship and on the wave state parameters.

As mentioned in section 3.1, this module could be used for verifying the limiting operation conditions of the channel if they are defined in terms of a maximum allowable bottom touching probability during transit (probabilistic approach).

3.8. Whole life costs

The whole life cost of the channel $C_{Lifetime}$ is estimated with Eq. (1)

$$C_{Lifetime} = C_{Ini} + \sum_{D=1}^{N_D} C_D + \sum_{T=1}^{N_T} \left(R_T + T_{Wait,T} C_{Wait} \right) \quad (1)$$

where C_D is the cost of each ones of the N_D maintenance dredging carried out during the lifetime, $T_{Wait,T}$ is the waiting time of each one of the N_T transits, C_{Wait} is the unit cost of waiting and R_T is the risk of touching the bottom during each transit, estimated as the probability of touching the bottom $P_{F,T}$ times the expected cost of the consequences E[C]

$$R_T = P_{F,T} \mathrm{E}\left[C\right] \quad (2)$$

The expected cost of the consequences of touching the bottom during a given transit is estimated with Eq. 3, considering a set of N_{Con} possible consequences. Each possible consequence Con_j has an associated cost $C(Con_j)$ and an occurrence probability conditioned to the bottom touching given by $P(Con_j$ | *bottom touching)*.

$$\mathrm{E}\left[C\right] = \sum_{j=1}^{N_{Con}} C\left(Con_j\right) P\left(Con_j \middle| \text{bottom touching}\right) \quad (3)$$

In Eq. (1) it is assumed that waiting for a transit results in a constant cost per waiting hour and any other adverse consequence arising from the waiting is considered unlikely and not analyzed. Given that the objective is to optimize the depth of the channel, only the waiting times caused by depth limitations are considered in costs estimation.

The consequences of bottom touching are more complex to analyze, and go from almost negligible (e.g. no damage and no inspection required) to the most severe (e.g. the ship grounds and blocks the channel, or even sinks). To simplify the calculations, in Eq. (1) and Eq. (2) it is assumed that: (a) the probability of touching the bottom at each transit state is independent of the other states that comprise the transit; (b) the set of possible consequences, their conditional probability and their cost are independent of the channel stretch and of the transit state.

It is noted that the expected risk of bottom touching during the lifetime of the channel cannot be estimated as the overall bottom touching probability in the lifetime ($P_{F,Lifetime}$) times the expected cost of the consequences given by Eq. (3), since during the lifetime of the channel more than one ship may touch the bottom, while E[C] is the expected cost of only one ship touching the bottom, i.e.:

$$\sum R_T \neq P_{F,Lifetime} \mathrm{E}\left[C\right] \quad (4)$$

4. Simulation model and calculation of the probabilities

This section presents details regarding the implementation of the proposed methodology and formalized some concepts required for the calculation of the bottom touching probability at each transit and during the lifetime of the channel.

The simulation methodology is based on Losada et al. (2009). The procedure, outlined in Figure 3, is to perform a large number of experiments (M experiments) to obtain the expected value and the probability distribution of the whole life cost and other objective variables (e.g. overall bottom touching probability in the lifetime of the channel, operability, waiting times). Each experiment is the simulation of a channel lifetime, which consists of N years. In each of the simulated years, a series of transits follow one another across the channel. Each transit is divided into transit states (see sections 4.1 to 4.3) in which the response of the ship is statistically stationary, making it possible to calculate the bottom touching probability as described in section 3.7.

Since the calculation method is based on the concept of *transit state*, that in turn is related with the concepts of *channel stretch* and *environmental state*, these three concepts are discussed next in sections 4.1 to 4.3. In section 4.4 it is shown how to calculate the transit and lifetime bottom touching probabilities from the probabilities estimated for each transit state.

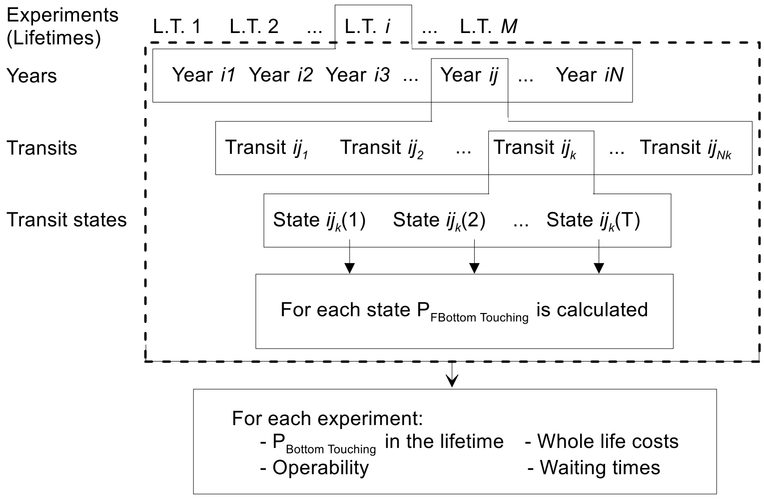

Figure 3 – Outline of the simulation methodology (modified from Losada et al. 2009).

4.1 Channel stretches

The channel is divided into stretches in which the level of the actions exerted on the ship is uniform. This condition can be expressed in terms of the environmental variables and the transit conditions. So, for a ship in a given stretch there should be uniform the height and direction of the waves, the intensity and direction of the current, the speed and wind direction, the sea level, and the speed and direction (and in its case the turning rate) of the ship.

4.2 Environmental state

The environmental state is the period of time during which the level of the actions exerted on the ship by the environmental variables, at a given channel stretch, can be assumed to be stationary or statistically stationary. For simplicity, instead of estimating the actions on the ship, the environmental state is defined in terms of the value of the environmental variables.

Each environmental variable has a characteristic time scale over which it is assumed stationary or statistically stationary. For waves and wind it is approximately one hour; tidal range is constant in a diurnal or semidiurnal scale, then depending on its amplitude, sea level can be considered stationary on a scale of minutes to hours, etc.

The time scale used in the model to define the environmental state duration must be equal to or less than the minimum time scale of the environmental variables involved.

4.3 Transit state

The transit state is the time step used for the calculation of the probability of touching the bottom. During a transit state the ship moves through a stretch of the channel under a given environmental state, i.e. the actions exerted over the ship are stationary or statistically stationary. Thus, the duration of a transit state ($\Delta T_{TransitState}$) is defined by Eq. (5) as minimum time required for one of two possible events to happen: (a) the environmental variables change their state ($\Delta T_{EnvState}$), or (b) the ship moves to another stretch ($\Delta T_{Stretch}$).

$$\Delta T_{Transit} = \min\left\{\Delta T_{EnvState}, \Delta T_{Stretch}\right\} \qquad (5)$$

It is noted that transit states comprising a given transit should be calculated for each specific transit, with $\Delta T_{TransitState}$ depending on the ship transit speed and on when the transit starts.

4.4 Transit and lifetime bottom touching probabilities

The probability of touching the bottom during a transit state ($P_{F,State}$) is calculated following section 3.7.

The probability of touching the bottom during a complete transit ($P_{F,Transit}$) is calculated with Eq. 6 as the complement of the probability of not touching the bottom during the transit, that is the product of the probabilities of not touching the bottom at every one of the N_E transit states that comprises the transit

$$P_{F,Transit} = 1 - \prod_{State=1}^{N_E} \left(1 - P_{F,State}\right) \qquad (6)$$

Analogously, the probability of touching the bottom during the lifetime of the channel ($P_{F,Lifetime}$) is calculates with Eq. 7 as the complement of the probability of not touching the bottom during the lifetime, that is the product of the probabilities of not touching the bottom at every one of the N_T transit that occurred during the lifetime of the channel.

$$P_{F,Lifetime} = 1 - \prod_{Transit=1}^{N_T} \left(1 - P_{F,Transit}\right) \qquad (7)$$

5. Case study

5.1. Bay of Cádiz Harbour

Bay of Cádiz Harbour is located on the south-west coast of Spain, at the Gulf of Cádiz, on the Atlantic Ocean. During 2007-2008 a project for a new container terminal was developed, for which deepening of the current harbour entrance channel was required (see Figure 4).

In order to optimize the depth to which the channel should deepen the model described in the previous sections was implemented, with some simplifications: the design fleet was composed by a single ship and the siltation rate of the channel was not considered. On the other hand, the manoeuvring circle was included in the model.

5.2. Project criteria

The project design criteria, shown in Table 1 (lifetime, maximum failure probability in the lifetime and minimum operability), were estimated following ROM methodology (ROM, 2001). The optimum depth and operational rules for the channel will be the ones that minimize the whole life cost of the channel, fulfilling the criteria listed in Table 1.

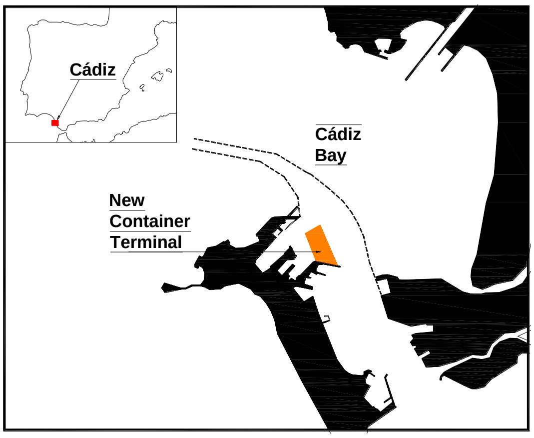

Figure 2 – Location of the Bay of Cádiz Harbour and outline of the projected expansion

Table 1 – Design criteria for the channel

Criteria	Value
Lifetime	25 years
Maximum failure probability in the lifetime	0,10
Minimum operability	95%

5.3. Initial design and operational rules

The initial design for the optimization is that of the existing channel at the time of the project.

Initial limiting operational conditions are established based on the analysis of the horizontal dimensions of the channel. A fast-track model is used to establish the limiting environmental conditions (waves, winds and currents) and towing requirements for a transit not to exceed the channel way marks. The response of the fast-track model is deterministic; that is, given a set of environmental conditions and a number and position of tows, the transit results in exceeding the channel way marks or in not exceeding it, but no probability of exceeding the way marks is given by the fast-track model. A total of 18,000 transits are simulated under different scenarios, covering a wide range of conditions: 50 wave conditions combined with 9 currents conditions, 40 wind conditions and with up to 5 tows in different positions.

Then, the limiting conditions established from the analysis of the horizontal dimensions is combined with the following function (Eq. 8) for establishing the operational condition of the channel

$$Op = \begin{cases} 1 \text{ si } & H_{m0} \geq H_{umb} \text{ y } NM \geq \alpha\left(H_{m0} - H_{umb}\right) \\ 1 & \text{si } \; H_{m0} < H_{umb} \\ 0 & \text{other cases} \end{cases} \tag{8}$$

where Op=1 means that the cannel is operating, Op=0 means is no operating, and α and H_{umb} are parameters to be determined through optimization. Eq. 8 is applied after checking the limiting conditions established from the horizontal analysis.

Operational rules regarding transit speeds were taken from ROM (1999) and only one ship is allow to use the channel at a time.

5.4 Simulation

Depths from 14 m to 14,5 m are simulated with the operational rules established above, with $\alpha=1$ and H_{umb} varying between 1,4 m and 2,8 m.

A total of 1,000 lifetimes are simulated for each combination of channel depth and H_{umb}, were each lifetime is 25 years long, as listed in Table 1. Then, the whole life cost is calculated for each one of the simulated lifetimes, along with the overall bottom touching probability, the mean operability and the probability distribution of the waiting times.

The calculation of the whole life cost is performed following the methodology described in section 3.8, using the cost estimation described in the Appendix.

5.5. Results

From the simulation it is obtained a sample of 1,000 data for the three objective variables, namely: whole life cost, overall bottom touching probability and mean annual operability. In order to take into account the uncertainty of the results, related in this case mainly with the stochastic nature of the environmental variables, 90% confidence intervals are estimated for each variable. The analysis that follows is performed with the upper limit of the confidence interval in the case of the whole life cost and the overall bottom touching probability, and with the lower limit of the confidence interval in the case of the operability.

Figure 6 shows the iso-cost curves for different channel depth and H_{umb}. The area in grey indicates the combinations of depth and H_{umb} that do not meets the minimum operability required by the project criteria, considering a 90% confidence interval. The area in blue indicates the combinations that results in an overall bottom touching probability higher than the maximum failure probability established on the project criteria (considering a 90% confidence interval). Optimal combination of depth and H_{umb}, from those simulated, is marked with a green dot, corresponding to a channel depth of *14,1 m* and H_{umb}*=1,6 m*.

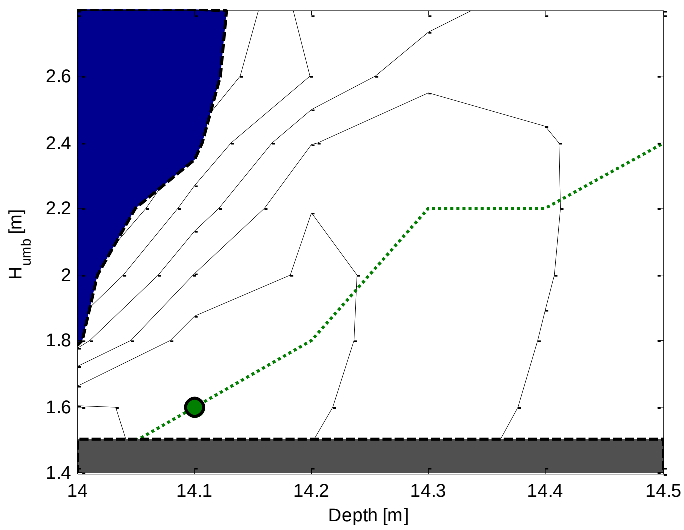

Figure 3 – Iso-cost curves as a function of cannel depth and H_{umb}. Grey area: operability under the minimum value establish by design criteria. Blue area: bottom touching probability over the maximum value given by design criteria. Green dot: optimal combination among those analysed.

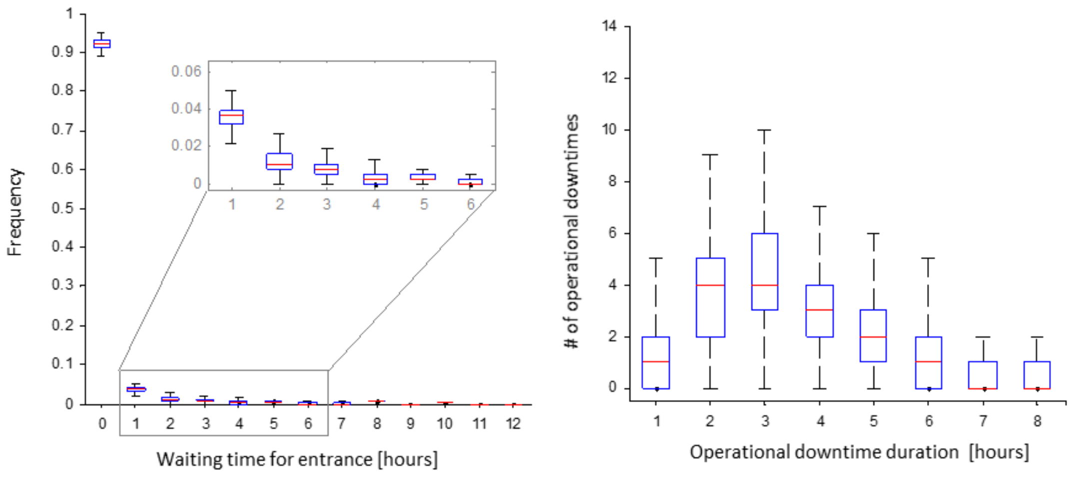

Figure 4 – Left: Frequency of the waiting times for entering the port. Right: Number and duration of operational downtimes produced by Eq. 8.

Figure 7 (left) shows the frequency of the waiting times for entrance transits, along with its confidence intervals, for the optimal combination of channel depth and H_{umb}. It is seen that approximately 92% of ships that call to port do not wait for entering the harbor. Figure 7 (right) shows the histogram of the channel downtimes produced by limiting conditions stated in Eq. 8, with $\alpha=1$ and $H_{umb}=1{,}6\ m$. It is seen that the most frequent operational downtimes last for no more than 3 hours, and that there is a high level of variability in the number and duration of the operational downtimes, as is evidenced by the confidence intervals.

6. Discussion and conclusions

During the design process of harbor approach channels it is sought to maximize their safety and operability, meeting the design criteria pre-established by current regulations or recommendations, minimizing total costs incurred during its lifetime, namely: initial investment, maintenance and consequences of the occurrence of failure modes and operational stoppages.

A methodology was proposed for optimizing channel depth and its operation rules and maintenance policy by minimizing the whole life costs associated with the vertical dimension of the channel, namely: initial investment for opening or deepening the channel, maintenance costs and costs associated with the operational downtimes and bottom touching risk. Detail description of the calculation procedure as well as general guidelines on the tools and references required to implement the model were given.

The case study exemplifies the results that are obtained with the proposed methodology, and makes clear the need to take account of the uncertainties that are inherit from the stochastic nature of the environmental variables when optimizing the channel dimensions and its operation rules.

The proposed methodology can be easily implemented to small- and medium-scale project using the tools and figures included in PIANC (2014) or ROM (1999), along with the simulation procedure summarized in Solari and Losada (2015), as was done in the case study. For bigger projects, more complex tools, as described in PIANC (2014), can be used for implementing the different modules of the methodology.

Some modules of the proposed methodology may have a high degree of uncertainty associated with the calculation tools and models (e.g. siltation rates) or to the input data (e.g. expected number of ships calling at port in the long term). However, the proposed methodology could be used during the lifetime of the channel to re-optimize the operation rules and the maintenance policy each time new relevant information is available.

In this work only the failure mode *exceeding way marks*, related mainly with the horizontal dimensions of the channel, was not included in the simulations, and was considered only when defining the operation rules in the case study. However, the proposed methodology allows to include the *exceeding way marks* failure mode in addition to the *touching the bottom* failure mode. This way, both vertical and horizontal dimensions of the channel would be optimized at the same time based on the minimization of the whole life cost. For this it would be required to include an additional module in the methodology that calculates the probability of exceeding way mark for any given transit state.

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Appendix – Estimation of the expected cost of the consequences of touching the bottom

In this work the assessment of the bottom touching consequences included in Abdelouarit (2010) is used. However, further analysis of the consequences may be required for future applications.

For waiting times produced by depth limitations (Eq. 8) a cost of 10.000 €/6hrs is assigned. No cost is assigned to waiting time produced by other causes.

Abdelouarit (2010) defines five scenarios of consequences for a ship that touches the, along with their absolute probability (listed on Table 2):

C_1: There is little to no damage to the hull; $E[C_1] = 1$ mill. €.
C_2: There is some damage to the hull, with possible minor loss of cargo and disturbance to the transit of other ships; $E[C_2] = 11$ mill. €.
C_3: The ship grounds but is able to sail with high tides; $E[C_3] = 1$ mill. €.
C_4: The ships grounds and needs rescue for sailing again; $E[C_4] = 5$ mill. €.
C_5: The ship grounds and sinks; $E[C_5] = 50$ mill. €.

Here, the absolute probabilities *$P(C_j)$* are used to estimate conditional probabilities *$P(C_j$ | bottom touch)*, by means of

$$P\left(C_j \middle| \text{ bottom touch}\right) = \frac{P\left(C_j\right)}{\sum_{i=1}^{5} P\left(C_i\right)}$$

Using the listed expected costs and conditional probabilities (Table 2), the expected cost of the consequences of a bottom touching is estimated using Eq. 3 as E[C]=4,35 mill. €.

Table 2 – Absolute and conditional probabilities assigned to the different consequences scenarios

Consequences	$P(C_j)$	$P(C_j\|\text{bottom touch})$
C1	$5x10^{-4}$	0,3267
C2	$5x10^{-4}$	0,3267
C3	$5x10^{-4}$	0,3267
C4	$3x10^{-5}$	$1,96x10^{-2}$
C5	$2,5x10^{-7}$	$1,63x10^{-4}$

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