

PORT OPERATIONALITY AND SAFETY ANALYSIS UNDER UNCERTAINTY

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A methodology for port management is proposed in this work. It takes into account the uncertainty of the port performance due to the action of random forcing agents, namely, climate agents and exploitation agents. It can be used to obtain optimal solutions for port management problems in which operationality and safety are involved. Multivariate simulation techniques are used to obtain realizations of the random processes that characterize the forcing agents. The port performance is then evaluated by a simulation model. The methodology is applied in a hypothetical port in which the influence of the climate thresholds on operational performance and safety is evaluated by the port simulation model. An optimization problem is then formulated and solved in order to reduce waiting times and costs without compromise the safety levels.

Keywords: uncertainty; simulation model; optimization; operational performance; safety

INTRODUCTION

The service level of a port is a crucial factor in building customer loyalty and attracting new trade routes. For this reason, port managers try to improve the operational performance of the ports by implementing different types of measures that range from soft management decisions, such as the redefinition of operation procedures, to harder measures, such as the reconfiguration of port areas or the improvement of infrastructures. Every action has an effect on the safety level in the performance of port activities. Moreover, operationality and safety are in most cases opposing concepts in the sense that quite often an increase in port operational levels is achieved at the expenses of safety and *vice versa*. A joint evaluation of both aspects is therefore required in port planning and management decision-making.

Operationality and safety have been widely studied in previous works. Bierwirth and Meisel (2010) gave a survey on works dealing with berth allocation, in which different optimization models for seaside operations in container terminals are given. Huang et al. (2012) proposed a simulation model to measure the improvement of port management strategies. However, the effect on safety was not considered in these works. Only a few works jointly consider operationality and safety. Quy et al. (2008) proposed a risk-based method to optimize channel depths that also considered transport increment, reduction of waiting times and maintenance costs. In Solari et al. (2010), a model that estimates waiting times and probability of vessel grounding is used as a tool for harbor verification and management.

In this work, a methodology for port management that jointly assesses port operationality and safety is proposed. It takes into account the uncertainty of the port performance, inherited from the randomness of forcing agents. The methodology can also be used as a management and decision support tool to obtain optimal solutions of port management problems.

Simulation techniques are used to obtain realizations of the random processes that characterize the random forcing agents. Then, a port model that simulates port operations is used to evaluate the port performance, that is then characterized through a set of indicators that measure operational and safety levels.

The methodology is applied to a hypothetical port. A threshold coefficient, C_u , that multiplies the reference operational thresholds defined in ROM 3.1-99 (Puertos del Estado, 2000) is considered as a variable for optimal design in this study. The port performance for different values of C_u is then analyzed, in order to obtain optimal solutions in which the operational performance is improved without compromising the safety of the port activities.

The article is organized as follows. Section 2 summarizes the proposed methodology. The hypothetical port in which the methodology is applied and the management problem are described in Section 3. Section 4 shows the results of the evaluation of the port performance, as well as the solutions for the optimization problem. Finally, the conclusions of this work are given in Section 5.

METHODOLOGY

This work proposes a methodology for the joint assessment of operational and safety performance in ports. The methodology can be used as a decision support tool in port management and planning, and allows to obtain optimal solutions in decision-making or design problems.

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The methodology consists of three steps. First, the design or management problem is defined by a set of variables of decision and their ranges of variation. Then, the influence of the decision variables on the port performance is evaluated and measured by a set of indicators of operational performance and safety performance. Finally, the optimal values of the decision variables are obtained with optimization techniques.

Assessment of the uncertainty in the port performance

This methodology considers the port as a system that responds to a set of random forcing agents that are characterized by a series of random processes (RPs): $X_1(t), \dots, X_F(t)$, where t denotes time. The agents considered in this work are climate and use and exploitation agents. In the first group are the significant wave height, mean wind speed, etc. The exploitation agents include the inter arrival vessel times and service times, among others.

A random realizations of the RPs ($x_1(t), \dots, x_F(t)$) during a selected period of time of duration D_t , can be obtained by means of multivariate simulation techniques. These time series are discretized into a sequence of states, where a state is defined as a period in which the agents can be assumed to be statistically stationary.

For a given set of realizations of the RPs, the response of the system can be obtained with a port simulation model. The response of the system is the port performance in terms of operational performance and safety performance, and it is measured by the set of indicators $\xi_1, \xi_2, \dots, \xi_N$.

If this process is repeated a large number of times, Q , a sample $\{(\xi_{1q}, \xi_{2q}, \dots, \xi_{Nq})\}_{q=1}^Q$ of the random vector $\vec{\xi} = (\xi_1, \xi_2, \dots, \xi_N)$ is obtained. With this sample it is possible to infer the corresponding joint probability density function that can be used for risk analysis, and thus, assess the uncertainty in the performance of the strategy. Figure 1 shows a diagram of this general procedure.

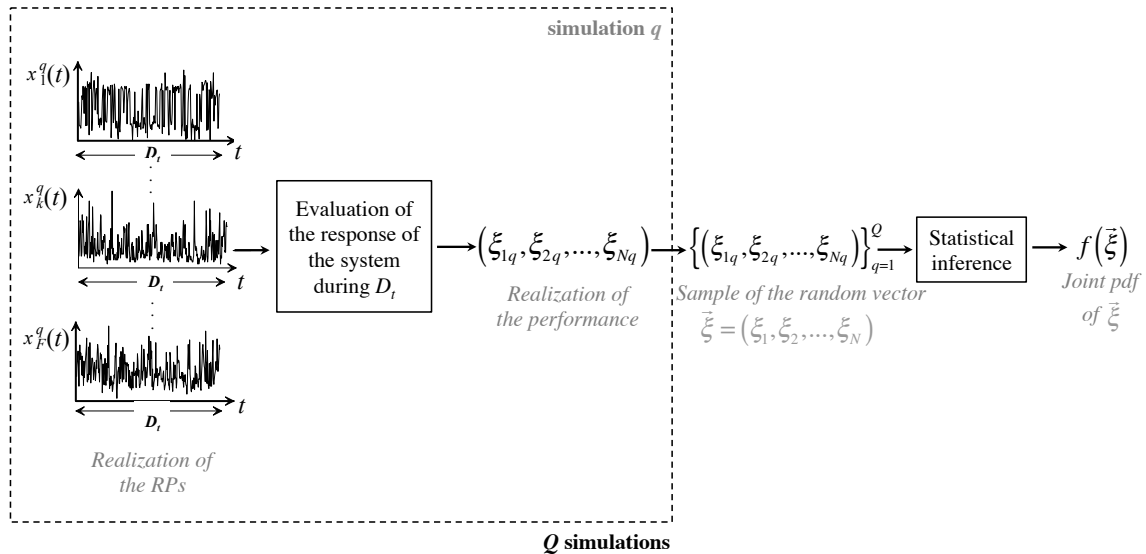


Figure 1: Diagram of the assessment of uncertainty

STUDY CASE

The application of the proposed methodology to a hypothetical port is explained in this section. First, the description of the port and its management problem is given. Then, the random generation of the forcing agents and the assessment of the port performance is described. Finally, the joint optimization of port operability and safety is given.

Description of the port management problem

The hypothetical port has two terminals and handles two types of shipping cargo, general container cargo and liquid bulk. The terminals share the technical-nautical services of pilotage and tug assistance. The services are provided by licensed companies, which offer three tugboats and two pilots per shift. The

container terminal handles roughly 400,000 TEUs per year and the wharf is 600 meters long. During the last five years, the mean number of vessel arrivals was 500. The containerships fleet has been modeled with three vessel types, whose characteristics are shown in Table 1.

Vessel type	Length (m)	GT	Capacity (TEU)	Probability	Tugboats demand	Pilots demand
1a	140	15000	900	0.10	2	1
1b	200	40000	1500	0.85	2	1
1c	300	60000	6000	0.05	3	1

Table 1: Characteristics of the container ship fleet

The oil products terminal has two jetties with one berth each. In the last five years, the mean number of vessel arrivals was 120 per year, which moved approximately 450,000 tons per year. The fleet consists of two types of liquid bulk vessels, whose characteristics are shown in Table 2.

Vessel type	Length (m)	GT	Capacity (TEU)	Probability	Tugboats demand	Pilots demand
2a	160	2500	3000	0.60	1	1
2b	190	4000	5000	0.40	2	1

Table 2: Characteristics of the liquid bulk vessel fleet

The operational stoppage of the port activities is assumed to occur when certain variables exceed pre-defined threshold values. In this work, the thresholds of the significant wave height (H_s) and mean wind speed ($V_{10,1min}$) for different activities and vessel types (see Table 3) given in the Spanish Recommendations ROM 3.1 (Puertos del Estado, 2000) were considered as reference values.

Activity	Containerships		Tankers	
	$H_s(m)$	$V_{10,1min}(m/s)$	$H_s(m)$	$V_{10,1min}(m/s)$
Vessel berthing	2	17	2	17
Loading and unloading operation stoppage	0,5	22	1,2	22
Vessel staying at quay	3	30	3	30

Table 3: Climate thresholds

The choice of these threshold values strongly influence the operational performance and safety of the port. Indeed, for high threshold values, the operational levels of the port will improve, at the expenses of an increase of the probability of occurrence of an accident during the realization of port activities. On the contrary, a reduction of the threshold values will certainly make safer port activities, but the number of operational stoppages and the waiting times will be higher.

In this work, a five years period of study was considered for the analysis. The port management target was to obtain the optimal values of the climate thresholds during that period of time using as a decision variable a coefficient threshold, C_u , that multiplies the reference values defined in the ROM 3.1-99. 41 cases in which C_u ranges from 0.8 to 1.2, were considered with the purpose of evaluating the influence of C_u on port safety and operational performance.

Random generation of forcing agents

Climate agents have been characterized by the following random processes: significant wave height, peak period, mean wave direction, and wind speed and direction. A seventh-order vector autorregressive model (Solari and van Gelder, 2011) has been used to the time series (realizations) of those random processes during the period of time under consideration. This model uses the non-stationary mixture distributions proposed by Solari and Losada (2012) for climate variables. The data were collected from the WANA2006008 hindcasting point (*source*: Puertos del Estado).

Exploitation agents have been characterized by the number of vessel arrivals, vessel types and service times. The arrival of ships to the port was assumed to behave as a Poisson process, therefore the time

between arrivals is an exponential distribution with parameter, λ , the mean number of arrivals per year. The vessel type has been simulated with a random discrete variable, V_T , with a probability mass function given by $\Pr(V_T = i) = p_i, i = 1, 2, \dots, n_{V_T}$, where $n_{V_T} = 3$ for the container terminal and $n_{V_T} = 2$ for the liquid bulk terminal. Probability values are shown in Tables 1 and 2. For each type, the characteristic length, GT, and capacity were then assigned using the values given in Tables 1 and 2.

The vessels service time at berth, t_s , is considered as an Erlang variable (Mettam, 1989) with shape parameter $K = 4$, corresponding to relatively regular service times and rate parameter $\lambda = K/\mu_S$, where the mean service times are $\mu_S = 15$ hours for the container terminal and $\mu_S = 12$ hours for the liquid bulk terminal.

Evaluation of the port performance

Given a realization of the random processes that characterize the forcing agents during the time period, D_t , for each case, the port performance has been evaluated with a discrete-event model simulating port operations. Port operations are simulated by taking into account the availability of port services, the occupancy of berths and navigation areas and the stoppage of activities due to severe climate conditions. When a vessel arrives at the port, the model computes its schedule and calculates the delays by checking the occupancy or availability of berths and services. At the same time, it tracks the stoppage of activities due to severe climate conditions, which are supposed to occur when the climate agents exceed the climate thresholds defined in each case. In order to measure the operational performance, two indicators have been selected, the mean waiting time, T_w , and the waiting related costs, C_w . These costs have been calculated by using the waiting time of each vessel and its freight rate (Autoridad Portuaria Nacional de Perú, 2012; UNCTAD, 2013).

The model also simulates the occurrence of failures or accidents during certain port activities. In this work, two failures have been considered, (1) vessel grounding during the access and berthing maneuvers and (2) the collision with port structures during the berthing maneuvers. The probability of occurrence of both failures depends on the intensity of the climate agents and ranges from 10^{-3} for the least severe climate conditions to 10^{-1} for the most intense climate conditions. Two other indicators were also selected to measure the safety performance, namely, the number of failures or accidents that occur during D_t , (N_f) and the direct and indirect consequences of the accidents in monetary terms, C_f . The direct consequences have been calculated by considering the states of consequences defined in Solari (2011). The indirect consequences have been assumed to be the incomings that the port would not receive from vessels that were expected to arrive to the port and did not arrive because of the accident.

Joint optimization of port operationality and safety

The final step of the methodology is the joint optimization of the operational and safety performance of the port. In this work, the indicators expressed in monetary terms, waiting related costs (C_w) and consequences of failures (C_f), have been used to formulate the optimization problem. Those indicators were normalized with the following expression:

$$\hat{C}_x = \frac{C_x - C_{x,min}}{C_{x,max} - C_{x,min}} \quad (1)$$

where C_x is the value of the indicator and \hat{C}_x the normalized indicator.

In order to reduce the multi-objective optimization problem into a single-objective optimization problem, the normalized indicators were combined into a linear utility function defined as $U = w_1 \cdot \hat{C}_w + w_2 \cdot \hat{C}_f$, where w_1 and w_2 are the weights of the criteria. In this study case, both criteria have been supposed to have the same importance, so $w_1 = w_2 = 0.5$.

The only constraint in this optimization problem is referred to the threshold coefficients, C_u . The problem was formulated as follows:

$$\begin{aligned} \min_{C_u} \quad & U = w_1 \cdot C_w + w_2 \cdot C_f \\ \text{s.t.} \quad & 0.8 \leq C_u \leq 1.2 \end{aligned} \quad (2)$$

Because C_w and C_f are random vector, the optimization problem is not deterministic but stochastic.

Simulations were used to infer the distribution function the random variable U . The optimal (minimum) utility in the stochastic sense and its corresponding threshold coefficient were obtained with three different

criteria. One was the mean value criterion that uses the mean value of the obtained sample of U . The second one was the Value at Risk (VaR) criterion that considers the values that are exceeded by $(100 - \alpha)\%$ of the sample. In other words, the $\alpha\%$ VaR is equivalent to the α -th percentile. And finally, the Hurwicz criterion, which combines two different criteria by using the following expression:

$$U_{Hurwicz} = \beta \cdot U_{opt} + (1 - \beta) \cdot U_{pes} \quad (3)$$

where β is an optimism coefficient, U_{opt} is the optimistic criteria and U_{pes} is the pessimistic criteria. In this case, the pessimistic and optimistic criteria were the 90th and 10th percentile, respectively, of the sample of U .

RESULTS

The results of the simulations are shown in this section. First, the values of the indicators that have been obtained for each case are presented. Then, the results for the utility function and the optimal value of the threshold coefficient for different criteria are exposed.

Assessment of the port performance

Figure 2 shows the mean values of the selected indicators of the operational performance and their 95% confidence intervals for each threshold coefficient. The indicator mean waiting time (T_w) is represented in Figure 2a and the indicator in monetary terms, waiting related costs (C_w) is represented in Figure 2b.

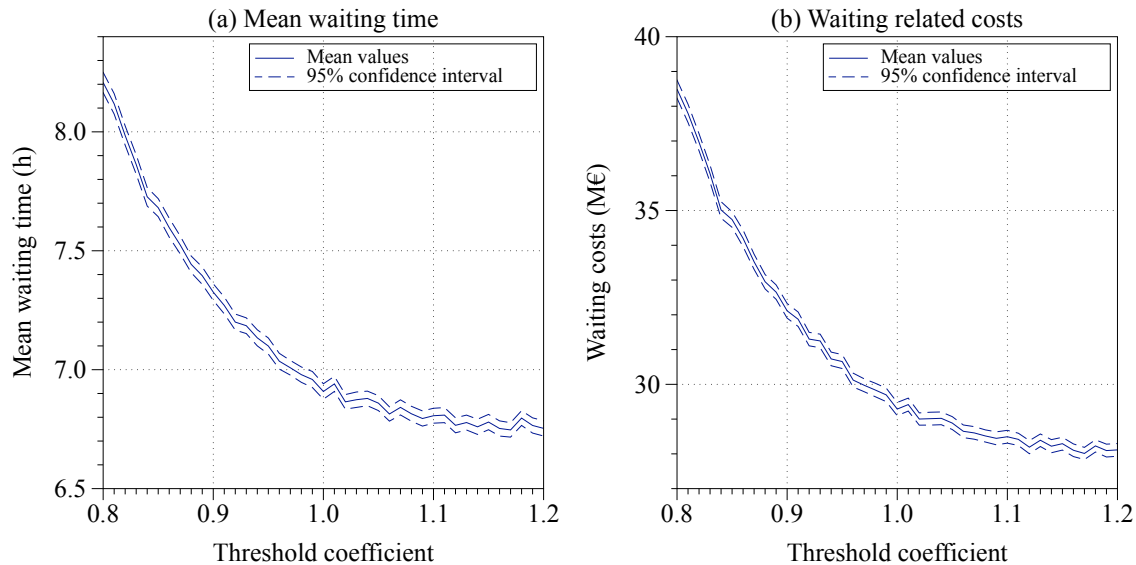


Figure 2: Indicators of operational performance. (a) Mean waiting time and (b) Waiting related costs

The qualitative behaviour of both indicators is very similar. As expected, the indicators improve their performance for higher coefficients for values up to 1.1. For example, an increase of C_u from 0.8 to 1 implies, on average, a reduction of the mean waiting time of 1.4 hours that would mean a reduction of waiting costs of roughly 10 M€. The curves, however, tend to stabilize indicating that an increase in C_u does not really imply a significant reduction of waiting times.

Figure 3 shows the results of the indicators related to safety performance. As in the previous figure, the mean value of the indicator and their bounds of the 95% confidence interval are represented for each case of threshold coefficient. The indicator number of failures, N_f , is shown in Figure 3a and the monetary consequences of the failures, C_f , is shown in Figure 3b.

It can be observed that safety decreases with increasing values of C_u with an almost linear relationship between both indicators, number of failures and their consequences, and the threshold coefficient. For example an increase of 0.1 of the threshold coefficient implies on average an increase of 1.3 failures and a consequent increase of 1.3M€ in failure costs during the study period.

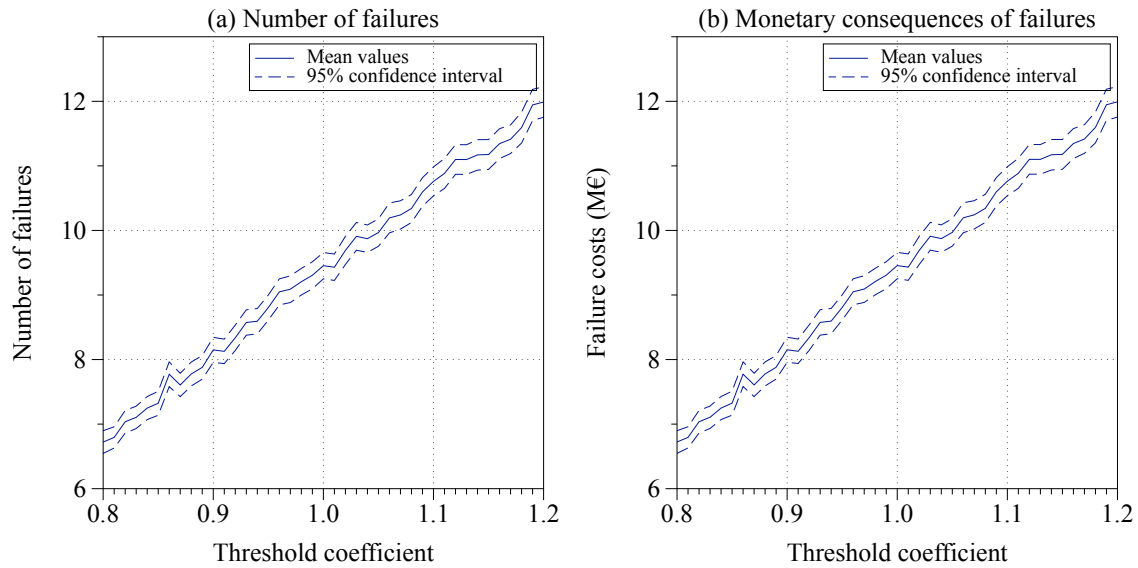


Figure 3: Indicators of safety performance. (a) Number of failures and (b) Monetary consequences of failures

Optimization of the port performance

Figure 4 shows the mean values of the utility function for each threshold coefficient. An optimal value is reached approximately for a threshold coefficient equal to 1.0.

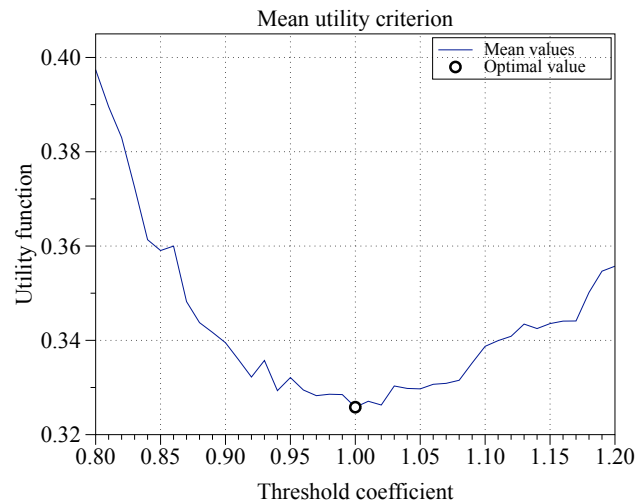


Figure 4: Mean values of utility function

Figure 5, shows the VaR of the utility for values of α ranging from 10% to 90%. The value where the optimum is achieved does not significantly change for values of α up to 40%, however for higher values it tends to decrease for increasing α .

Finally, the Hurwicz criterion was used using as the optimistic criterion the 10th percentile and the pessimistic one the 90th percentile. Figure 6 shows the results of the utility function for different optimism coefficients, β , from 10% to 90%. Except for very high/low values of beta that correspond to very optimistic/pessimistic formulations of the problem, the optimum is not sensitive to relative importance given to each criterion.

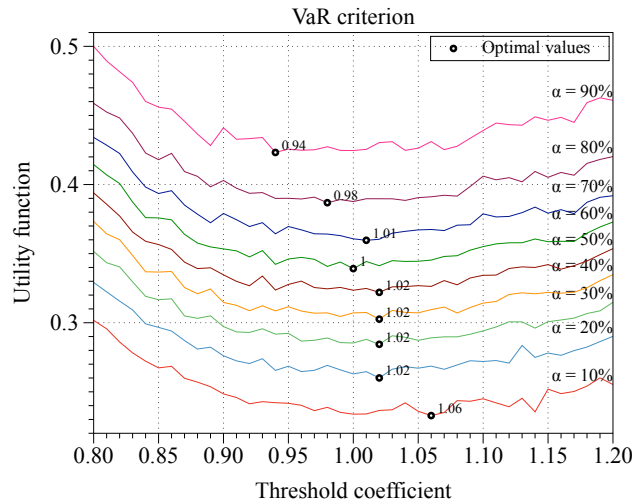


Figure 5: Value at Risk of utility function

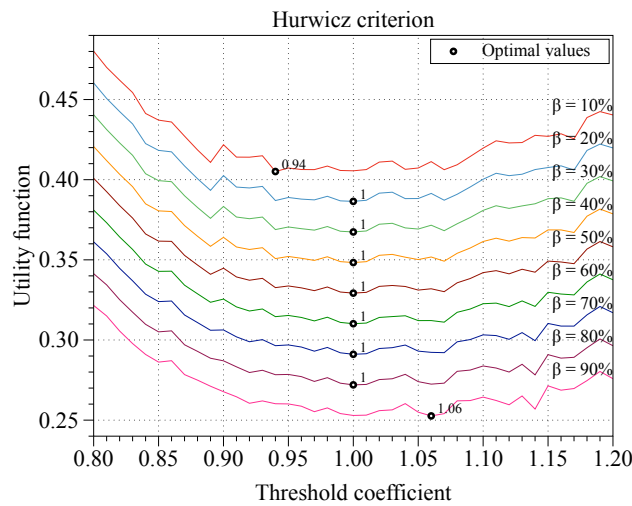


Figure 6: Utility function for Hurwicz criterion

CONCLUSION

This work proposes a methodology for port management that takes into account the uncertainty of the port performance, inherited from the randomness of the climate and exploitation agents. The methodology can be used as a management support tool to optimize operational performance and safety in ports.

The methodology is applied to a hypothetical port with the purpose of increasing the operational performance without jeopardizing the safety levels. The coefficient C_u that multiplies the climate thresholds of reference is considered as variable of decision, and its range of variation, from 0.8 to 1.2, is defined.

The performance of the port for different cases of C_u is evaluated by a model that simulates port operations that takes into account the availability of port services, berths and navigation areas, as well as the operational stoppage of the port activities caused by severe climate conditions. The model also simulates the occurrence of failures and computes their direct and indirect consequences. The performance is assessed for a set of indicators that measure the operational performance and safety.

The analysis of the indicators selected to measure the operational performance, mean waiting times and waiting related costs, decrease for increasing values of the threshold coefficient. However, this improvement becomes less significant for higher values of C_u . Regarding safety, an increase in thresholds involves an increase of the values of indicators of safety, that is approximately lineal for the selected indicator variables.

(number of failures and their consequences).

In order to obtain the optimal thresholds, a stochastic optimization problem is formulated that searches the minimum value of a linear utility function that combines the two stochastic criteria. Three different approaches to obtain the optimal value are compared. For the mean utility value, the optimal threshold coefficient is 1, which implies that the reference thresholds used in Spanish Recommendations for maritime works would be optimal in our study case. Results obtained for the other approaches indicate that the optimal coefficient is greater for an optimistic decision maker, which implies that a pessimistic decision maker gives more importance to safety.

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