OPTIPORT: AN INNOVATIVE HARBOUR DECISION-MAKING TOOL

by

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Abstract

The planning and management of a port and its resources have become a difficult task because of the increasing number of elements involved in port operations, their nature and the relations between them. Traditional methods, like empirical formulas or queuing theory are useful to simple cases. However, in the case of complex systems, the problem needs to be tackled from a holistic point of view, and more advanced methodologies should be considered. In these cases, simulation may turn out to be an appropriate solution, especially nowadays, when computation and data management are increasingly more efficient.

In this work, OptiPort, a reliable, robust, user friendly and agile software tool, to be used by port managers as a decision support tool for the management and planning of the port and its resources, is presented.

OptiPort is based on a probabilistic methodology. For a given port management strategy, OptiPort uses simulation techniques to obtain realizations of the time series that characterize climate and ship-related variables. With these variables, it reproduces port operations and obtains a series of indicators that measure the performance of the port regarding operationality, waiting times, occupancy and use of harbour services. The port performance is characterized from a statistical point of view. The tool also implements a multicriteria decision method that considers the uncertainty of the results, compares different port strategies and ranks them according to their performance.

1 INTRODUCTION

International shipping trade, and therefore, port activity, has increased dramatically in the recent decades. Harbours have become dynamic places where many operations are performed simultaneously and with many interrelated elements. Thus, dealing the port management and planning in a holistic way, considering all the port elements and their relationships, has turned into a difficult task, not only because of the high number of elements but also because of the random nature of the agents involved in port operations. And, in this context, efficiency has become an important issue in port management and planning, where delays are not easily assumed.

Simultaneously, the advances in information technologies and the increasing computing power have allowed the generalisation of certain tools or routines, like simulation.

In the recent years, simulation tools have been evolved deeply, so that they have become in useful tools to predict the performance of ports and terminals. However, they usually focus on a particular aspect of the port operations, such as a specific terminal, navigation channel dimensions, etc.

In this work, a simulation software tool based on a probabilistic and holistic methodology of port operations is presented. For a given port management strategy, the software uses simulation techniques to obtain realizations of the time series that characterize random variables -climate and ship variables-. With these variables, it reproduces port operations and obtains a series of indicators that measure the performance of the alternative in regards to operationality, waiting times, occupancy and use of harbour services. The software also compares different strategies or alternatives, which are ranked taking into

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account uncertain multiple criteria according to the Stochastic Multicriteria Decision Method SMAA-2, Lahdelma, R. and P. Salminen (2001).

The paper is organised as follows. First, section 2 describes the methodology in which the software is based. Then, the main utilities and functionalities of the software are shown in section 3. In section 4, the case study used to validate the software is shown, as well as the results of the validation process. Finally, some potential applications of the software are presented in section 5.

2 METHODOLOGY

A holistic methodology to evaluate port performance through a simulation model and taking into account the uncertainty of the random variables involved in the process has been developed. The bases of the methodology were established in Benedicto et al., (2013). Garcia Morales et al., (2015) and CIT-460000-2009-021 (2011).

The methodology is based on probabilistic methods and Monte Carlo simulations, and it allows obtaining the statistical characterisation of the port performance under some circumstances or situations at the port (future extensions, future traffic growth, alternative models of port services provision, etc.).

The application of the methodology has four basic steps: (1) define the case study, (2) reproduce port operations, (3) analyse the results and (4) compare different alternatives or scenarios.

In the following sub-sections, the main bases of the methodology are described: the procedure to reproduce port operations, the simulation of the input random variables, and the multicriteria decision method.

2.1 Reproducing port operations

To reproduce port operations, a discrete-event simulation model is used:

- A time axis is stablished, with an accuracy of one second, and the year as the time interval to be analysed.
- As the year progresses, ships make demands (e.g., when a ship arrives at the port and needs to operate at a certain quay or when a ship finishes its operations at a certain berth and desires to leave).
- The process involves analysing –as they arise– if ships' demands can be satisfied.
- To achieve this, each time a demand arises:
    a. All information related to the ship and its demand is read: ship's characteristics, the specific demand, the port services needed to satisfy that demand (pilot, tugs, etc.), climate thresholds that determine that ship operation and the port management criteria and rules that can influence the operation.
    b. A flowchart verification process begins. Step by step, availability of ship's needs to satisfy the specific demand is checked: destination (berth, anchorage, etc.), navigation channels and port services, as well as values of climate variables, and port management criteria and rules.
    c. If results obtained are positive, all the resources needed are reserved for the ship and the demand is satisfied. If any of the steps cannot be carried out, the ship will have to wait.
    d. Either way, all the information is stored accordingly.

- One by one, the demands that take place throughout the year are analysed, and all information related to occupancy of port destinations and services, delays and operationality[1] is recorded.
- At the end of the year, the information recorded is processed to obtain a set of indicators that describe the performance of the port in that iteration[2] (e.g. mean waiting time due to different reasons, occupancy rate of berths or occupancy rates of port services).

The port system is outlined in Figure 1 while a general diagram of the methodology used to reproduce port operations is given in Figure 2.

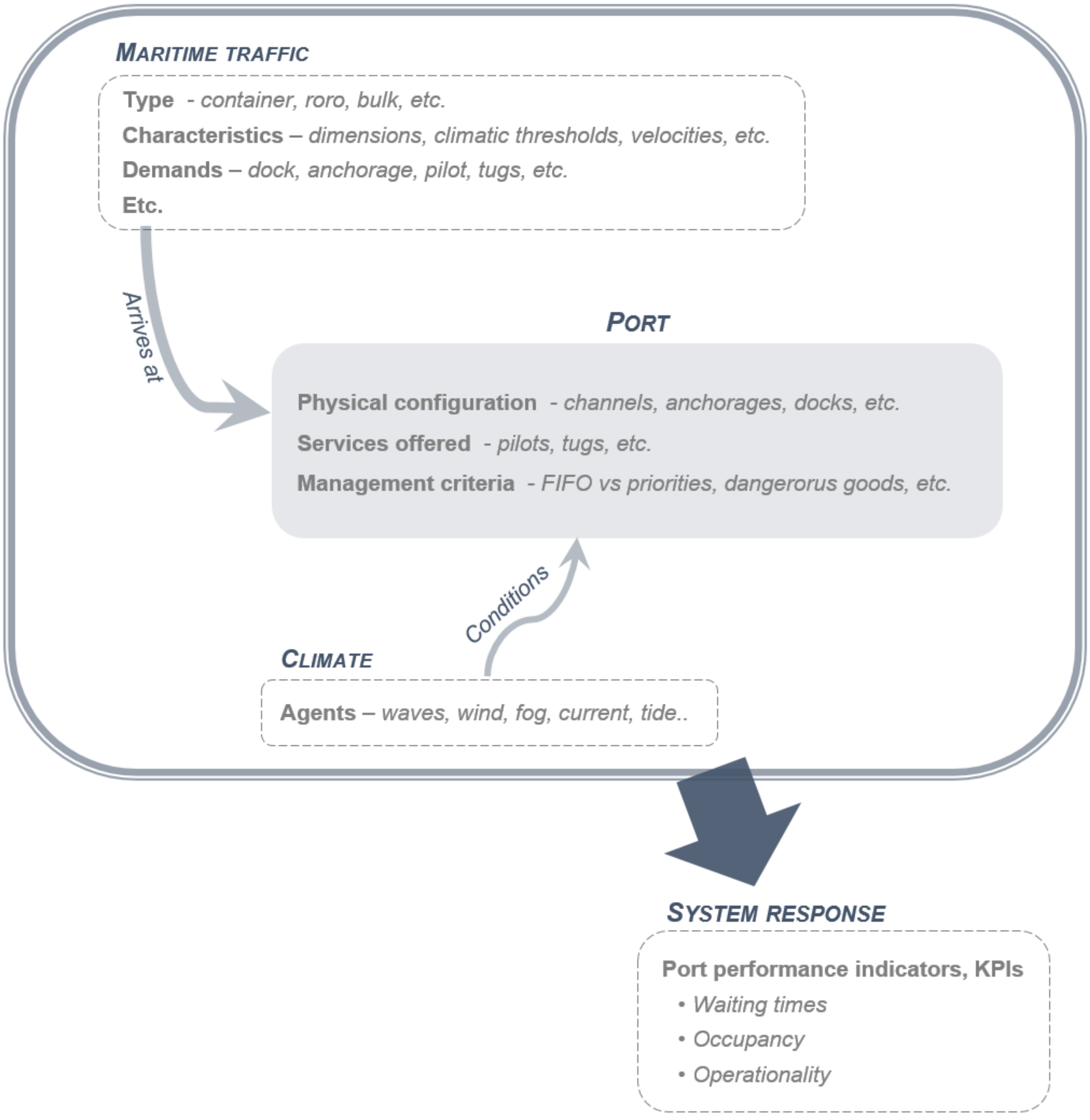

Figure 1. Port system

[1] Operationality represents the percentage of times something that is asked for is available the moment it is requested (without delay).

[2] Iteration stands for one the reproduction of the year port operations

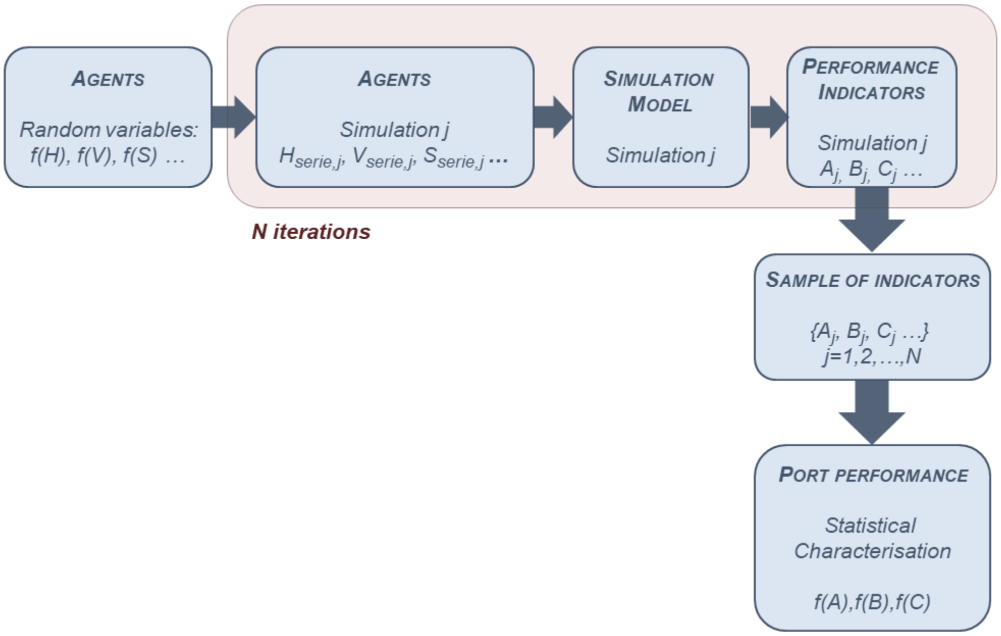

Figure 2. General diagram of the methodology

2.2 Simulation

Upon considering interrelation between elements that determine port operations, the methodology enables obtaining the result from a holistic point of view.

However, due to the random nature of some of the elements (climate agents and maritime traffic), one reproduction of the year operations does not give a representative result of the real operations at the port.

In order to have a real picture of the port operations, simulations need to be carried out. Port operations along the year need to be reproduced a high number of times (N), so that each time (iteration) a set of inputs is generated and therefore, a set of results is obtained. At the end of the simulation (N iterations) a sample of results is recorded and a statistical analysis is carried out to obtain the probabilistic characterization of the port performance.

Climate agents

Climate agents, such as waves, wind, currents, tide or fog, determine port performance.

Operations are subjected to safety procedures related to the intensity of agents such as waves or wind. For example, containers handling is not allowed when the wind speed exceeds certain thresholds. Thus, characterizing the climate agents along the year is essential to reproduce port operations.

In order to obtain series of the climate agents at the port location, the methodology proposed by Solari et al. (2011) and Solari and Losada (2012) is implemented in the software. This methodology considers an autoregressive model that uses non-stationary mixture distributions for climate variables. From climate data -wind and wave- in a point outside the port, the model analyses and generates random series that have the same characteristics as the real data.

For fog simulation, a specific probabilistic model that takes into account monthly probability of fog events, their intensity, duration of the event and event starting time has been developed.

Ship traffic

Ship traffic is simulated assuming different distribution functions for their random variables (arrivals at port, ship sizes, etc.). The inference of these distributions can be made through traffic forecasts and data analysis, as well as distribution functions defined in bibliography. For example, for some type of traffic, ships arrival can be assumed to follow a Poisson process, and the time between two consecutive ship arrivals can be modelled with an exponential distribution. However, this is not always the case, and Gamma or Erlang distributions may be more appropriate to reproduce ships arrivals. The methodology allows choosing the distribution in order to reproduce ships arrival process in the best way. It allows also taking into account that ships arrivals are made on a regular timely schedule. Vessel service times, namely, the time in which a ship stays berthed, can be modelled with continuous distributions (normal, lognormal, gamma, etc.). Bernoulli distributions are used for other random variables, like the dimension of the ships.

2.3 Decision making - Multicriteria decision method

Besides the evaluation of the port performance of a certain alternative, the software includes a module with a multicriteria decision method to compare different alternatives. This module gives the best alternative among a set of them, according to a set of defined criteria and decision maker preferences. A classic multicriteria method uses deterministic values of the criteria and weights that are combined to obtain the evaluation of each alternative. In this case, there are two aspects to take into account:

- The values of the criteria are not deterministic but uncertain. As seen in previous paragraphs, the software gives a statistical characterisation of the port performance through distribution functions of a set of indicators.
- The preferences of the decision makers about the criteria are not known, so it is not possible to define a deterministic weight.

In order to deal with these two aspects, a SMAA-2 method (Lahdelma and Salminen, 2001) was included in the multicriteria decision method module. This analysis ranks alternatives and calculates the relative importance of each criterion in the decision-making process.

3 THE SOFTWARE

The software presented in this work follows a methodology to evaluate the performance of a port through a simulation model taking into account the uncertainty associated with the random variables involved (climate agents, traffic characteristics).

The software comprises several modules to (1) define the case study, (2) reproduce port operations, (3) analyse the results and (4) compare different alternatives or scenarios.

3.1 Case study - Scenario definition module

To define a case study or scenario the following need to be addressed: port configuration, climate data, ship traffic, port services and management and operational criteria.

Port configuration

The configuration of the port (docks, anchorages, channels, etc.) is defined by the user drawing the different elements in a GIS-based map of the port area. The elements that can be defined within the software are those that are used by the ships during their operations at the port:

- Entrance of the port
- Navigation channels
- Manoeuvring areas
- Docks

- Jetties and berths
- Single-buoys

Anchorages

Figure 3 shows a screenshot of the configuration of the port of Algeciras defined within the software.

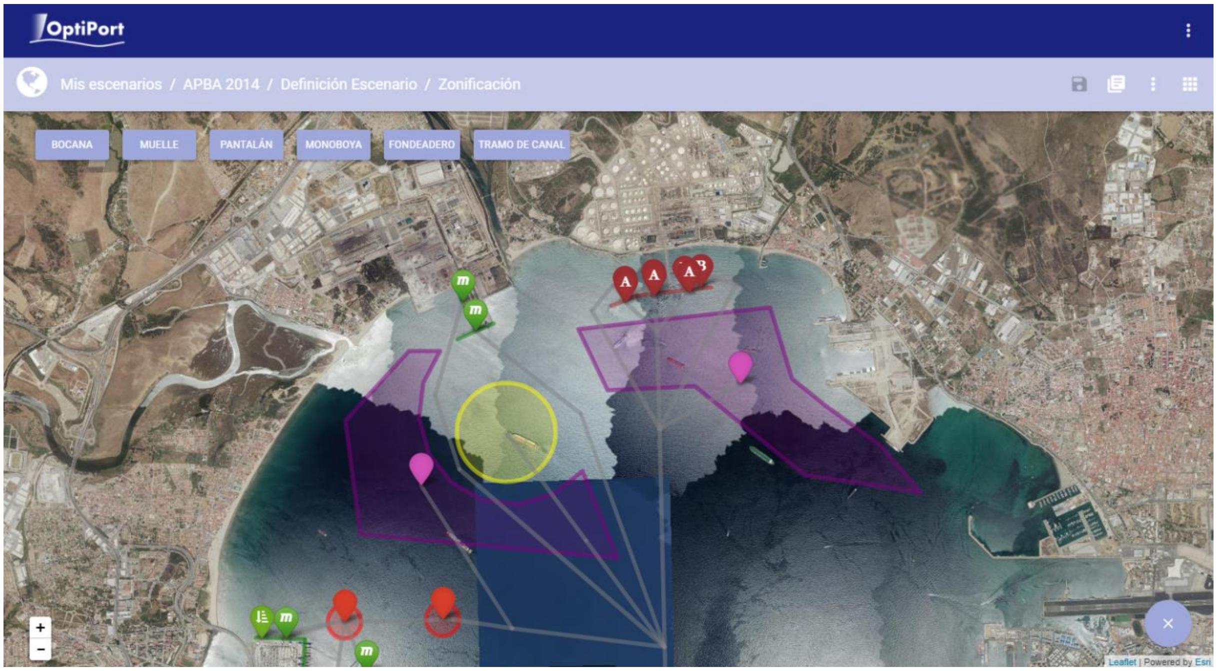

Figure 3: Screenshot of harbour configuration module

Once an element is drawn, its properties can be defined. The properties depend on the type of the element, for example, a berth is defined by – besides its location–, the depth and the maximum length of ships allowed in it.

Climate data

Port operations are subjected to the action of climate agents. Operational and safety procedures are based on the values that some agent variables reach during a certain ship operation. For example, some operations, like ship berthing, must be delayed if the wave height or the wind speed during the manoeuvre exceeds an operational threshold.

The climate agents considered in the software are waves, wind, current, visibility and sea level. The user provides the information that is necessary to generate random series of the agents in different points of the harbour:

- Wind and wave historical data (SIMAR or GOW data or similar).
- Wave propagation coefficients and port areas related to those points, so that the climate in each port destination can be computed.
- Tidal harmonic constituents.
- Probabilistic characterisation of fog events to simulate the visibility at the port.

The software gives the user the option to simulate the current generated by wind.

Ship traffic

The ship traffic module allows the user to define all the variables related to ships that arrive to the port and how they behave during their operations. This module has three parts.

Ship routes. Once the navigation channels are defined (*Port configuration*), the paths that ships follow between two points in the port are defined in this module. The routes can be defined by the user or computed automatically by the software, in which case a minimum distance criterion is used.

Ship velocities. Ship's navigation velocity is defined in this module through a set of reference points in which the entrance and exit velocity is set.

Fleets. A fleet is defined like a group of ships of a certain type (container, tanker, etc.), that share some characteristics or patterns. In this module, the user can define as many fleets as the port under study has. For each fleet, the software allows defining:

- Arrival patterns, defined by distribution functions and their related parameters or by a regular schedule.
- Dimensions, defined by a histogram. Figure 4 shows a screenshot of the definition of the dimensions of a group.
- Climate thresholds for certain operations, like berthing or loading/unloading.
- Destinations or group of destinations in which ships can operate within the port.
- Schedule of the ships at the port, like the number of destinations they go to in the same call.
- Harbour services demand, like the number of tugs that they demand depending on their size, type of operation, etc.
- Service time, namely, the time that they spend at a certain destination (dock, berth, anchorage, etc.), defined by a distribution function and their related parameters.

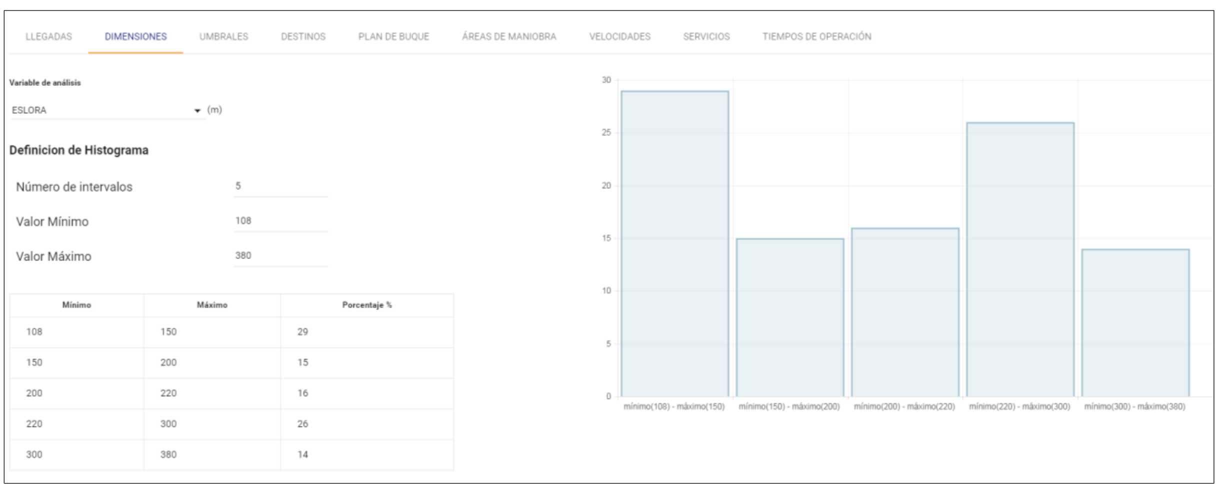

Figure 4. Screenshot of ship dimensions definition

Port services

The harbour services that are considered in the software are pilot assistance, tug assistance and mooring/unmooring. In this module, the variables to define how these services are provided by the port are defined. Some of those variables are the following:

- Areas of provision depending on the destination or the place where the resources are based.

- Season variations of the number of available resources.
- Working shifts times and number of available resources per shift.

Management and operational criteria

The software includes general operational criteria, such as FIFO method to allocate port spaces and resources and a safety clearance between two consecutive ships navigating along the same navigation channel. Besides, the software allows to define exceptions to general criteria or to create new ones, such as:

- Giving priority to some type of ships, like big containerships.
- Allowing ships pass other ships when they have different speed.
- Creating special procedures for fog events.
- Creating zones in which ships cannot navigate simultaneously because, for example, they carry dangerous goods.
- Closing the port when the climate agents exceed certain thresholds.

3.2 Simulation module: Reproducing port operations

Once the scenario is complete and correctly defined, the software simulates the scenario according to the information introduced in the previous module. For each iteration, the software:

- Generates the information for the simulation: series for climate agents, ship arrivals, etc.
- Simulates port operations for every ship and registers the information related to ship movements.
- Aggregates the registered information in order to obtain indicators that measure the port performance for that iteration.

The number of iterations is chosen by the user, and it should be enough to characterise in a correct way the performance of the port.

After the simulations, the software uses the results obtained in all the iterations to statistically characterise the performance of the scenario through distribution functions or mean values of the indicators of the port performance.

3.3 Results module: Assessing port performance

The results module shows the results obtained in the simulations in a user-friendly way. This module shows different kind of results, like mean values, distribution functions or values per iterations of the indicators. The indicators that are computed and shown are:

- Operationality, defined as the percentage of times in which a ship demanded a space at any dock or berth or a resource of any port service and the call was attended without waiting times.
- Occupancy rate of port destinations, either mean values or time distributions.
- Occupancy rate of port services and other indicators related to the use of those services, like the number of resources working simultaneously. Like destinations, the module provides mean values and time distributions.
- Waiting times caused by climate, unavailability of docks or unavailability of port services.

Figure 5 shows a figure created by the software. This figure represents the percentage of time in which a certain number of resources are providing a service at the same time under a certain situation or configuration.

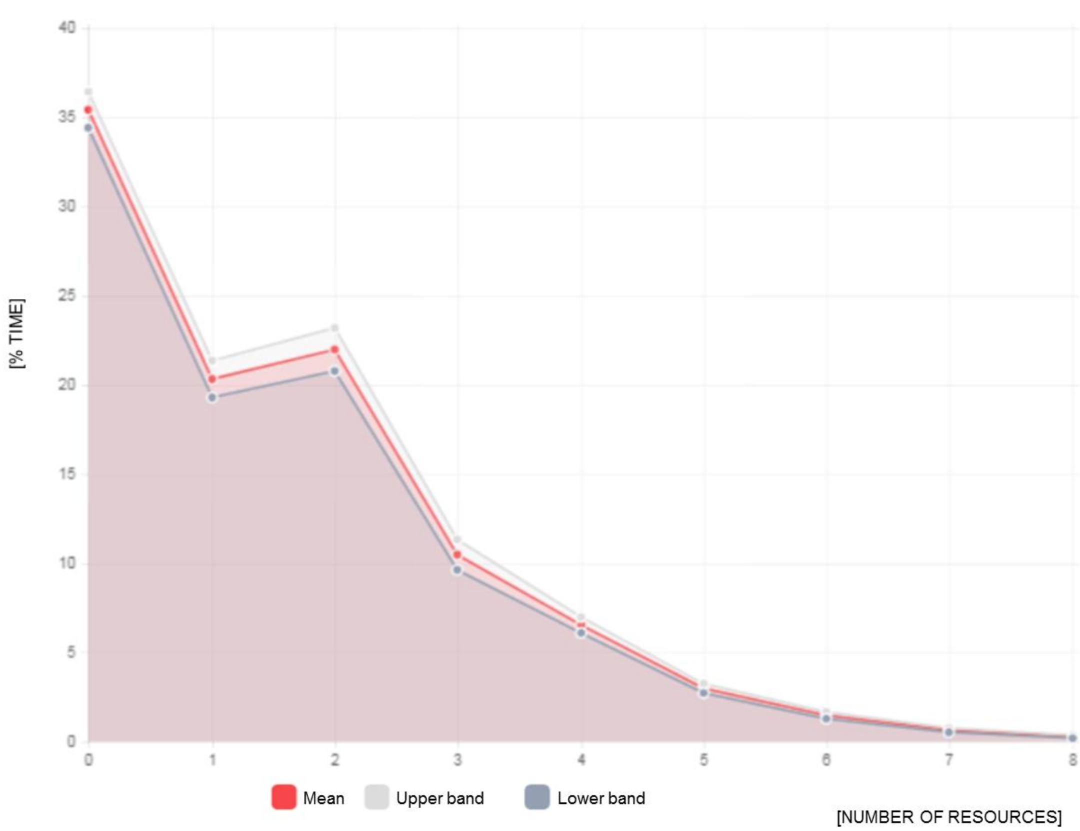

Figure 5: Number of tug boats operating simultaneously

The amount of different variables and values that are obtained with the simulations, and the flexibility and usability of the module that shows the results make this software a powerful tool to analyse the behaviour of a certain port configuration. The results can be observed and classified according to destinations, ship groups or cause of waiting, among many other criteria.

3.4 Optimization module: Comparing different alternatives

The software includes a tool to compare different alternatives through a multi-criteria decision method that takes into account the randomness of the port performance indicators. In the optimization module, the alternatives to be compared are selected, as well as the performance indicators to be used as criteria in the decision making process.

The results of the optimization module are the following:

- A ranking of the selected scenarios as alternatives.
- Acceptability index of each alternative, namely, the probability to be the best (optimal) alternative of the analysis.
- Central weight vector of each alternative, which gives an idea of how important is a criterion to select that alternative.

3.5 Technical characteristics of the software

The application has two different parts: a web application for user interface and a desktop application to compute and simulate.

Web application. The user introduces the information to define the scenarios using the web application. This application also allows the user launch the simulations and multicriteria analysis. This part has two modules:

- Front-end module, related to the visual aspect of the user interface. It has been developed using HTML5+CSS3+Javascript technologies.
- Back-end module, related to business and data layers. It has been developed using JAVA technology.

Desktop application. The second part includes the modules and engines to simulate, aggregate results, multicriteria analysis and auxiliary computations. All modules have been coded using C++ language.

4 VALIDATION CASE

4.1 The port of Algeciras: pilot port of the software

The software has been validated with a real case study at the port of Algeciras, which also took part at the software development as the port pilot.

The port of Algeciras is located at the south of Spain, next to the strait of Gibraltar. With this strategic location, at the entrance of the Mediterranean Sea and in the way of many of the main interoceanic shipping routes, the port is an important logistic hub in maritime shipping. The port is the Spanish busiest port and the fourth in Europe, with more than 100 millions of tons handled in 2016 and 2017.

Figure 6. General view of Algeciras port.

The port of Algeciras is suitable to validate the methodology and the software because of some of its characteristics:

- The port of Algeciras handles different kinds of cargo, such as container, solid and liquid bulk, roro traffic or passenger traffic.
- There are different types of berthing elements, like docks, docks with roro ramps, jetties, single-buoys and anchorages.
- The port receives a high number of ship calls every year, of the order of 22 thousand in the year 2014.

4.2 Modelling the pilot port

The port has been modelled within the software after collecting the input information of each module. The information has been provided by the Algeciras Port Authority, and it includes, for example, the following:

- Inventory of elements (docks, berths, anchorages, etc.) and their characteristics, like length, depth or largest vessel dimensions allowed.

- Historic climate data, like wave and wind registers.
- Navigation routes and procedures.
- Traffic information: ship arrivals, ship dimensions, service times at berths, port services demand, AIS data, etc.
- Provision of port services: shifts, number of resources, provision areas, etc.
- Other rules, like ship priorities or safety procedures for dangerous cargo.

This information was analysed and processed to obtain the models and needed inputs that were introduced in the harbour configuration module of the software. This is an important step, since obtaining accurate results will depend on the quality of input information and how the defined models reproduce that information.

Furthermore, the information provided by the port was analysed to obtain the real performance of the port through a set of indicators that measure occupancy rates of port elements and services. The main obtained indicators are:

- Occupancy rates of docks, berths and anchorages.
- Occupancy rate of tug boats.
- Utilisation of tug boats indicators, like the number of tug boats working simultaneously.

These indicators were used to compare with the results obtained from the simulations.

4.3 Results

Once the definition of the scenario that models the port of Algeciras is finished, the performance of the port is simulated. As said above, the optimal number of iterations depends on the variability and randomness of the data and defined models. In the validation case, it was observed that, after 20 iterations, steady mean values for most variables were obtained.

The simulated values obtained by the software and the real calculated values were compared to validate the models and the methodology. In the following paragraphs, the comparison of those indicators is described.

First, the real and simulated occupancy rates are compared. This rate depends on many variables, like the schedule of the ship at the port or the expected time to be spent by the ships at docks or berths and their dimensions. The average occupancy rate of each terminal has been calculated. Table 1 shows the difference between real and simulated values (unfortunately real occupancy values cannot be shown because of their confidentiality).

It can be seen that the simulated results were close to the real ones in most cases. The lowest observed difference is 0,03% (CLH) and the highest observed difference is 5,6% (Acerinox). The mean difference is lower than 0.7%. In general, the simulated values are similar to real values.

Terminal/Area	Type of traffic	Difference between real and simulated occupancy rates
APM Terminal	Container	-1,1
Hanjin Terminal	Container	2,6
Cepsa	Oil products	0,7
Single-buoy	Oil	1,2
Acerinox	Solid bulk	5,6
Endesa Descarga	Solid bulk	1,6
Vopak	Oil products	-0,4
Galera	Ro-Pax	-0,1
Ro-Ro ramps	Ro-Ro	-0,2
CLH	Oil Products	0,0
Anchorage areas	-	-2,2

Table 1. Terminals average occupancy rate - difference between real and simulated values.

Figure 7 shows the distribution of the occupancy at a certain dock, namely, the percentage of time in which the dock has a certain percentage of occupancy. It can be seen how the simulated values reproduces in an accurate way the trend of the curve related to real values.

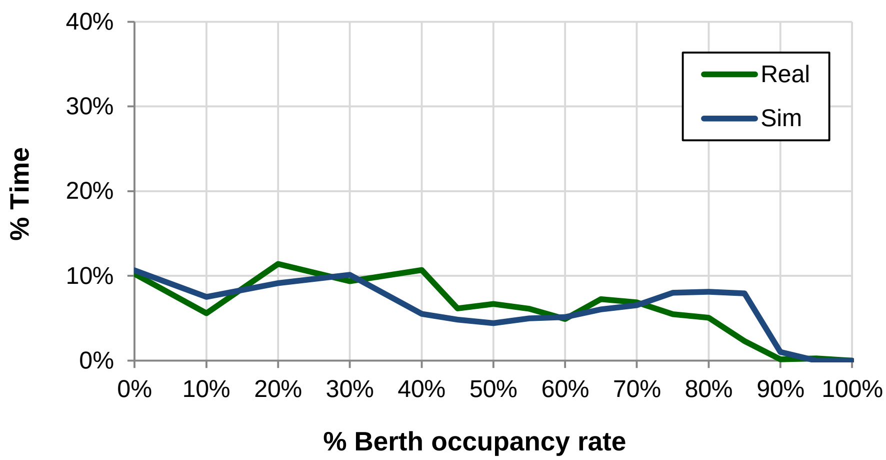

Figure 7. Time distribution of the occupancy rate.

Regarding harbour services, the information available about the provision of tugs service allows the calculation of many indicators about the performance of this port service. For example, the occupancy rate of the tugs and the distribution of time in which a certain number of tugs are working simultaneously were obtained based on the data.

The difference between the real and simulated occupancy rate of tug service is about 1%. The difference between the real and simulated time distributions of simultaneous working tugboats fluctuates between 0,0% and 2,9%. These results show that the software reproduces accurately the use and occupancy of tug boats at the port of Algeciras.

In conclusion, it has been proven that the software reproduces precisely the port performance. That allows its use to many applications to port management and planning. In the next section, examples of some of those applications are described.

5 APPLICATIONS

OptiPort is a tool to be used by port managers as a decision support tool in decision making processes related to the management and planning of the port and its resources. In this section, a set of planning and management situations or problems in which OptiPort can be applied is described. Some of these planning and management problems can be dealt with traditional tools or methodologies. Even in those cases, OptiPort gives the user additional information and a different approach, which makes the decision making process more transparent.

The evaluation of the port performance made by OptiPort allows a wide range of applications. The first and most simple one is to make a diagnosis of the operational performance of the port and its resources. Regarding the port services (pilot assistance, tug assistance and mooring/unmooring), OptiPort can detect if there are excessive delays due to the unavailability of port services resources, by analysing the waiting times causes. The occupancy rate and utilisation indicators are also good indicators of the operational performance of the port services. It is possible to detect if the occupancy rate is over a reasonable value or if there are underused resources.

The influence of climate agents on the performance of the harbour can also be measured by OptiPort, analysing the waiting times caused by the climate variables (wave, wind and currents) and by the operational procedures related to visibility. It is not possible to change the climate agents in a port, but it does enable to modify the operational procedures or thresholds related to climate agents, as well as to plan a new facility taking climate influence in port operations into account.

The utilization of berths, docks and other berthing or flotation areas is also obtained with OptiPort. Indicators, like occupancy rate and number of simultaneous ships at docks, give important information about how overused/underused are berths and docks. This information and the delays caused by the unavailability of destinations can be used to detect bottlenecks and ways to improve the management of the port.

Once the diagnosis of the port has been made, port managers can use OptiPort to evaluate different management strategies to improve the performance of the port. The strategies can be long-term ones or short-term. The first ones need appropriate traffic forecast, not only the number of expected ship calls in a certain year in the future, but also the characteristics of the those ships, for example, ship dimensions.

If inefficient performance is detected related to port services provision, OptiPort allows port managers to evaluate the efficiency of an increase of the number of resources (medium to long term, depending on the service) or another short term solutions, such as modify the location of the base of the port resources or the areas in which the services start or are provided.

Related to port infrastructures (docks, berths, anchorage areas, etc.), OptiPort can be used to detect how traffic evolution will affect the occupancy rates and waiting times, and to evaluate future port extensions. For example, OptiPort gives decision-makers more information to select the best alternative in a harbour Master Plan.

As well as port services and port infrastructures, OptiPort allows evaluating changes in port operations procedures and how they affect the harbour performance. For example, prioritizing certain traffics (large containerships) will improve the performance of those ships, but maybe other are seriously penalized. Safety procedures are also evaluated by OptiPort, related to climate agents or to dangerous goods. For example, ships carrying dangerous goods need special clearance procedures during their navigation, like areas of exclusive navigation, which will cause delays that can be evaluated by OptiPort.

OptiPort is a useful tool that helps port managers at the decision making process, having the possibility to evaluate the performance of different strategies related to port services, port infrastructures and port operations procedures.

6 CONCLUSIONS

This paper presents OptiPort, an innovative software tool, to be used by port managers as a decision support tool for the management and planning of the port and its resources.

Optiport has been developed in Spain by the companies Proes Consultores and FCC Industrial, and the Port of Algeciras as pilot port.

The software, that evaluates the performance of a port based on simulation and probabilistic techniques, is reliable, robust, agile and user friendly, to be used by port managers.

For a given port management strategy, OptiPort uses simulation techniques to obtain realizations of the time series that characterize climate and ships-related variables. With these variables, it reproduces port operations and obtains a series of indicators that measure the performance of the port regarding operationality, waiting times, occupancy and use of harbour services. The port performance is characterized from a statistical point of view. The tool also implements a multicriteria decision method that considers the uncertainty of the results, compares different port strategies and ranks them according to their performance.

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