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A DECISION SUPPORT TOOL FOR PORT PLANNING BASED ON MONTE CARLO SIMULATION

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ABSTRACT

Port planning and management has become a difficult task due to the increasing number of elements involved in port operations, their nature (random in some cases), and the relationships between them. Generally, traditional methods involving empirical formulas or queuing theory can be useful though only for simple cases. In the case of complex systems, the problem needs to be approached from a holistic point of view, and more advanced methodologies should be considered. In such cases, simulation may be the most appropriate solution, especially nowadays, when computation and data management are increasingly more efficient. A methodology for port planning and management, based on Monte Carlo simulation, is presented in this paper. A new software application, OptiPort, has been developed based on this methodology, proposed for use by port managers and planners. The methodology and the software have been validated with real data from the Port of Algeciras.

1 INTRODUCTION

International shipping trade and, therefore, port activity, has increased dramatically in recent decades. Harbors have become dynamic places where many operations are performed simultaneously and with many interrelated elements, some of which have a random nature. Therefore, dealing with port management and planning in a holistic way, considering all the port elements and their relationships, has turned into an increasingly difficult task. Furthermore, in this context, efficiency has become an important issue in port management and planning, due to the fact that a higher efficiency entails a lower maritime cost (Dwarakish and Salim 2015).

Simultaneously, the advances in information technology and increasing computing power have allowed the generalized application of certain tools or routines, like simulation. For example, in Van Asperen et al. (2003) it was demonstrated that simulation is an effective and suitable tool to study and minimize ship delays.

In recent years, simulation tools have evolved extensively, becoming useful tools to predict the performance of ports and terminals. However, they usually focus on a particular aspect of port operations, such as multi-modal terminals (Kotachi et al. 2016), planning and operation of container terminals (Shütt

2011), berth allocation planning (Arango et al. 2011), navigation channel dimensions (Puertos del Estado, 2000), grounding risk (Quy et al. 2008), land-side traffic planning at ports, and congestion (Li et al. 2016), etc.

In this paper, a probabilistic and holistic methodology based on simulations of harbor operations is presented. For a given port management strategy, the methodology uses simulation techniques to obtain realizations of the time series that characterize random variables including climate and ship related variables. Accounting for these variables, the methodology reproduces port operations and establishes a series of indicators that measure the performance of potential alternative strategies with regard to operationality, waiting times, occupancy, and use of harbor services.

The software application OptiPort, developed by Proes Consultores and FCC Industrial with the collaboration of the Algeciras Port Authority, includes the developed methodology, so that it can be used as a decision support tool by port managers and planners. OptiPort allows port managers and planners for predicting the performance of a port under different traffic assumptions, establishing alternatives to solve capacity problems or to improve the provision of port services, such as creating new berthing areas, increasing port services resources, or changing operations procedures (navigation rules, priorities, etc.). The software also compares different strategies or alternatives, which can be ranked taking into account uncertain multiple criteria according to the Stochastic Multicriteria Decision Method SMAA-2 (Lahdelma and Salminen, 2001).

The paper is set out as follows: Section 2 presents the developed methodology, Section 3 charts the implementation process for the methodology, Section 4 presents the case study used to validate the software as well as the results of the validation process, and finally, Section 5 offers some potential applications of the methodology and the software.

2 DESCRIPTION OF THE METHODOLOGY

A holistic methodology to evaluate port performance using a simulation model that accounts for the uncertainty of the random variables involved in the process has been developed. The basis of the methodology has been developed 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 simulation, and it facilitates obtaining the statistical characterization of the port performance under various circumstances at the port (future extensions, future traffic growth, alternative models of port services provision, etc.). The methodology to evaluate the port performance considers that the port operates as a system. Basically, the port system is forced by a set of agents (ships wanting to use the system, and climate conditioning the system operation), whose actions through a defined period of time (a year) provide the system’s response. The system response can be measured by a set of key performance indicators (KPIs), such as waiting times or occupancy rates. The port system is outlined in Figure 1.

The aim of this methodology is to reproduce how the system works and responds to a predefined scenario. For that, the following steps are needed. As a first step, the port system and the variables that characterize the forcing agents are defined. Second, the values corresponding to deterministic variables are read and values corresponding to the random variables are generated. Third, the model reproduces port operations within the port system. Finally, the model analyses the results and gives a set of variables that measure the port performance. However, due to the random nature of some of the elements (climate agents and maritime traffic), one reproduction of the operations (iteration) during one year does not give a representative result of the real operations at the port.

In order to have a real picture of the port operations, more than one iteration needs to be carried out. Port operations along the year need to be reproduced a large number of times (N), so that during each iteration, a new set of random variables is generated and a new realization 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.

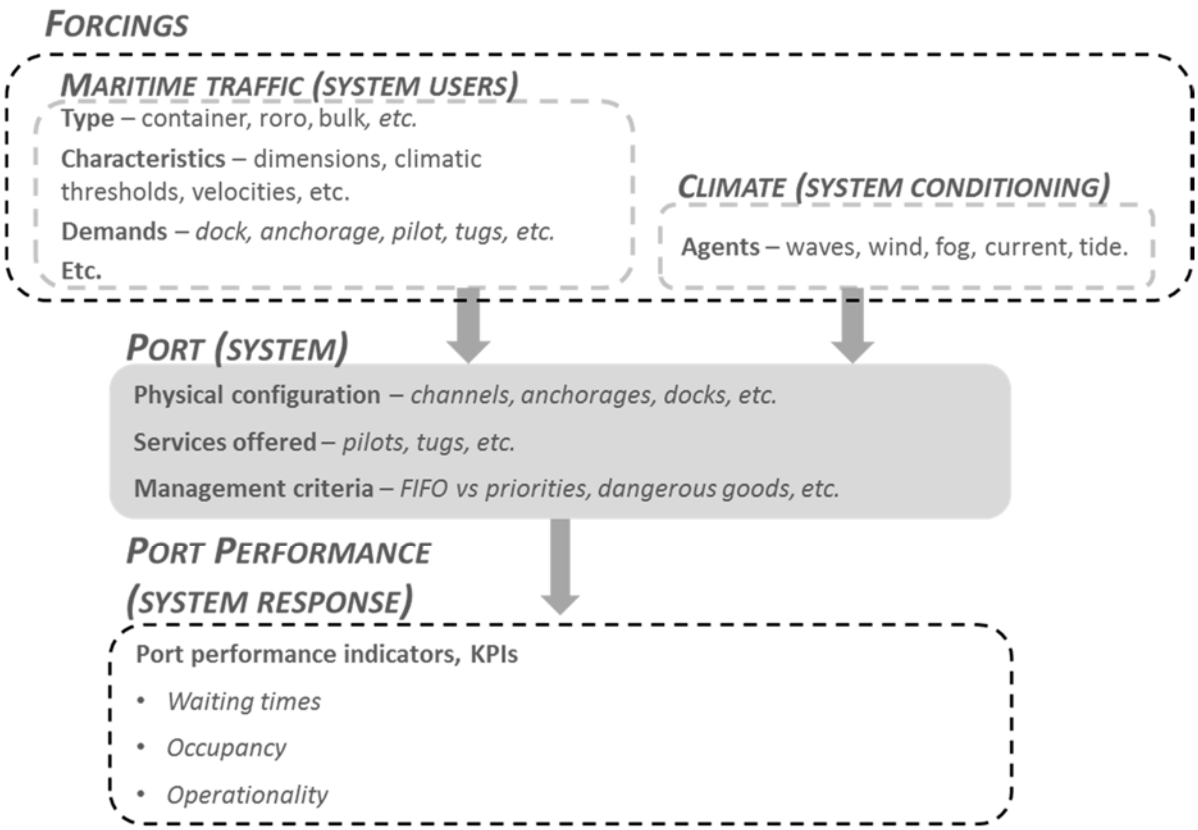

Figure 1: Port system.

Figure 2 depicts a general diagram of the methodology.

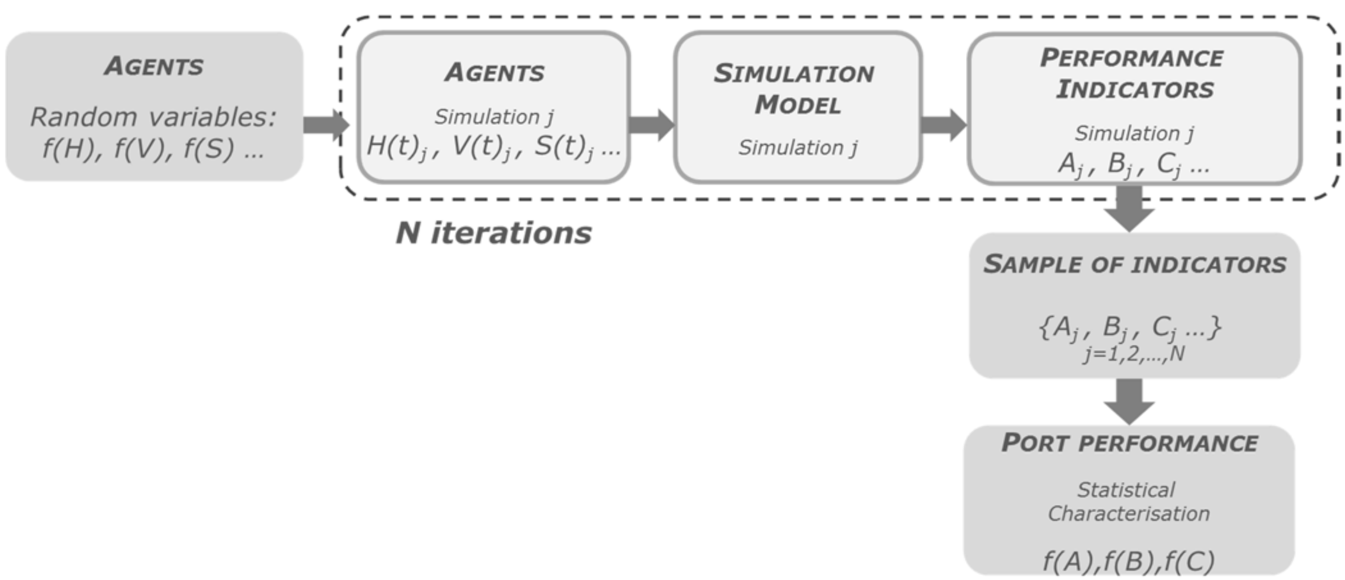

Figure 2: Overview diagram of the methodology.

2.1 Random Generation of Model Inputs

2.1.1 Climate Agents

Climate agents, such as waves, wind, currents, tide, or fog, determine port performance. Operations are subject to safety procedures related to the intensity of agents such as waves or wind. For example, container handling is not allowed when the wind speed exceeds certain thresholds. Therefore, characterizing the climate agents along the year is essential to reproduce port operations.

In order to obtain a series of the climate agents at the port location, the methodology proposed by Solari and Losada (2011) and Solari and Losada (2012) is adopted and 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 information) at 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. The model uses Bernoulli distributions to generate the type of visibility for each day (low, medium, or good) according to probabilities inferred from analyzed data. For low and medium visibilities, the starting time of the fog event is randomly generated. Finally, the duration of the event is assigned in a deterministic manner.

2.1.2 Maritime 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 theoretical distribution functions (Kuo et al. 2006). For example, for some type of traffic, ship arrivals 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 ship arrivals. The methodology allows for selecting the distribution in order to reproduce ship arrivals in the best way. It also takes into account that ship arrivals are made on a regular timely schedule. Vessel service times, more specifically 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, such as vessel dimensions.

2.2 Harbor Operations Simulation

A discrete-event simulation model has been developed to reproduce port operations. The model considers the maritime operations from the entrance of the port to the maritime-land interface (land operations and goods handling are not considered). The simulation process can be summarized as follows:

1. A time axis is established, with an accuracy of one second, and the year as the time interval to be analyzed.
2. 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).
3. The process involves analyzing if ships' demands can be satisfied as they arise.
4. To achieve this, each time a demand arises (i) all information related to the ship and its demand is reviewed: ship characteristics, the specific demand, the port services needed to satisfy that demand (pilot, tugs, etc.), climate thresholds that determine the ship operation and the port management criteria, and rules that can influence the operation; (ii) a flowchart verification process begins. Step by step, availability of what is needed to satisfy the specific demand of the ship is checked: destination (berth, anchorage, etc.), navigation channels and port services, as well as values of climate variables and port management criteria and rules; (iii) 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; and (iv) either way, all the information is stored accordingly.

5. One by one, the demands that take place throughout the year are analyzed, and all information related to occupancy of port destinations and services, delays and operationality is recorded (operationality represents the percentage of times in which a demanded resource is provided without any delay).
6. 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 (one year of port operations) (e.g. mean waiting time due to different reasons, occupancy rate of berths or occupancy rates of port services).

2.3 Decision Making – Multicriteria Decision Method

Besides the evaluation of various port performances, an additional step has been included in the methodology in order to assist the decision making process (choosing which alternative is best). This step consists of a traditional multicriteria method using deterministic values of the criteria and weightings that are combined to evaluate each alternative. However, in this case, the following aspects require consideration:

First, the values of the criteria are not deterministic but uncertain. As discussed in previous paragraphs, the software gives a statistical characterization of the port performance through distribution functions of a set of indicators. Second, the preferences of the decision makers about the criteria are unknown.

In order to address these two aspects, a SMAA-2 method (Lahdelma and Salminen 2001) has been incorporated within the multicriteria decision making methodology. This analysis ranks alternatives and calculates the relative importance of each criterion in the decision-making process.

3 OPTIPORT: IMPLEMENTING THE METHODOLOGY IN A SOFTWARE TOOL

So far, a methodology to evaluate the performance of a port using simulation models that take into account the uncertainty associated with inherent random variables (climate agents, traffic characteristics) has been presented. In order to improve functionality as a usable tool for the planning and management of a harbor, it has been developed into the software OptiPort. This software, developed by Proes Consultores and FCC Industrial with the collaboration of the Algeciras Port Authority, is a reliable, robust, agile, and user friendly software tool that can be used as a decision support tool for the planning and management of a harbor and its resources. The software comprises several modules for: (i) defining the study scenario/port; (ii) reproducing port operations; (iii) analyzing the results; and (iv) comparing different alternatives or scenarios. The modules are described in the following sections.

3.1 Scenario Definition Module: Case Study

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

3.1.1 Port Configuration

The configuration of the port (docks, anchorages, channels, etc.) is defined by the user on a GIS-based map of the port area. This module also allows for defining the properties of each element (i.e., depth, capacity, etc.).

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

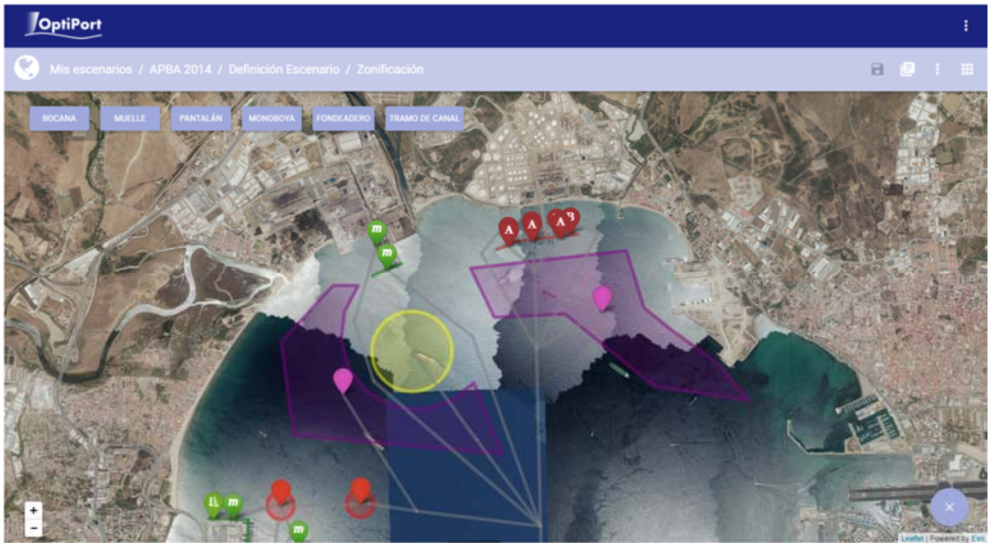

Figure 3: Screenshot of harbor configuration module.

3.1.2 Climate Data

Port operations are subject to the influence of climate agents. The climate agents considered in the software are waves, wind, current, fog, and sea level. The user provides the information that is necessary to generate random series of the agents in different points of the harbor, which include wind and wave historical data, wave propagation coefficients, and tidal harmonic constituents.

3.1.3 Ship Traffic

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

- *Ship routes*, in which the paths that ships follow between two points in the port are defined.
- *Ship velocities*, defined through a set of reference points in which the entrance and exit velocity is set.
- *Fleets*. A fleet is defined as 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. A fleet can be characterized by its arrival patterns, its dimensions, the climate thresholds for certain operations, destinations, schedules, and harbor services demand or service times. Random variables are defined in a probabilistic way, so that they can be randomly generated for the simulation.

3.1.4 Port Services

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

- Areas of provision, depending on the destination or the place where the resources are based.
- Seasonal variations of the number of available resources.
- Working shift times and number of available resources per shift.

3.1.5 Management and Operational Criteria

The software includes general operational criteria, such as the "First-in First-out" 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 for defining exceptions to general criteria or for creating new ones, such as:

- Giving priority to some type of ships, like large containerships.
- Allowing ships for passing 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 conditions exceed certain thresholds.

3.2 Simulation Module: Reproducing Port Operations

Once the scenario is completely and correctly defined, the software simulates the scenario according to the information introduced in the previous module. For each iteration, the software (i) generates the information for the simulation: series for the climate agents, ship arrivals, etc; (ii) simulates port operations for every ship and registers the information related to ship movements; and (iii) 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. There should be enough iterations to correctly characterize the performance of the port. Once the simulation has been completed, the software uses the results obtained in all the iterations to statistically characterize 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 presents the results obtained in the simulations in a user-friendly way. This module shows different categories of results, like mean values, distribution functions or values per iteration 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. As in the case of destinations, the module provides mean values and time distributions.
- Waiting times caused by climate, unavailability of docks, or unavailability of port services.

The results can be observed and classified according to destinations, ship groups, or cause of waiting, among many other criteria. 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 analyze and assess the behavior of a certain port configuration.

3.4 Optimization Module: Comparing Different Alternatives

The software includes a module to compare the results of different alternatives (scenarios) that have been previously simulated. This is undertaken using a multi-criteria decision method that takes into account the random nature of the port performance indicators. In this module, the user selects the alternatives to be compared and the indicators to be used as criteria in the decision making process. Among other results, the optimization module ranks the selected scenarios and shows the probability of each of them to be the best (optimal) alternative of the analysis.

3.5 Technical Characteristics of the Software

The software is made up of two parts: a Web application for the user interface and a desktop application to compute and simulate. Within the Web application, the user introduces the information to define the scenarios. This application also allows the user for launching the simulations and multicriteria analysis. This part has two modules.

The first module is the front-end module, related to the visual aspect of the user interface. It has been developed using HTML5+CSS3+Javascript technologies. The second module is the back-end module, related to business and data layers. It has been developed using Java technology.

The desktop application includes the modules and engines to simulate, aggregate results, apply multicriteria analysis and auxiliary computations. All modules have been coded using the 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 was also the pilot port for the software development. The Port of Algeciras is located in 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 busiest Spanish port and the fourth in Europe, with more than 100 millions of tons handled in 2016 and 2017.

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 (about twenty two thousand in 2014.

4.2 Modelling the Pilot Port

To model the port, information for every module has been collected. 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 has been analyzed and processed to obtain the needed models and inputs for the definition module of the software. This is an important step for the software validation, since obtaining accurate results will depend on the quality of input information and on how the defined models reproduce that information.

Furthermore, the information provided by the port has been analyzed to obtain the real performance of the port through a set of indicators that measure occupancy rates of port elements and services. The main indicators obtained have been (i) occupancy rates of docks, berths and anchorages; (ii) occupancy rate of tug boats; and (iii) utilization of tug boats indicators, like the number of tug boats working simultaneously. These indicators have been used to compare the real values 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 previously outlined, 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 from 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 discussed.

Real and simulated occupancy rates are compared. This rate depends on many variables, such as the schedule of the ship at the port, the expected time to be spent by the ship at docks or berths, or the ship 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). In general, the simulated values are similar to real values. The highest differences correspond to fleets that need more information than available to model them correctly (such as shipping lines or ship operations).

Table 1: Terminals average occupancy rate - difference between real and simulated 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	0.03
Anchorage areas	-	-2.2

Figure 4 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 reproduce in an accurate way the trend of the curve related to real values.

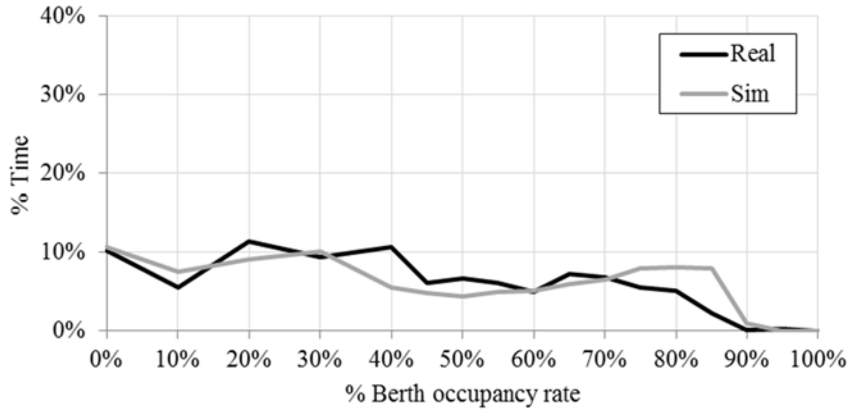

Figure 4: Time distribution of the occupancy rate.

Regarding harbor services, the information available about the provision of the towing service allows for 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 the towing 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 when the available information is sufficient to characterize the port variables. This shows that it is a useful software to be applied to decision-making processes in port management and planning. In the next section, examples of some of those applications are described.

5 APPLICATIONS

The software 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 addressed with traditional tools or methodologies. Even in those cases, this methodology gives the decision makers additional information and a different approach, which makes the decision making process more transparent.

The evaluation of the port performance facilitated by OptiPort can be used in a wide range of applications. The first and most straight forward 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 analyzing the causes of the waiting times. The occupancy rate and utilization 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 harbor can also be measured by OptiPort, analyzing 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, but the knowledge of this influence allows for adopting mitigation measures based on their effectiveness, such as modifying 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 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 or underused berths and docks are. 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 issues in the port have been identified, 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 enables port managers to evaluate the efficiency of an increase of the number of resources (medium to long-term, depending on the service) or other short-term solutions, such as modifying 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.

As well as port services and port infrastructures, OptiPort facilitates evaluation of changes in port operations procedures (due to management criteria, safety measures, etc.) and how they affect the port performance. For example, prioritizing certain traffics (large containerships) will improve the performance of those ships, and the program will inform on this. However, it will also provide information on what services might be inhibited by this decision, providing a comprehensive range of consequences and, thus, optimizing the decision making process.

All of the above uses as well as many other further applications make OptiPort a useful tool for a harbor Master Plan development.

6 CONCLUSIONS

This paper presents a methodology that can be used by port managers as a decision-making support tool for the management and planning of the port and its resources. The methodology considers the harbor operations in a holistic way and it is based on probabilistic and simulation techniques. The methodology has been included in the software OptiPort. The software is reliable, robust, agile, and user-friendly, to be used by port managers and planners. The software has been developed in Spain by the companies Proes Consultores and FCC Industrial, and the Port of Algeciras as pilot port.

For a given port management strategy, the methodology 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 harbor 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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