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Simulation and feasibility analysis of the operation of port ballast water treatment stations in the port of Santos (SP, Brazil)

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Abstract: This study analyses the feasibility of installing a ballast water system in the port of Santos (Brazil); For this purpose, a discrete event simulation model was carried out that was verified and validated and represents an approximation to the current behavior of the port and the proposed treatment system. In a first stage, a review of the literature was carried out on the fundamental issues for understanding the problem and analysis of the system: ballast water, the Brazilian port system, the port of Santos in São Paulo and the simulation of discrete events. Subsequently, the scope of the study was defined, and the analysis was limited to the export terminals of bulk cargo of soy products, corn, sugar, and citrus juices, since these are the ones that receive the vessels that will require water treatment ballast. Subsequently, the conceptual model for the port system was built, which once validated served as the basis for formulating and building the computational model that would represent the operation of the system, initially the current situation of the port and later the scenario where the operation. The normal operation of the port will be adapted to the operation of a ballast water treatment system. The model went through several verification and validation processes, necessary to determine its operation as the real system and the validity of the results obtained; It was determined that the model, under the previously established assumptions, responds in a similar way to the system before the entry of information and / or changes in the parameters. As a result of the evaluation of the addition of a ballast water treatment system to the port operation, four scenarios were proposed with different sizes of the treatment fleet and their respective implications in terms of operation within the model.

Keywords: Ballast water; bulk cargo, computational, discrete events, simulation, model, operation, port, system.

I. INTRODUCTION

The international maritime industry transports approximately 90% of the world's merchandise and is essential for the development of the global economy, since the transport of raw materials, food, commodities and other products between countries and continents would not be possible without the use of this medium [1]. Thus, the development of this industry is decisive for growth in economies and improvements in global living conditions, given the availability, efficiency, and low cost that the industry can achieve when transporting its goods by sea. There is an evident and justified trend that the exchange of goods between countries continues to increase, according to a study by the International Chamber of Shipping (ICS), the volume of maritime trade will go from approximately 9 Billion tons in 2015 to around 17 billion by 2030 [2]. This trend is not isolated from the growth in population and gross domestic product in the countries; As shown in Fig. 1, these two variables are increasing for the 2030 period, which will generate an increase in demand and needs at a global level. The goods exchange increasing worldwide, will require an expansion of international trade directly linked to the port operation, in addition to flexible and integrated supply chains.

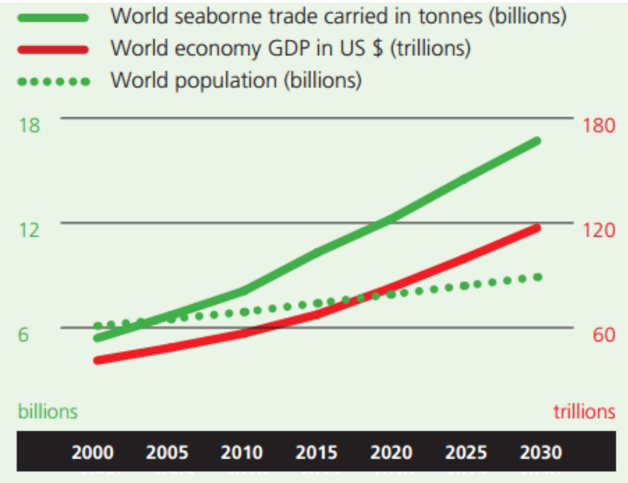

Fig. 1 Projections for increased maritime trade, GDP and population worldwide

The increasing needs for freight transport must be optimized, so that they affect to a lesser extent the products cost at the end of the chain. Countries like China will play a decisive role in the naval market, but emerging economies such as Vietnam, India, the Philippines, and Brazil will increase their shipments and will also be world leaders in that market [2].

Another determining aspect in the growth of this industry is the urban concentration that is occurring in the countries, more than half of the population lives in urban areas and the trend is increasing for the coming decades: the global urban population is expected to grow by 2.5 billion between 2014 and 2050, that is, 66% of the population will be concentrated in urban areas [3]. One of the implications of this urbanization process is the environmental deterioration caused by the greater intervention in the ecosystem, exploitation of resources and generation of waste caused by the industrial operation, and it is of interest for this study, the environmental deterioration derived from the operation of the maritime industry.

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The interoceanic movement of vessels generates various sources of pollution, such as C02 emissions, cargo residues and ballast water. Ballast water is the water transported by ships to submerge their propellers and ensure their stability and structural integrity, which, while essential for modern, safe, and efficient transport operations, is causing serious ecological, economic, and environmental problems. public health due to the number of marine species it carries. Different organizations have wanted to take action on the issue in the sense of seeking a solution to the problem, the IMO - International Maritime Organization and its marine environment protection committee (MEPC) - which since 1948 regulates transport and maritime activities, adopted in 1997 resolution A.868 (20) "guidelines for the control and management of ships' ballast water to minimize the transfer of harmful aquatic organisms and pathogenic agents" as an invitation to all countries to take action in order to mitigate the problem. This resolution is still in force and has been integrated with other programs such as GloBallast (global ballast water management program) and at the national level with standards such as NORMAM-20 / DPC in Brazil [4].

This paper studies the local environmental problems derived from the use of ballast water in the port of Santos, BR, the largest in the country and classified as the second in Latin America in terms of cargo movement. (Latin American Association of Ports and Terminals, 2014). The port of Santos was responsible for the transport of 111,159,485 tons of cargo in 2014, of which 76,574,936 (69%) corresponded to export cargo and the remaining 31% in imports. The main products that were dispatched from the port in 2014 were sugar (17,276,544 tons), soybeans (16,464,584 tons) and corn (8,967,526 tons) [5].

The current operation of the port was analyzed as a base scenario to evaluate the incorporation of a ballast water treatment system, which would alter port operations and the logistics costs associated with them to a lesser extent. The alternative treatment analyzed consisted of the operation of treatment stations in vessels dedicated only to this task, which wait in the canal and in the anchorage area due to the requirements of the vessels that arrive to load with bulk. These treatment barges are connected to the vessels and shed the water as the cargo tanks fill up, to maintain stability throughout the operation.

To analyze the operation of the water treatment system, we started from the verified and validated port operation model and the addition of the system and its implications on the performance were evaluated; this to present the investment in a treatment system as a viable option for port operators, who, although they would incur other costs for the installation and maintenance of the system, would prefer to preserve the performance of their operations which is a priority [6]. Furthermore, this treatment is not a need for logistics operators given the lack of regulation on the subject and if it is included in their planning, it is for other benefits for the company [7].

This study did not evaluate the operation of the port, that is, the system was simulated with input data demands, pre-operation, operation, and post-operation times, under the assumption that cargo is always available at each dock and that once the vessel is docked, it begins its operation, ignoring the probability of delays in loading, bankruptcy of equipment and other variables that undoubtedly affect the operation.

II. PROBLEM SITUATION

The world economy is highly dependent on maritime transport, an average that a year transports approximately 90% of the loads that move around the world; Advances in the growth of this maritime industry and international maritime trade are determined by macroeconomic conditions around the world [3]. Over the years, various impacts that this industry is causing to the environment have been identified, the IMO highlights the pollution caused by hydrocarbons, chemicals, wastewater, garbage, and atmospheric emissions. Although initiatives to mitigate these impacts have been and should be carried out, some of these are generated by accidents that are difficult to foresee, so the industry must work on attention plans to these events that make a precise and timely response when necessary. The case of water pollution occurs in two ways, on the one hand, the wastewater generated by the operation of ships and, on the other, the impact of the discharge of ballast water in the environment [8], [9].

Ballast water is that which gives stability to ships, its transport helps to maintain safe conditions during the trip, thanks to the fact that stress on the hull is reduced, provides transversal stability, improves propulsion, maneuverability and compensates for changes in Weight presented according to load level and fuel and water consumption during the tours. Quantities of marine species are transported on ships by ballast water, including bacteria, microbes, small invertebrates, eggs, among others. These species, which are unloaded in the port where the vessel picks up merchandise, can survive in the new ecosystems where they arrive, but they become competition for native species and multiply in the environment as pests.

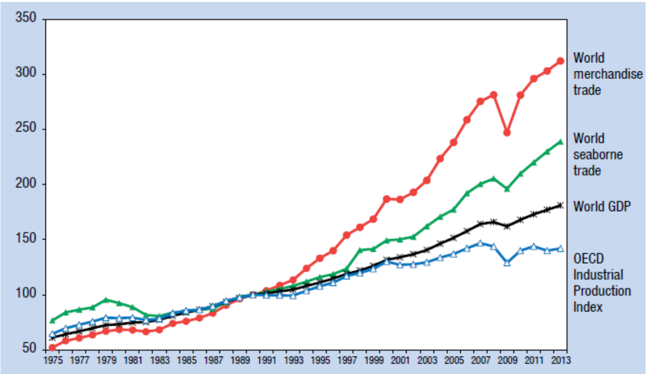

Fig. 2. Behavior of the OECD countries production index vs world indicators.

This problem is now recognized as one of the greatest threats to ecological and economic well-being worldwide. The introduction of species by ballast water causes great damage to the biodiversity and natural resources that we have, in addition to having increasingly serious effects on human health [4]. Even so, this problem has not yet reached its highest point, as mentioned, it is derived from the growing expansion of trade and the greater volumes of merchandise that are transported by sea, which continue to tend to increase over the years. and to reach out and affect new areas.

III. METHOD

To study the problem, the methodology used is adapted from [10], which is shown in the figure 3.

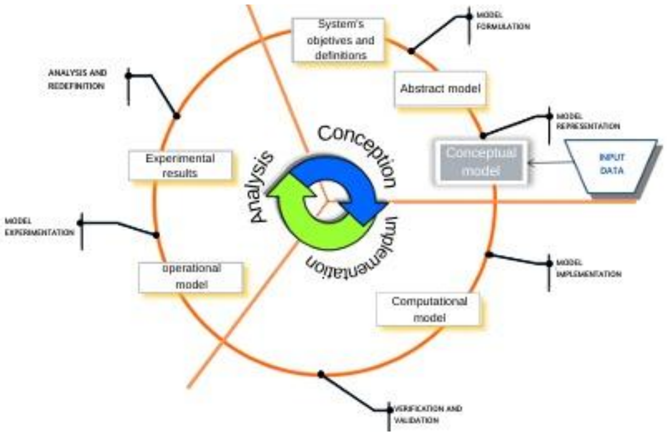

Fig 3. Methodology for of discrete event system simulation.

An initial stage of conception of the study, the objective of the study was defined to analyse the operation of a ballast water treatment system in port for the port of Santos. As already mentioned in other points, ballast water is transported by ships that sail without or with little load, that is, ships that arrive at the port to export and, in general, only bulk carriers transport ballast, for this reason, the study was delimited to the terminals exclusively dedicated to export activities of bulk cargo: soybeans, corn, sugar, juices and fertilizers. Of the 65 terminals that currently operate within the port, 14 terminals were identified as bulk cargo export terminals as shown in Table 1.

Table 1. Terminals and export products in the port of Santos. Source Author.

Terminal	Productos
ADM	Soy / Corn
COREX	Soy / Corn
Cutrale	Soy / Corn / Juices
Citrosuco	Soy / Corn / Juices
TGG	Soy / Corn
TEAG	Soy / Corn / Sugar
TEG	Soy / Corn
TERMAG	Solid bulk / Fertilizers
Armazem 12A	Soy / Corn / Sugar
T-grão - silos	Soy / Corn / Juices
Rodrimar	General Cargo / Fertilizers
Rumo/Cosan	Soy / Corn / Sugar
Copersucar	Sugar
Pérola	Fertilizers

Once these terminals and the products to be worked had been identified, the conceptual model was formulated that would represent the operation of the port-system without the adaptation of the ballast water treatment system shown in Fig 4, which was necessary to validate the normal operation of the port and on this subsequently analyse the operation of the ballast water treatment system.

The operation of the port system involves several events that have already been mentioned in the theoretical framework of this work. In the first place, the ships arrive at the anchorage area where the port authority registers their arrival and it is defined when the ship will be able to enter the terminal where it will load the respective merchandise; the anchorage area is the row of all the ships that are waiting to dock at the respective docks, it should be noted again that these rows for the case study (Port of Santos) are the bottleneck of port operations and the main port performance problem.

Once the ship has channel and dock availability to dock, in addition to the environmental conditions being favourable for navigation, the manoeuvring operation begins, which consists of navigating the access channel to the area where the turn and navigation is carried out. to the dock of attraction. Once the ship docked at the respective dock of the terminal where it will operate, the pre-operation begins, where the documents of the ship and the cargo are inspected and it is verified that the conditions for the operation are being met to begin the loading of the merchandise, which is the next process. Once the loading operation is finished, in this case of the bulk cargo tanks, the post operation begins, where the ship's departure order is inspected and given, environmental conditions for channel navigation and availability of the same to proceed to carry out the departure navigation and leave for the cargo destination.

The scope of the study was defined, and the conceptual model of its operation built, we proceeded to define and search for the input data for the model.

II. METHODOLOGY

Collection of input data to the model: There are 3 different public databases on the port of Santos, information on the port, the ANTAQ and the company that carries out the piloting operation; the origin of the information used in the model was mainly from the data of the port and the ANTAQ, given the greater availability and reliability of the data [11].

The construction of the model required several input data, which are presented below:

Quantities of merchandise for each type of product transported in 2013 by each terminal: This information was obtained from the port's database. The record of the year 2013 was taken from all the ships that passed through the port and only the data related to the export terminals included within the model were used, particularly, the transported quantities of four products: soybeans, corn, sugar, and citrus juices, which represent the largest volume of exports within bulk cargo export terminals. Although the fertilizer export terminals were included in the elaboration of the model, they were not analyzed within this study due to the insufficient information, however, in a later study, the operations of these three terminals (TERMAG, Rodrimar and Pérola) and evaluate the treatment system operating on them as well [5].

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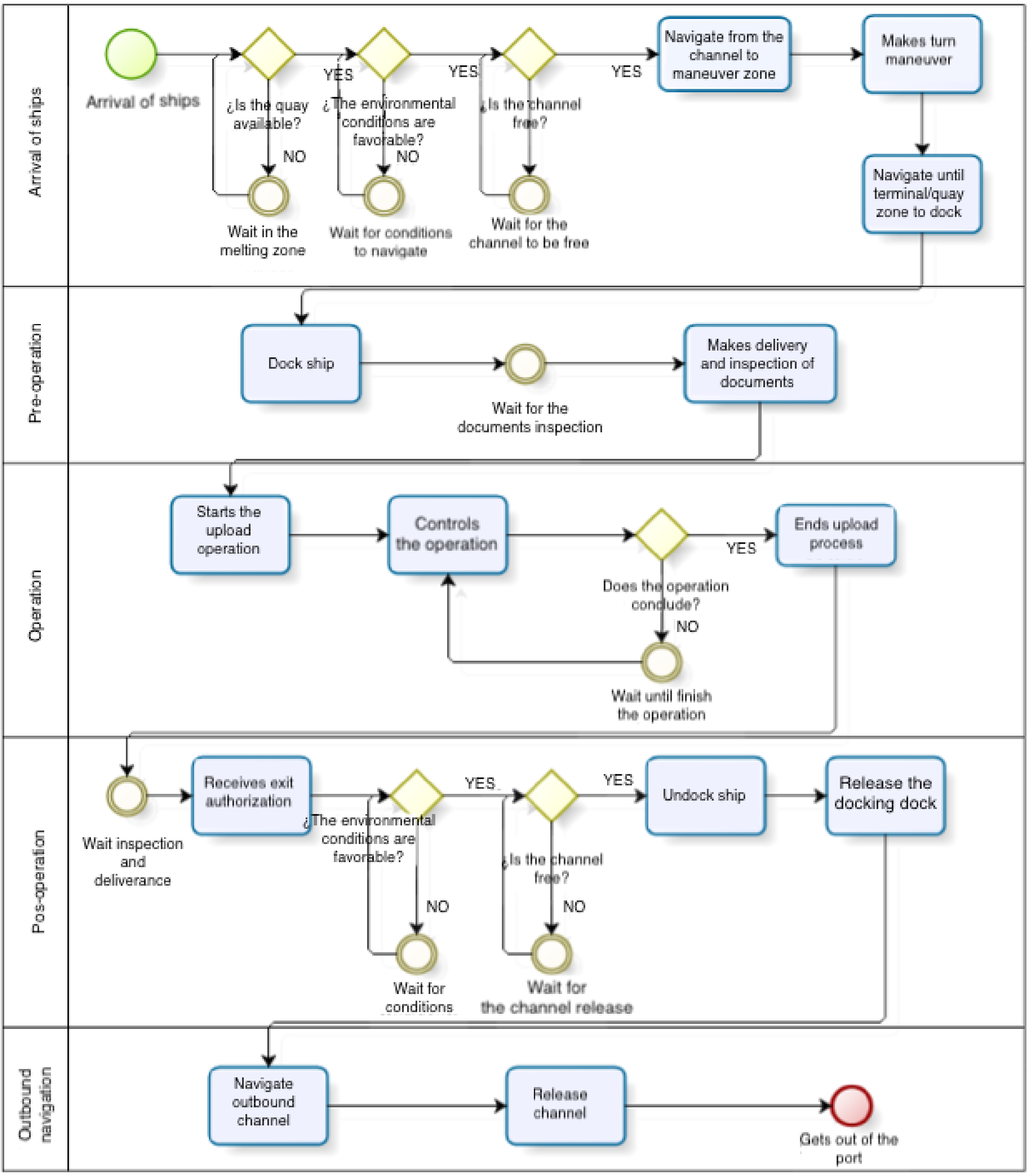

Fig 4. Conceptual operation model of the port of Santos, Br. Source Author.

Average weight of the vessels that frequent the terminals: this parameter is one of the assumptions that will be mentioned later, the average size of the vessels that enter the port to transport bulk cargo was taken as 60,000 tons.

Product amount transported in the year (by harvest season): This information was taken from the website of the national association of grain exporters. The entity arises with the purpose of promoting the development of activities related to grains and cereals, in addition to defending the interests of its 35 associated companies before public and private authorities. The organization is the one who monitors the evolution of grain exports, on the website you can find information from the quantities exported of each product in each port to the quantities exported each month for each product during a year, which was essential. for the distribution of the total quantity shipped.

Operations Times (Pre-operation, operation, and post-operation): This information was taken from the Master Plan of the port of Santos prepared by the Secretariat of ports of the Presidency of the Republic in agreement with the Federal University of Santa Catalina.

The canal journey time: it was estimated by dividing the canal into three sections, measuring the distance of each of the sections and dividing by the navigation speed within the canal.

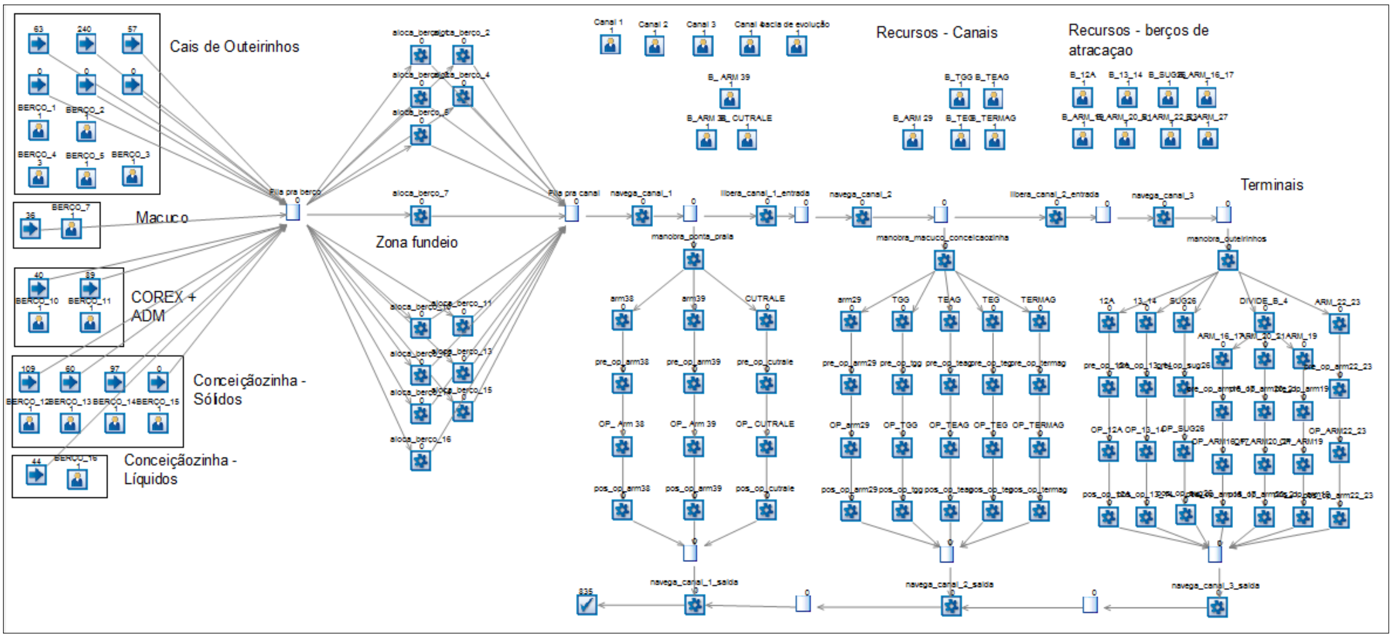

Fig 5. Simulation model of operation of the port of Santos, Br.

The distance of each stretch was measured using the Google Earth tool in nautical miles; The speed for navigation within the channel is given in the literature, on average, the ships sail at eight or nine nodes of speed, given the conditions of the channel, an average speed of 9 nodes was taken as a measure for this study for all the ships.

Travel time between terminals for treatment barges: This time was calculated similarly to the travel time for the canal, with an average speed of 12 nodes. (See annexes). The lengths were taken very close to the continent, contrary to those of the channel, this because the barges can navigate close to the dock, the large vessels cannot.

Defined scope, conceptual model, and input data for the model, a second stage called according to the implementation methodology was entered, where the computational model was built and its functionality and precision in representing the real system studied was verified and validated. Initially, the assumptions that were considered to formulate the model were raised: Cargo is always available at the export terminals, the vessels that enter to load merchandise at the related ports are mostly of the Panamax class, the service of the ships that arrive at the port is FIFO (first in first out), no terminal has priority, the ships are attended in order of arrival and the environmental conditions do not represent major inconveniences for the operation within the port, the ships dock at the respective dock in the direction of departure from the port, that is, all the ships when entering the channel, navigate to the end where the turning area is, make the turning maneuver and return to the terminal and dock to perform the operation.

The model run under the logic of "first to arrive first to be attended", none of the terminals has priority over another to enter the first operation of navigating the channel. As shown in **Fig 5**, the system has three major operations that were also described within the theoretical framework of the work: the arrival of the ships to the anchorage area, the navigation channel, and the terminals and docking bays. Initially, the figure shows the generation of the ships for each terminal, organized by zones as they are distributed in the port (See annexes), once they enter the system, they go to the waiting line for dock assignment, the so-called zone of anchorage, which is where ships wait for the availability of the dock, channel, and the necessary conditions to be able to enter and go into operation. In the model, this row was divided, initially the vessels are in line for dock availability, they go on to an activity of "dock assignment" and enter the last wait for channel release, this to analyze and reveal the neck Port bottle, which is the channel availability as it will be shown later in the results and analysis point.

Once the ships have a channel and dock available, they proceed to carry out the entry navigation to the port, an operation that was divided into sections according to the location of the destination terminal; Once they navigate channel 1, 2 and / or 3, they proceed to perform the turning manoeuvre, where for the ease of the model, the turning manoeuvre and navigation of the rest of the sections, entry and exit required for the ship to be in direction of exit as determined within the assumptions to the model. Once the manoeuvre has been carried out, the ship is ready to dock at the assigned dock and carry out the pre-operation, operation and post-operation and navigate the exit channel.

Based on the input data collected for the model, the distributions for arrivals and the activities involved were determined; It is worth mentioning that month by month the model updates the input data since the calculations consider the harvest times of the products, especially soybeans and corn, which are the products that have a more variable behaviour during the year (see annexes). Each of the main processes carried out and the way in which the distributions and other times necessary for the operation of the model were determined are briefly explained below:

The arrival of vessels to the port was separated by terminal, this to characterize the entrances by dock to which they were going to dock, channel, section of the channel that they required to navigate and type of product that entered each time (according to product distribution).

To estimate times between arrivals at the terminals in each month, the starting point was the amount of cargo per product transported per year multiplying it by the proportion of product that was exported in that month (See annexes); Thus, the load that was transported of the specific product during the month was determined. With this figure, it was sought to determine the number of ships that would be necessary to transport such cargo, dividing it by the ship's capacity (Panamax, 60,000 tons) and rounding this figure to the largest integer. Given the number of vessels that would be required per product in each terminal, the total for each terminal was determined and the total hour-month was divided by the number of vessels, and this last figure was used as the mean for the exponential distribution that would describe the entry of the boats to the model. The exponential distribution is the one that best describes the entries in a queuing system, given the uncertainty that the times between user arrivals represents for the system.

Canal navigation was divided into sections to size the distance traveled by the terminals according to the area in which they are located within the port, as shown in Fig 6. The first terminals, located in the area called "conceiçaozinha" both Liquid as well as solid bulk, they travel entering the port only section 1, the terminals that are part of the Export Corridor (COREX), ADM and Macuco travel sections 1 and 2 and the other terminals in the area called “Outeirinhos” travel to the entrance the three sections.

Fig 6. Distribution of terminals within port areas.

The entry navigation times depended on the distance measured for each section and the speed that is currently allowed in the port for medium and large vessels, for these channel navigation times in the three sections the average distribution was used that the software offers, which is a normal distribution with a predefined coefficient of variation of 25%.

Ships arrive and enter the queue waiting for the availability of the pier to which they are going, which is represented as a resource within the model. Once this resource is available, the vessel goes to the “dock assignment” activity that follows a fixed distribution at zero because it is simply where the use of the resource is assigned to the vessel that is only released in the post operation. Once the "dock" resource is assigned, the vessels enter the queue for channel availability, which is the one that really represents a bottleneck for the operation.

Input channel navigation: Canal navigation is one of the assumptions within the model. In general, the vessels dock at the terminal after making the turning maneuver and with their bow in the exit direction, although some vessels can also do so at the entrance. Given the little information found in this regard, that is, there is no document or information on the network that says when the vessels dock at each of the terminals, it was assumed, as the common denominator of the port, that all vessels they dock once they have made a turning maneuver.

Maneuver at the tip of the beach: This activity is the one that describes the navigation to the turning area, the turning operation, and the arrival to the export terminal, that is, the assumption that the ships dock at the port exit. This maneuver then includes, in addition to the turn time, the travel times that are lacking for each vessel to reach the respective terminal, for example, for ships heading to some of the first terminals in the “Conceiçaozinha” area, After navigating channel 1, they arrive at this maneuvering activity where the travel time of section 2 and 3 (round trip) plus the turning time is considered twice; for vessels bound for COREX, ADM and Macuco, which have already sailed sections 1 and 2, the navigation time of section 3 and the turn time are taken into account twice and, finally, for the terminals located in “Outeirinhos” it is considered only the turn time, since the boats have already covered the three sections and once the turn is made they are in the area where they will dock.

Table 2. Zero turn and navigation times scenario

		Low 95% Range	**Average Result**	High 95% Range
Canal Queue	Average Queue Size	0.00	0.00	0.00
	Average Queuing Time	0.00	0.00	0.00
Berco queue	Average Queue Size	3.32	4.00	4.69
	Average Queuing Time	34.99	41.89	48.80
Total ships	Number Completed	817.17	829.20	841.23
	Average Time in System	90.74	97.84	104.95

Pre operation, operation, and post operation: Once the vessels carry out the turning maneuver, they go through an activity that within the model has the name of the terminal, this activity does not influence in terms of time within the operation, but it is where the dock to which it is going to dock is assigned. To give clarity at this point about the "dock" resource, there are two within the model for each terminal given the need to quantify the time in which the resource is "reserved", that is, the time allocated from the beginning until it is released in the post-operation and the time in which the resource is used within the

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operation, that is, it is assigned in the activity that precedes the pre-operation.

The pre-operation and post-operation times also follow a mean distribution within the model with a value equal to 1.2 h for all terminals, this value corresponds to an approximation validated by the experts to the duration of these operations, given the non-existence of this data within the databases reviewed. The operating times were taken from the Master Plan of the port of Santos of the year 2013, although there is not complete information for each terminal and the products, an average of 50 hours was considered for the operation except for some terminals that do present in the literature more detailed information of time according to the type of product that is being loaded.

Exit navigation: Finally, the vessels go through the departure navigation activity where they travel the distance that is necessary to leave the channel and finish their operation within the port.

Model verification and validation

The processes of verification and validation of the model were transversal to its construction, that is, once the computational model was built, tests of its operation were carried out and possible errors were identified and resolved before advancing to the next stages, as more were added. restrictions, variables, and parameters to the model that would complicate the identification and solution of possible inconsistencies. For verification, the response of the model against degeneracy tests or extreme values, continuity and simplified runs is shown in table 3.

Table 3. 200,000-ton vessel operation scenario

		Low 95% Range	Average Result	High 95% Range
Canal Queue	Average Queue Size	0.00	0.01	0.01
	Average Queuing Time	0.09	0.10	0.12
Berco queue	Average Queue Size	0.49	0.60	0.71
	Average Queuing Time	10.15	12.17	14.19
Total ships	Number Completed	405.83	423.50	441.17
	Average Time in System	72.06	74.31	76.56

Degeneration tests: This test consists of checking the model by using extreme values in the inputs to the model.

In the first place, a scenario was evaluated where there is no demand for cargo to be transported in any of the terminals, so it is expected that vessels will not enter the system and therefore no operations will be carried out nor will there be departures at the end of shot, that as there is no demand, no terminal generates ships and all operations have zero value. The scenario where the navigation and turn times are equal to zero was also tested, under these conditions it is expected that no queue will be generated due to channel availability, since this activity would not take any time.

Finally, a last test of extreme value was carried out where the ships that entered the port were larger, for the case about 200,000 tons of merchandise, where it is expected that the number of ships served would be much smaller and the lines would be similarly reduced considerably.

Continuity tests: This type of test consists of running the model several times with small variations in the input parameters, where a small change in the initial value of any parameter is expected to produce only small variations in the results. For example, the pre-operation and post-operation time was changed from 1.2 hours to just one hour, the changes in the results are shown in the table 4 and table 5.

Table 4. Results with pre and post operation times equal to 1.2 hours.

		Low 95% Range	Average Result	High 95% Range
Canal Queue	Average Queue Size	0.02	0.02	0.02
	Average Queuing Time	0.22	0.23	0.25
Berco queue	Average Queue Size	3.76	4.60	5.43
	Average Queuing Time	36.97	48.09	56.51
Total ships	Number Completed	816.90	829.10	841.30
	Average Time in System	97.98	106.61	115.24

Table 5. Results with pre and post operation times equal to one hour

		Low 95% Range	Average Result	High 95% Range
Canal Queue	Average Queue Size	0.02	0.02	0.02
	Average Queuing Time	0.21	0.22	0.23

Berco queue	Average Queue Size	3.68	4.48	5.28
	Average Queuing Time	38.81	46.86	54.91
Total ships	Number Completed	816.76	829.00	841.24
	Average Time in System	96.72	104.97	113.23

Simplified runs test: this test seeks to run simpler or simplified cases and analyze the behavior. In this case, the model was run generating load only for the ADM terminal, so it is expected that only this one operates, and the outputs are consistent with the inputs, that is, they correspond only to this terminal. Additionally, the row for channel should be equal to zero and the bottleneck in this case would be the availability of the dock.

Table 6. Simplified runs test, only ADM terminal generates load.

		Low 95% Range	Average Result	High 95% Range
Fila para canal	Average Queue Size	0.00	0.00	0.00
	Average Queuing Time	0.00	0.00	0.00
Fila para berco	Average Queue Size	0.79	1.29	1.78
	Average Queuing Time	72.47	116.83	161.20
Total navíos atendidos	Number Completed	89.80	93.20	96.60
	Average Time in System	135.53	180.02	224.52
OP_Arm 39	Number Completed Jobs	89.80	93.20	96.60
Navega_ canal_1	Number Completed Jobs	90.30	93.50	96.70

The model validation was carried out by experts, the research professors associated with the Center for Innovation in Logistics and Port Infrastructure - CILIP of the University of Sao Paulo - USP, who accompanied the process from the formulation, data collection and experimentation.

Once the model had been built, verified, and validated, the final analysis phase was completed, where initially the operational model of the system to be evaluated is completed, that is, the port system with operation of a ballast water treatment system.

The conceptual model that represents the operation of the terminals under study, with the addition of the ballast water treatment system can be seen in Fig 8. For the operation of the water treatment system, the system does not undergo major changes in terms of its operation, the ballast water in the ships is treated while they operate, which will not affect the operation since the only thing that changes in the system is the intervention of a new resource, the treatment barges, and a certain time of their operation, which is less than that of the operation in total, including enlistment and post-operation.

Conceptually, a new sub-process is generated within the pre-operation called ballast water treatment, which would operate as shown in the diagram in fig. 8.

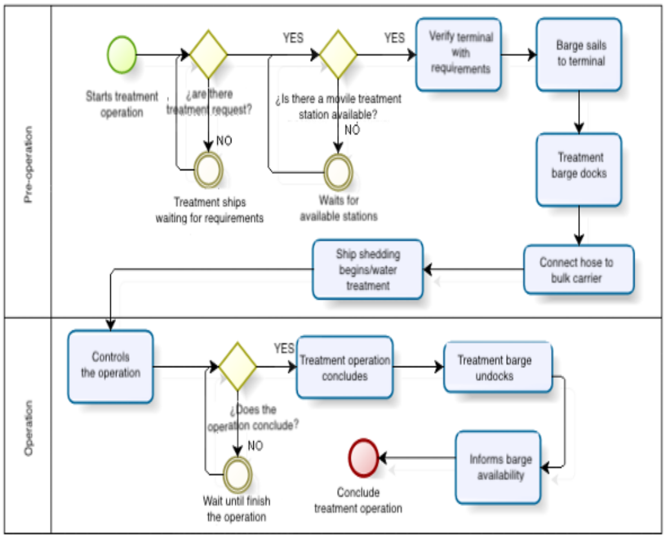

Fig 8. Ballast water treatment system conceptual model. Source author

For the operation of the water treatment barges, it was necessary to calculate the time between each terminal as mentioned at the point of data collection, it should be noted that these barges do not have navigation restrictions in the channel, that is, given its characteristics (size, draft, etc.) the barges could cross both with large vessels and with each other, in addition the speed is greater than that of the vessels entering the port (12 nodes) and the turning maneuver times are not are taken into account given the simplicity of this operation.

The addition of the ballast water treatment system within the port operation does not cause major interventions to the computational model either, it maintains its structure, only a new resource called "treatment barges" is added and the respective navigation times between terminals, which are of great relevance because the barges will be serving the ships while they operate and once they end in one of the terminals they will be required in some other. These times within the model are read through a logic of "set resource travel time", where the time is entered for each of the possible journeys that are going to be required. For the subsequent analysis, the costs associated with the operation of the treatment stations were estimated, as shown in the following point.

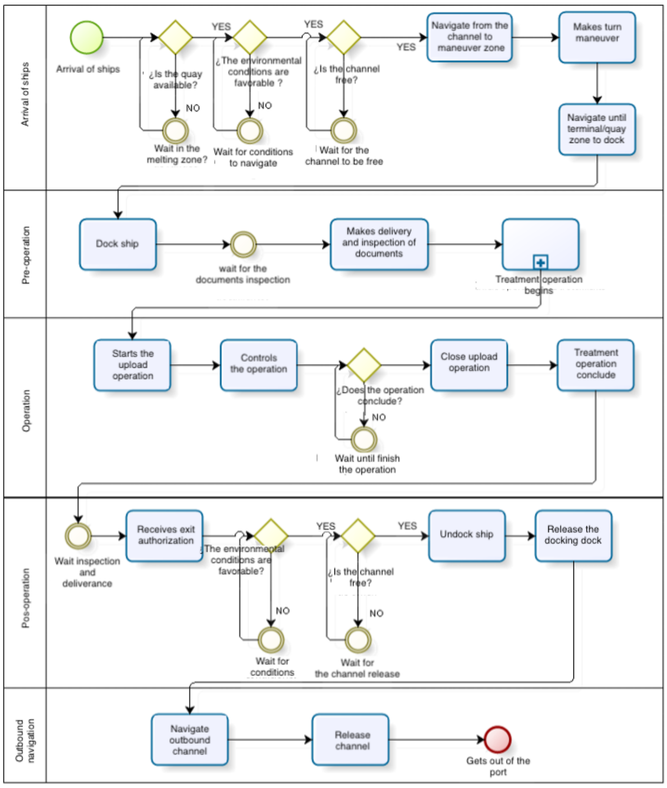

Fig 9. Conceptual model of operation of the port of Santos with ballast water treatment system. Source author

IV. ANALYSIS AND RESULTS

For an experimental design of ten runs of one year, the base period for which it was necessary to evaluate the operation of the port, the results obtained are very close to the reality of the system, also considering the assumptions under which it was worked; The Table 7 summarizes the main results of the system's operation:

Table 7. Performance results of the model without a ballast water treatment system.

		Low 95% Range	Average Result	High 95% Range
Canal Queue	Average Queue Size	0.02	0.02	0.02
	Average Queuing Time	0.19	0.21	0.24
Berco queue	Average Queue Size	1.69	1.97	2.25
	Average Queuing Time	17.82	20.72	23.63
Total ships	Number Completed	818.30	830.00	841.70
	Average Time in System	63.82	66.86	69.90
B_ARM 39	Utilization %	49.86	51.23	52.60
B_CUTRALE	Utilization %	30.78	32.36	33.94
B_12A	Utilization %	28.23	29.51	30.78
B_13_14	Utilization %	0.0	0.00	0.00
B_ARM 29	Utilization %	19.98	21.79	23.59
B_ARM 36	Utilization %	28.46	30.51	32.57
B_ARM_16_17	Utilization %	24.69	26.80	28.91
B_ARM_19	Utilization %	24.84	26.59	28.35
B_ARM_20_21	Utilization %	24.70	26.74	28.78
B_ARM_22_23	Utilization %	0.00	0.00	0.00
B_ARM_27	Utilization %	0.00	0.00	0.00
B_SUG26	Utilization %	34.40	36.96	39.51
B_TEAG	Utilization %	34.24	35.42	36.61
B_TEG	Utilization %	42.26	44.24	46.22
B_TERMAG	Utilization %	0.00	0.00	0.00
B_TGG	Utilization %	49.79	51.69	53.60

For the system, it is important to analyze the rows first. As mentioned in the theoretical framework of this work, the port presents large lines given the bureaucracy for the arrival and departure of vessels, the number of available berths, the impossibility of crossing vessels in the canal and the high number of anchored ships. As can be seen in the results, the waiting line for dock availability (row for berço) is the largest within the system, given that the number of available docks is not enough to meet all the demand that is being generated.

In the literature, an average row of 16 hours is mentioned for the year 2012 and with a tendency to increase, in the simulated system this time is on average 21 hours, which in comparison is not very far from the reality of the system, considering that this model waits for each vessel to carry out its entire operation to free the channel, while in reality the piloting team can coordinate this operation more efficiently and, additionally, the model takes all the vessels that enter the Panamax class terminals, while that smaller vessels can enter the real system that, given their structure, do not require a large draft to navigate, so they do not require channel availability to navigate. The vessels attended to were 830, while in the real system this figure was 818 vessels. This difference is due to the calculation that was made for the generation of the ships, because when dividing the demand in the terminal by the capacity of the vessel, the figure was rounded to the largest integer, so they could have been required, for example 0.14 vessels, but the model received the request for 1 vessel.

The use of the docks is another data of great interest for the port operator, in general, it is expected that the use of the dock will be greater than 60%, because otherwise it would not be profitable to operate in a dock that less than half of the time is operating. For the model, this utilization after the runs that were made and the best result that was achieved, is very low. This result can be explained given that within the study only four products and the quantities exported were considered; These docks in some terminals also receive goods and are shared with other terminal products.

For the treatment system, it is required that this new operation does not greatly affect the performance of the system, but there are trade-offs involved that the port entity must evaluate to adopt the treatment system, since each barge implies additional costs. When compared to the efficiency of the treatment system as such, the acquisition may not be decisive, that is, there is a point at which having one more barge will not mean shorter row times but an even more significant cost for the business.

The results of the four scenarios evaluated for the installation of the treatment system are presented below, characterized as the ideal scenario, the one in which 8 treatment barges are acquired, a desirable scenario with 7 barges, an acceptable scenario with 6 treatment stations and finally an unfavourable scenario for the operation of the system with 5 barges for treatment.

Table 8. Ideal scenario, port performance is maintained, and eight treatment stations are acquired.

		Low 95% Range	Average Result	High 95% Range
Canal Queue	Average Queue Size	0.02	0.02	0.02
	Average Queuing Time	0.18	0.20	0.22
Berco queue	Average Queue Size	1.69	1.97	2.26
	Average Queuing Time	17.81	20.74	23.67
Total ships	Number Completed	818.21	829.90	841.59
	Average Time in System	63.76	66.84	69.91

B_ARM 39	Utilization %	49.90	51.30	52.70
B_CUTRALE	Utilization %	30.85	32.44	34.03
B_12A	Utilization %	28.36	29.60	30.84
B_13_14	Utilization %	0.00	0.00	0.00
B_ARM 29	Utilization %	19.99	21.80	23.61
B_ARM 36	Utilization %	28.50	30.56	32.62
B_ARM_16_17	Utilization %	24.79	27.01	29.23
B_ARM_19	Utilization %	24.88	26.53	28.19
B_ARM_20_21	Utilization %	24.89	26.89	28.88
B_ARM_22_23	Utilization %	0.00	0.00	0.00
B_ARM_27	Utilization %	0.00	0.00	0.00
B_SUG26	Utilization %	34.44	36.98	39.52
B_TEAG	Utilization %	34.30	35.48	36.66
B_TEG	Utilization %	42.42	44.37	46.32
B_TERMAG	Utilization %	0.00	0.00	0.00
B_TGG	Utilization %	49.81	51.79	53.77

Table 8 shows the scenario that maintains the normal performance of the port and operates with eight barges, this alternative is also the most expensive in terms of acquisition of barges, acquisition of treatment systems, maintenance of equipment and annual operation (labor, fuel, among others); The desirable and acceptable scenario still represent benefits in terms of operation at lower costs in relation to the desirable scenario. These benefits must be analyzed in greater depth and a detailed economic evaluation of each of the alternatives is required (Tables 9 to 11).

Table 9. Desirable scenario, the total time in the system increases less than two hours and seven treatment stations are acquired.

		Low 95% Range	Average Result	High 95% Range
Canal Queue	Average Queue Size	0.02	0.02	0.02
	Average Queuing Time	0.18	0.20	0.24

Berco queue	Average Queue Size	1.73	2.02	2.32
	Average Queuing Time	18.26	21.29	24.32
Total ships	Number Completed	818.31	829.90	841.49
	Average Time in System	64.60	67.78	70.96
B_ARM 39	Utilization %	50.13	51.65	53.17
B_CUTRALE	Utilization %	31.06	32.67	34.28
B_12A	Utilization %	28.65	29.90	31.15
B_13_14	Utilization %	0.00	0.00	0.00
B_ARM 29	Utilization %	20.09	21.90	23.71
B_ARM 36	Utilization %	28.66	30.81	32.97
B_ARM_16_17	Utilization %	24.95	27.28	29.61
B_ARM_19	Utilization %	25.83	27.36	28.89
B_ARM_20_21	Utilization %	25.11	27.05	28.99
B_ARM_22_23	Utilization %	0.00	0.00	0.00
B_ARM_27	Utilization %	0.00	0.00	0.00
B_SUG26	Utilization %	34.62	37.17	39.72
B_TEAG	Utilization %	34.55	35.69	36.83
B_TEG	Utilization %	42.79	44.73	46.67
B_TERMAG	Utilization %	0.00	0.00	0.00
B_TGG	Utilization %	50.27	52.38	54.50

Table 10. Acceptable scenario, the time in the system is four hours longer than the base scenario and six treatment barges are acquired

		Low 95% Range	Average Result	High 95% Range
Canal Queue	Average Queue Size	0.01	0.02	0.02
	Average Queuing Time	0.17	0.19	0.22
Berco queue	Average Queue Size	1.94	2.33	2.71
	Average Queuing Time	20.59	24.45	28.31
Total ships	Number Completed	818.23	829.80	841.37
	Average Time in System	68.21	72.54	76.88
B_ARM 39	Utilization %	51.36	53.10	54.84
B_CUTRALE	Utilization %	31.87	33.51	35.15
B_12A	Utilization %	29.78	31.10	32.42
B_13_14	Utilization %	0.00	0.00	0.00
B_ARM 29	Utilization %	20.64	22.49	24.35
B_ARM 36	Utilization %	29.17	31.43	33.69
B_ARM_16_17	Utilization %	26.69	28.97	31.64
B_ARM_19	Utilization %	27.16	29.11	31.06
B_ARM_20_21	Utilization %	26.39	28.41	30.43
B_ARM_22_23	Utilization %	0.00	0.00	0.00
B_ARM_27	Utilization %	0.00	0.00	0.00
B_SUG26	Utilization %	35.45	38.21	40.97
B_TEAG	Utilization %	35.31	36.60	37.89
B_TEG	Utilization %	44.77	46.57	48.38
B_TERMAG	Utilization %	0.00	0.00	0.00
B_TGG	Utilization %	51.52	54.28	57.03

Finally, from five barges or less it is not beneficial for the company to implement a ballast water treatment system, because even if the water was being treated, the loss in the operation is so high that it would not be economically viable under any circumstances and the company could jeopardize the operation of the terminals within the port.

Table 11. Unfavorable scenario, the time in the system increases by more than one day and five treatment barges are acquired.

		Low 95% Range	Average Result	High 95% Range
Canal Queue	Average Queue Size	0.02	0.02	0.02
	Average Queuing Time	0.18	0.19	0.21
Berco queue	Average Queue Size	3.09	4.85	6.61
	Average Queuing Time	33.01	50.70	68.38
Total ships	Number Completed	818.03	829.80	841.57
	Average Time in System	86.19	106.08	125.97
B_ARM 39	Utilization %	57.47	60.80	64.12
B_CUTRALE	Utilization %	34.28	36.94	39.60
B_12A	Utilization %	33.36	35.72	38.07
B_13_14	Utilization %	0.00	0.00	0.00
B_ARM 29	Utilization %	22.39	24.62	26.86
B_ARM 36	Utilization %	31.65	34.82	37.99
B_ARM_16_17	Utilization %	32.54	36.75	40.96
B_ARM_19	Utilization %	32.25	36.38	40.51
B_ARM_20_21	Utilization %	31.27	34.94	38.61
B_ARM_22_23	Utilization %	0.00	0.00	0.00
B_ARM_27	Utilization %	0.00	0.00	0.00
B_SUG26	Utilization %	38.23	41.74	45.24
B_TEAG	Utilization %	38.23	40.84	43.44
B_TEG	Utilization %	52.71	55.20	57.68
B_TERMAG	Utilization %	0.00	0.00	0.00
B_TGG	Utilization %	59.04	63.82	68.61

A future detailed economic evaluation of each of the alternatives can further support the decision process by informing the decision maker not only of the effects of the treatment system on the port operation, but also the precision of the costs and investment needs. that would be required to start operating the system.

V. CONCLUSION

The installation of a ballast water treatment system in port, although it is still optional for port agents, is a tendency to become a requirement for operations, which makes this type of analysis and the evaluation of alternatives essential. of water treatment in port. There is evidence in the literature that the ballast water treatment of ships represents a great benefit in terms of sustainability in the three axes: environmental, social and economic for the port, improves its corporate image and in general may represent lower costs in the long-term.

An alternative analysis for the adoption of a treatment system such as the one proposed in the study is the simulation of discrete events, this tool is widely used to analyze port operations, it is a way of representing this type of complex systems that does not allow operation Directly on them and achieve a greater understanding of the system being studied, additionally, it enables the analysis of changes within the operation such as the operation of a dock or an additional treatment barge.

For the case study, the adoption of a ballast water treatment system in port may not affect the port operation, although this requires a greater investment by the company. Decision-makers must evaluate the losses in performance due to a lower cost of the treatment system and thus make a better decision where the benefits may be the greatest.

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