MODEL OF PRIORITY ASSIGNMENT OF VESSEL TRAFFIC IN A MULTIPORT ACCESS CHANNEL UNDER TIDAL CONDITIONS

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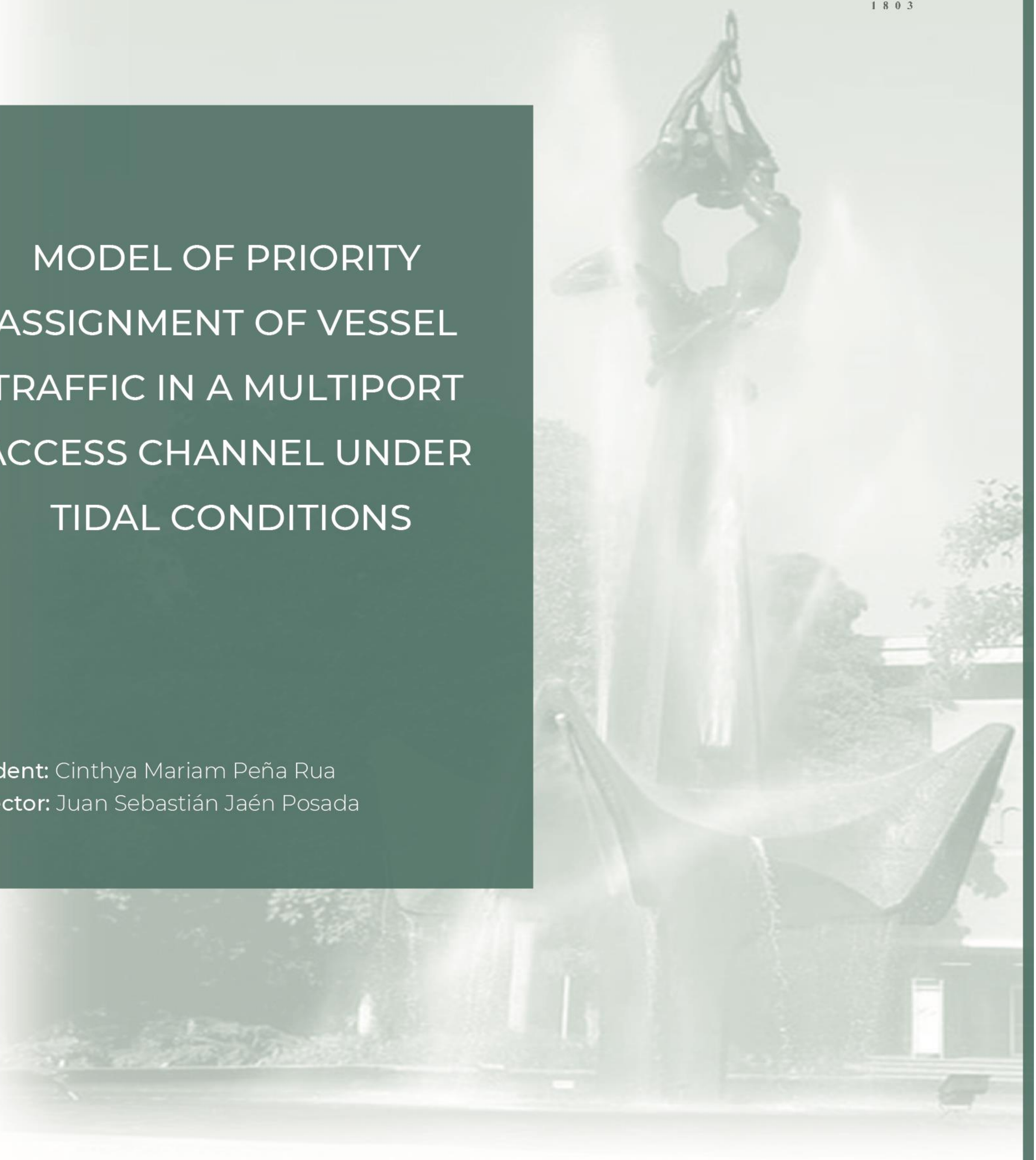

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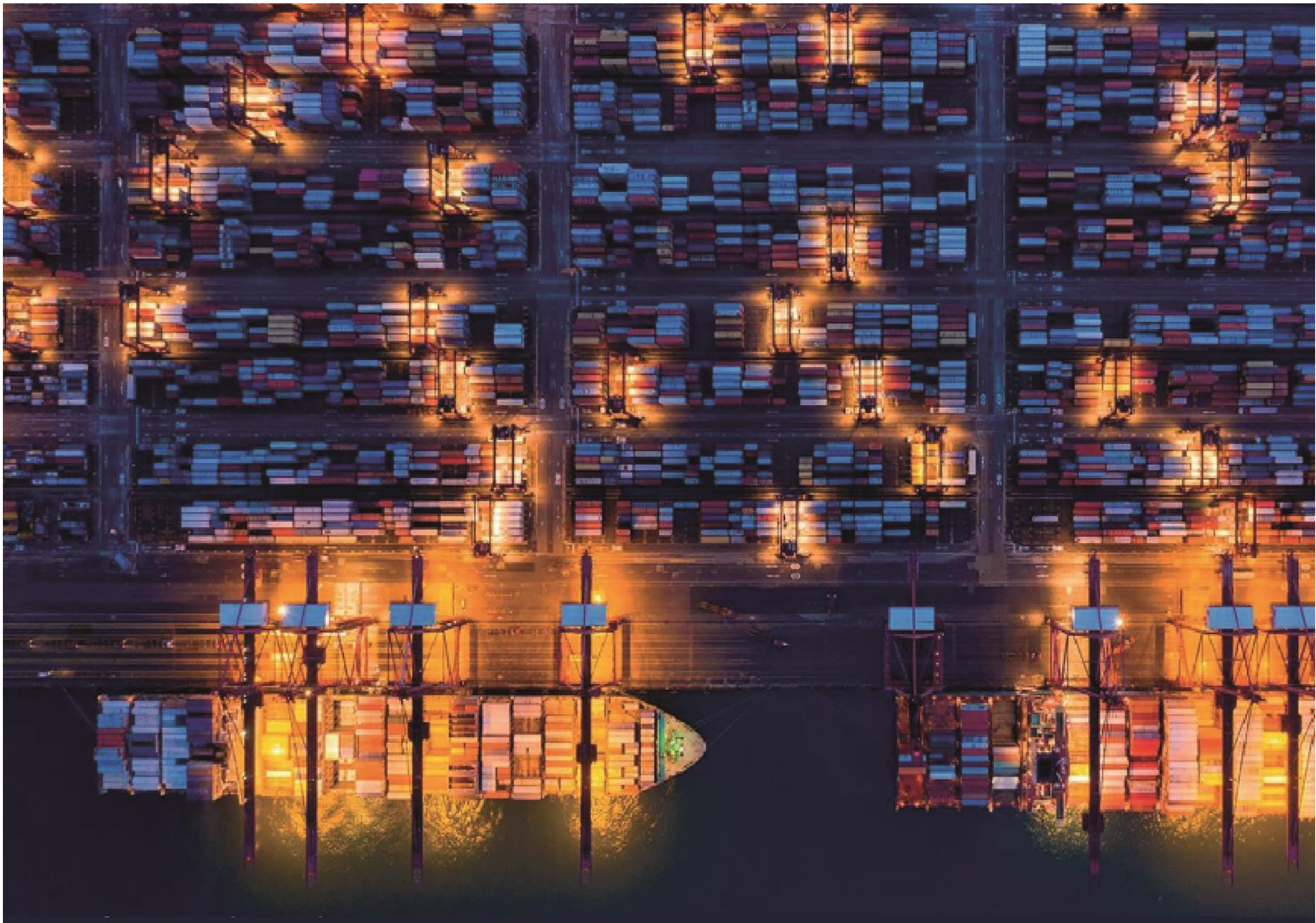
Abstract

This work addresses the problem of scheduling ships (incoming and outgoing) in access channels subjected to tidal action. The document is divided into 4 sections. The first one gives a context of the problem, its components and a literature review and research trends identified in the literature. The second section contains the modeling of the problem under the linear integer modeling perspective. Chapter 3 outlines a case study (Buenaventura's multiport terminal) and describes its characteristics and data collection methodology. Finally, in chapter 4 some experiments are presented with their results aimed at answering these research questions: 1. What is the minimum safety time that can be available between ships without affecting safety and the minimum waiting times of the ships? 2. What is the minimum average speed that can be used in the navigation of the ships without affecting the safety and the minimum waiting times of the ships? 3. Can the best times for annual navigation in the channels be determined considering the variations of the tide? 4. What is the maximum capacity of entities supported by the model without significantly affecting the processing times of the data?

Content



Chapter 1

Context

1.1. Introduction and problem statement

1.1.1. Port sector

The port sector plays a critical role in global value chains as it provides the necessary infrastructure for the movement of goods between countries and regions. A port is a facility that serves as a gateway for the import and export of goods by sea, and it typically includes infrastructure such as berths, cranes, storage facilities, and other services. Ports are competitive and functional only if they have the capacity to provide international trade and the logistics chain with agile, efficient, and secure services (Yu et al., 2019). In addition, they are axes of combined transport by linking maritime and land transport with the various elements of cargo distribution (Colebrook, 1992).

The importance of the port sector in value chains lies in its ability to facilitate the movement of goods from their point of origin to their destination. For many industries, ports serve as a crucial link in the supply chain, enabling the transfer of raw materials, components, and finished products between different stages of the production process (Bhagwati, 1988). So, the impact of ports on the logistics activity and competitiveness of a country's international trade is of great relevance. Thus, the current port units do not carry out their activities as an autonomous and independent element, since they are a dynamic element of the logistics chains of production, transport, and distribution (Ullah et al., 2020). On the other hand, the characteristics of the maritime terminals of units that promote and produce global trade have led to the execution of specialized productive activities and to a competitiveness in three dimensions: between ports, within each port and maritime transport with respect to other modes of transport (Haezendonck et al., 2000).

The consideration of a port from the logistical point of view implies that not only the activities carried out in the port environment must be considered, but also the influence that these activities have on the transport before and after the port. Seaports, as axes of international trade, have an economic dynamic focused on three strategies: joint and integration, intensification of transport and concentration (Álvarez-SanJaime et al., 2015). Thus, these strategies aim to increase the qualities of the port services offered: Reduction of ships stay time, agility of services with cost reduction, increase in maritime traffic, intermodally, multimodality, hinterland[1], and valorization of the geographical location (González, 2005, 2019; Moghaddam et al., 2020).

The typical activities carried out in a port also include the transfer between the maritime and land modes of transport (loading-unloading of goods from ships and the embarkation-disembarkation of passengers), the handling of goods, their storage, the inspection, and control of the merchandise in addition to the management of the information that is exchanged between the different agents involved in all these activities (Rúa Costa, 2006).

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[1] The hinterland represents the land area of origin or destination of goods or passengers passing through a given port. It is, in short, its area of territorial influence (De Langen & Chouly, 2004)

Ports are one of the most important infrastructures of a country, since they have a large participation in the transport of goods. In addition, they are a key point that allows the connection of the maritime environment with the terrestrial one (Colebrook, 1992; World Bank, 2022). One of the reasons that have made vesselping the engine of many industries is the ability to transport large loads efficiently (Wilson et al., 2003).

A commercial seaport, according to its physical infrastructure and operational capacity, will be able to receive different types of cargo. According to the United Nations, 26.7% of the gross world tonnage mobilized in 2022 corresponded to bulk (iron ore, cereals, and coal), 25% to transport on oil tankers (crude oil, petroleum products, gas, and chemicals); 23.5% to containerized cargo and 24.8% corresponding to general and gaseous loads (fertilizers, vehicles, forest products and others) (United Nations, 2022).

1.1.2. Port operation and logistics

FIGURE 1. UNLOADING AND LOADING PROCESSES IN CONTAINER TERMINALS. SOURCE: OWN ELABORATION

The process of moving cargo within the port, as shown in Figure 1., begins by assigning ships a berthing position. Once the vessel has moored, one or more dock cranes unload the vessel following an unloading plan. The download time normally shows great variability. Dock cranes take the imported cargo from the hold or deck of the vessel and deposit it in the dock area or directly into the (internal) transport vehicles which then move the cargo from the dock area to the storage area. Bulk cargo is of a more complex handling because it represents the goods or materials that are transported without packaging, or packing, in large quantities and its disposition will be linked to transport with pumping and pipes until its storage or immediate dispatch. Cargo that is temporarily stored is arranged in a block configuration for containers or in sheds, silos, or tanks for bulk until its departure from the port in external trucks, external trains, or other ships. Import cargo leaves the terminal after its documentation is checked and inspected (if selected for inspection) (Carlo et al., 2014). Normally, the same container vessel moves both import and export cargo, that is, cargo that enters and leaves the port. Export loading occurs then, after all the imported cargo has been unloaded and follows a stowage plan (strategic location of the cargo to ensure the stability of the vessel). As for bulk carriers (liquid or solid), the mobilization of cargo is generally given in one direction, that is, rarely a vessel with import merchandise loads export goods, this due to the specific requirements of each type of cargo (Burns, 2013).

Scheduling the large number of concurrent operations with all the different types of transportation and handling equipment involved is an extremely complex task. In view of the ever-changing operational characteristics of each port terminal, and the limited predictability of future events, the task of monitoring must be performed in real time (Günther & Kim, 2006).

The most widely researched problems in port logistics are berthing assignment, dock crane scheduling, and internal freight transport operations. This, given that the high productivity and performance of the cargo from the dock to the ground and vice versa are closely linked to these nodes of the operation and are key in the competitiveness of the port with other terminals (Bierwirth & Meisel., 2015).

Berthing assignment is the most addressed problem in the literature for which minimization of cost and time is regularly sought. It refers to the allocation of mooring space in docks for ships in port terminals. Ships arrive over time and the terminal operator must assign them to the docks to be serviced (loading and unloading goods) as soon as possible. The variability of the arrival time of the ships and the time of handling of loads are the causes of the difference between the planned schedule and the actual time of berthing. These differences reduce spring productivity because loading and unloading time is not predictable. It should be noted that the most used methodology within the investigations focuses on the variation of programming models of mixed integers solved by heuristics or interactive heuristics (Bierwirth & Corry, 2018; Bierwirth & Meisel., 2015; Branch, 2008; Liu, 2020; Ullah et al., 2020).

The scheduling of the dock crane in port terminals is a problem that has also been extensively researched aiming primarily at reducing total costs. It consists of the determination of the sequence of unloading operations of a vessel that will perform a certain number of dock cranes (Al-Dhaheri & Diabat, 2015). This sequence, given under the fulfillment of the specifications of each load or unloading as a priority of handling of each bay of the vessel (typical longitudinal division of a vessel into holds and decks) and the fulfillment of limitations associated with the storage and transport of the cargo (availability of resources and equipment on land). Currently, the topic is being approached from perspectives of simulation and programming of mixed integers usually approached from heuristic algorithms. It should be noted that recently, the combination of simulation techniques – optimization or simulation – artificial intelligence are the vanguard of research (Abou Kasm & Diabat, 2020; Castilla-Rodríguez et al., 2020; Lee et al., 2008).

Dock cranes remove the cargo from the hold or deck of the vessel and leave it in the dock area or directly into (internal) transport vehicles that then move the cargo from the dock area to the storage area until it leaves the port by land (on external trucks or trains) or is loaded onto another vessel. Regarding to transport, three main decisions should be considered; firstly, select the type of vehicle to use, secondly, determine the number of vehicles required, and finally, the routing and dispatch of vehicles. The recurrent methodologies of approach to this theme use agent-based simulation or the discrete events simulation (Carlo et al., 2014; Dos Santos et al., 2020; Kotachi et al., 2013).

1.1.3. Access channels

The port infrastructure consists of several elements, including the area for vessel maneuvers, protective structures (such as breakwaters and locks), docks and piers, storage areas, internal transport routes, and access channels to the port (AMP, 2010).

An access channel is a pathway (natural or man-made) that allows ships to enter the port. These channels can accommodate ships of different sizes, depending on their width and draft, and can be classified as navigable for smaller ships, larger ships, or both. As illustrated in Figure 2 (Jaimurzina & Wilmsmeier, 2017), the width of the channel is limited by the available maneuvering space, which can restrict the passage of ships with a wider beam (i.e., transverse length). In addition to the width, external factors such as winds, currents, and tides must also be considered when determining the channel's dimensions. Operational constraints may require the use of pilots, who are experienced in maneuvering through access channels. These pilots are not part of the vessel's crew and serve as advisors to the captain during the crossing of the access channels (AMP, 2010; PIANC et al., 1992).

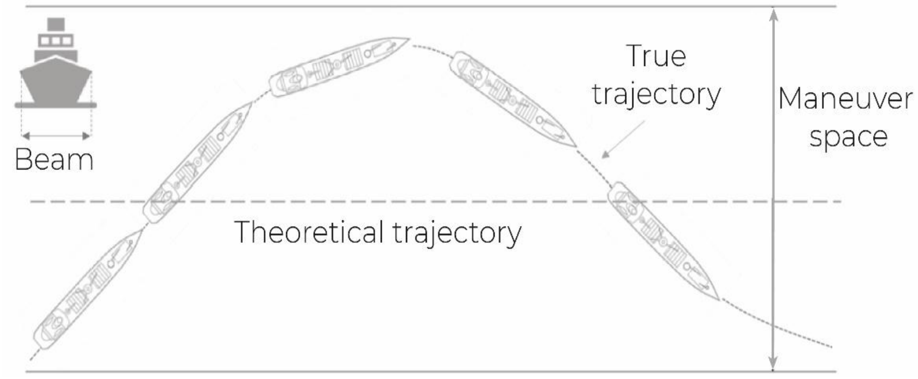


FIGURE 2. BASIC MANEUVER WIDTH. SOURCE: (PIANC ET AL., 1992)

The flow of ships through the canal may occur in both directions, in a single direction or in sections (some bidirectional and others unidirectional) according to the navigation conditions of the channel and the beam of the ships to transit through it (Tezdogan et al., 2016). The depth of the channel will impose restrictions associated with the hydrodynamic resistance to the movement of a vessel in restricted waters that will depend on the speed of travel, depth, and gravity (Terziev et al., 2018). On the other hand, ships tend to increase their immersion and vary their longitudinal seat during navigation. Thus, to ensure safety during passage through the canal, a free distance from the bottom of the vessel to the bottom of the channel is required. It should be noted that depth constraints will be highly influenced by tidal changes (Jiao et al., 2018; Mora et al., 2013; PIANC et al., 1992).

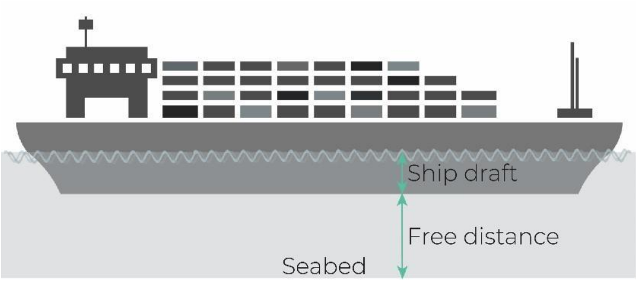


FIGURE 3. BASIC CHANNEL DEPTH RESTRICTIONS ON THE VESSEL'S DRAFT. SOURCE: (JIAO ET AL., 2018)

1.1.4. The tide

Tides refer to the change in the level of sea waters, as an effect of astronomical or meteorological conditions. The meteorological tide is mainly governed by the wind that generates the waves and increases in sea level. The astronomical tide on the other hand refers to the semi-periodic movement of ascent and descent of the waters of the sea produced by the attraction of the stars, mainly the sun and the moon (Díaz, 2009).

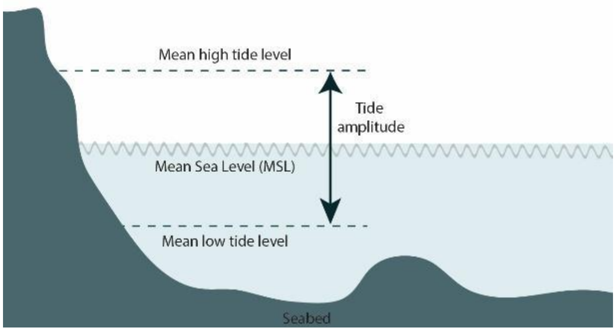


FIGURE 4. GRAPHICAL REPRESENTATION OF TIDES. SOURCE: OWN ELABORATION

The maximum height is called high tide and the minimum low tide. The ascent and descent of the sea prior to the high tide generate flows (incoming) and ebbs (emptying) that have characteristics of direction and speed that restrict or condition the navigation of ships (PIANC et al., 1992). The tide can be diurnal, semi-diurnal or mixed. The semi-diurnal tide has a high tide and a low tide every lunar day. The semi-diurnal tide on the other hand has two high tides and two low tides with almost equal height daily. Mixed tide is characterized by an evident diurnal inequality in the elevation of high tides and low tides between successive tidal cycles (Chang et al., 2012).

The tide imposes restrictions on the depth and width of the access channel to a port, especially in low tide conditions that represent the lowest level of the water surface and thus the height available for the transit and maneuver of ships; Also, there are restrictions associated with the current generated by the movement of water in its path of ascent or descent (PIANC et al., 1992).

According to the International Association of Ports and Harbors (IAPH), tidal changes are a key factor affecting port access channels and can cause significant disruptions to port operations, resulting in delays, increased costs, and safety hazards (Ozer & Isin, 2016).

Fitting to the tide cycle, the decision must be made whether a specific vessel can maneuver in the channel. In case you are unable to transit, a suitable tidal time space should be chosen considering the commercial consequences of downtime (Jiao et al., 2018; PIANC et al., 1992). Port operators may also use tidal windows to schedule vessel traffic in and out of the port. Tidal windows are specific periods during which the tide is at a suitable depth and velocity for ships to enter or exit the port. By scheduling vessel traffic during these periods, port operators can minimize the impact of tidal changes on port operations (Huang, Wei, & Yang, 2014).

1.1.5. Problems of port access channels

Access channels are an essential part of port infrastructure, providing a navigable path for ships to enter and exit a port (Zhang et al., 2022). However, access channels can pose several problems that need to be addressed to ensure safe and efficient port operations. The width and depth of access channels can pose limitations on the size and draft of the ships that can enter the port. The width of the channel is usually restricted by the available maneuvering space, which can limit the passage of ships with a wider beam. Additionally, the depth of the channel can limit the draft of ships, which can pose a challenge for larger ships, causing delays in the access and exit of ships and with it throughout the operation of the ports. The traffic conflict substantially affects the safety and efficiency of ships' navigation (Li et al., 2021).

The navigation conditions in an access channel are mainly limited by the natural narrowing of the channel that prevents ships from simultaneously transiting some sections regardless of their trajectory (Lin et al., 2019). Also, there are limitations due to changes in depth that are usually linked to tidal variations . Thus, it is important to consider the problem of sequencing vessel access to canals considering the time needed for each vessel to transit through a canal (Lalla et al., 2018).

To address this problem, three strategies have been identified and adopted: Expansion of infrastructure, constant dredging of channels and optimization of vessel transit scheduling. Infrastructure expansion is time-consuming and costly. The effects of dredging are limited and costly (Dadashi et al., 2017). Traffic scheduling focuses on the classification of ships for vessel sequencing ensuring the safety and efficiency of vessel navigation in port. However, in the actual process of scheduling port vessel traffic it is complex, especially in multiport terminals (Li et al., 2021).

Scheduling involves the careful coordination of vessel movements to ensure the safe, efficient, and timely passage of ships through the access channels. Scheduling traffic in access channels is critical because ports handle large volumes of vessel traffic and require the use of a variety of resources, such as tugs and pilots, to safely guide ships through the channel (Atencio & Casseres, 2018). The first step in scheduling traffic in port access channels is planning and coordination. Port authorities work with vessel operators and service providers such as pilots and tugboat operators to plan and coordinate vessel movements. This coordination ensures that all parties are aware of the timing and sequence of vessel movements and that the necessary resources are available to support those movements (Barros et al., 2011).

To manage vessel traffic in the access channel, port authorities may implement a queuing system (Legato & Mazza, 2018). This system involves ships waiting in a designated area until they are called to enter the channel. The queuing system helps to prevent congestion and ensures that ships enter the channel in a controlled and orderly manner. Traffic separation schemes may also be implemented to guide vessel movements through the access channel. These schemes involve designated lanes for inbound and outbound ships, as well as rules for vessel speed and direction to prevent collisions and ensure safe passage. Additionally, Environmental factors, such as tide and weather conditions, must also be considered when scheduling traffic in port access channels (Nzualo et al., 2021). For example, wind or current direction can affect the course or trajectory of a vessel and must be considered when determining the best time for a vessel to enter or exit the channel.

The following are some of the key reasons why scheduling traffic in port access channels is essential (Le et al., 2020; Sheikholeslami et al., 2014; Zhen et al., 2017):

- **Preventing Congestion:** Congestion in access channels can lead to delays in vessel traffic, which can have significant economic impacts. Scheduling traffic helps to prevent congestion by ensuring that ships enter and exit the port in a timely and efficient manner.
- **Enhancing Safety:** Port access channels can be dangerous, with the potential for collisions, groundings, or other incidents that could cause harm to people and property. Scheduling traffic helps to reduce the risk of these incidents by ensuring that ships enter and exit the channel in a safe and controlled manner.
- **Optimizing Use of Resources:** Scheduling traffic can help to optimize the use of resources, such as tugs and pilots, that are required for safe and efficient passage through the access channels. By coordinating vessel traffic, these resources can be allocated efficiently to maximize their use and reduce costs.
- **Meeting Regulatory Requirements:** Many ports are subject to regulatory requirements that govern the safe and efficient movement of ships through access channels. Scheduling traffic can help to meet these requirements by ensuring that ships enter and exit the channel in compliance with regulations.

1.2. Study problem

1.2.1. Definition

The objective of this work is to solve the traffic allocation problem for ships that transit access channels subject to tides. It refers to the problem of scheduling incoming and outgoing ships from port units for the time periods available to transit the canal with variable water levels due to tides. This problem is common and occurs in ports where the depth of the channel can vary significantly depending on the tide, making it necessary to assign specific time windows to the ships to avoid running aground or other safety problems given their physical characteristics such as beam and draft.

1.2.2. Importance of a programming of ships in access channels

The solution or facilitation of the problem of allocation of vessel traffic by access channels is of great importance due to the various implications it has in the maritime and port industry. In the first place, an inadequate allocation of transit times can generate dangerous situations for ships and their crews, especially in access channels with variable tides. If a vessel tries to transit the canal at the wrong time, it can run aground or damage canal structures, which could pose catastrophic problems for the operation of the terminal and surrounding logistics. On the other hand, a conservative programming of the transit of ships could represent serious economic losses for the port units.

The proper allocation of transit times can improve the efficiency and profitability of port operations. By ensuring that ships arrive and leave port in a timely manner and at the right time, traffic congestion is avoided, downtime is reduced, and the use of available resources is optimized. This in turn can reduce operating costs and improve the competitiveness of the port.

Likewise, efficient allocation can reduce the environmental impact of port operations. Ships lining up to transit the canal consume fuel and emit greenhouse gases, which can contribute to climate change. By reducing the number of ships on hold, the environmental impact of port operations is reduced, and more sustainable management of resources is promoted.

1.3. Literature review

The programming of ships in port access channels is a complex problem that involves multiple factors, such as vessel characteristics, channel conditions, environmental conditions, and traffic density. The literature reports a recent interest in the study of vessel traffic programming in canals and although the limitations of the channels studied differ, but the purpose of the studies is the same, to ensure the safety and efficiency of the navigation of ships in the channel. Most of the research found in the literature has been published between 2019 and 2021 and in Asian countries.

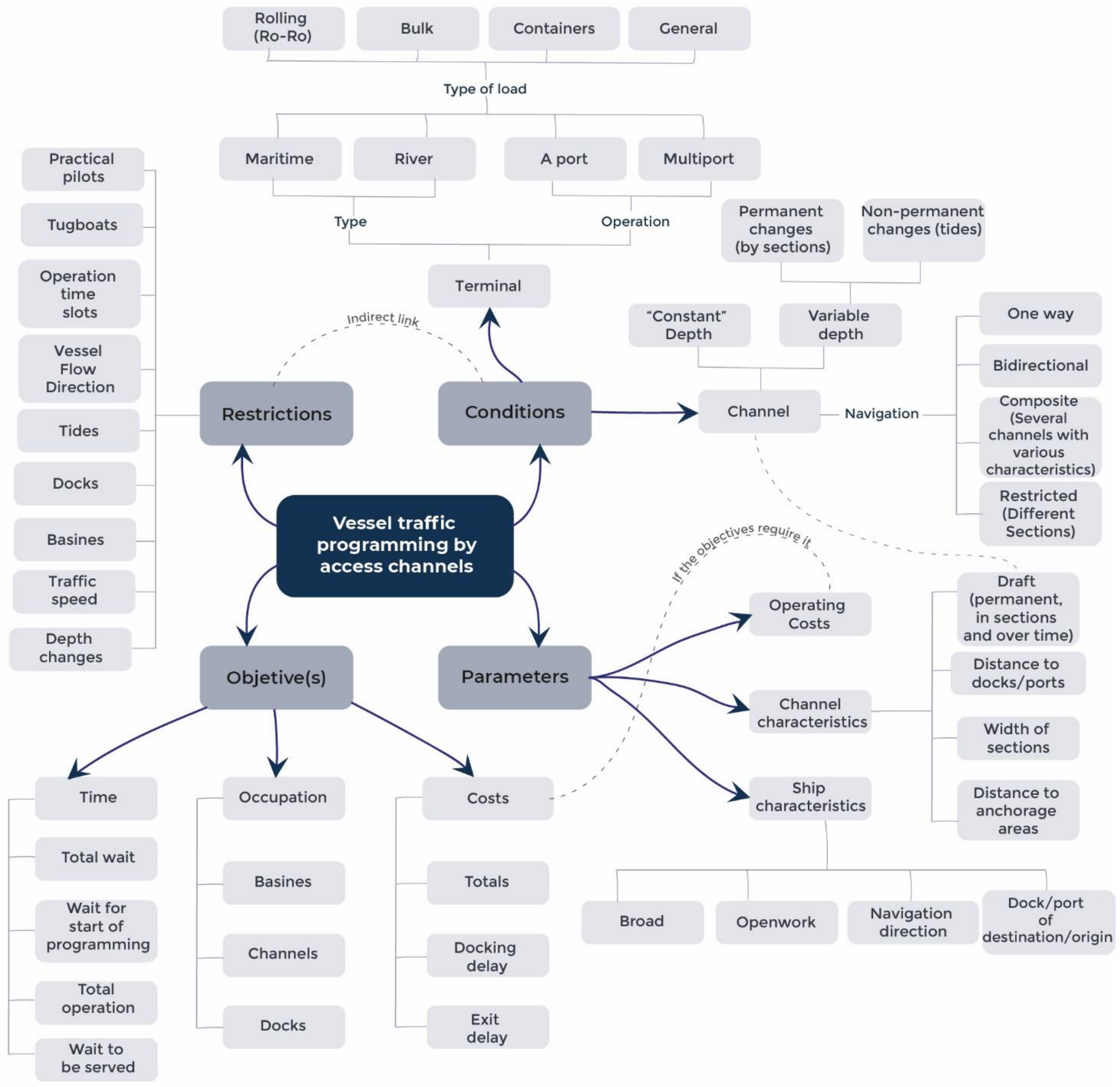


FIGURE 5. THE PROBLEM OF ACCESS CHANNELS

There is an important segmentation in the approach of the problem according to the directions of flow of ships through the channel, however, most have as their object of study bidirectional channels (ships can travel in opposite directions at the same time) and a minority percentage focuses on unidirectional or composite channels. There is little research imposing tidal restrictions and models that include it also restrict docking, walking speed and the number of ships in the channel. The objectives of this research are mainly aimed at reducing waiting time, but it also seeks to improve indicators such as total programming time, the percentage of use of the access channel and the total associated costs (delay in docking, delay in departure, service requests, etc.). As for solution methods, the use of heuristics is the most used followed by simulation.

Below is a review of current literature on the problem, the columns of Table 1 represent the following variables:

Variables related to the type of channel:

- A: Unidirectional (ships travel in one direction at the same time)
- B: Bidirectional (ships travel in opposite directions at the same time)
- C: Composite (two or more navigable channels with different navigable depths in the same design section of the main channel)
- D: Restricted (Bidirectional/Unidirectional)

Terminal type:

- E: One port
- F: Multiport

Constraints within the model:

- G: Port hours
- H: Safety times
- I: Tide
- J: Berths
- K: Anchorage
- L: Boat speed
- M:Traffic conflict
- N: Pilots and tugships

Model objective:

- O: Min or Max
- P:Total programming time
- Q: Total waiting time
- R: Total cost (delayed docking, delayed departure, service requests, etc.)
- S: Total transit time
- T: Channel occupancy time

Resolved Instance Type:

- U: Number of ships resolved in the model
- V: Simulated (S) / Real (R) / No information (-)

Solution used:

- W: Genetic algorithm
- X: Mixed-Integer Programming
- Y: Simulation
- Z: Mixed-Integer Linear Programming (MILP)

TABLE 1. COMPARISON OF RECENT DOCUMENTS ON VESSEL TRAFFIC PROGRAMMING IN PORT ACCESS CHANNELS

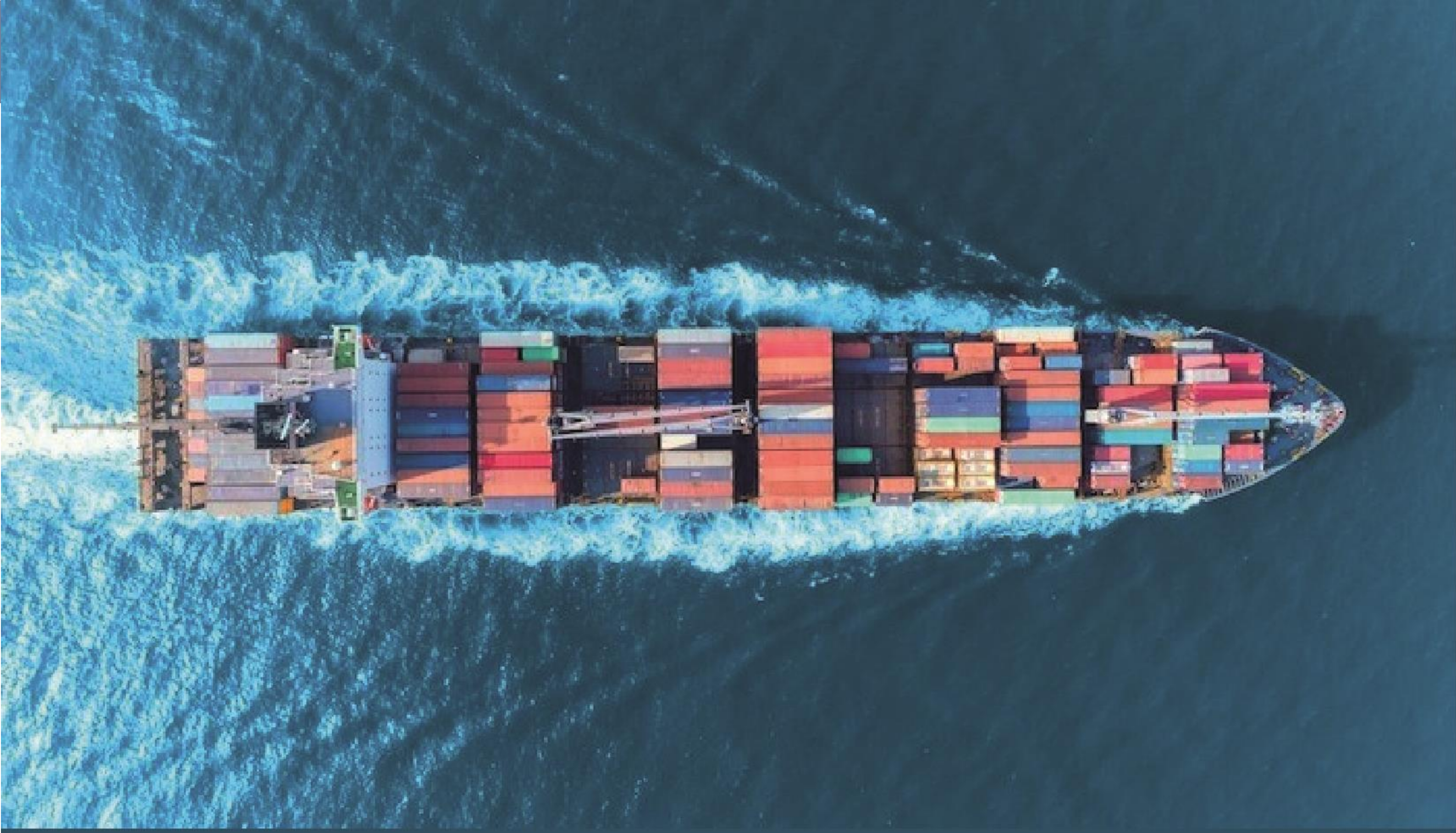
Reference	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
(Jiang et al., 2023)		x			x		x	x	x	x			x	x	min		x				6	R	x			
(R. Li et al., 2022)		x			x			x		x		x	x		min		x		x		13	R	x			

(Guo et al., 2021)	x				x					x	x		x		min	x	x				17	R	x			
(D. Liu, Shi, & Kang, 2021)	x				x		x	x	x				x		min		x				25	S	x			
(Nzualo et al., 2021)		x			x		x	x	x				x		min	x					15	S	x			
(Corry & Bierwirth, 2019)				x			x		x	x			x		min		x				10	R				
(D. Liu, Shi, & Hirayama, 2021)	x				x		x	x	x	x			x		min	x					6	S	x			
(J. Li et al., 2021)				x			x	x	x			x	x	x	min	x	x				15	R	X			
(B. Zhang et al., 2019)		x			x		x	x	x				x		min		x				20	S			x	
(le Carrer et al., 2020)		x				x	x		x	x			x								-	-			x	
(B. Zhang et al., 2019)															-						20	R				
(Hill et al., 2019)		x			x		x		x						min				x		23	S		x		
(Jia et al., 2019)	x						x		x		x				min			x			5	R				
(X. Zhang et al., 2019)	x	x					x		x						min		x				20	S				
(Meisel & Fagerholt, 2019)		x					x					x	x		min				x		110	S				
(S. Li & Jia, 2019)		x					x		x		x				min			x			-	-				
(Liang et al., 2019)	x						x								-		x				30	S				
(Sheikholeslami & Ilati, 2017)	x				x		x		x						min			x	x		10	S	x			
(Bierwirth & Corry, 2018)		x			x				x						min		x				60	R		x		
(X. Y. Zhang et al., 2018)		x					x			x					min	x	x				12	S	x			
(Lalla-Ruiz et al., 2018)				x			x		x						min				x		15	S				
(Dadashi et al., 2017)	x				x				x				x		min			x			27	R				x
(X. Zhang et al., 2016)	x						x			x					min		x				10	S				
(Sheikholeslami et al., 2014)	x					x			x		x		x		min		x				9	S	x			

The information presented in Table 1, includes the main studies published regarding the programming of ships in port access channels. Within the investigations the solutions with genetic algorithms stand out. It can also be seen that as the complexity of the restrictions increases, the number of ships that can be scheduled decreases. There is also a direct relationship between the data source used to build instances. When the data is simulated, models perform better, and this is linked to the complexity of real-world programming.

On the other hand, although authors such as Li et al., (2021); Meisel & Fagerholt, (2019) used speed restrictions within their models, this is commonly used as a parameter due to the few admissible variations within access channels due to hydrodynamic conditions that could put navigation at risk.

It is also important to point out that all the investigations consulted were tested in Asian ports, whose tidal variations are like those presented on the American Pacific coast (countries such as Chile, Colombia, Ecuador, and others) since they are governed by the same tidal race.



Chapter 2

Modeling

2.1. Model description

In previous chapters, the issue of assigning priority access to ships in port access channels was addressed. In this context, an allocation model is proposed as an academic contribution. From the literature review, a trend was observed in research towards heuristic and simulation models using robust frameworks, but with limited capacity to solve large instances. Linear models addressing large instances, albeit lenient in constraints, were less prevalent. To include a substantial set of constraints to make the model realistic and increase its programming capacity, a linear model is proposed. This model incorporates specific conditions in port access channels, restricting the free navigation of ships in the channel.

Within this abstraction, a model is presented to tackle the complexity of ship traffic scheduling in a port terminal. The central objective is to minimize the total waiting time for ships, defined as the non-negative difference between the scheduled time at the dock and the time the vessel reaches the discharge node or dock. This approach considers various constraints such as safety intervals between ships in the same channel segment, unloading periods at ports, and specific time windows for the entry and exit of ships from the access channel. These time windows are governed by tidal conditions and are designed to prevent grounding situations. Additionally, other constraints associated with continuity in ship routes are incorporated to ensure coherent planning, linking the physical reality of navigation with its scheduling. Restrictions are also implemented to avoid overlapping docks.

The total transit time of each ship is defined as the sum of the times it takes to cross each segment of its route within the channel. The model uses an abstract representation of arcs and nodes, where each node reflects variations in navigation conditions, and each arc represents a segment of the channel. This structure adapts flexibly to case studies, as the layout of the analyzed access channel becomes a model parameter. This facilitates analysis with variations in channel layout, branches, changes in navigation conditions, etc.

The optimization approach employs decision variables to determine transit start times in the arcs and allocate priorities among ships, avoiding overlaps. The first variable is the time at which each vessel starts segments within its route, i.e., the time it crosses the starting node of each arc. This variable is of great relevance as it indicates delays or advances within the itinerary of each ship. Additionally, it is significant within the model as it prevents overlap of ships in physical spaces. Considering that the studied problem has cyclic events associated with tides, another decision variable is necessary to determine if ships can initiate their transit in the channel according to the start and end windows of tides. It is important to note that this modular variable has been linearized to ensure the linearity of the model.

Finally, the addition of four binary decision variables, complementary to each other, is necessary to avoid overlapping of ships in the canal sections. In their conception, these variables indicate, in a pair of ships that transit the same arc, which one will transit the arc first. In this sense, two variables prevent them from overlapping in the same direction of transit (that is, both entering and exiting the channel). The remaining two variables prevent overlaps between an incoming ship and an outgoing ship. In summary, the model is designed with the intention of finding an efficient schedule assignment that minimizes the total waiting time at the port, while respecting the representative constraints associated with the operation of the port terminal.

The formulation assumes the following assertions to be true:

- Unimodal tides (a single high and low tide during the day (24h)
- The anchorage zone within the channel is not considered a resource.
- Travel times are constant (transit speeds).
- The discharge dock for each vessel is fixed.
- No discretization or prioritization is given based on cargo type (vessel type).
- Tugboat and pilots are unrestricted resources.
- Each vessel will be located only at its pre-assigned dock.
- The channel is completely unidirectional or completely bidirectional.

2.2. Model

2.2.1. Sets:

- $K = Set\ of\ ships, \quad K = \{1,2,3 \dots\}$
- $N = Set\ of\ nodes, \quad N = \{1,2,3 \dots\}$
- $P = set\ of\ ports, \quad P = \{1,2,3 \dots p\}$
- $A = set\ of\ arcs\ , \quad A = \{(1,2); (2,3); (3,4) \dots\}$

2.2.2. Parameters:

- $R_k: Route\ of\ ship\ k\ \forall\ k\ \in K,\ e.g. R_k = [1, 4, 6, 7, 6, 4, 1]$
- $t_{viaje_{ij}}: Arc\ transit\ time\ (i,j)\ \forall\ i,j\ \in N$
- $t_{programado_k}:\ Scheduled\ dock\ time\ for\ vessel\ k\ \forall\ k\ \in K$
- $ts_{ij}: Safety\ time\ between\ vessels\ in\ the\ arc\ (i,j)\ \forall\ i,j\ \in N$
- td_k: Vessel k unloading time $\forall\ k\ \in K$
- $tl_k: Release\ time\ of\ the\ ship\ k\ (time\ in\ which\ it\ is\ available\ for\ transit)\ \forall\ k\ \in K$
- $V_i(k,i,j): Tidal\ start\ window\ for\ vessel\ k\ in\ arc\ i,j\ \forall\ i,j\ \in N, k\ \in K$
- $V_f(k,i,j): Tide\ end\ window\ for\ vessel\ k\ in\ arc\ i,j\ \forall\ i,j\ \in N, k\ \in K$
- $a: Number\ of\ periods\ in\ the\ model\ that\ represent\ 24h\ (Tidal\ Period)$
- $P_u(k,j) = \begin{cases} 1\ if\ ship\ k\ unloads\ at\ node\ j \\ 0\ otherwise \end{cases} \quad \forall\ k\ \in K. j \in N$
- $M = Sufficiently\ large\ constant,\ e.g. M = 10000$

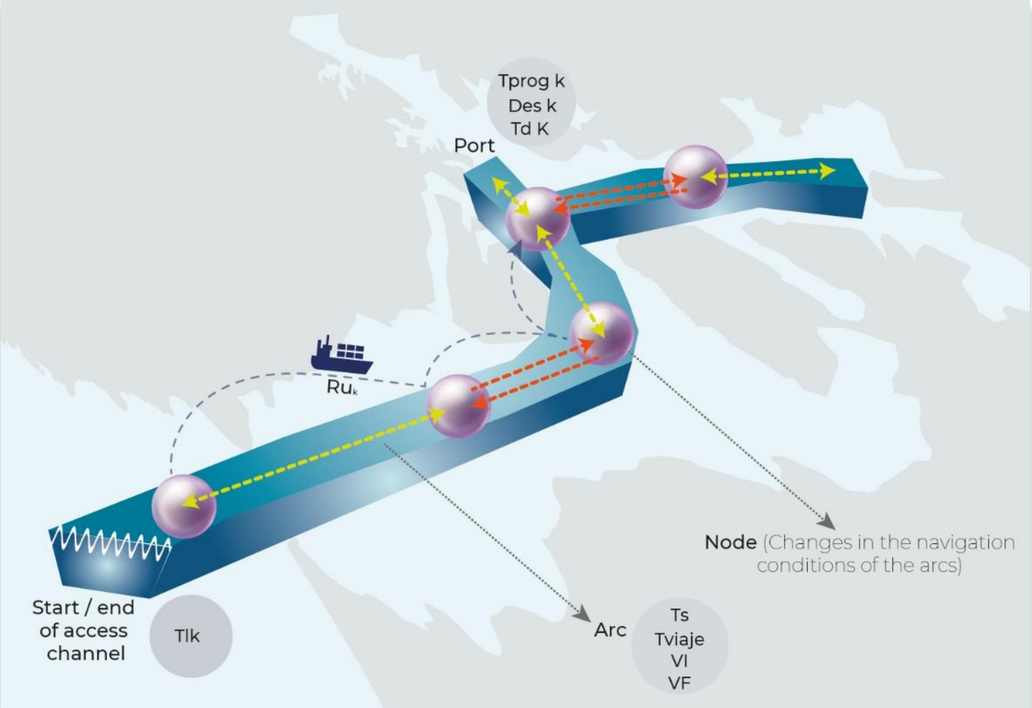


FIGURE 6. SPATIAL DISTRIBUTION OF VARIABLES.

2.2.3. Decision variables:

- $x_{(i,j,k)}: Transit\ authorization\ time\ of\ the\ ship\ k\ in\ arc\ (i,j)$

2.2.4. Auxiliary variables:

- $k_{(i,j,k)} = Integer\ number\ that\ represent\ the\ quotient\ of\ the\ division\ of\ x_{(i,j,k)}\ and\ a\ for\ the\ ship\ k\ the\ arc\ (i,j)$
- $y_{(i,j,k)} = Represents\ the\ module\ of\ the\ start\ time\ (x) over\ the\ number\ of\ periods\ (a) for\ ship\ k\ the\ arc\ (i,j)$
- $wkr(i,j,k,r) = \begin{cases} 1\ if\ ship\ k\ begins\ to\ cross\ arc\ (i,j)\ before\ ship\ r\ begins\ to\ cross\ arc\ (i,j) \\ 0\ otherwise \end{cases}$
- $wrk(i,j,r,k) = \begin{cases} 1\ if\ ship\ r\ begins\ to\ cross\ arc\ (i,j)\ before\ ship\ k\ begins\ to\ cross\ arc\ (i,j) \\ 0\ otherwise \end{cases}$
- $ykr(i,j,k,r) = \begin{cases} 1\ if\ ship\ k\ begins\ to\ cross\ arc\ (i,j)\ before\ ship\ r\ begins\ to\ cross\ arc (j,i) \\ 0\ otherwise \end{cases}$
- $yrk(i,j,r,k) = \begin{cases} 1\ if\ ship\ r\ begins\ to\ cross\ arc\ (i,j)\ before\ ship\ k\ begins\ to\ cross\ arc (j,i) \\ 0\ otherwise \end{cases}$
- $z_{(i,j,k)} = Non - Negative\ Variable\ that\ represents\ the\ delay\ in\ arrival\ at\ the\ port\ of\ the\ ship\ k\ \ the\ arc\ (i,j)$

2.2.5. Objective Function:

$$min \sum_{(i,j)\in A} \sum_{k\in K} z_{i,j,k}$$

2.2.6. Constraints:

1. Linearization:

$$z(i,j,k) \geq \left[x(i,j,k) - t_{prog}(k)\right] \quad \forall\, k \in K, \forall\, (i,j) \in A : P_u(k,j) = 1$$

2. Release:

$$x[R_k(1), R_k(2), k] \geq tl(k) \;\; \forall\, k \in K$$

3. Restriction of continuity of the route of the ship k:

$$x[R_k(i+1), R_k(i+2), k] = x[R_k(i), R_k\,(i+1), k] + t_{viaje}[(R_k(i), R_k(i+1)] + td(k) * P_u(k, i+1) \;\; \forall\, k \in K, i > 1, i \in 1 \cdots Long(R_k)$$

4. Non-overlapping flow constraints:

$$x(i,j,k) - x(i,j,r) \geq ts(i,j) - M * wkr(i,j,k,r) \qquad \forall\, (i,j) \in A, (k, r \in K \mid k \neq r), (i,j) \in R_k; (i,j) \in R_r$$

$$x(i,j,r) - x(i,j,k) \geq ts(i,j) - M * (1 - wrk(i,j,k,r)) \qquad \forall\, (i,j) \in A, (k, r \in K \mid k \neq r), (i,j) \in R_k; (i,j) \in R_r$$

5. Non-Overlapping Constraints in Opposite Directions:

$$x(i,j,k) - x(j,i,r) \geq t_{viaje}(j,i) - M * \left(\, ykr(i,j,k,r)\right) \forall (i,j) \in A, i > j, (k, r \in K \mid k \neq r), (i,j) \in R_k; (i,j) \in R_r$$

$$x(i,j,r) - x(j,i,k) \geq t_{viaje}(j,i) - M * \left(1 - yrk(i,j,k,r)\right) \forall (i,j)\ en\ A, i > j, (k, r \in K \mid k \neq r), (i,j) \in R_k; (i,j) \in R_r$$

6. Non-Overlapping Constraints on Dock:

$$x(i,j,r) + t_{viaje}(i,j) \geq x(j,i,k) - M * \left(wkr(i,j,k,r)\right) \forall\, j \in P, (i,j) \in N, (k, r \in K \mid k \neq r), (i,j) \in R_k; (i,j) \in R_r$$

$$x(i,j,k) + t_{viaje}(i,j) \geq x(j,i,r) - M * \left(1 - wrk(i,j,k,r)\right) \forall j \in P, (i,j) \in N, (k, r \in K \mid k \neq r), (i,j) \in R_k; (i,j) \in R_r$$

7. Tidal start time module:

$$x(i,j,k) = a * k(i,j,k) + y(i,j,k) \qquad \forall\, k \in K, (i,j) \in A$$

8. Time window restrictions on tides:

$$y(i,j,k) \geq v_{inicio}(k,i,j) \qquad \forall\, k \in K, (i,j) \in A$$

$$y(i,j,k) \leq v_{fin}(k,i,j) \qquad \forall\, k \in K, (i,j) \in A$$

9. Domain variables

$$x[i,j,k] \geq 0$$

$$z[i,j,k] \geq 0$$

$0 \leq y[i,j,k] \leq a - 0.01$

$k[i,j,k] \in Z$

$wkr(i,j,k,r) \in \{0,1\}$

$wrk(i,j,r,k) \in \{0,1\}$

$ykr(i,j,k,r) \in \{0,1\}$

$yrk(i,j,r,k) \in \{0,1\}$

The objective of the model is to minimize the total delay of the start of transit on the arcs for all ships and considers the following constraints:

1. **Linearization constraint:** The linearization constraint is used to linearize a part of the model's formulation. This constraint is defined for each ship, arc, and node in the model. If the arc is on the ship's route, the constraint is activated. Otherwise, the constraint is omitted.
2. **Release constraint:** The release constraint ensures that the start time of transit on the first arc of the ship's route is greater than or equal to the ship's release time. This constraint is defined for each ship in the model.
3. **Port continuity constraint:** The route continuity constraint ensures that the transit start time at each arc of the ship's route is correctly related to the previous and next arcs of the route. This restriction is defined for each ship and position on the route. If the position is the ship's port, route continuity considers the unloading time at the port. If the position is the first arc of the route, a relationship is established between the start time of the transit on that arc and the ship's release time. For other positions, a relationship is established between the start time of the transit in the current arc, the previous arc and the travel time between them.
4. **Flow non-overlap constraint:** The flow non-overlap constraint prevents two different ships from occupying the same arc at the same time. This constraint is applied to each pair of ships, arcs, and nodes in the model. If the arc is present in the model, the ships are in different routes, and the arc is on both ships' routes, a relationship is established to ensure that the start time of transit on the arc for the first ship is greater than or equal to the start time of transit on the same arc for the second ship, plus a minimum time difference. Otherwise, the constraint is omitted.
5. **Opposite direction overlap constraint**: It prevents two vessels sailing in opposite directions from crossing each other within the traffic arc. It is important to note that in experimentation this constraint is always considered active, but in other scenarios of complete bidirectionality it might not be considered.
6. **Dock non-overlap constraint**: The dock non-overlap constraint prevents two different ships from occupying the same dock at the same time. This constraint is applied to each pair of ships, arcs, and nodes corresponding to a dock in the model. If the node is a dock and the arc is present in the model, the ships are in different routes, and the arc is on both ships' routes, a relationship is established to ensure that the start time of transit on the arc for the first ship plus the travel time from the arc to the dock is greater than or equal to the start time of transit at the dock for the second ship, plus a minimum time difference. Otherwise, the constraint is omitted.

7. **Time Windows Constraints:** For each ship, arc, and node in the model, this constraint checks if the arc is present in the model and if it is part of the ship's route. If both conditions are met, it enforces that the start time of transit on the arc for the ship is greater than or equal to the specified start time of the corresponding time window. If the conditions are not met, the constraint is skipped.
8. **Start Time Module Constraint:** For each ship, arc, and node in the model, this constraint checks if the arc is present in the model and if it is part of the ship's route. If both conditions are met, it enforces that the start time of transit on the arc for the ship is equal to the product of a specific adjustment factor and a binary variable indicating whether the arc is used in the ship's route, plus the start time of transit on the arc without adjustment. If the conditions are not met, the constraint is skipped.
9. **Domain restrictions:** Sets of values allowed for each variable.

Chapter 3

Study Case

3.1. Context

Colombia is in a privileged maritime geographical area in terms of vesselping routes, as it is the only country in South America with connections to the Atlantic and the Pacific. In addition, it is close to the Panama Canal and represents a connection point between countries of North and South America which makes it a convergence site for sea and air routes. In Colombia, maritime transport is experiencing an annual growth rate close to 8.1% and this has led to the increase in the size and capacity of ships arriving in Colombian waters (Vega et al., 2019) Consequently, Colombian ports are modernizing to diversify their services and maximize their efficiency by reducing their costs that are closely linked to the time of stay of ships and cargo within the port (Vega et al., 2019) The main ports of Colombia are Cartagena (2'862.787 TEU[2]), Buenaventura (1'369.139 TEU) and Barranquilla (154.533 TEU) that are shown in Figure 7 along with others of lesser relevance. These ports currently operate through private concessions to regional port companies and register operations for a total of 4,582,712 TEU for 2018, being surpassed in Latin America only by Brazil (10,030,121 TEU), Mexico (6,987,820 TEU), and Panama (6,872,369 TEU), which has allowed the country's positioning at the top of the region (CEPAL, 2019). On the other hand, the Economic Commission for Latin America, and the Caribbean (ECLAC) prepares the ranking of volume of movements where the Colombian ports of Cartagena (fourth most important port in Latin America) and Buenaventura (twelfth in Latin America) stand out (CEPAL, 2019). Additionally, excluding hydrocarbons (oil and coal)- 32% of Colombia's export and import cargo is mobilized through the Port of Buenaventura (SuperTransporte, 2019)

FIGURE 7. LOCATION OF PORTS IN COLOMBIA. SOURCE: OWN ELABORATION

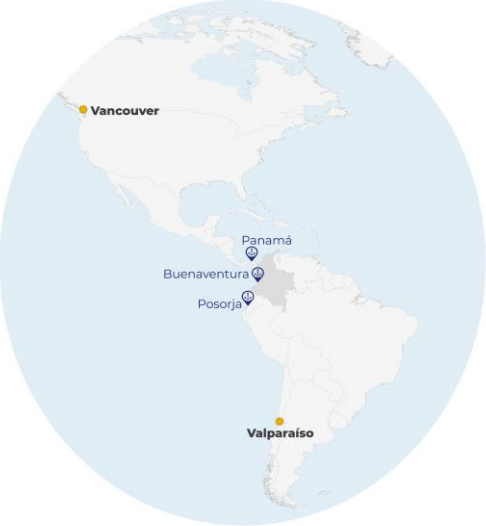


FIGURE 8. GENERAL LOCATION OF THE PORT AREA OF BUENAVENTURA. SOURCE: OWN ELABORATION

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[2] The quantification of port activity is given in TEU; the unit refers to a container 20 feet long by 8 feet wide and 8 and a half feet high. This represents an external volume of 38.51 cubic meters; maximum weight of 21,600 kilograms without tare and maximum capacity of 33 cubic meters (González & Novo, 2016)

Thus, the maritime terminal of Buenaventura is the most important in the Pacific and the second nationally, its location is strategic because it is the port of South America closest to Asian markets (8,443 nautical miles to Shanghai (China) compared to 8,680 nautical miles away from its main competitor, the port of Posorja in Ecuador). It is also equidistant from Vancouver (Canada) and Valparaíso (Chile) (IIRSA, 2003; SPRB, 2020). However, despite its geostrategic advantages and its national relevance, according to the World Bank, Buenaventura has lags in terms of time spent on maritime operations compared to other ports (World Bank, 2022). The problems caused by delays in the delivery of goods translate into higher costs, risks of breakdowns, losses, and theft (Pace & Ricci, 2018); with it, a decrease in the reliability of the port.

In the Pacific logistics corridor (Pacific Alliance market formed Chile, Peru, Colombia, and Mexico) the port area of Buenaventura is the access point of Colombia, and this results in the need to meet the maritime services of large capacity ships and drafts between 13m or 14m (ANDI, 2015).

Among the main operational problems of the port area of Buenaventura, is the access channel (Burns, 2013; Rodriguez, 2013). This has a length of 31.5 km equivalent to 17 nautical miles and a variable depth of 12.5m at low tide with oscillations between 2.5m and 3.5m per day according to the tide that in the area change approximately every 6 hours (COMPAS, 2018; IIRSA, 2003; Osorio et al., 2014). The canal is public and has a width of 200m on the outside and 160m on the inside. Its capacity is given by its width and draft that restrict transit to and from the component ports of the port area according to the tide. The delays in embarkation and disembarkation of goods linked to the narrow window of time available to access and leave the port even lead some vesselping companies to prefer not to dock in Buenaventura to avoid non-compliance in their appointments to cross the Panama Canal (Rodriguez, 2013).

The port area of Buenaventura is made up of five ports; Sociedad Puerto Industrial Aguadulce SA that mobilizes 24% of the cargo in the port area, Sociedad Portuaria de Buenaventura SA that moves 48%, TCBUEN SA that moves 16%, COMPAS SA with a 5% stake and Grupo Portuario SA that moves 7% (SuperTransporte, 2019). All share the access channel for the entry and exit of ships to their facilities.

Transit on the canal is under the responsibility of the nation (COMPAS, 2018). Thus, the circulation of ships in the canal, in addition to some maneuvers prior to docking, are those controlled by the General Maritime Directorate (DIMAR) through the traffic control office of this agency (COMPAS, 2018). The priority of arrival of ships of international transit, under normal conditions of navigation will be ships of forced arrival, military ships, passenger ships, container cargo ships, general cargo and bulk ships and finally ships that do not apply in the categories (DIMAR, 2020). However, it has been shown that this allocation is not efficient because variables of great relevance such as the time window available for transit according to the draft of the vessel, the waiting time or the operational plan of each port are currently not linked to the assignment of transit priority.

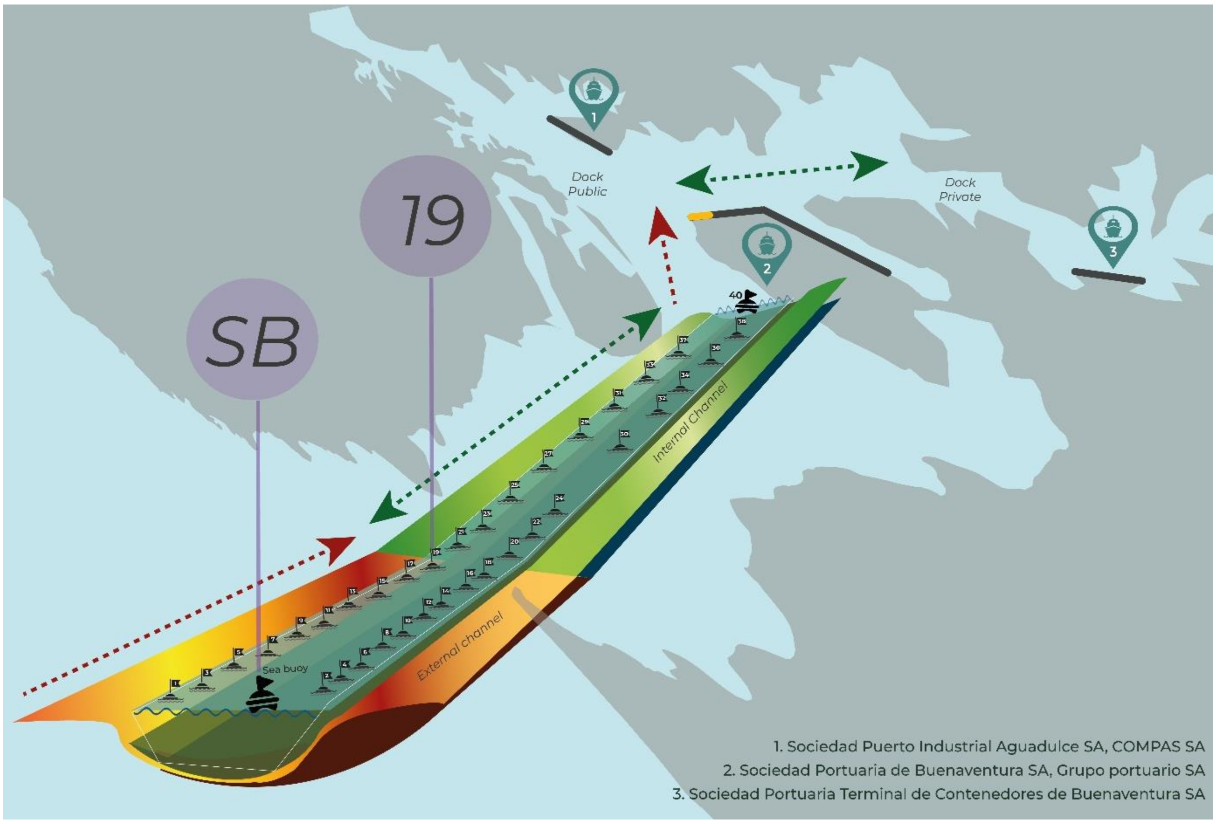


FIGURE 9. ACCESS CHANNEL PORT AREA OF BUENAVENTURA. SOURCE: OWN ELABORATION

The canal has a structure restricted (sections bidirectional and other sections one-way). Between the sea buoy and buoy 19 shown in Figure 9, the channel is unidirectional given the accumulation of sediments in the area; between buoy 20 and 40, the channel is bidirectional if the sum of the sleeves of the ships in transit does not exceed 80m. Additionally, it is not a composite channel because there is a single path. To access each port, it is necessary the presence of practical pilots and some motorships to dock the ships at the docks.

On the other hand, there is a public dock in which ships in transit can dock momentarily prior to their docking maneuvers.

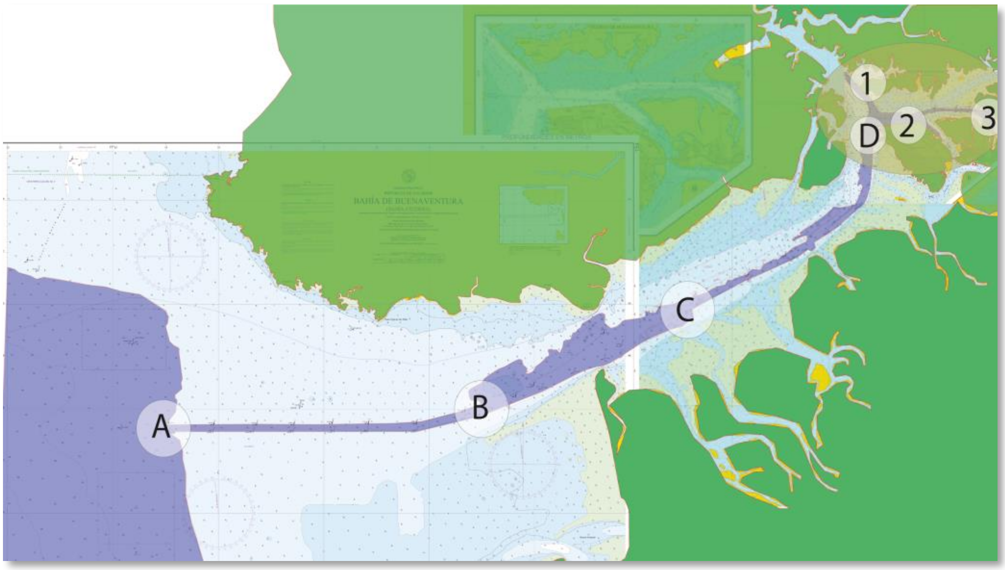


FIGURE 10. CHARACTERIZATION OF THE STUDY PROBLEM. SOURCE: OWN ELABORATION

Figure 10 shows the structure of the channel. In A, incoming ships enter the canal and outgoing ships leave it. Between node A and node B, only one boat can pass because the navigable width and depth is close to 300 meters, but the depth is highly variable in the surroundings due to the presence of sandbanks.

The arc between B-C is considered bidirectional because there is a width of 1,500m that could be used to have 2 ships simultaneously in the same arc, however C-D is once again unidirectional given its 300m width. From node D, the routes traveled by the ships will present variations given the branch structure of the canal. Ships going to infrastructure 1 (Puerto Aguadulce and Compas) will turn west, while those going to 2 (Sociedad Portuaria and Grupo Portuario) and 3 (TC Buen) will do so to the east.

3.2. Data collection and processing

3.2.1. Access channel

The data of the instances were built based on external and real sources associated with the ports of Buenaventura. The geometric characteristics of the channel were modeled based on the official navigation charts of the port, from which the following data was extracted:

- Selection of sections that form the arcs of the model and the nodes into which the problem is subdivided
- Set of problem port nodes
- Channel navigability characteristics (depths, widths, bidirectional zones, etc.)

To demarcate the arcs of the model so that they were a good abstraction of the case study, the sections of the channel in each of the sections were analyzed to classify them into sectors of typical sections and little variation in width and depth that the main arcs

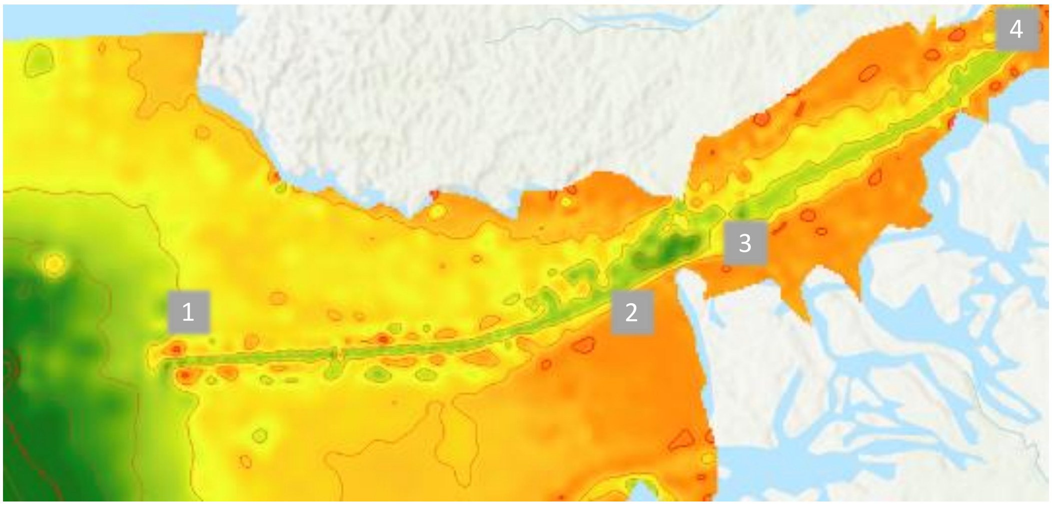
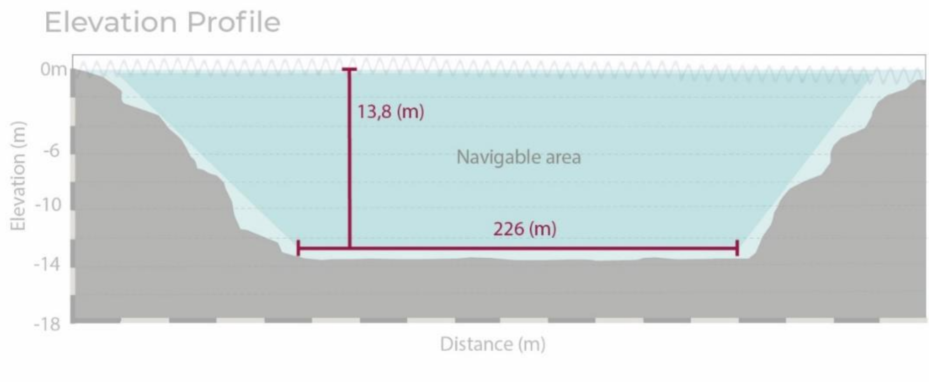


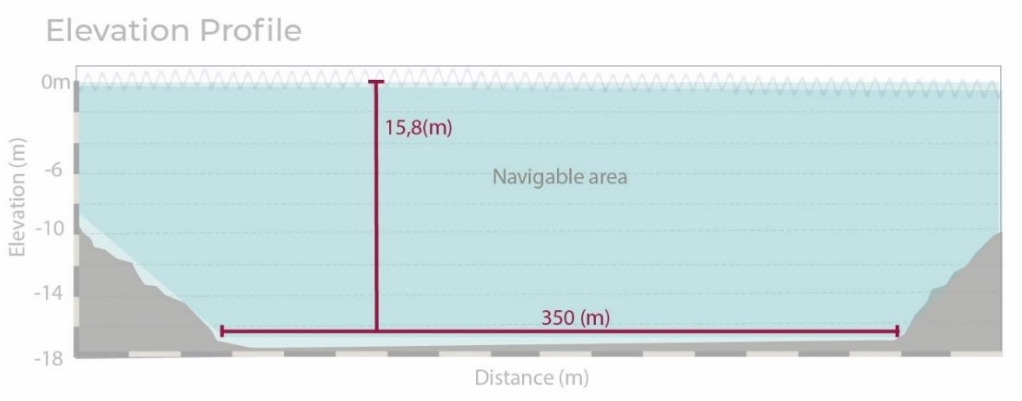
FIGURE 11. STUDY CASE DEPTHS PROFILE.

As indicated in figure 11, according to the physical characteristics, 3 arcs or sections have been generated in the first instance: 1-2, 2-3, 3-4. These have the following typical elevation profiles:

- 1-2; 2-1:



- 2-3; 3-2:



- 3-4; 4-3:

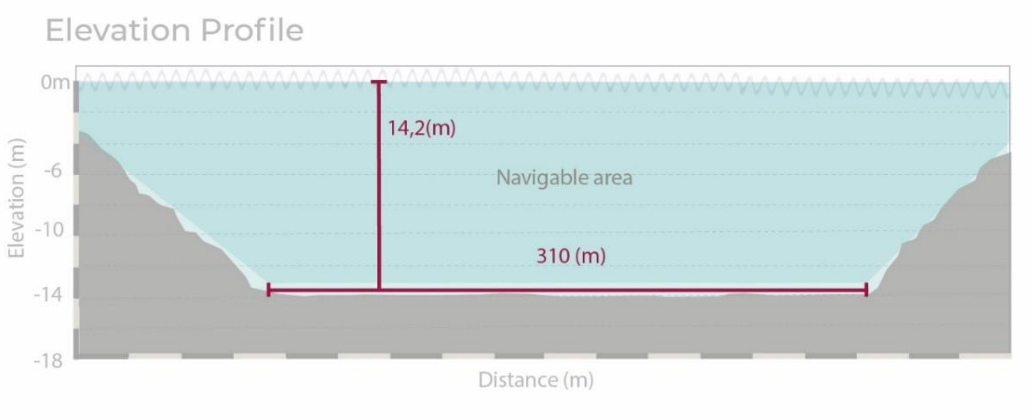


FIGURE 12. DEPTHS PROFILE.

On the other hand, the internal channel was segmented based on changes in navigation conditions; that is, marking patterns of possible directions changes in depth, width and directionality that affect the crossing of the ships as indicated in figure 13 (It is worth mentioning that nodes 1,2,3 and 4 are only symbolized in the image because spatially They are more distant.)

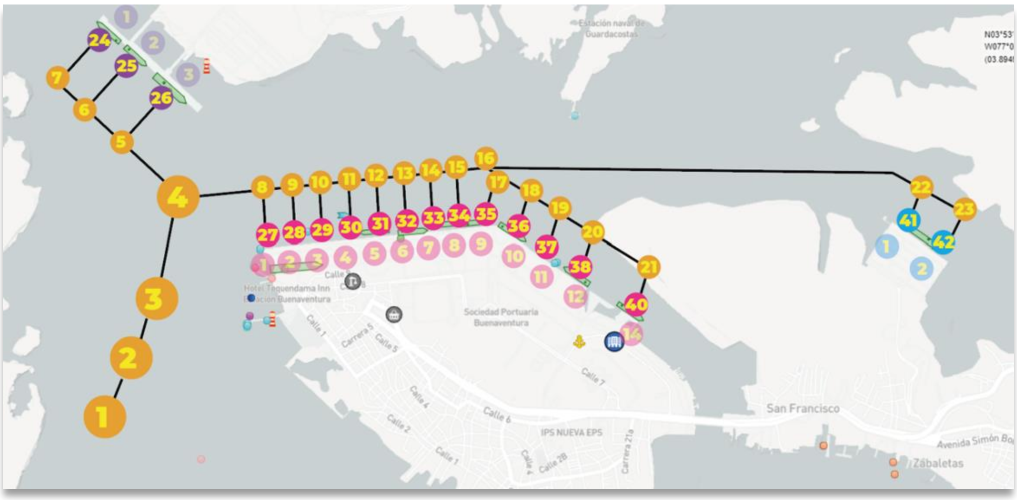


FIGURE 13. STUDY CASE - PORT DISTRIBUTION.

3.2.2. Scheduled ships (Dock time)

The instances of the ships for testing the model were built based on the Marine Traffic real-time vessel observatory. From there, the programming of each vessel (expected schedule and characteristics of the vessel such as draft and beam) was taken as input for the model. The distinctions of the type of cargo of the vessel (bulk, container or other) are not relevant within the model since it is not necessary to assign cranes or dock resources.

Additionally, said information nourished the instances of the model because the instances were built based on the test instances.

3.2.2.1. Ships Validation data

As mentioned in the previous numeral, the validation data was obtained from the marine traffic portal and the following data was recorded:

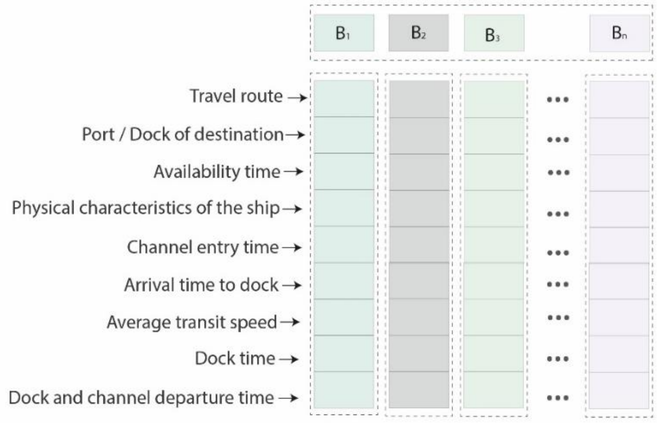


FIGURE 14. STRUCTURE OF COLLECTED DATA

3.2.2.2. Ships Experimental data

The experimental data were built based on the registered instances for data validation and tidal prediction of the Buenaventura port area. Each data used within the model was obtained as follows:

- Travel route: The travel routes described by the real ships were chosen to model a typical behavior of port activities
- Transit speed: The transit speeds of the ships along the canal are observed and recorded, and the average speed was obtained for the sections of the model.
- Minimum safety times and maximum speeds: Those consulted in the literature were recorded (maximum speed 35km/h) (minimum safety time 20min)
- Start and end windows of the ships: According to hydrodynamic principles, the free distance between the seabed and the bottom of the vessel must be 12% of the draft (Jiao et al., 2018). Thus, having the draft of the ships selected for the travel routes, information on their draft was available. Then, comparing with the tide charts of the port, the approximate height was obtained on a typical day of each month and from there it is known that the trip could start if the time in which it starts complies with the draft restriction. Then the completion window will be the moment in which the vessel can no longer transit the section as the restrictions described above are not met.
- Unloading time: It will be the average of the unloading time of the type of vessel in the validation data set
- Dock time: It will be the time in which the entry of the ships to the dock was registered.
- Availability time: 2 hours before the dock time scheduled

Within the structuring of the problem, the allocation of specific resources was not included because it could reflect the idea that these resources are shared among multiple ports or are easily transferable, and this is not the case in reality. In this sense, detailed resource allocation requires a modular approach, where each port can manage its own internal resources without overly depending on others.

In this scenario, access priority might suffice to coordinate the arrival and departure of ships, while resource allocation can be handled internally at each port. Additionally, modeling resource allocation at the dock could introduce additional layers of complexity that might be unnecessary to address the central issue of priority, which has been identified as a gap in the literature.

Chapter 4

Experiments and Results

4.1. Model validation

For the validation of the model, an experiment was carried out with 36 ships whose real data was recorded during 10 days of operation of the terminal. Base data and model results were recorded for each of the ships to compare the model assignment vs. the actual assignment of the ships. The results were forced with the parameters of availability time and dock time of each vessel to verify that under this scenario the results were consistent with those observed and the results are as follows:

The known real data are:

- Scheduled dock time for each vessel
- Arrival time at the dock
- Availability time of each vessel
- Time of each vessel in dock (unloading time)
- Tide start and end windows for each vessel

Thus, with the input data, the real assignment results are compared, biasing the expectations of each vessel.

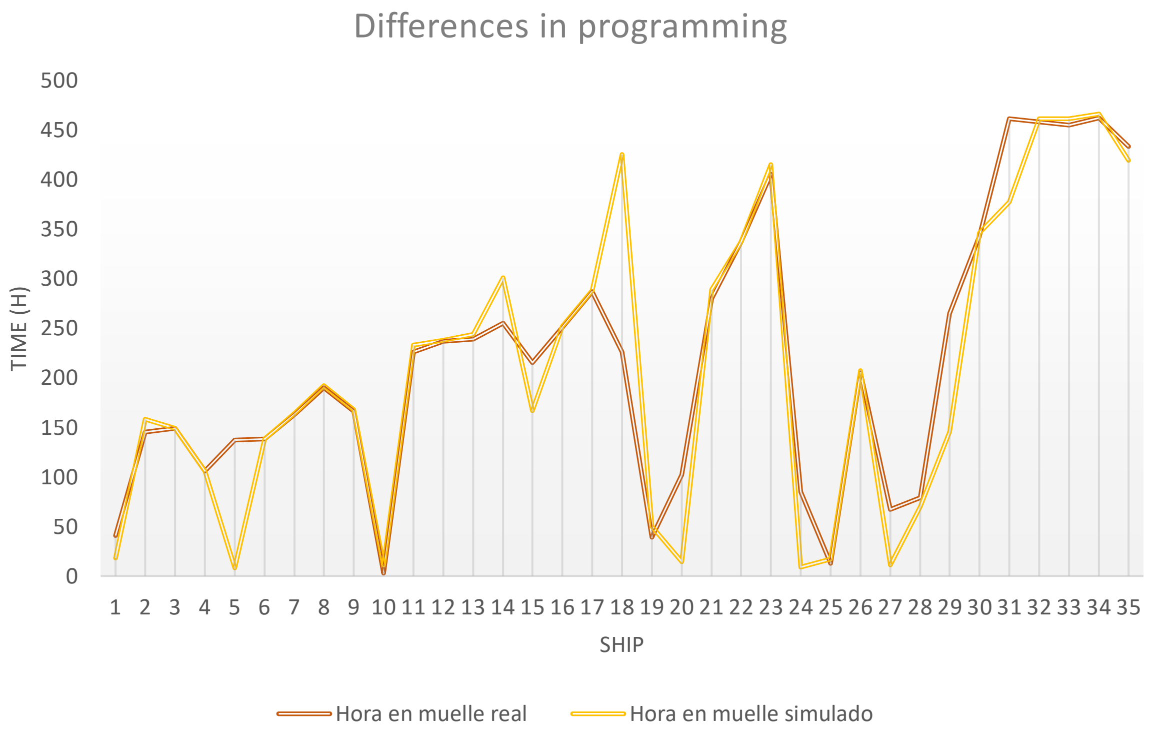


FIGURE 15. COMPARISON BETWEEN REAL AND SIMULATED CASE

According to the data obtained, the model describes a behavior very similar to that of the real behavior instance generated. There are no significant differences in the planning horizon, neither by vessel nor by total.

On average there was a difference between the real times and the simulated times of 1%.

. 4.2. Model capacity

The model was executed with spyder 4.3 using the Guribi 10.0.0 optimizer with a GAP of 2%. The computer on which the execution was carried out has the following characteristics:

- Processor: Intel(R) Core(TM) i7-10510U CPU @ 1.80GHz 2.30 GHz
- RAM: 16GB
- System type: 64-bit operating system, x64 processor

And the following execution times were obtained:

TABLE 2. RESULTS OF MODEL CAPACITY

Ships	Time (s)	Time (min)	Time (h)
10	4,62	0,08	0,00
20	17,37	0,29	0,01
30	68,72	1,15	0,04
40	158,67	2,64	0,09
50	287,21	4,79	0,16
60	454,36	7,57	0,25
70	660,11	11,00	0,37
80	904,46	15,07	0,50
90	1187,41	19,79	0,66
100	1508,95	25,15	0,84
110	1869,10	31,15	1,04
120	2267,85	37,80	1,26
130	2705,20	45,09	1,50
140	3181,15	53,02	1,77
150	3695,69	61,59	2,05
160	4248,84	70,81	2,36
170	4840,59	80,68	2,69
180	5470,94	91,18	3,04

Among the main conclusions to highlight is that the model has a good capacity to model the case study, since approximately 36 vessels are mobilized within the canal in 2 weeks and this instance can be completed in approximately 2 minutes, which facilitates decision making. in real time in the event of any change in itineraries. Furthermore, with this formulation the case study could be changed by varying input parameters, and it could be adjusted to more congested channels considering that an instance of 180 vessels can be resolved in 3 hours. This speed may be due to:

- The linearity of the model and the configuration of nodes and arcs
- The simplicity of modeling the tides (unimodal)
- The limitation on speeds and safety times that are estimated to be constant

- That the priority assignment model has as its input the arrival dock of the vessel

It is worth mentioning that some of the reasons previously stated could be focused as benefits of the model and others as future studies and some characteristics that could be modeled in the future should be mentioned:

- Add practical pilot and tug restrictions
- Model bimodal tides
- Consider changing the berth of the ships (as an alternative for ships that arrive early but their unloading berth is busy)

Based on the information presented in Table 2, where the execution times of the model with different instances are observed, it is evident that it has good performance and low execution times given its linear structure.

Furthermore, based on observations in maritime traffic, it is found that in a period of 2 weeks (which is a common horizon used in the literature for similar problems) an average of 36 ships pass through the access channel.

4.3. Traffic speeds

4.3.1. Justification of the experimentation

Speed is an important factor to consider when navigating in restricted waters because it can directly impact the safety of the vessel, the crew, and other ships in the area (Kotachi et al., 2013). When navigating in these areas, a vessel's speed must be carefully monitored to avoid collisions with other ships or objects and to minimize the potential for damage to the vessel itself. High speeds increase the risk of collisions, and the consequences of a collision in restricted waters can be severe due to the limited maneuvering room (Zhang et al., 2016).

Additionally, high speeds can create large wakes, which can be dangerous for other ships and can cause damage to nearby structures and shorelines. Large wakes can also create dangerous turbulence, making it difficult for other ships to maintain their course or to dock safely.

On the other hand, the increase in the immersion of the ships with high speed is a hydrodynamic phenomenon that occurs when the speed of the vessel increases. As speed increases, the resistance of the water against the hull of the boat also increases, causing the hull to sink further into the water. The additional hull immersion can have several effects on navigation, including decreased boat speed and efficiency, increased fuel consumption, and a greater chance of hitting objects or colliding with other ships due to the increased draft.

Additionally, increased immersion can have a negative impact on boat stability, especially on smaller ships, which can increase the risk of capsizing and accidents. It is important that boat operators adjust their speed according to water conditions, boat characteristics, and safety recommendations to avoid excessive hull submersion and maintain safe and efficient boating.

The maximum transit speeds in port access channels may be regulated by the port authority to guarantee safe navigation and protect the port infrastructure. These regulations may vary depending on the size and type of vessel, channel conditions, and geographic location. Maximum transit speeds can be influenced by several factors, such as the depth of the channel, the amount of vessel traffic, the presence of piers, buoys, or other obstacles in the channel, and weather conditions.

In general, port authorities set speed limits to ensure safe navigation and minimize the risk of damage to port infrastructure and other ships. It is important that vessel operators are familiar with the specific local port authority regulations and recommendations before entering a port access channel and adjust their speed according to channel conditions and safety recommendations.

4.3.2. Experimentation question

As mentioned, the average transit speed plays a relevant role both in optimizing vessel waiting times and in navigation safety. With this experimentation, it is intended to know, under the same navigation conditions, what is the minimum speed with which it is possible to travel through the access channel without affecting the waiting times of the ships (average transit speed clearance)?

4.3.3. Experiment Description

The maximum transit speed of ships in the access channel to Buenaventura may vary according to the specifications of the port authority and the conditions of the channel at any given time.

In general, it is recommended that ships navigate at a safe speed appropriate to channel and weather conditions to ensure the safety of navigation and minimize the risk of damage to port infrastructure and other ships. As a minimum level of analysis, the references were taken, which set the maximum speed in restricted waters for deep-draft ships of 24km/h ≅ 13 knots (COMPAS, 2017).

During the experimentation, the speeds were varied systematically between the average observed in the field and the maximum reported in the literature. It should be noted that for each instance the other parameters remained constant to clearly visualize the specific effects of the variations in the average speed.

Within the experimentation, 9 instances of 36 ships were evaluated.

With these parameters, the model was run, recording the results and the variation was carried out until it descended to a minimum that did not affect the optimality.

4.3.4. Results

TABLE 3. EXPERIMENTAL RESULTS WITH SPEED

Ships	Average transit speed (kn)	Average transit speed (km/h)	Average wait
36	13	24,05	5h 30 min
36	12	22,2	5h 30 min
36	11	20,35	5h 30 min
36	10	18,5	5h 30 min
36	9	16,65	5h 30 min
36	8	14,8	5h 30 min
36	7	12,95	5h 30 min
36	6	11,1	6h 40min
36	5	9,25	7h 2min

With the experimentation, it is observed that speeds between the maximum allowed national (13kn) up to 7kn, the average wait of the ships was maintained. However, there are substantial increases in waiting times when the speed is less than 7kn ≅ 11.1km/h.

In this sense, it would always be ideal to navigate at the lowest possible speeds that do not affect optimality, since slower transits generate greater safety in the maneuverability of the ships.

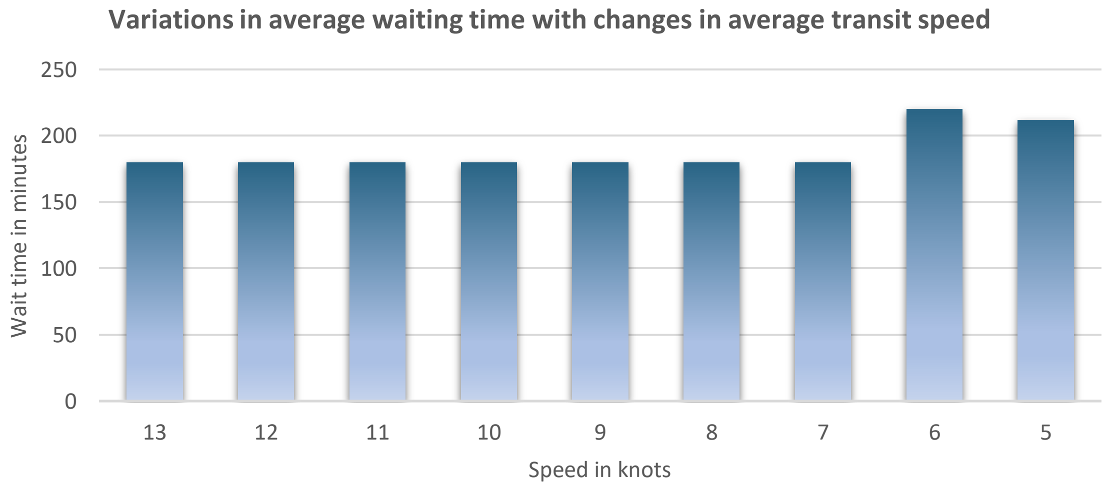


FIGURE 16. RESULTS OF EXPERIMENTATION WITH SPEEDS

4.4. Safety times

4.4.1. Justification of the experimentation

The safety times between ships in access channels are important to guarantee the safety of navigation. Access channels are areas with limited room to manoeuvre, and heavy vessel traffic is common in these areas, increasing the risk of collisions. Safety times are the time intervals required between the departure of one vessel and the entry of another into a specific section of the access channel. These safety times are established to prevent two ships from being in the same section of the canal at the same time, which could cause collisions or dangerous maneuvers. In some cases, safety times may also be set to ensure ships have enough room to maneuver and avoid collisions with fixed objects or structures in the channel.

It is important that boat operators respect the established safety times to avoid dangerous situations in the access channel. Additionally, safety times can vary based on weather conditions, vessel characteristics, and operator experience, so it is important that operators are aware of established safety times and carefully follow them to ensure navigation safety.

Although it is important to maintain adequate security times in access channels to ensure safe navigation, it is also important to minimize these security times as long as an adequate level of security is maintained.

Minimizing security times can have several benefits, such as:

1. **Increase traffic efficiency:** By minimizing security times, the number of ships that can pass through an access channel in each period can be increased. This can help reduce delays and wait times, which can increase traffic efficiency.
2. **Reduce operating costs:** By decreasing wait times and increasing traffic efficiency, the operating costs of ships can be reduced. For example, fuel and labor costs can be reduced.
3. **Improve port competitiveness:** If a port can offer shorter waiting times and higher traffic efficiency, this can improve its competitiveness compared to other ports.

However, it is important to consider that the minimization of security times must not compromise the safety of navigation. Therefore, a proper balance between security and traffic efficiency must be found when setting security times on access channels.

It is important to establish a maximum-security time that does not affect the optimal waiting time in a port access channel, since this can help guarantee efficiency and security in maritime traffic. If the safety time is too long, this can cause unnecessary delays and increase the operating costs of the ships. In addition, it can decrease the efficiency of the traffic and reduce the competitiveness of the port in comparison with other ports. On the other hand, if the safety time is too short, this can compromise the safety of navigation and increase the risk of collisions in the access channel.

By setting the maximum-security time that does not affect optimal waiting, a proper balance can be found between security and traffic efficiency. This can help reduce the operating costs of the ships, improve the competitiveness of the port, and ensure the safety of navigation in the access channel.

It is important to note that the maximum safe time can vary depending on several factors, such as weather conditions, the type of boat and the experience of the operator. Therefore, it is essential to carry out regular evaluations and adjust security times accordingly to guarantee safe and efficient navigation in the port access channel.

4.4.2. Experimentation question

In access channels, it is essential to consider the minimum safety times between ships to guarantee safe and efficient navigation. These safety times are necessary to prevent collisions, sudden maneuvers and risk situations that may endanger the integrity of the ships, the cargo transported and human life. However, it is equally important to ensure that these minimum-security times do not negatively affect optimal navigation times, as this could result in delays, congestion, and decreased operational efficiency in access channels.

Therefore, the following question arises: what is the minimum-security time that guarantees optimal navigation times in the access channels, maximizing both security and navigation efficiency?

4.4.3. Experiment Description

For the experimentation, the test instance of 36 ships has been tested. This has been run with the constant parameters before the variation only of the security times with the objective of identifying variations in the optimality of the problem. For this purpose, limits were established for the minimum regulatory time in the access channel (8min between ships traveling at 7kn) and it was tested with variations based on the minimum until the time in which the variation of the average waiting time for the ships changed.

4.4.4. Results

In Buenaventura, there must be at least 1 nautical mile between ships. Bearing in mind that the speed has been considered constant, the minimum safety time between ships will be 8m at a speed of 7kn. After evaluating the optimality with an instance of 36 ships, the following results are obtained:

TABLE 4. EXPERIMENTAL RESULTS WITH SAFETY TIME

Ships	Average transit speed (kn)	Average security time (min)	Average wait
36	7	9	5h 30 min
36	7	12	5h 30 min
36	7	15	5h 30 min

36	7	18	5h 30 min
36	7	21	5h 30 min
36	7	24	5h 30 min
36	7	27	5h 45 min
36	7	30	5h 45 min
36	7	33	6h 8min

According to the results and considering the relevance of the safety times, it is feasible to state that for the case study, with an average speed of 7kn and safety times of a maximum of 24min between ships, there are no alterations in the optimality of the case study. It is also important to indicate that the model could be an ultimate tool to determine said limits in other port units.

4.5. Best time to sail

4.5.1. Justification of the experimentation

The best time of year to navigate tidal access channels can vary based on geographic location and local conditions. However, in general, the highest tides are usually the best conditions for navigating the access channels.

In some places, the tides can be higher during the winter due to winter storms and variations in water temperatures. Elsewhere, the highest tides can occur during the spring or fall due to seasonal currents.

It is important to consider that, in addition to the tides, weather conditions can also affect navigation in the access channels. For example, storms can increase the height of the waves and make navigation more dangerous, even if the tides are high.

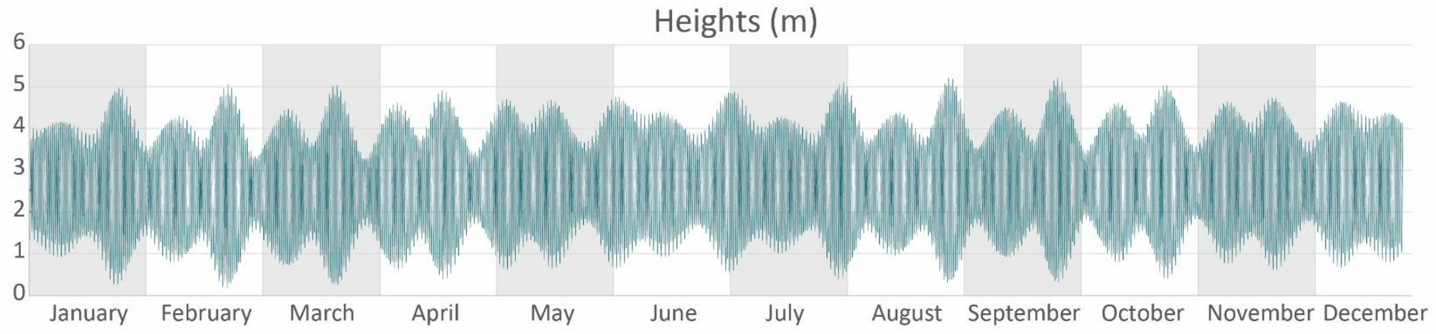


FIGURE 17. CASE STUDY ANNUAL TIDAL PREDICTIONS

The highest average tides in the Buenaventura Access Channel generally occur during the months of August through November. During these months the water level is higher in some periods, which facilitates navigation and reduces the risk of stranding, however, during these months there are also lower tides as shown in table 5.

TABLE 5. AVERAGE MONTHLY VARIATIONS OF THE TIDE

	Average of Minimums (m)		Average of Maximums (m)		Average (m)
January	1,12	January	4,11	January	2,60
February	1,00	February	4,09	February	2,56
March	1,07	March	4,03	March	2,54
April	1,12	April	4,10	April	2,61
May	1,23	May	4,16	May	2,58
June	1,25	June	4,22	June	2,73
July	1,23	July	4,21	July	2,72
August	1,14	August	4,25	August	2,69
September	1,13	September	4,27	September	2,70
October	1,16	October	4,30	October	2,73
November	1,25	November	4,23	November	2,70
December	1,23	December	4,16	December	2,61

The variability of the tidal conditions in the case study and in general in each case is systematically variable and global conditions. In other words, there will be systematic changes between days and at monthly scales. As previously mentioned, particularly for the case study, the average tides are highest between November and December. However, the global maximums are presented for the second halves of the months of January, February, and March with the condition that the minimum minimums are also presented. Figures 18 and 19 show the detailed behavior of the tides during the first and last days of each month. The purpose of this analysis is to determine what conditions will be most favorable for navigation (without considering climatic factors).

4.5.2. Experimentation question

Are navigation conditions more favorable with high average high tides (low variability) or when there are very high local tides but accompanied by very low tides?

4.5.3. Experiment Description

To answer this question, the tidal patterns of the study case were analyzed, and divisions were made into time periods with variability of the tidal windows but keeping constant the instance of 36 ships and the other parameters of the model.

In the first instance, the tides were divided into periods of time with evident visual changes in the behavior of the wave. Then, the average of the maximums and the average of the minimums were calculated to obtain an average behavior during the period. After that, the model was executed with the average data set according to each case.

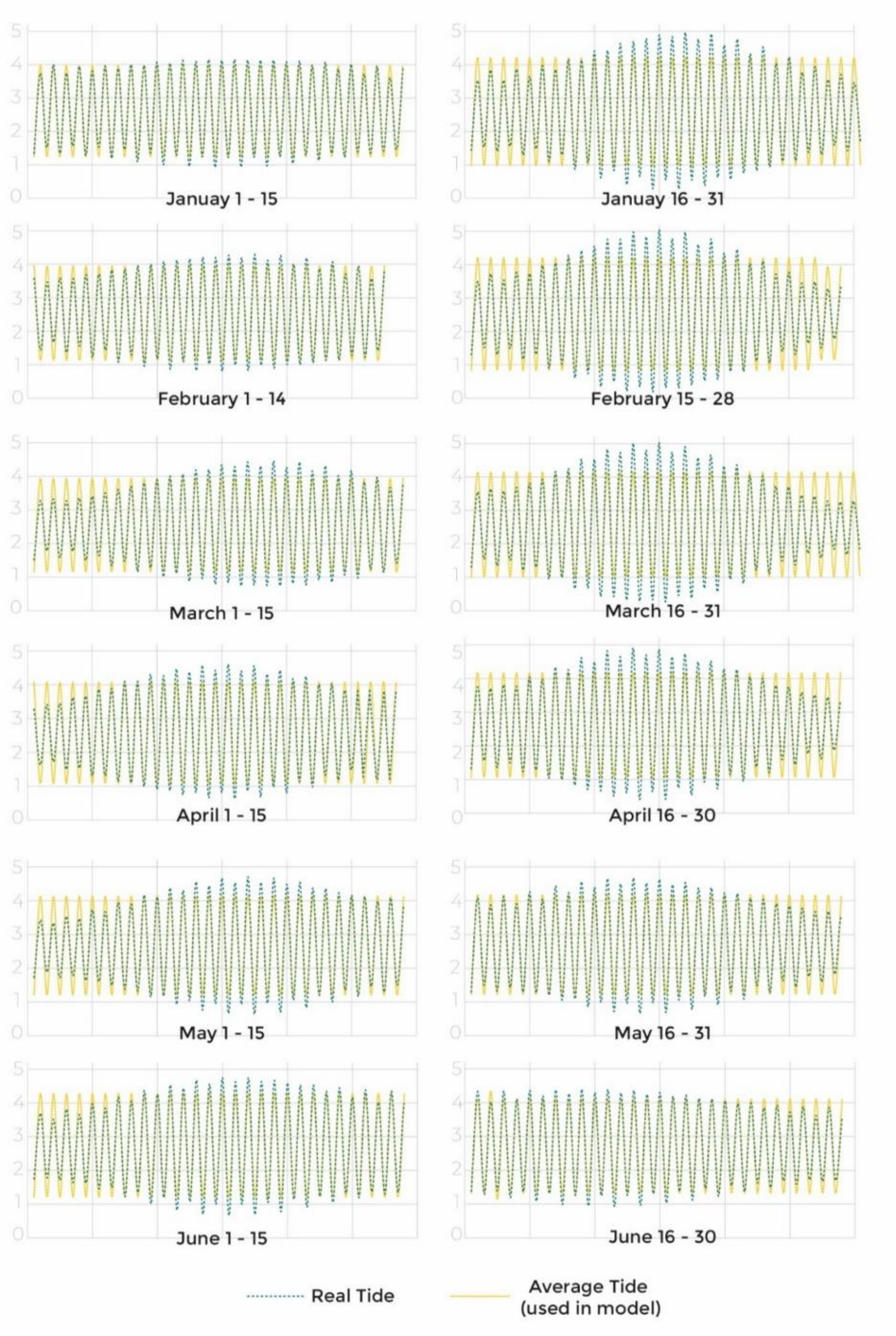
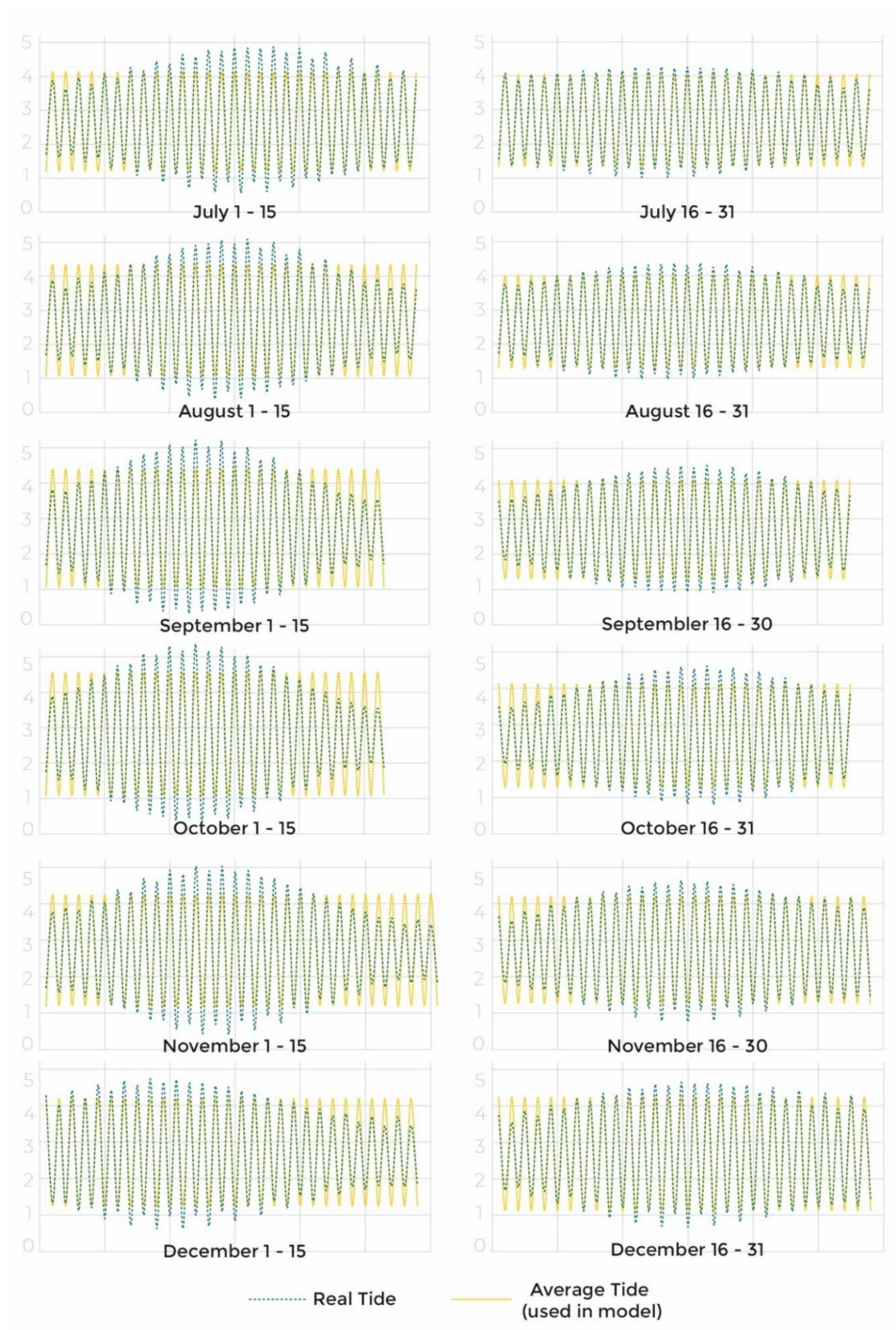


FIGURE 18. ANALYSIS PERIODS IN THE FIRST HALF OF THE YEAR



July 1 - 15

July 16 - 31

August 1 - 15

August 16 - 31

September 1 - 15

Septembler 16 - 30

October 1 - 15

October 16 - 31

November 1 - 15

November 16 - 30

December 1 - 15

December 16 - 31

FIGURE 19. ANALYSIS PERIODS IN THE SECOND HALF OF THE YEAR

TABLE 6. AVERAGE MAXIMUM AND MINIMUM VARIATIONS OF THE TIDE IN ANALYSIS PERIODS

Period	Average of the minimum delta drafts	Average of the maximum delta drafts
January 1 - 15	1,24	3,977
January 16 - 31	0,98	4,210
February 1 - 14	1,14	3,948
February 15 - 28	0,85	4,208
March 1 - 15	1,16	3,941
March 16 - 31	1,02	4,145
April 1 - 15	1,08	4,075
April 16 - 30	1,07	4,167
May 1 - 15	1,21	4,133
May 16 - 31	1,23	4,171
June 1 - 15	1,21	4,277
June 16 - 30	1,32	4,105
July 1 - 15	1,14	4,346
July 16 - 31	1,35	4,040
August 1 - 15	1,08	4,338
August 16 - 31	1,31	4,010
September 1 - 15	1,07	4,392
September 16 - 30	1,30	4,096
October 1 - 15	1,05	4,424
October 16 - 31	1,28	4,123
November 1 - 15	1,21	4,252
November 16 - 30	1,27	4,200
December 1 - 15	1,25	4,194
December 16 - 31	1,13	4,232

4.5.4. Results

From the real data it was possible to determine that about 33% of the ships that use the canal require high tides to transit, for this reason the following instance of 36 ships was chosen, of which 14 require tidal windows for their transit. It is important to point out that, as previously stated, the literature reports that for a vessel not to sink when navigating in restricted waters (in our case an access channel) it requires a free draft of 12% of its total draft. In this sense, the draft necessary to transit will be its total draft plus that free safety draft. The depths of the experimental instance are presented below:

TABLE 7. CHARACTERISTICS OF THE MODELED SHIPS

	Vessel Draft	12% height necessary	Required draft in the channel
Vessel 1	14,40	1,73	16,13
Vessel 2	14,39	1,73	16,12
Vessel 3	14,38	1,73	16,11
Vessel 4	14,37	1,72	16,09
Vessel 5	14,36	1,72	16,08
Vessel 6	14,35	1,72	16,07
Vessel 7	14,34	1,72	16,06
Vessel 8	14,33	1,72	16,05

Vessel 9	14,32	1,72	16,04
Vessel 10	14,31	1,72	16,03
Vessel 11	14,30	1,72	16,02
Vessel 12	14,29	1,71	16,00
Vessel 13	14,28	1,71	15,99
Vessel 14	12,60	1,51	14,11
Vessel 15	11,50	1,38	12,88
Vessel 16	11,30	1,36	12,66
Vessel 17	11,10	1,33	12,43
Vessel 18	10,90	1,31	12,21
Vessel 19	10,70	1,28	11,98
Vessel 20	10,72	1,29	12,00
Vessel 21	10,57	1,27	11,83
Vessel 22	10,42	1,25	11,67
Vessel 23	10,27	1,23	11,50
Vessel 24	10,12	1,21	11,33
Vessel 25	9,97	1,20	11,16
Vessel 26	9,82	1,18	10,99
Vessel 27	9,67	1,16	10,83
Vessel 28	9,52	1,14	10,66
Vessel 29	9,37	1,12	10,49
Vessel 30	9,22	1,11	10,32
Vessel 31	9,07	1,09	10,15
Vessel 32	8,92	1,07	9,99
Vessel 33	8,77	1,05	9,82
Vessel 34	8,62	1,03	9,65
Vessel 35	8,47	1,02	9,48
Vessel 36	8,32	1,00	9,31

According to the results, the following indicators were chosen that could be relevant in the choice of a port terminal according to its effectiveness:

- Individual maximum wait: Individual maximum wait refers to the maximum waiting time that the model assigned to any vessel
- Average wait: It refers to the average waiting time of the ships that had to wait. If a vessel is serviced before its scheduled time, the wait will be taken as 0.
- Percentage of ships waiting: It refers to the percentage of ships of the instance that had to wait

TABLE 8. RESULTS OF THE EXPERIMENTATION OF THE BEST TIME TO SAIL

Period	Individual maximum wait	Average wait	Percentage of ships waiting
January 1 - 15	13h 48min	5h 30 min	23%
January 16 - 31	14h 00min	5h 40 min	26%
February 1 - 14	13h 43min	5h 35 min	23%
February 15 - 28	14h 17min	5h 45 min	26%
March 1 - 15	13h 35min	5h 35 min	23%
March 16 - 31	13h 41min	5h 30 min	23%

April 1 - 15	13h 40min	5h 35 min	23%
April 16 - 30	13h 35min	5h 30 min	23%
May 1 - 15	13h 09min	5h 30 min	23%
May 16 - 31	13h 21min	5h 35 min	23%
June 1 - 15	13h 32min	5h 30 min	23%
June 16 - 30	12h 50min	5h 15 min	20%
July 1 - 15	13h 17min	5h 30 min	23%
July 16 - 31	12h 20min	5h 20 min	20%
August 1 - 15	14h 29min	5h 45 min	26%
August 16 - 31	13h 16min	5h 30 min	23%
September 1 - 15	14h 35min	5h 45 min	26%
September 16 - 30	13h 218min	5h 30 min	23%
October 1 - 15	14h 44min	5h 45 min	26%
October 16 - 31	13h 28min	5h 30 min	23%
November 1 - 15	14h 42min	5h 45 min	26%
November 16 - 30	13h 25min	5h 30 min	23%
December 1 - 15	13h 48min	5h 35 min	23%
December 16 - 31	14h 45min	5h 45 min	26%

According to the results, it is evident that even though there are times of the year that present higher high tides, these do not generate the optimal programming of the ships. In the tidal graphs, it is evident that periods such as the second half of January or February present maximum high tides compared to the other periods, but these are accompanied by minimum low tides that reduce the transit window of the ships.

Thus, it is evident that the periods with higher maximum averages (despite not being the maximum tides) facilitate the navigability of the access channel. It is important to note that there are other variables that are not being analyzed within the modeling, such as tidal transition speed, winds, and rainfall. However, it seems logical to point out that in the periods like the one between June 16 to 30 and July 16 to 31 they could offer better conditions since the depth variability is lower and this implies that the movement speeds of the water would be lower, and this would also facilitate negativity.

Additionally, it can be affirmed that the proposed model could offer a feasible alternative to determine the best times to navigate in other ports with their tidal conditions. Another aspect to highlight is that for periods with high variability, the magnitude of the tides could be over or under-estimated and if more detailed data is required, shorter periods of analysis could be taken.

4.5. Conclusions

The prioritization of vessel traffic in port access channels is a complex challenge that requires efficient and safe solutions. Throughout this research, the importance of simplifying models of this nature into linear structures has been demonstrated, as their complexity can hinder understanding and application. The results obtained in this study have provided valuable contributions to both academia and the maritime industry, allowing for a better understanding of the factors that influence navigation in access channels and facilitating informed decision-making and implementation of specific solutions different from the ones analyzed in the case study.

One of the most significant findings of this study relates to the best times for navigating the access channel of the Buenaventura multipurpose terminal. Through experiments and data analysis, it was determined that the months of January and February present more favorable weather and tidal conditions for navigation, reducing the total waiting time for ships and potentially improving terminal efficiency and other performance indicators. These results are of great importance to planners and port operators as they allow for more efficient scheduling and allocation of resources during specific periods of the year. For example, planning the transit of deep-draft ships that are not regular customers during these periods of improved conditions.

Another crucial aspect addressed in this research is the safety times between ships. Based on the collected data and analysis, it was established that a minimum safety time of 24 minutes between ships traveling at 7 knots is necessary to ensure safe navigation and optimal waiting times. These results are fundamental for the implementation of collision prevention measures and the mitigation of risk situations in access channels with similar conditions to the ones studied.

Furthermore, the importance of optimization models in the prioritization of vessel traffic should be highlighted. Linear models and heuristic models are approaches used in this field, each with its advantages and limitations. Linear models offer optimal or near-optimal solutions, which is beneficial for maximizing efficiency in navigation. However, their implementation may require a significant amount of data and simplifying assumptions. On the other hand, heuristic models provide flexibility and adaptability in solving complex problems, although they do not guarantee global optimality.

In the case of the analyzed model, the use of linear models proves to be an effective strategy in prioritizing vessel traffic in port access channels. Through linearization, efficiency is achieved in obtaining results, which can be advantageous when using the tool as a complement to programming in channels leading to port facilities, as the scheduling can be readjusted within short time periods.

This research has demonstrated the importance of simplifying complex models in the prioritization of vessel traffic in port access channels. The results obtained, such as the best times for navigation and the required safety times, are valuable contributions to academia and the maritime industry. Additionally, the significance of linear and heuristic optimization models is emphasized, and their combination is recommended to achieve efficient and safe solutions in the navigation of port access channels.

Future research could focus on overcoming the identified limitations in the exclusion of dock resources. The underutilization of available spaces at the docks, stemming from a lack of consideration for real-time capacity and availability, poses a significant challenge. The omission of variables related to the temporal availability of docks also emerges as a restrictive factor, especially in dynamic scenarios where availability conditions can change rapidly. To appropriately address these challenges, future research should expand the current formulation by incorporating a broader range of variables and constraints. The inclusion of the temporal dynamics of dock resources is presented as a crucial measure to enhance the model's capacity and provide optimal and efficient solutions in complex port environments. It is important to note that as the model has been formulated, it allows the conception of a totally unidirectional or totally bidirectional problem with or without overlapping restrictions in opposite directions. However, it should be noted that response times may vary when structuring this restriction in more detail and represents an opportunity for research. In summary, the integration of these resources in future studies will constitute a significant advancement in addressing the inherent challenges of port management.

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Appendix 1: Practical case

In this appendix, a practical and simplified example of a fictional application case solved with the model presented in Chapter 2 of this work is provided. For the example, we consider a port area with 2 ports (5 and 7) as depicted in Figure 20; in the exercise, one day corresponds to 288-time units. Additionally, it is essential to note that safety times on all arcs are 2-time units. The problem is modeled with an instance of 5 ships that will have to start their journey at node 1 and finish it at the same node (i.e., the entry and exit of the ships will be assigned to their respective ports).

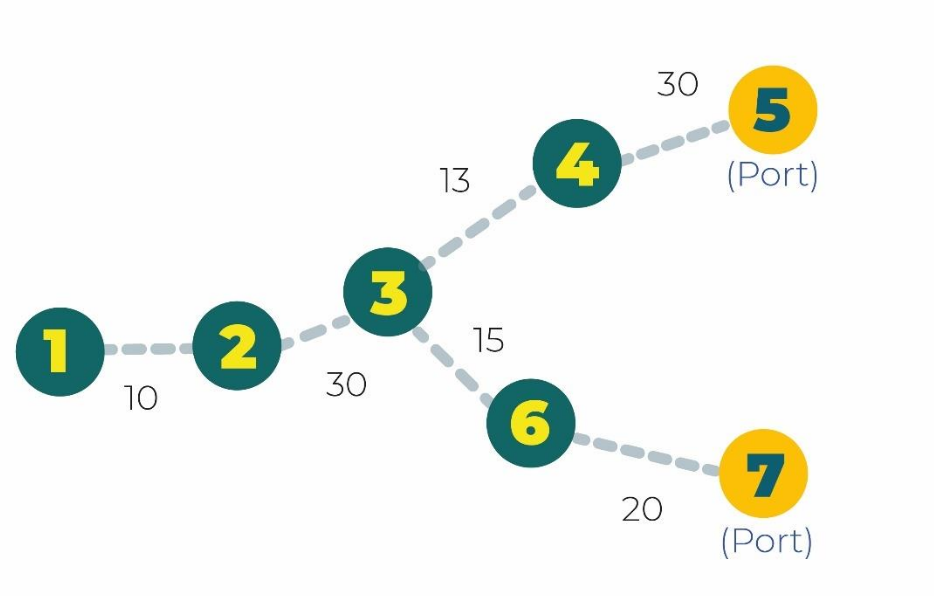

FIGURE 20. CONSIDERED PROBLEM WITH TRAVEL TIMES IN ARCS

The routes of the 5 ships in the problem will be the following:

Ships 1,2,3: [1, 2, 3, 4, 5, 4, 3, 2, 1]

Ships 4,5: [1, 2, 3, 6, 7, 6, 3, 2, 1]

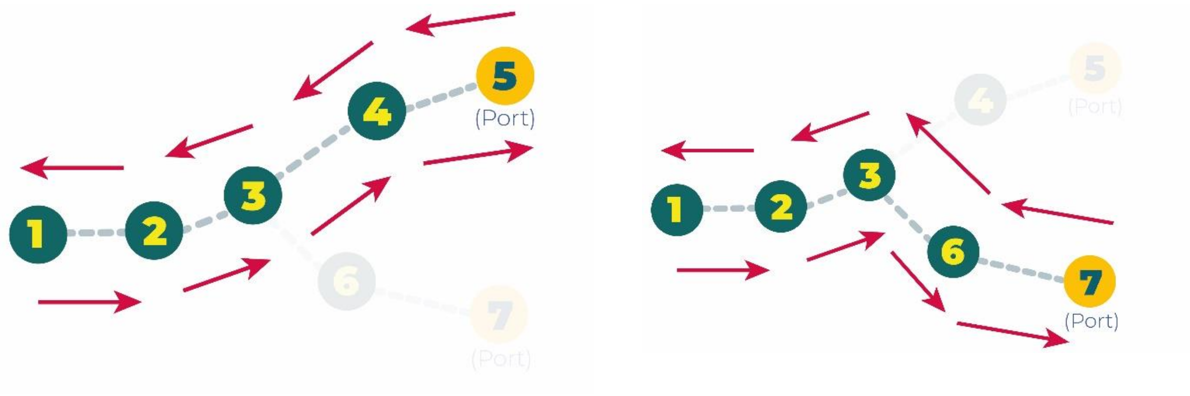

FIGURE 21. TRAVEL ROUTES OF THE PROBLEM SHIPS

And the parameters for each ship will be:

TABLE 9. PARAMETERS OF THE ANALYZED SHIPS

Ship	Scheduled time	Download time	Release time	Startup window	End window
1	16	30	10	-	-
2	20	19	10	-	-
3	42	19	43	60	250
4	63	19	60	60	250
5	85	50	80	-	-

Thus, the results for each ship will be the times in which each arc begins for each ship:

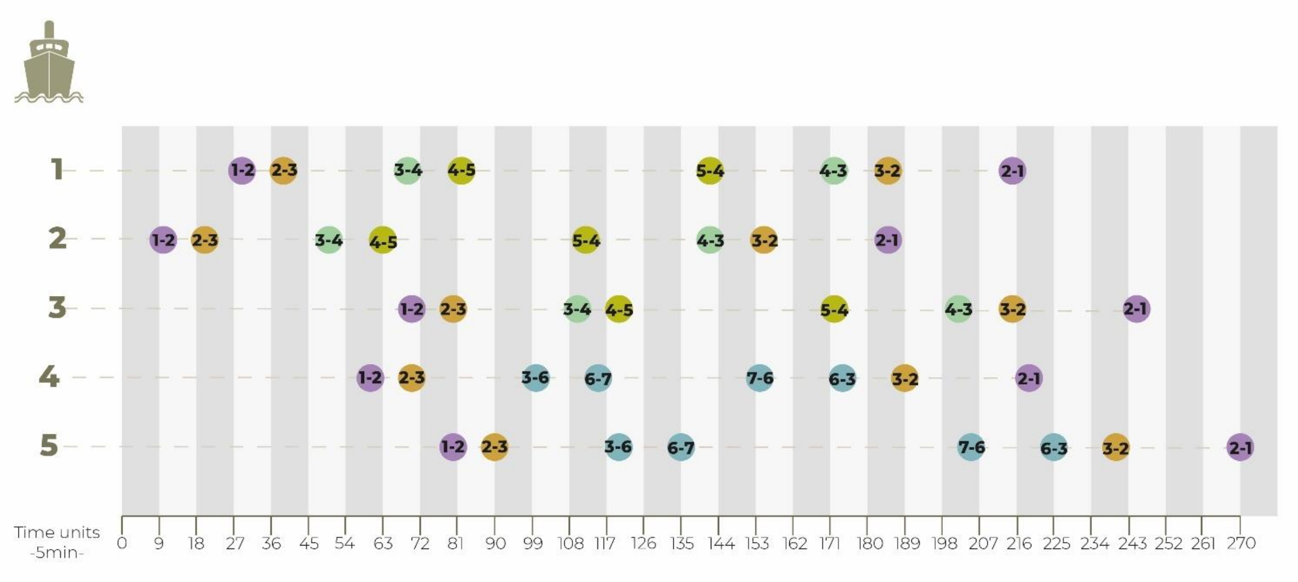

FIGURE 22. BEGINNING OF THE JOURNEY OF EACH ARC AND SHIP OF THE PROBLEM

The times for each ship and arch will be:

TABLE 10. RESULTS

time	i	j	Ship
29	1	2	1
39	2	3	1
69	3	4	1
82	4	5	1
142	5	4	1
172	4	3	1
185	3	2	1
215	2	1	1

time	i	j	Ship
10	1	2	2
20	2	3	2
50	3	4	2
63	4	5	2
112	5	4	2
142	4	3	2
155	3	2	2
185	2	1	2

time	i	j	Ship
70	1	2	3
80	2	3	3
110	3	4	3
123	4	5	3
172	5	4	3
202	4	3	3
215	3	2	3
245	2	1	3

time	i	j	Ship
60	1	2	4
70	2	3	4
100	3	6	4
115	6	7	4
154	7	6	4
174	6	3	4
189	3	2	4
219	2	1	4

time	i	j	Ship
80	1	2	5
90	2	3	5
120	3	6	5
135	6	7	5
205	7	6	5
225	6	3	5
240	3	2	5
270	2	1	5

And the results for the objective function correspond to the time in which each ship reaches its discharge node (port) as follows:

$$Ship\ 1{:}\ 82 + 30 = 112 \rightarrow Delay\ = 112 - 16 = 96$$

$$Ship\ 2{:}\ 63 + 30 = 93 \rightarrow Delay\ = 93 - 20 = 73$$

$$Ship\ 3{:}\ 123 + 30 = 153 \rightarrow Delay\ = 153 - 42 = 111$$

$$Ship\ 4{:}\ 115 + 20 = 135 \rightarrow Delay\ = 135 - 63 = 72$$

$$Ship\ 5{:}\ 135 + 20 = 155 \rightarrow Delay\ = 155 - 85 = 70$$

$$Total\ delay = 422$$