Cruise Ship Itinerary Design

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ABSTRACT:

The cruise tourism is a fast-growing industry worth more than $150 billion dollars. One of the key factors of success in this industry is the ability to create great value itineraries, which attracts tourists meanwhile maximizing the total profit of the cruising company. To do this, a route must be carefully selected, combining a maximization of the total attraction value of the itinerary, given by the destinations and attractions included, with the minimization of the total cost of the travel. Following this necessity, there has been an increase of academic interest at this topic, with papers discussing about different models and algorithms to calculate the optimal route of a cruise itinerary. The objective of this thesis is to develop an optimization code using CPLEX solver and mixed integer programming technique, and to evaluate possible new cruise itineraries at the Iberian Peninsula and Brazilian coast. The model chosen in this thesis calculates the cost and the revenue of the itinerary separately, using a cost structure based on the size of the ship and the duration of the itinerary, and a revenue structure based on the month of the year and the ports selected. Validation is done through comparing it with a Monte Carlo model for the Iberian Peninsula and with typical itineraries for this region. The results showed an opportunity of new itineraries routes at the Iberian Peninsula region, calling at ports which are not traditionally famous for cruising activities, such as Setúbal, Safim, Huelva, and Motril. For the Brazilian coast however, the results showed no improvement of profit using alternative itineraries in comparison with typical itineraries of that region. Furthermore, in a general way, the model showed that cruise ships have a different cost structure in comparison with merchant ships, given the size of crew required, the high price of the ship, and the quantity of supply onboard. All of that combined results in a huge fixed cost structure, meaning that when searching for an optimal itinerary, given a fixed duration, which is normally a constraint of the model (usually expressed as a cruiser preference that can change for different regions of the world) it is more valuable to properly estimate the attraction value of each destination than focusing on finding the route with minimal costs.

Keywords:

Cruise industry, Cruise itineraries, Itinerary Design, Optimization, Logistics

RESUMO:

O mercado de cruzeiros marítimos é uma indústria com rápido crescimento, valendo atualmente mais de $150 mil milhões. Um dos fatores de sucesso nessa indústria é a capacidade de criar itinerários de alto valor, que sejam atrativos aos olhos dos turistas, e também que maximizem o lucro total da companhia de cruzeiros. Para isso, a rota escolhida precisa combinar a maximização do valor atrativo do itinerário com a minimização dos custos totais da viajem. Seguindo essa necessidade, houve um aumento do interesse acadêmico nesse tópico, com publicações científicas discutindo sobre algorítimos e modelos para calcular uma rota óptima de um navio de cruzeiro. O objectivo dessa tese é desenvolver um modelo de optimização usando o solver CPLEX e MIP para tal, como também estudar novas oportunidades de itinerários na Península Ibérica e na costa brasilieira. O modelo escolhido para isso nessa tese calcula separadamente os custos, com base no tamanho do navio e a duração, em dias, do itinerário, e a receita, com base no mês do ano e nos portos escolhidos. A validação do modelo é feita através da comparação de seus resultados, gerados para a região da Península Ibérica, com um modelo usando simulação de Monte Carlo e também dos itinerários típicos da região. Os resultados mostraram uma oportunidade de novos itinerários de cruzeiro na Península Ibérica, utilizando portos que não são tradicionalmente famosos pela atividade de cruzeiro, como por exemplo Setúbal, Safim, Huelva, e Motril. Já para o caso da costa brasileira, os resultados alternativos não apresentaram benefícios em comparação com as rotas tradicionais da região. Além disso, de uma maneira genérica, o modelo desenvolvido mostrou que, navios de cruzeiro possuem uma estrutura de custo completamente diferente de um navio mercante, por causa da quantidade expressiva de tripulação necessária, do alto preço do navio e da grande quantidade de suprimento consumido à bordo, Graças à esses fatores, o custo fixo da viajem é muito expressivo, significando que, para um modelo de optimização de um itinerário de cruzeiro, dada uma duração fixa para o itinerário (geralmente a duração é entendida como uma preferência pré-fixada do turista, que pode variar de região para região) é preferível melhor estimar o valor atrativo de cada destino da região do que focar em calcular o itinerário com o menor custo total.

Palavras-chave:

Cruzeiros Marítimos, Itinerários de cruzeiros, Desenvolvimento de itinerários, Optimização, Logística

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ACRONYMS:

CLIA: Cruise Lines International Association

VRP: Vehicle Routing Problem

TSP: Travelling Salesman Problem

RVRP: Rich Vehicle Routing Problem

CSID: Cruise Ship Itinerary Design

LP: Linear Programming

MIP: Mixed Integer Programming

TS: Tabu Search Algorithm

SA: Simulated Annealing Algorithm

GA: Genetic Algorithm

STSP: Symmetric Traveling Salesman Problem

ATSP: Asymmetric Traveling Salesman Problem

L.F.: Load Factor

L.F.P.: Port Load Factor

N.C.R: Normal Continuous Rating

S.F.O.C.: Specific Fuel Oil Consumption

IFO: Intermediate Fuel Oil

MGO: Marine Gas Oil

IDE: Integrated Development Environment

SYMBOLOGY:

P:	Set of all ports
n:	Number of ports
$\widehat{hp}_i$:	Homeport possibility parameter
g:	Number of speeds
S:	Set of all speeds
v_i:	Speed
E:	Set of arcs considering different ports and different speeds
L:	Set of all arcs considering different ports
$d_{i,j}$:	Distance between port i and j
$t_{i,j,k}$:	Voyage time between port i and j traveling at speed k
Δ:	Itinerary duration
M:	Set of months
m:	Month of the itinerary analyzed
s_{min}:	Minimum time in port
s_{max}:	Maximum time in port
t_{leg}^{max}:	Maximum voyage leg time
$c_{building}$:	Ship building cost in USD
c_c:	Capital costs
c_w:	Crew wages
c_s:	Storage and provisions cost
c_{rm}:	Regular maintenance cost
c_i:	Insurance cost
c_a:	Administration cost
c_{pm}:	Periodic maintenance cost
$sfoc_{M_i}$:	Main engine specific fuel oil consumption at speed i
$sfoc_{aux}$:	Auxiliary engine specific fuel oil consumption
hfo:	IFO 180 fuel price in USD/ton
mgo:	MGO fuel price in USD/ton

ncr:	Normal continuous rating
v_{cruise}:	Design cruise speed
p_{M_i}:	Main engine power consumption at speed i in kW
p_{aux}:	Auxiliary engine power consumption in kW
$p_{installed}$:	Total installed power in kW
c_{main_i}:	Main engine fuel cost in USD/hour
c_{aux}:	Auxiliary engine fuel cost in USD/hour
c_{tariff_i}:	Tariff cost of port i
$V_{i,m}$	Total port attractiveness of the port i for the month m
P_i	Attractiveness of the port itself
A_i	Attractiveness of a city or attraction located near the port of call
Ta_i	Time, in hours, from the port i to the attraction located near the port of call
$Tm_{i,m}$	Average daily temperature, in degrees Celsius, in the port i for the month m
$S_{i,m}$	Average monthly sunshine hours in the port i for the month m
$Hs_{i,m}$	Average significant wave height, in meters, in the port i for the month m
n_{pax}:	Number of passengers
L_{ship}:	Length of the cruise ship in meters
B_{ship}:	Breadth of the cruise ship in meters
D_{ship}:	Draught of the cruise ship in meters
H_{ship}:	Depth of the cruise ship in meters
$x_{i,j,k}$:	Ship leg variable from port i to j at speed k
y_i:	Itinerary composition variable
hp_i:	Homeport i variable
$\hat{x}_{i,j}$:	Day at sea between ports i and j variable
a_i:	Port i arrival variable
b_i:	Port i departure variable
u_i:	Subtour elimination variable
s_i:	Time in port i
$t_{leg_{i,j}}$:	Time of the voyage leg from port i to port j

t_{sea}:	Total sea voyage time
$t_{onboard}$:	Total onboard time
$t_{waiting}$:	Total waiting time
c_{fixed}:	Total fixed costs
c_{main}^{total}:	Total main engine costs
c_{port} :	Total auxiliary engine costs running while docked
c_{aux}^{total}:	Total auxiliary engine costs at sea
$c_{tariffs}$:	Total port tariff cost
$c_{waiting}$:	Total waiting cost
C_{total}:	Total cost
R:	Voyage revenue

1. INTRODUCTION

1.1. Background and Motivation

Cruise shipping is a tourism activity which offers to passengers a pleasure ship voyage experience combined with shore excursions at touristic places, a unique travel experience since the cruise ship is the transportation mode and one of the attractions at the same time.

In 2018 approximately 28.5 million passengers traveled in cruise ships and from that total, about 50% came from North America, 24% from Western Europe and 15% from Asia (CLIA, 2018). At the same year, Caribe and Mediterranean were the two most important destinations, accounting respectively for 35.0%, and 16.7% of the global cruise fleet deployment, measured in bed days (MedCruise, 2018). The cruise industry is growing fast: between 2008 and 2018 the average annual growth rate was 5.7%, employing in 2018 almost 1.2 million persons which earned a total of $50.2 billion in wages (CLIA, 2018). The evolution of cruise passengers worldwide and origin and destination of cruise passengers are shown in Figure 1 and Figure 2 respectively.

This industry is constituted by an oligopoly market, being that Carnival Corporation, Royal Caribbean, Norwegian Cruise Lines and MSC combined owns more than 80% of the global fleet (Statista, 2019), although these big companies uses a strategy of having multiple brands (for instance, Carnival Corporation owns Carnival Cruise Lines, Princess Cruises, Holland America Line and Costa), focusing each company in only one segment of the market, creating the impression that there is plenty of competition between companies.

The cruise itineraries sold are classified in four categories: contemporary, premium, luxury and special. Contemporary itineraries are the most popular type of cruising, with large cruise ships offering a lot of onboard activities for a great value (Pallis, 2015).

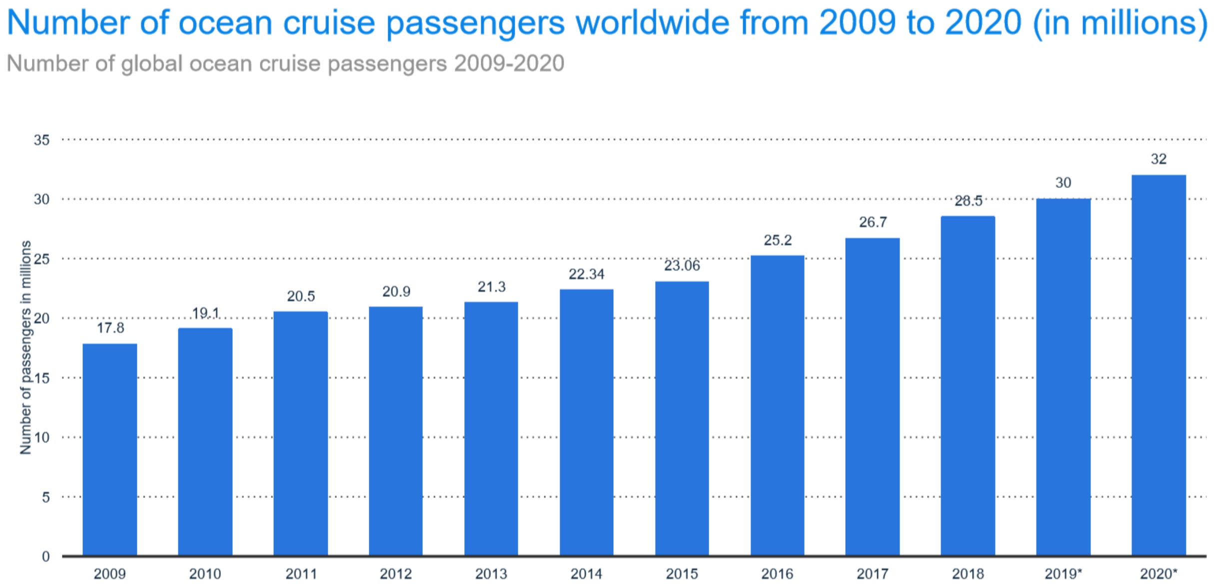

Figure 1: Cruise passenger's growth worldwide in millions. Source: STATISTA, 2019

Figure 2: Passenger volume, in thousands, by trade and source regions in 2018. Source: CLIA, 2018

Nowadays, cruise liners are observing Brazilian, Australian, and Chinese markets as they are considered markets with growth opportunity (CLIA, 2017; Dowling, 2011). Australia and Brazil both have an extensive coastline, a more stable weather throughout the year and are in the south hemisphere. Those characteristics are attractive because it facilitates domestics itineraries, gaining attention of persons which do not want to travel long distances to start their journey and simplifies the bureaucracy, since passengers do not have to worry about requesting visas to visit the destinations. Additionally, because both countries are in the south hemisphere, they are good alternatives places to reposition of the global fleet during the Winter in the north hemisphere. In 2018, China, Australia and Brazil ranked respectively 2nd, 5th and 10th in relation to the volume of passengers per country (CLIA, 2018). Despite of the big number of Chinese passengers, penetration remains low, with approximately only 0.2% of the population taking a cruise every year (BRS, 2018).

Given the seasonality characteristic of tourism demand, cruise operators reposition their fleets around the globe to take advantage of regions with high demand for cruising during the whole year (Rodrigue *et al.*, 2012). One good example of this practice is the movement of ships between the Caribbean Sea and the Mediterranean Sea. During Summer, the ships are deployed in the Mediterranean Sea, whereas during Winter, the demand for cruise voyages in the Mediterranean Sea decreases and the cruise ships are repositioned to the Caribbean Sea.

If considered also the number of passengers in transit at ports, the number of passengers transported by the cruise industry raises to 146 million passengers, meaning that on average, a passenger visits 3 ports during their trip, showing an opportunity to cities trying to improve their tourism sector. Only in

2018, on average a cruise passenger spent $375.97 at the homeport and $100.79 at the other ports, resulting in a total of $10.7 billion spent at the homeport and $9.1 billion spent at the other ports (CLIA, 2018). The reason why expenditures at homeports are higher is because many tourists travelling to these cities to start their journey extend some days before or after the trip.

Although homeports earn more money, it is also true that they must have a good infrastructure, capable of receiving large cruise ships, and with a good water and air connectivity (Niavis *et al.*, 2016). In regions of beautiful natural landscapes and beaches but with a poor infrastructure, such as the Caribbean islands, cruise companies are building an extensive infrastructure, from terminals to restaurants in private secured areas, to satisfy the cruisers desires of visiting the Caribe.

Rodrigue *et al.*, (2012) argued that the cruise industry differentiates from any other traveling industry because they are not trying to sell travels or destinations. Instead, the cruise industry sells itineraries, a whole package with destinations and activities previously determined. This fact means that the demand for this service is given by the attractivity of the itinerary as a whole, showing that when designing an itinerary, factors such as time at destinations, distance between destinations and traveling speed must be taken into consideration.

Historically, this problem has not received so much attention in the past since cruise companies never found difficulties in filling their ships, especially at the Caribbean Sea. However, this scenario is changing recently, given that the Caribbean Sea market is reaching a saturation point in demand, many cities in Europe are experiencing problems with the cruise industry and new markets are arising. These factors lead to an urgency in finding new possible itineraries across the globe.

As mentioned before, finding good cruise itineraries is not an easy task. First, a list of possible ports of call must be known as well as the sailing distance between each port. Secondly, a balance between sailing distance and sailing speed must be found for each leg of the voyage so that the cruise ship arrives at destinations at morning and afternoon, moments where cruise passengers can fully enjoy the city. Third, when choosing the itinerary, factors such as operational costs, time at sea, passenger demand and ticket price must be taken into consideration. The objective is to find the perfect combination of factors which will bring the biggest profit to the cruise company.

This problem, called cruise ship itinerary design problem, is a type of vehicle routing problem, one area of operational research which is becoming more and more important throughout the years, being applied to transportation problems such as vehicle routing network, delivery trucks, air transport. A reason for this increase in importance is the improvement in computational capacity, which allowed cheaper and accessible computers to solve at least some of the vehicle routing problems. Examples of optimization software’s which can be used in a simple computer are CPLEX and GUROBI.

Cruise ship itinerary problems have not been properly studied and companies could benefit from such techniques, exploring new profitable itinerary routes which are not offered today. Cruise itinerary design cannot be treated as a simple ship network design, in cruise ships the demand depends on the itinerary whereas for a merchant ship, the demand is previously known, and the route is then created. This contrasting characteristic of the demand makes designing cruise itineraries a unique challenge, which has yet to be improved.

Moreover, after finding new possible cruise itineraries, this is not a guarantee that cruise ships will be assigned to it. Véronneau *et al.* (2009) investigated the operational challenges of a large cruising company, concluding that short time window at homeports and difficulties in sustaining a large global deployment while maintaining service quality are two major concerns which makes the company to research about a possible itinerary with more than one year prior to the date of departure. Short time windows mean stock out problems result in big impacts to the operation and therefore, contracts with suppliers and an investigation of the logistic network of the homeport must be carefully made. Additionally, different cultures present different demands for the onboard amenities and food dishes served, which are also taken into consideration when planning a new itinerary.

1.2. Objectives

The objectives of this thesis are the following:

1. Understanding how cruise ship itineraries are designed, identifying which are the most important parameters in the selection of ports of call, including port attractiveness, location within a geographic region, nautical limitations, and weather conditions, among others.
2. Developing an algorithm for optimizing cruise itineraries, selecting the ports of call of the itinerary, time of arrival and time of departure at each port and the ship's speed in each leg of the itinerary.

The optimum itinerary is to be determined so as to maximize the net profit per voyage for the cruise shipping company given a list of possible ports of call in a given geographic region, a specific ship size, a fixed duration of the voyage and the season of the year.

A commercial software will be used to implement the algorithm and test its performance in two case studies, one at the Atlantic coast of the Iberian Peninsula and the other at the Brazilian coast. Two different scenarios are tested in the first case study, as more possible ports of call are added to the existing ports, in order to evaluate whether these additional ports might facilitate the task of developing profitable new cruise itineraries.

1.3. Structure of the Thesis

This thesis is organized in six chapters and respective appendices.

Chapter 1 is the introduction of the topic to be discussed and the related background, including the goals, structure of the work and motivation.

Chapter 2 is a literature review about cruise shipping industry, focusing on four main topics which are important to the knowledge of the shipping industry in general and to the itinerary design process: ports of call and destinations, cruise passengers, tickets price and revenue management and, cruise ship itinerary design.

Chapter 3 details the methodology applied to this thesis, giving an introduction about linear and integer programming, defining the traveling salesman problem, the vehicle routing problem, and the cruise ship itinerary problem.

Chapter 4 presents the formulation used in this thesis, showing all assumptions and equations considered.

Chapter 5 shows the results for the cases studied in this thesis, presenting the optimal itineraries obtained, its cost and revenue structure, and analyses for the results obtained.

Finally, the chapter 6 provides the main conclusions of this thesis and outlines a set of recommendations for further works in this field of study.

2. LITERATURE REVIEW

Most of the research about the cruise industry was published in recent years, focusing on passengers' behavior and expectations, impacts of cruise tourism, and growth and development of cruise tourism (Wondirad, 2019). In this chapter, a literature review about the cruise industry was conducted and divided in four categories: ports of call and destinations analysis, cruise passengers behavior, tickets price and revenue management and, cruise ship itinerary design. The first category covers publications which are concerned in evaluating how cities and destinations are affected by cruise ship activities, analyzing the economic, social, and environmental impacts on the ports or cities. The second category focus on the passengers, trying to characterize the cruise passenger profile, including their preferences, motivations, and satisfactions. The third category studies how to determine cabin prices and marketing strategies to return maximum revenue as possible. Finally, in the last category will be discussed about researches dealing with cruise itineraries design, which is the topic of most interest for this thesis. In this category, a detailed discussion about which are the most important variables, restrictions and assumptions used to model the problem, how the model is solved, and which important information can be obtained from these models.

2.1. Ports of Call and Destinations

Ports of call are a crucial part of the itinerary planning since passengers uses them constantly to embark and disembark and modern cruise ships requires an infrastructure that not all ports may provide. They are the link between cruise ships and destinations. Despite of the cruise industry fast growth during this decade, fostering cruise activity does not mean that a city or port will have direct economic benefits from it. As pointed by London *et al.* (2014), this relation between cruise line, city and ports is very complex. Cruise lines can choose to call or not into the destination, ports may create bureaucracy and barriers to the cruise ships operation since it may compromise the core business of the port, commercial ships, and local communities or local government may express dissatisfaction and complain about cruise tourists. All these factors lead to a situation where the success of cruising activities at a destination depends on the cooperation of the three parties.

Looking from the side of the port authorities, McCalla (1998) investigated the perception of port administrations about which factors attracts cruise lines the most. Those factors were divided into two categories, site, and situation. Site factors are connected to infrastructure and geographical restrictions of the port, whereas situation factors are related to passenger demand and local city attractivity. The data was gathered at the Seatrade Cruise Shipping Convention ports displays interviews and then confronted to a questionnaire answered by the cruise ports. Results of the questionnaire showed that ports of call attributes situation factors, especially regional attractions, as the most important elements to define the cruise port success, whereas homeports believe both factors have the same importance. One interesting thing though is that results from both tests where not coherent. Looking from the side of the cruise lines, Wang *et al.* (2014) sent a questionnaire to cruise lines, asking which are the most important factors when choosing a port of call. According to the answers, tourism attractions is the most import element in a destination, followed by port connectivity and agility. This later element is important to a cruise line because it means ships calling can have a lower length period without prejudicing the utility time perceived by passengers.

In the Mediterranean Sea, there is a high concentration of traffic of passengers, being that the major 10 cruise ports account for 60% of the passenger traffic (MedCruise, 2018). This high concentration of passengers occurs in ports located at destinations such as Barcelona, Civitavecchia (Rome) and Venice, important touristic destinations which many tourists wants to visit. Cusano *et al.* (2017) analyzed cruise itineraries sailing at the Mediterranean and observed that if by one hand a small quantity of ports receives a lot of cruise ships regularly, by the other hand, the majority of the ports in this region don't have a strong attractive capacity, rarely receiving more than one cruise line itinerary and facing competition with ports located geographically close.

Continuing the study of this problem, Gui *et al.* (2011) looked deeper at the relation between local ports and cruise lines, showing cities and cruise lines have different interests from the cruise industry. Destinations are concerned about the tourism activities at the city and how does it affect the local community (improvement on the local economy, environmental impacts, social impacts). Cruise lines sees ports and cities as a way of attracting more passengers to their ships, demanding from cities and ports an infrastructure capable enough so that the passengers have a smooth experience. Cruise lines and cities experiences a big conflict of interests: a significant part of the cruise company revenue came from onboard expenditure and onshore excursion packages, which directly compete with the local excursion packages and expenditure at the destinations, which is in the best interests of the city.

Ports appears in an intermediate situation. Cruise activities might require infrastructure improvements and may hamper the commercial operation existent at the port, making that the port authority perceiving it as a risky investment. Additionally, uncertainties regarding the impact this activity will cause to the city is another factor that can influence the port's decision depending on the existence purpose of that port. Moreover, the authors affirm that cruise companies are in a process of vertical integration of the entire supply chain, building private terminals, selling excursions and, in the extreme case of some Caribbean destinations, owning the entire island where the ship call, gaining a piece of the revenue of all activities that happens in the island. Two alternatives that ports and destinations have are: create stronger partnerships with cruise lines, forcing them to include the destination in the itinerary due to the high degree of investments made by the cruising companies or improve the number of excursions other touristic activities, creating a more desired destination and making passengers desires to visit the destination.

A meta-analysis (statistical analysis of a compilation of different published results) was made by Chen *et al.* (2019) to investigate the hypothesis that tourists, crew members and cruise lines expenditures have a positive influence on direct port economic impact and whether a longer length of stay in a port has a positive direct economic impact to the port. It was concluded that a positive direct economic impact can be seen from the following factors: number of passengers, number of cruise lines, number of crew members, expenditure per passenger and expenditure per cruise line.

More specific studies about the economic impacts of the cruise industry on specific ports or cities has been conducted throughout the years, using different methodologies. Demirel *et al.* (2011) investigated the problem of finding the best place for a cruise port at Istanbul. Chang *et al.* (2016) evaluated the economic impact of the cruise industry at Incheon, a South Korean port of call, using an input-output analysis, concluding that the city has a small positive economic impact in comparison to homeport cities and that investments on touristic activities in the city could provide more economical benefits to Incheon. Paoli *et al.* (2017) studied the economic impact of cruise ships at the Gulf of Tigullio, where Portofino, Santa Margherita and Rapallo ports are located, using an energy analysis, a technique which quantifies different factors such as environmental impacts, economic impacts and landscape beauty in a common unit, making it easy to assess the importance of different factors which could not be compared otherwise. Finally, Gouveia *et al.* (2019) estimated the total economic value of cruise tourism at the port of Funchal in €47.2 millions, separating it in passenger expenditure (€30 millions), crew members expenditures (€8.3 millions) and cruise lines expenditures (€8.8 millions).

With the objectives to identify which factor makes ports potential homeports, Niavis *et al.* (2016) proposed an empirical model, relying on data of Mediterranean ports. The factors analyzed were divided into two categories, similar to what McCalla proposed in 1998: ports' characteristics and hinterlands' characteristics. The variables used to measure the port characteristics are port efficiency, type of management of the cruise terminal, berth length and port connectivity. The variables used to measure the hinterland characteristics are air connectivity index, capacity of tourist infrastructure and gross domestic product per capita. Results showed that efficient ports, private managed, with long berths in terms of length (higher than 350 meters) and directly cooperating with one cruise line are more likely to become homeports.

As an attempt to investigate the most visited areas of cruise tourists the port of Palermo, Cantis *et al.* (2016) used traditional surveys and GPS tracking technology. From this study was seen that approximately 80% of the cruise passengers disembarked at the city, with an average tour of almost 4 hours. More than 80% of the passengers that visited Palermo stayed in a region of less than 3.5km distant form the port, corresponding to the city center. Not surprisingly, the most visited attractions were located close to the port.

Environmental pollution is also another problem that ports, cities and governments are concerned about. Caric *et al.* (2014) discussed about the cruise tourism impact in the Adriatic Sea, a fragile region because of the slow water exchange rate and its high biodiversity. Cruise shipping can impact the environment in the form of waste, hazardous emissions, air emissions, wastewater, ballast water, biocides, physical disturbances and collisions, noise, and light. The authors also point out that despite of increasingly regulation over the ship's pollution, lack of control, intentional pollution and bad anti-pollution systems installed onboard are still a reality.

Pallis (2015) published a state-of-the-art paper presenting a review, among other topics, about cruise ports characteristics, performance, and competition. In the paper, a deeper analysis is made about location and growth of cruise ports, type of management in different regions, effects of seasonality, performance, competition and cooperation, economic and environmental impacts, perception of value for the local community.

2.2. Cruise Passengers

Studies about passengers are one of the most researched areas of the cruise industry. These publications focus on creating or validating hypothesis about the passengers' profile, expectations, and motivations. The common approach for this type of study is to conduct interviews and questionnaires. Since culture, age and economical position plays an important role on the people's behavior and expectations, it is expected that studies will vary a lot their results, depending on the persons interviewed. Qu *et al.* (1999) interviewed Hong Kong cruise travelers', investigating motivation factors, satisfaction attributes and the cruiser's profile. Results showed an equal number of male and female cruisers, with age varying from 18 to 44 years, motivated by “escaping from normal life”, “social gathering” and “beautiful environment and scenery”. In terms of satisfaction, food and beverage facilities, quality of products and services and staff performances gave a positive image to the cruise whereas attractiveness, variety and organization of entertainment, sport, shopping, and childcare facilities were motives for complaining. Also, the majority of the cruisers indicated a desire for repeating this experience.

Xie *et al.* (2012) investigated motivations factors for cruisers and potential cruisers based on reviews randomly selected from a worldwide cruise company website. The socio-demographic characteristics of the respondents are composed by predominance of females (60%), with an average age of about 50 years, married. The results showed that potential cruisers give more importance to attributes related to recreation and sport, fitness and health and supplementary services (for instance laundry and computer rooms) while factors such as crew service, room service, restaurant and food are perceived as extremely important for cruisers and potential cruisers. Whyte (2018) conducted interviews in Vancouver using open-ended questions to assess the onboard and onshore attributes that contributes to the cruise tourists' perceptions of the cruise destination, in a qualitative analysis. From the answers, 36 onboard attributes, 38 onshore attributes and 25 pros of cruising versus other types of vacations were selected. Petrick (2011) examined the relation between reputation of a cruising company and the passenger willingness to pay by interviewing cruise passengers. Conclusion about this study showed that the reputation of a cruising company has a significant effect on the passengers' perceptions of price sensitivity, quality, value, satisfaction, world of mouth and repurchase intentions.

Sun *et al.* (2019) attempted to evaluate the cruiser experience with shore excursions or activities of a cruise ship departing from Shanghai to a China-Japan route, using a questionnaire divided in three parts: importance of onshore activities, cruiser satisfaction with these activities and demographic information from cruisers. The proportion of male and female that answered the questionnaire was almost 1:1 and more than 85% were married, with an average age over 45 years old. This questionnaire also showed a gap between cruisers expectation and satisfaction, being that the most expected activities of the trip, such as sufficient sightseeing time and diverse attractions, were the ones which received the higher dissatisfaction scores among cruisers.

Mahadevan *et al.* (2017) made a step further, studying the relation between cruiser willingness to pay with different attributes of a cruise voyage. To do so the authors distributed cards with different cruise package options, asking cruisers to select which one they preferred. The mean age of the sample was

64 years, with slightly more females than males and 70% of them were married. Results showed that, price, cabin with ocean view, variety of attractions, bigger space to relax on the deck. Moreover, cruisers do not naturally associate self-organized excursion as more economical and the study also concluded that baby boomers (45 to 64 years) and generation X (25 to 44 years) have different preferences, meaning that cruise lines must do different market campaigns to different generations. Also, the generation X are the ones willing to pay the most for more comfort and luxury onboard.

Larsen *et al.* (2013) interviewed tourists visiting Norway about their expenditures, comparing it with other types of tourists concluding that despite of the per hours spending value of cruise tourists and other tourists are similar, cruise passengers' expenditures are lower than the expenditures of the other tourists. Larsen *et al.* (2016) conducted another study to investigate if cruise tourists spend more if more opportunities arise if they are more likely to return to the city later and if they make positive recommendations about the destination. The conclusion of this research showed that there is no significant difference in the expenditure behavior of cruise tourists during weekdays or holidays, and that cruise tourists and land tourists have a comparable probability of returning to the city or making positive recommendations of it.

2.3. Tickets Price and Revenue Management

Cruise companies most important sources of revenue are tickets, onboard activities, and excursion packages. Despite nowadays onboard activities and excursions are becoming more important in terms of percentage of the total revenue, tickets are still the major source of revenue for those companies. The ticket price is crucial to the success of an itinerary: if by one side ticket price affects the demand for a cruise voyage, by the other side, tickets are sold with antecedence of months before the voyage, giving to the company a good knowledge about the occupancy of the ship. Also, in a capital-intensive business as the cruise industry, earning the money before the costs expenditures is very helpful since it reduces the risk of liquidity problems.

Throughout the years, some authors studied the use of revenue management techniques, commonly seen at the airline and hotel industry, in the cruise industry. Basically, revenue management is the class of practices used to maximize the revenue of a product which have limited inventory capacity (such as seats in an airplane, rooms in a hotel of cabins at a cruise ship) by segmenting customers and selling the same product to different segments with a different price. Sun *et al.* (2011) conducted a concise review about marketing research and revenue optimization for the cruise industry, giving a better view about how it is applied in the cruise industry as well as in other industries.

Ladany *et al.* (1991) introduced this technique to the cruise industry, by calculating the total revenue that the cruise company would earn from different price strategy scenarios and assuming a linear demand curve: optimal single-market single-price strategy, maximal market-separation strategy, market segmentation of the unused capacity, unconstrained market segmentation of all cabins and unconstrained market segmentation of all cabins assuming customer infiltration. The first case is very simple, where given the demand curve, ticket price, fixed and variable costs of the ship, the optimal ticket price can be obtained and therefore the optimal number of occupied cabins. In some cases, a single price strategy results in unutilized cabins and allowing market segmentation could boost the profits. To know the maximum profit that could result from a market segmentation strategy, the maximal market-separation is calculated, where for each ticket sold, the price of the ticket is reduced until all cabins are occupied. Although this method returns the maximum profit possible, is very unlikely that such price policy would be used. More realistic methods divide the ship's cabins into n segments where each segment has a fixed price, using the same idea of the maximal market-separation strategy without changing the ticket price so aggressively. Also, one last thing that must be taken into consideration is that some consumers may be tempted to "infiltrate" into a lower market segment, saving some money. The results of the calculation for all market strategies mentioned above showed that revenue management might increase the total profit of a cruising company without changing the total number of tickets sold.

Niavis *et al.* (2018) studied the price structure of a cruise ticket, proposing the decomposition of this price as a combination of tourism and transportation characteristics, using a hedonistic pricing modelling method, which consist of decomposing a products into attributes and describing the product price as an additive function of all attributes. The tourism characteristics of the product used are onboard amenities and leisure activities, service quality, duration of trip, season, and itinerary attractiveness. The transport characteristics considered are sailing speed and itinerary closeness. The price function was calculated based on the online published catalogues of prices and itineraries of MSC and Costa Cruises for the Mediterranean 2013 season. The result showed that tourism-drive characteristics have a large effect on the price formation, being that onboard amenities was the most significant price shaper.

2.4. Cruise Ship Itinerary Design

The objective of the cruise ship itinerary design problem is to encounter the best route giving a set of possible ports of call. Usually, the homeport location and the duration of the voyage are previously defined. A big problem arises at determining the demand for each route, since it depends on the itinerary itself and no universal method is known to estimate passengers demand. This problem is found at the literature under various names: cruise itinerary design, cruise ship itinerary design, cruise ship itinerary and schedule design, and so on. In this document, the acronym CSID will be used to designate this problem, which stands for cruise ship itinerary design.

Wang *et al.* (2016) argues that itinerary design, fleet management, ship deployment and service planning are unknown areas of the industry which have an important effect on the profitability of cruise companies. Lee *et al.* (2013) compared the effect of different cruise itineraries in the occupancy ratio of cruise ships departing from the U.S. and concluded that the itinerary has a significant effect on the cruise ship occupancy ratio, being that Caribbean itineraries attracts more passengers that alternative destinations such as South America and South Pacific itineraries.

Itinerary designs are part of a major class of problems, known as vehicle routing problem (VRP), which is an important topic of operations research field, being studied since 1960 and which can be applied to an extensive list of real-world problems such as liner ship routing and delivery truck routing. The basic VRP consists of finding the best route given that it must start and end at the same place and the vehicles must pass only one time through each destination. This problem is also a generalization of the travelling salesman problem (TSP), which is one of the most famous combinatorial optimization problems. In recent years, VRP problems with more complexes constrains (such as time windows, capacity constraints and service time) lead to the creation of a newer class of problems, called rich vehicle routing problems (RVRP), as suggested by Lahyani *et al.,* (2015), where the cruise itinerary schedule design problem can be included. Additionally, is also possible to consider the CSID problem in a category called traveler salesman problems with profits, which incorporates the idea of profits into the typical traveling salesman problem, as discussed by Feillet *et al.*, (2005).

Despite of, at first instance, these different classifications for the same problem may seem confusing, it does not affect the formulation of the CSID problem. A deeper study of all these categories just shows how closely related these problems are and therefore, how important are the TSP and its variations for the real-world practical applications. Table 1 summarizes all the itinerary design papers discussed in this section, which are going to be presented below.

The VRP is a np-hard problem, meaning that the number of steps an algorithm needs to solve this problem increases exponentially with the number of destinations the vehicle needs to pass. For that reason, direct search algorithms are not recommended to solve big VRP problem, since it would take an incredible amount of computational power to solve them. One alternative then is to use heuristics approaches, albeit not guaranteeing optimality, it reduces considerably the computational power required. Optimization procedures to solve vehicle routing related problems can be found at the literature (Al-Hamad *et al.*, 2012; Christiansen *et al.*, 2019; Fagerholt *et al.*, 2000; Reinhardt *et al.*, 2010; Yao *et al.*, 2014). Although this section is focused on CSID papers, a simple explanation for the TSP, VRP and some common heuristics are presented in the section 3 of this thesis.

Table 1: Summary of the CSID works.

AUTHORS	TYPE OF PROBLEM	OBJECTIVE FUNCTION	OPTIMIZATION METHOD
Ladany et al. (1989)	CSID with a planning horizon	Maximize revenue	Dynamic programming
Ladany et al. (2001)	CSID	Maximizing attractiveness	Heuristics
Verdet et al. (2011)	CSID with a fleet assignment	Maximize revenue	-
Yang et al. (2016)	CSID	Maximize passengers and minimize costs	Genetic algorithm based on matrix coding
Wang et al. (2017)	CSID	Maximize the monetary value of the itinerary attractions minus costs	Dynamic programming
Wang, Kai et al. (2017)	CSID with a planning horizon	Maximize profit	CPLEX 12.5
Asta et al. (2018)	CSID	Maximize profit	Gurobi 7.0.2
Mancini et al. (2018)	CSID with fleet assignment	Minimize costs	Large neighbourhood search with matheuristic
Carillo et al. (2019)	CSID	Maximize attractiveness and minimize costs	Tabu-search and genetic algorithm
Zheng et al. (2019)	CSID	Minimum fuel consumption	Artificial neural network
Guo et al. (2019)	CSID with cabin price optimization	Maximum profit	Matrix-coding genetic algorithm and annealing algorithm

Despite of cruise itinerary design not attracting so much interest of the academy, this situation appears to be changing since half of the papers quoted in this section are from 2018 or 2019. Ladany *et al.* (1989) made one of the first attempts to solve a problem in this topic by studying how to maximize the revenue given by a leased luxury cruise ship sailing at Caribbean seas. The problem was divided in 2 parts: estimate the demand curve and fares and maximize the net revenue. To estimate the demand curve and fares, a regression analysis was made using a database of cruises sailed in the previous years, with the dependent variable being passenger bookings and the independent variables being length of the cruise, departure date, fare per sailing day and ports of call. After that, a dynamic programming model was used to optimize the maximum revenue for the season, obtaining the optimal itinerary for the entire season.

Continuing the study in this area, Ladany *et al.* (2001) presented an intuitive near-optimal heurist method for solving the cruise itinerary problem with an objective function of maximizing the local attractiveness of the itinerary, therefore assuming the more attractive the itinerary is, the more profitable it is as well. To calculate the objective function, an attractiveness function was defined, which returned the attractiveness of a city to the itinerary in function of the visit duration, attractiveness coefficient and an attractiveness index. Additionally, three assumptions were made to facilitate this problem. First, in the optimal solution, the marginal attractiveness value of the visit at all nodes should be equal. Secondly, in any given coastline, the optimal order to visit nodes for a TSP must follow the order that they appear along the coastline. Third, if the order of visit in an optimal n-nodes TSP is the same after any node is removed, then the algorithm yields the optimal cruise itinerary route.

Verdet *et al.* (2011) showed how the complexity of these problems increases when multiple ships must be considered at the same time, combing the problem of itinerary design with the problem of fleet assignment. A simple, non-realistic multi-objective linear programming model is then proposed, which tries to maximize the revenue of the tickets and the vessel capacity. Additionally, is proposed one heuristic to make this model more realistic, by considering that companies sometimes operate non-profitable routes to offer competitive destinations to their clients.

Yang *et al.* (2016) studied the cruise itinerary optimization problem in the coastline of China. The model developed uses dual objectives, trying to maximize the quantity of passengers with the minimum operating costs. To estimate the demand function, the authors conducted face-to-face interviews, asking about preferred voyage duration, ports of call and activities. The model is solved by using a genetic algorithm based on matrix coding and converged after 400 calculations in the numerical example shown in the paper.

Wang *et al.* (2017) published a mathematical model to solve the itinerary schedule design problem given the departure time and arrival time at homeport. Instead of estimating the passenger's demand for each destination, a utility distribution is used to measure the advantages of spending more time at a city instead of spending that same time at the sea. The objective function of this model is to maximize the monetary value of the utilities brought to cruise passengers at port cities minus the bunker fuel cost of the ship. To solve it, first all possible sequences of ports of call are enumerated. Then, a dynamic programming algorithm is used to find the optimal arrival and departure time at each port of call of all possible itinerary's sequences. After that, is possible to calculate which option is the best itinerary. In this case, to improve the algorithm efficiency, a heuristic method is proposed to not require enumerating all possible combination of ports of call. To access the heuristic performance, a problem was solved using the mathematical model in MATLAB and CPLEX12.1. The results showed that the heuristic approach produced the same itinerary as the direct approach and saves on average 80% of the computational time.

A more complex problem was presented by Wang, Kai *et al.* (2017), who tried to maximize the total profit of a cruise itinerary during a planning horizon, considering the berth availability of each port of call and a decreasing marginal profit. Both assumptions made this model even more realistic, because it considered two big problems of itinerary design not presented in any other paper found in the literature, which is the berth availability at each port and the fact that profits of a given cruise itinerary decreases with time since customers loses interest for a given route with time. Also, because the objective is to maximize total profit in a planning horizon, the model can assign different itineraries to the optimal solution, depending on the duration of the planning horizon chosen. Because the model developed is non-linear, two linearization methods are proposed. To assess the performance of both linear methods, tests with a planning horizon of 180 days have been conducted, using CPLEX12.5. This model can be also seen as an attempt of combining itinerary design and fleet assignment into the same model.

Another itinerary optimization model which has been elaborated in collaboration with a cruising company is presented by Asta *et al.* (2018). In this study, a purely cruise itinerary design model is developed, requiring as input a set of possible ports of call, voyage duration and homeport location. For the set of ports of call, is required that they are in areas with no political issues or risks and that the port facilities have a decent infrastructure, granting a safety operation. To facilitate the problem, days are divided in four slots (morning, afternoon, evening and night) and ships stops at ports can only be half day (one slot) or full day (two slots), being that is forbidden to arrive at night. Moreover, to measure the attraction value associated with each port, they are grouped in clusters with analogous characteristics and the attractive value of a port is reduced when there is more than one port of its category in the itinerary. Revenues are estimated based on sales of tickets and onboard activities and the costs are calculated only by the fuel costs and port's costs. The objective function is given by the maximization of accessibility and appealing values of the entire itinerary and the revenue deriving from the sale of excursions and onboard activities minus fuel and port costs. A case study to design a new itinerary in the west Mediterranean area has been made. The set of ports of call included 18 ports, clustered in the following categories: Italian culture, French culture, Spanish culture, seaside destination and others. The model was implemented by mathematical programming language and solved using Gurobi 7.0.2, achieving the optimal solution in within 10 seconds.

Mancini *et al.* (2018) used a variant of the vehicle routing problem to propose a model of cruise itinerary design combined with fleet assignment problem. The objective function of the model is to minimize the total costs considered, which are the port's costs and fuel costs. Additionally, some ports may be considered fixed to the itinerary, depending on the degree of attraction it represents, and ports may only be visited during specific time windows. Since for large problems the computational time required makes it infeasible to solve in a reasonable time using a commercial solver, a large neighbourhood search is proposed. Large neighbourhood search is a metaheuristic framework which is based on the idea that searching a large neighbourhood results in finding better solutions, avoiding local minima. To do so, solutions are destroyed and then rebuilt through different process until the optimal solution is found. In this paper, giving a current solution, the destroyer operator works on the ports-to-vessels assignment variables, forcing a number of ports of the current solution to be part of the new solution and a number of ports outside the current solution to be out of the new solution, reducing the number or possible ports to be included to the new solution. A comparison is made between the results for a real case with 4 cruise ships and 49 possible ports of call, calculated with the large neighbourhood search and with the mathematical model, observing a large difference between computational time to solve this problem with the different approaches: on average 225 seconds for the metaheuristic approach and 3600 seconds for the model solution. Testing even larger problems shows that the metaheuristic method outperforms the mathematical model solution in terms of time required and minimal cost find.

A different approach was made by Chen *et al.* (2018) which used the Weibull duration model to measure which factors influences in the time a cruise ship stays at a given port. The data used was taken from five Japanese ports: Muroran, Yokohama, Kyoto, Fukuoka, and Nagasaki. The variables studied which is believed to influence the length of stay of the cruise are ship tonnage, number of passengers, sailing distance from the previous port, sailing distance from the next port, regional cruise call duration, international cruise line call duration, homeport call duration and attractiveness of the port. Among these variables, was concluded that duration of stay in a port is influenced by ship's gross tonnage, number of passengers, sailing distance from previous and next port, type of cruise line (international or regional), type of port (homeport of port of call) and attractiveness of the destination.

Also, following recent trends of cloud computing, Carillo *et al.* (2019) evaluated time and cost of solving the cruise ship itinerary design problem using the cloud with an optimization via simulation process. The optimization uses a tabu-search approach, a local search method which takes an initial solution and try to improve it by searching its immediate neighbours solutions, allowing the algorithm to choose a worse solution when the algorithm cannot find a better solution. The fact that worse solutions can be chosen are what gives the name of this method as tabu-search approach, since the algorithm is doing precisely the opposite of what it is intended to do, and are used to avoid problems of local minima solutions. The moves are stored in a list and the solutions are iteratively computed until a stopping criteria is satisfied.

In this study, a genetic algorithm is used to optimize the parameters of the heuristic search. The objective function is to minimize the total cost of the cruise and maximize commercial attractiveness of the cruise. Results showed the use of cloud allows for easy improving of time required to solve the problem with a small increase in cost when compared to the use of cloud with small quantity of memory. For instance, using 15 GB of memory, the problem was solved in 27165 seconds and costed \$3.79 whereas when using 480 GB, the problem was solved in 2005 seconds and costed \$8.96.

Environmental impact is also an important topic in the cruise shipping industry and Zheng *et al.* (2019) used an artificial neural network model to predict fuel consumption of cruise ships based on automatic identification system data and design cruise itineraries with minimal fuel consumption. Artificial neural network is an adaptive system with non-linear statistical data modelling tool which simulates the structure and function of a biological neural network. The model is applied in a case study of a ship traveling at Norwegian waters, showing a fuel consumption reduction from 97.4 tons to 86.6 tons.

In an attempt to combine itinerary design with revenue management strategies, Guo *et al.* (2019) used a two-stage optimization model where during the first stage, the best itinerary is chosen and, at the second stage of the optimum cabin price is calculated. During the first stage, the itinerary design, a two-objective problem whose objectives are to minimize the average daily voyage cost and maximize the potential demand is transformed into a single objective using weighting and solved with a matrix-coding genetic algorithm for three different sceneries: 2-3 days trip, 3-4 days trip and 4-5 days trip. After that, a simulated annealing algorithm is used to calculate the optimum cabin ticket prices, considering competition with land tourism.

Although using a simple mathematical model, this study presented an interesting approach where itinerary design and cabin prices are combined into one problem, using a cost minimization and demand maximization objective function to develop the optimum itinerary, as many authors have done before, but also giving a step further to calculate the cabin price of each itinerary, finally obtaining the profit of each itinerary, a value that is more useful to a cruise company than the total cost.

3. OPERATIONS RESEARCH IN CRUISE SHIP ITINERARY DESIGN

In this chapter, a discussion about optimization programming methods is made, defining linear and integer programming, the traveling salesman problem, and the vehicle routing problem. Its application to the cruise ship itinerary design (CSID) problem that is the subject of this thesis is fully described, including its costs and revenues parameters. The software used to implement this problem, the CPLEX solver, is also briefly outlined. Finally, a brief review of heuristic algorithms and Monte Carlo simulation is made, and it is explained how these methods can also be used to solve linear optimization problems.

3.1. Linear and Integer Programming

Before properly describing the problem, will be explained the mathematical theory used to create and solve the model. Linear and mixed integer programming are powerful tools used to optimize mathematical problems to its maximum or minimum value possible. When the problem is described with linear constraints and the objective function is also a linear function, then some special algorithms can be applied to solve the problem to optimality. These algorithms described in this section are divided into the linear programming problem and the mixed integer programing problem. Furthermore, CPLEX solver will be introduced, explained what it is and how it is used to solve mathematical programming problems.

3.1.1. Linear Programming

Linear programming (LP) is a field of study dedicated to obtain solutions of a maximization (or minimization) problem represented only by the use of linear functions. The standard formulation of a linear programming problem is given by:

$$\begin{array}{cc} Maximize & c^T x \\ Subject\ to & Ax \leq b \\ And & x \geq 0 \end{array} \tag{1}$$

where, x is the vector of variables, c and b are coefficient vectors and A is a coefficient matrix. The objective function is defined by the term $c^T x$ and the constrains are given by the functions $Ax \leq b$ and $x \geq 0$. Any set of values for the vector x is known as a solution. If this solution respects all constrains of the problem, then it is also known as a feasible solution. The space of all feasible solutions is defined as the feasible region of the problem. When there is a solution inside the feasible region which maximize (or minimize) the objective function, this solution is known as an optimal solution.

There are innumerous algorithms designed to solve these problems. The most famous one, which will be explained later, is the simplex algorithm. Moreover, dual simplex algorithm, parametric linear algorithm, upper bound technique and interior-point algorithms are examples of other algorithms designed to obtain an optimal solution out of a linear programming problem.

Simplex algorithm was developed in the middle of the 20th century and is used until today to solve linear problems. Instead of searching for solution in the entire feasible region, given that this space is always a convex polytope, is possible to prove that the optimal solution of a linear programming problem, if exists, will always be a vertex (corner) of the feasible space. Therefore, the simplex searches for solutions only on the vertexes of the feasible region, limiting the space of the optimal feasible solution from the original feasible region, which have an infinite number of elements, to the vertex of this region, which have a finite number of elements.

3.1.2. Mixed Integer Programming

One of the requirements for linear programming is that all variables must have real values. However, for many problems of real life, the variables can only assume integer values. When some of the variables in a linear programming model are integers, this model is then referred to as a mixed integer programming model (MIP), as shown below. This type of problems generally demands more computational time than linear programming ones.

$$\begin{array}{cc} Maximize & c^T x \\ Subject\ to & Ax \leq b \\ And & x \geq 0 \\ & x_i \in \mathbb{N} \\ & x_i \subseteq x \end{array} \tag{2}$$

Solving integer programming problems is not easy because there is not a known efficient algorithm to do it and, in many cases solving a MIP will require solving a combinatorial problem. However, if a relaxed LP can be formulated in such a way that the feasible space of the MIP is a subset of the feasible solution of the relaxed LP and all vertices of the LP problem are a feasible solution for the MIP, then an optimal solution for the MIP can be found using the LP algorithms, such as the simplex method. The difficulty though is to find this relaxed LP problem, known as the perfect relaxed LP. In reality, the relaxed LP formulated will not have all vertices as feasible solutions of the MIP problem and therefore, other algorithms must be used to obtain the optimal solution of the problem.

One famous algorithm used to solve this type of problems is called branch and bound algorithm, which consists of analyzing a relaxed problem, a linear programming model that its feasible region contains the feasible solution space of the original problem. This relaxed model is then divided into different models (branched) in such a way that the feasible space of these new models forms a partition of the originally relaxed model. Then, those models are solved and theirs solution compared. If the optimal solution for all these partitions is contained in the feasible space of the original model, then this solution is also a solution for the original problem. The optimal solution of the relaxed problem is an upper (lower) bound for the MIP problem, since this objective function value will be always higher (lower) than the objective function optimal solution value for the MIP. Similarly, any feasible solution for one of the branches analyzed, if also a feasible solution of the MIP problem, is called as a primal bound. When the value of the primal bound and the upper or lower bound are equal, than the problem have been solved to optimality. A big problem of this algorithm is to develop an efficient way of branching and analyzing the solutions, to avoid unnecessary computational time.

The branch and bound algorithm provide an exact solution to the MIP problem with the cost of not knowing in advance the computational time required to solve the problem. When the time required to solve this algorithm becomes too large, then heuristics algorithms becomes a good alternative, although heuristics not guarantees to find an exact solution to the problem. Some of the most common algorithms used have already been discussed during the literature review and are tabu search algorithms (TS), simulated annealing algorithms (SA), genetic algorithms (GA), and greedy algorithms.

3.1.3. Heuristic Algorithms

Heuristic algorithms are extremely helpful to solve large instances of a TSP. As mentioned above, the trade-off of using such algorithms are the fact that optimality is not guaranteed. Although this might not seem a viable option at first, the velocity that some of those algorithms solve large problems and the quality of the results provided by them made these algorithms a good option. The idea those algorithms designed for the TSP, according to Feillet *et al.*, (2005), relies heavily on the following four operations:

1. Adding a vertex to the route.
2. Deleting a vertex from the route.
3. Resequencing the route.
4. Replacing a vertex of the route with a vertex outside the route.

Greedy insertion algorithms are constructed to tackle the problem locally, starting with an empty solution and adding the most efficient possible vertex to the solution at each step. Conversely, greedy deletion algorithms might do the opposite, starting with a known solution and deleting the least efficient vertex at each iteration. Algorithms such as the tabu search, simulated annealing and the genetic algorithms are classified as metaheuristic algorithms. These examples are more sophisticated algorithms that search in a large set of feasible solutions, avoiding being trapped into local optima. A deeper research into this topic for the TSP and VRP is reported by Laporte *el al.* (1992), Nguyen *et al.* (2010), Al-Hamad *et al.* (2012) and Liong *et al.* (2008).

3.1.4. IBM ILOG CPLEX

IBM ILOG CPLEX is an optimization software capable of solving models using mathematical programming techniques and constraint programming technics. Mathematical programming models are solved with the CPLEX Optimizer Engine whereas constraint programming models are solved by the CP Optimizer Engine. One of the greatest advantages of using an optimization software is the ability of solving optimization models with an intuitive programming language, such as OPL (optimization programming language), that allows for coding mathematical models in a very similar way as one may write it on a paper.

In this thesis will be used the CPLEX Optimizer Engine, commonly known as CPLEX, originally based on the simplex method, but that nowadays have incorporated different algorithms in order to provide faster solutions to a bigger broad of optimization models. The CPLEX solver accepts even the use of logical constrains and some non-linear constraints in its formulation.

3.2. The Traveling Salesman Problem and Vehicle Routing Problem

The traveling salesman problem consists of finding the optimal tour (cycle) passing through all the destinations exactly once, given only the costs of traveling between them. Although this problem does not provide an accurate solution for many of the routing problems faced by the industries today, it is still widely studied given its simplicity, the difficulties to solve it and that the TSP is equivalent to others np-hard problems, which means that finding a solution for the TSP would automatically find a solution to many other problems.

Moreover, the TSP is divided into two broad classes of problems: the symmetric TSP (STSP) and the asymmetric TSP (ATSP). Those classifications are directly linked to the definition of a direct graph and an undirect graph. A graph G is defined by two different sets, written as $G = (V, A)$, where V is the set of nodes and A is the set of ordered or unordered pairs of vertices of V. When A is an ordered set, each element of this set is called an arc and G is said to be a direct graph. Conversely, when A is an unordered set, each element of this set is called an edge and G is said to be a undirect graph. Following this definition, it is easy to observe that the STSP is related to an undirect graph whereas the ATSP is related to a direct graph. Despite of these differences, a STSP can be transformed into an ATSP problem simple by adding to the graph a set of arcs in opposite direction of all existing edges. Therefore, all algorithms described by the ATSP can be used for solving the STSP, although on many occasions the performance of the algorithm is compromised. Gutin *et al.* (2007) shows different variations of the TSP and techniques to solve it, including exact and approximated solutions.

Albeit many ways of defining this problem mathematically is known, here will be presented only one relevant formulation of the ATSP as a MIP which will be used as a basis for the development of the CSID problem in this thesis.

Let D be a complete direct graph, given by $D = (V, A)$ and let $c = \{c_{i,j}\colon\ i,j \in V \mid c_{i,j} \geq 0\}$ represent the cost of traveling from any two nodes i and j of the graph. Then, introducing the decision variables $x = \{x_{i,j} : (i,j) \in A\}$, we can express the formulation as:

$$\min \sum_{\substack{i,j \in V \\ i \neq j}} c_{i,j} x_{i,j} \tag{3}$$

subject to:

$$\sum_{\substack{i \in V \\ i \neq j}} x_{i,j} = 1 \; \forall j \in V \tag{4}$$

$$\sum_{\substack{j \in V \\ i \neq j}} x_{i,j} = 1 \; \forall i \in V \tag{5}$$

$$Subtour\ constraints \tag{6}$$

$$x_{i,j} \in \{0,1\} \;\; \forall (i,j) \in A \tag{7}$$

where the subtour constraints represents the use of additional constraints that forbids appearances of subtours in the optimal solution, which are the cases when the optimal solution satisfy all constraints defined above except the subtour constraint, but it consists of two or more separated cycles. Two examples of subtour constraints are the clique packing constraints and the MTZ constraints.

Clique packing constraints are based on the idea that for any subgraph Q of the original TSP induced by all nodes excluding the depot, the number arcs in this subgraph must be at most $|Q| - 1$. Assuming that the depot is located at the first node, these constraints are mathematically expressed as:

$$\sum_{i,j \in Q} x_{i,j} \leq |Q| - 1 \ \forall \emptyset \neq Q \subset V \setminus \{1\} \tag{8}$$

The MTZ constraints, firstly published by a paper of Miller, Tucker and Zemlin (hence the acronym MTZ), uses a different approach to define the subtour constraints. It uses additional variables, not presented in the formulation above and is given by:

$$u_i - u_j + (n-1)x_{i,j} \leq (n-2) \ \forall i,j \in V \setminus \{1\} \tag{9}$$

This different formulation guarantees that no subtour is formed in the TSP using $(n-1)^2$ additional constraints and $(n-1)$ additional variables, whereas for the clique packing constraints in a worst case scenario is required 2^{n-1} constraints. Although this is true, the former constraints may be added in steps until no subtour is obtained while the MTZ constraints must be added all at once to guarantee that no subtour is formed.

Finally, the VRP is a generalization of the TSP, designed mainly to be used for assigning an optimal route for a fleet of vehicles. Usually, each node has a specific demand to be attended and there may be many tours in the final solution as there are vehicles available in the problem. Typically, in a VRP, each vehicle has a limited capacity, and a fixed cost is associated with its use. Golden *et al.* (2008) discusses in more details about the vehicle routing problem and its variations. A formulation for the VRP is shown in the paragraph below.

Let D be a complete direct graph, given by $D = (V, A)$, where the first node represents the depot, the set $M = \{1,2,\ldots,k\}$ is the set of types of vehicles available in the fleet, $c = \{c_{i,j}\colon\ i,j \in V \mid c_{i,j} \geq 0\}$ represents the cost of traveling from any two nodes i and j of the graph, $F = \{F_k\colon k \in M\}$ be the fixed cost of using each vehicle, $Q = \{Q_k\colon k \in M\}$ is equal to each vehicle capacity, $q = \{q_i\colon i \in V \setminus \{1\}\}$ represent the demand at each node and $m = \{m_k\colon k \in M\}$ is the total number of each type of vehicles available in the fleet. Then, introducing two decision variables, $x = \{x_{i,j}^k : (i,j) \in A, k \in M\}$ which tells whether a type k vehicle is assigned to pass travel from node i to node j, and $y = \{y_{i,j}\colon i,j \in V\}$, which tells the quantity of cargo carried from node i to node j, one may express the formulation as:

$$\min \sum_{k \in M} F_k \sum_{j \in V \setminus \{1\}} x_{0,j}^k + \sum_{k \in M} \sum_{\substack{i,j \in V \\ i \neq j}} c_{i,j}^k x_{i,j}^k \tag{10}$$

subject to:

$$\sum_{k \in M} \sum_{\substack{i \in V \\ i \neq j}} x_{i,j}^k = 1 \ \forall j \in V \setminus \{1\} \tag{11}$$

$$\sum_{i \in V} x_{i,p}^k - \sum_{j \in V} x_{p,j}^k = 0 \ \forall p \in V \setminus \{1\}, \forall k \in M \tag{12}$$

$$\sum_{j \in V \setminus \{1\}} x_{0,j}^k \leq m_k \ \forall k \in M \tag{13}$$

$$\sum_{i \in V} y_{i,j} - \sum_{i \in V} y_{j,i} = q_j \ \forall j \in V \setminus \{1\} \tag{14}$$

$$q_j x_{i,j}^k \leq y_{i,j} \leq (Q_k - q_i) x_{i,j}^k \ \forall (i,j) \in A, \forall k \in M \tag{15}$$

$$y_{i,j} \geq 0 \ \forall (i,j) \in A \tag{16}$$

$$x_{i,j}^k \in \{0,1\} \ \ \forall (i,j) \in A, \forall k \in M \tag{17}$$

3.3. Monte Carlo Method

The Monte Carlo Method is a technique implemented through a group of algorithms that uses random numbers generated for uncertainties to obtain results for probabilistic problems. This method can be used to solve the traveling salesman problem with the following steps:

1. Generating a large random sample of routes, regardless of its feasibility.
2. Excluding all unfeasible routes.
3. Calculating the costs and/or revenue for all feasible routes generated.
4. Sorting these routes accordingly with the objective function of the problem.
5. Picking the best route generated as the solution for the problem.

Although not having the guarantee of finding the optimal solution, the more simulations one carries out, always with different values for the random variables, which are described with specified probability distributions, closer to the optimality the solution obtained will be. Additionally, in some algorithms, the number of runs carried out is defined by an iteration process, where the solution obtained is compared with a solution previously obtained for a smaller number of runs and the algorithm stops only when this solution converges to a fixed value.

3.4. Cruise Ship Itinerary Design Problem Description

The problem studied consists of identifying the most profitable itinerary route in a certain geographical region given a list of possible ports of call for that region. The cruise ship is known and therefore its main dimensions and passenger capacity are given parameters. Additionally, the month of the year and the duration of the itinerary, in days, are also previously defined. For each voyage leg, the ship is assumed to sail at a constant speed, selected from a set of possible speeds, and restricted by a maximum number of hours at sea. Higher sailing speed means higher achievable sailing distances in each leg but also implies in a higher fuel consumption. Every itinerary must have one homeport and each port of call must be visited only once. When convenient, the cruise ship can stay a full day at sea, in order to avoid having to visit cities not so attractive or in order to visit an extremely interesting destination very distant from the previous destination visited in the itinerary.

In resume, the problem analyzed involves identifying the sequence of ports of call to be visited and the sailing speed in each itinerary leg, so that the highest net profit for the cruise company is obtained. The structure of costs and revenues considered in this problem is shown below.

3.4.1. Costs

Costs can be divided into fixed costs, represented in this case as a fixed value per day, and variable costs, which its values depending on other variables. The variable costs considered in this problem are the fuel costs associated with main machinery and auxiliary engines and port tariffs, whereas the fixed costs considered are crew wage, provisions and storage cost, routine maintenance cost, insurance cost, administration cost, and periodic maintenance cost.

3.4.2. Revenue

Revenue is calculated using an attractiveness function and accordingly with the number of ports visited by the itinerary. Each possible port of call has a value of attractiveness points, in function of touristic attractions close to the port and weather conditions (temperature, precipitation, sunshine and wave height) for the month considered, being that more points means more revenue that this port will return for the itinerary. On top of that, spending a day at sea also has a positive impact on the attractiveness function, although not as positive as if the day were spent at quay in some attractive port of call. From this value, an estimation of the additional revenue generated because of visiting the ports of call is calculated. In this problem, the ship is assumed to operate at full capacity, regardless of the itinerary route.

4. MATHEMATICAL MODEL

The mathematical model presented in this chapter is a natural generalization of the formulations presented in the chapter above, considering the particularities of the CSID problem, such as the time windows and the location of the homeport which is not a parameter. It is a mixed integer linear programming with some logical constrains formulations, built to be solved with CPLEX 12.10. For an easier understanding, the presented model is divided into the following topics: assumptions, parameters, variables, expressions, and constraints.

4.1. Assumptions

The assumptions used to develop this model are:

1. Voyage time between two ports depends only on the distance between those ports and the ship speed, assumed constant for the entire trip.
2. The cruise itinerary must end in the starting port.
3. Each port of call must be visited only once.
4. The ship can visit at maximum one port per day.
5. The itinerary must have precisely the duration time desired.
6. Main engine power of the ship is proportional to the cubic power of the speed.
7. Load factor (L.F.) of the auxiliary power is constant during the entire voyage (at sea and at port).
8. The specific fuel oil consumption (S.F.O.C.) for the main engine and auxiliary engine are assumed to be constant, regardless of the engines load factor.
9. Main engine consumes intermediate fuel oil (IFO 180) and auxiliary engines consumes marine gas oil (MGO). The prices of these oils are input parameters and therefore constants.
10. The fixed costs are constant, regardless of the month studied or the ports included in the itinerary.
11. The cruise ship is assumed to operate with two passengers per cabin always.
12. The revenue collected depends exclusively on the month and the ports included in the itinerary.
13. Ships can only arrive at ports between 7:00 and 14:00 and can only depart during 16:00 and 23:00.

4.2. Parameters

The parameters are divided in route parameters, fixed costs parameters, variable costs parameters, revenue parameters and dimensional parameters, as show below. Sets are defined starting with capital letters and the other parameters starts with lowercases.

4.2.1. Route Parameters

Let n be the number of all possible ports for this problem and $P = \{1, \dots, n\},\ P \subset \mathbb{N}$ be the set of all possible ports and $\widehat{hp}_i = \{0,1\},\ \forall i \in P$ the parameter representing whether a port can be a homeport or not (if a port i can be assigned as a homeport, $\widehat{hp}_i = 1$ and if not, $\widehat{hp}_i = 0$). Similarly, let g be the number of speeds being considered and $S = \{1, \ldots, g\},\ S \subset \mathbb{N}$ be the set of all possible ship speeds. The speeds values considered, in knots, are given by $v_i,\ i \in S$.

Let $E = \{(i, j, k) \mid i, j \in P, k \in S : i \neq j\}$ to be the set of all possible arcs formed by two different ports and the different speeds and let $L = \{(i, j) \mid i, j \in P : i \neq j\}$ to be the set of all possible arcs between two different ports.

The ports distance is given by $d_{i,j}$, $(i, j) \in L$, given in nautical miles and the time between ports is given by $t_{i,j,k}$, $(i, j, k) \in E$.

The duration of the itinerary, in nights, is given by the parameter Δ. In relation to the month when the itinerary will occur, let $M = \{january, \ldots, december\}$ be the set of months of the year and m the month when the itinerary occurs.

4.2.2. Time Constraint Parameters

Let s_{min} and s_{max} being respectively the minimum and maximum time in port at each port of call, in hours, t_{leg}^{max} being the maximum travelling time during each voyage leg, in hours.

4.2.3. Fixed Costs Parameters

The fixed cost parameters are enumerated in the following list and their value is expressed in USD/day:

1. c_c: Capital costs.
2. c_w: Crew wages.
3. c_s: Storage and provisions cost.
4. c_{rm}: Regular maintenance cost.
5. c_i: Insurance cost.
6. c_a: Administration cost.
7. c_{pm}: Periodic maintenance cost.

4.2.4. Variable Costs Parameters

The specific fuel oil consumption (S.F.O.C.), in Kg/kWh, consumption for each possible speed of the main engine and the S.F.O.C., in Kg/kWh, for the auxiliary engines are given respectively by $sfoc_{M_i}, i \in S$ and $sfoc_{aux}$. Additionally, its prices, in USD/ton, are given by the parameters hfo and mgo. Normal continuous rating (N.C.R) of the ship, in kW, and the cruise speed, in knots, are given by ncr and v_{cruise} respectively. The power consumption of each speed, in kW, for the main engine and the auxiliary engine are given by p_{M_i} , $i \in S$ and p_{aux}. The value of main engine power for speeds different than the cruise speed is given by:

$$p_{M_i} = \left(\frac{v_i}{v_{cruise}}\right)^3 * ncr \tag{18}$$

The value of the main engine fuel cost, in USD/hour, is given by:

$$c_{main_i} = p_{M_i} * sfoc_{M_i} * \frac{hfo}{1000}, i \in S \tag{19}$$

The value of the auxiliary engines fuel cost, in USD/hour, is given by:

$$c_{aux} = p_{aux} * L.F * sfoc_{aux} * \frac{mgo}{1000} \tag{20}$$

Ports tariffs will depend on the ports included at the analysis and is denoted by the parameter ${c_{tariff}}_i, i \in P$, expressed in USD.

4.2.5. Revenue Parameters

The total revenue of the itinerary, in USD, is calculated as described in the Cruise Planner Manual (Santos, 2020), and is a function of the attractiveness of each port, shown by the formula below:

$$V_{i,m} = P_i + A_i \frac{(12-2Ta_i)}{12} + 2(Tm_{i,m} - 15) + 0.1(S_{i,m} - 200) - 5(Hs_{i,m} - 1.5),\ i \in P\ and\ m \in M \tag{21}$$

where,

1. $V_{i,m}$ is the total port attractiveness of the port i for the month m, in USD/passenger.
2. P_i is the attractiveness of the port itself.
3. A_i is the attractiveness of a city or attraction located near the port of call.
4. Ta_i is the time, in hours, from the port i to the attraction located near the port of call.
5. $Tm_{i,m}$ is the average daily temperature, in degrees Celsius, in the port i for the month m.
6. $S_{i,m}$ is the average monthly sunshine hours in the port i for the month m.
7. $Hs_{i,m}$ is the average significant wave height, in meters, in the port i for the month m.

This formula combines weather and geographical factors of each destination with the attractiveness of the location itself to calculate the total attractiveness of the port. The first two terms are related to the attractiveness of the port and the attractions nearby, if any, taking into consideration the distances to the port t (the further the nearby attractions are to the port, the less attractive it became). For the weather characteristics, namely average daily temperature, average monthly sunshine hours and average significant wave height, it can influence linearly the final value of the port attractiveness. Higher average daily temperature and average monthly sunshine hours influence positively the port attractiveness whereas bigger average significant wave height influence negatively the total port attractiveness. These weather factors are the only parameters that varies depending on the month analysed.

Weather values were taken directly from the internet, with exception of the average wave height value which were calculated using the program ERA5. To estimate the attractiveness of a port or a nearby attraction, the following formula is used, taking as a parameter the number of tourists that visits the city annually:

$$P_i = 25 + 150 * \frac{number\ of\ tourists\ visiting\ the\ city\ i\ annually}{maximum\ number\ of\ tourists\ visiting\ a\ city\ in\ the\ selection\ annually},\ i \in P \tag{22}$$

4.2.6. Dimension Parameters

The final parameters to be considered are the dimensional parameters of the ship and each port. The ship parameters considered are:

1. n_{pax}: Number of passengers.
2. L_{ship}: Length of the cruise ship in meters.
3. B_{ship}: Breadth of the cruise ship in meters.
4. D_{ship}: Draught of the cruise ship in meters.

The port parameters considered are the maximum allowed length, breadth and draught of the ships docking at the port, expressed by:

1. $L_i, i \in P$: Maximum allowed length, in meters, for the port i.
2. $B_i, i \in P$: Maximum allowed breadth, in meters, for the port i.
3. $D_i, i \in P$: Maximum allowed draught, in meters, for the port i.

4.3. Variables

For this problem there are Boolean variables, integer variables and real variables. The Boolean variables are:

1. $x_{i,j,k}$, $(i,j,k) \in E$: 1 if the ship travels from port i to port j with speed k.
2. y_i , $i \in P$: 1 if the port i is part of the itinerary.
3. hp_i , $i \in P$: 1 if the port i is the homeport.
4. $\hat{x}_{i,j}$, $(i,j) \in L$: 1 if the ship stays one day at the sea between the arc l.

The integer variables are:

1. a_i , $i \in P$: Hour of the day that the ship arrives at the port i.
2. b_i , $i \in P$: Hour of the day that the ship departs of the port i.

Finally, the real variable is:

1. u_i , $i \in P$: Subtour elimination variable.

4.4. Expressions

in order to facilitate the comprehension of the objective function and the constrains, some expressions will be defined and used later on. These expressions are divided in three categories, time related expressions, cost related expressions and revenue related expressions, as shown below.

4.4.1. Time Related Expressions

Time in port is the total time that the ships stays at each port, given by:

$$s_i = b_i - a_i , \forall i \in P \tag{23}$$

The time at sea during the cruise voyage for each two ports and the total sea time for the entire voyage are given by:

$$t_{leg_{i,j}} = \sum_{k\in S}\left(t_{i,j,k} * x_{i,j,k}\right)\ ,\forall(i,j) \in L \tag{24}$$

$$t_{sea} = \sum_{(i,j)\in L} t_{leg_{i,j}} \tag{25}$$

The total onboard time is a measure of the total time passengers stay onboard the ship, which included the sea time and the waiting time, as seen below.

$$t_{onboard} = \sum_{(i,j)\in L}\sum_{k\in S}\left[\left(a_j + (24 - b_i) + 24 * \hat{x}_{i,j}\right) * x_{i,j,k}\right] \tag{26}$$

Moreover, knowing the total sea time and the total onboard time, is possible to calculate the total wating time for the itinerary:

$$t_{waiting} = t_{onboard} - t_{sea} \tag{27}$$

4.4.2. Cost Related Expressions

The fixed cost is given by the sum of all fixed cost parameters:

$$c_{fixed} = \Delta * \left(c_c + c_w + c_s + c_{rm} + c_i + c_a + c_{pm}\right) \tag{28}$$

where the cost components were defined 4.2.3. These are relative to the ship's characteristics and are an input.

The main engine fuel consumption total cost is given by:

$$c_{main}^{total} = \sum_{(i,j,k)\in E}\left(x_{i,j,k} * \mathrm{t}_{i,j,k} * c_{main_i}\right) \tag{29}$$

Auxiliary engines cost is divided in two situation: auxiliary engine cost when the ship is docked (equation 30) and auxiliary engine cost when the ship is sailing (equation 31). The difference between these two situations are the number of hours that the ship spent in each situation and the reduced electrical power consumption when the ship is docked. This reduction in auxiliary power consumption is defined by the load port factor (L.P.F) parameter.

$$c_{port} = c_{aux} * \mathrm{L.F.P} * \sum_{i\in P}(s_i * y_i) \tag{30}$$

$$c_{aux}^{total} = c_{aux} * \sum_{(i,j,k)\in E}\left(x_{i,j,k} * \mathrm{t}_{i,j,k}\right) \tag{31}$$

The total port tariffs is calculated by:

$$c_{tariffs} = \sum_{i\in P}\left(c_{tariff_i} * y_i\right) \tag{32}$$

The waiting cost is added to apply a small penalty for having the ship waiting at the port, as shown below. The idea is that while this value will not represent a significant difference, it will incentive the cruise ships to not stay waiting to enter at the port unless necessary.

$$c_{waiting} = t_{waiting} * n_{pax} * 10 \tag{33}$$

The total itinerary cost can be obtained by:

$$C_{total} = c_{main}^{total} + c_{aux}^{total} + c_{port} + c_{fixed} + c_{waiting} + c_{tariffs} \tag{34}$$

4.4.3. Revenue Related Expressions

The total gross revenue collected in the itinerary is given by:

$$R = \sum_{i \in P} \left(2 * V_{i,m} * n_{pax} * y_i\right) + \sum_{(i,j) \in L} \left(10 * n_{pax} * \hat{x}_{i,j}\right) \tag{35}$$

4.5. Objective Function

The objective function of this model is to maximize the itinerary net profit, expressed by:

$$\boldsymbol{max}\ (R - C_{total}) \tag{36}$$

4.6. Constraints

Finally, the last part of the model to be showed are the model constraints. Variables constraints represents all constraints related to the nature of the variables and its allowed values. Flow constraints are used to guarantee that the ship will visit each port only once, there will be at least one port at the itinerary included at the list of possible homeports assigned and that the maximum traveling is respected in each leg. The time constraints guarantee that the ship arrives and departs at each port during the allowed time window period and that the itinerary has the exact duration desired. Dimensions constraints are used to check whether the ship can dock at all ports in the itinerary. Finally, the sub route constraint is used to eliminate possible subtour solutions.

4.6.1. Variables Constraints

Equations (37), (38), (39) and (40) are related to the arrival and departure time, as well as to the fact that the ship can only enters or leave the port at full hours. Equations (41), (42), (43) and (44) are related to the fact that those variables are binaries and equation (45) is related to the fact that the sub route variable is a real variable.

$$a_i \in \mathbb{N}, \forall i \in P \tag{37}$$

$$7 \leq a_i \leq 14\ , \forall i \in P \tag{38}$$

$$b_i \in \mathbb{N}, \forall i \in P \tag{39}$$

$$16 \leq b_i \leq 23\ , \forall i \in P \tag{40}$$

$$x_{i,j,k} \in \{0,1\}, \forall (i,j,k) \in E \tag{41}$$

$$y_i \in \{0,1\}, \forall i \in P \tag{42}$$

$$hp_i \in \{0,1\}, \forall i \in P \tag{43}$$

$$\hat{x}_{i,j} \in \{0,1\}, \forall (i,j) \in L \tag{44}$$

$$u_i \in \mathbb{R}, \forall i \in P \tag{45}$$

4.6.2. Flow Constraints

Equations (46) and (47) guarantees that if the ship makes round voyages, although it not necessarily guarantees that there is only one route in the optimal solution. Equation (48), (49) and (50) forces the desired homeport to be part of the itinerary. Equation (51) constrains the ship to have only one possible speed during each leg and, equations (52) and (53) forces the variable $\hat{x}_{i,j}$ to be true only on possible scenarios (when the ship is traveling is traveling through this route). Although not required in the model, the constraint (5354) showed to decrease significant the solving time. Finally, equation (55) forces a and b values to be physically possible.

$$\sum_{k \in S} \sum_{\substack{j \in P \\ i \neq j}} x_{i,j,k} = y_i \text{ ,} \forall i \in P \tag{46}$$

$$\sum_{k \in S} \sum_{\substack{i \in P \\ i \neq j}} x_{i,j,k} = y_j \text{ ,} \forall j \in P \tag{47}$$

$$hp_i \leq \mathrm{y}_i, \forall i \in P \tag{48}$$

$$\sum_{i \in P} hp_i = 1 \tag{49}$$

$$hp_i \leq \widehat{\mathrm{hp}}_i, \forall i \in P \tag{50}$$

$$\sum_{k \in S} x_{i,j,k} \leq 1 \text{ ,} \forall (i,j) \in L \tag{51}$$

$$\sum_{\substack{j \in P \\ i \neq j}} \hat{x}_{i,j} \leq 1 \text{ ,} \forall i \in P \tag{52}$$

$$\sum_{\substack{i \in P \\ i \neq j}} \hat{x}_{i,j} \leq 1 \text{ ,} \forall j \in P \tag{53}$$

$$if\ (\hat{x}_{i,j} = 1)\ then\ \left(\sum_{k \in S} x_{i,j,k} = 1\right) \text{,} \forall (i,j) \in L \tag{54}$$

$$a_j + (24 - b_i) + 24 * \hat{x}_{i,j} \geq t_{leg_{i,j}} \text{,} \forall (i,j) \in L \tag{55}$$

4.6.3. Time Constraints

Equations (56) and (57) constrains applies the maximum time at sea constrains. Equations (58) and (59) defines the minimum and maximum time of each port visit, excluding the homeport, and the equation (60) forces the itinerary to have the desired duration.

$$t_{leg_{i,j}} \leq t_{leg}^{max} + 24 * \hat{x}_{i,j} \text{ ,} \forall (i,j) \in L \tag{56}$$

$$t_{leg}^{max} = 15 \tag{57}$$

$$s_i \geq s_{min} * (1 - hp_i) \text{ ,} \forall i \in P \tag{58}$$

$$s_i \leq s_{max} + (24 - s_{max}) * hp_i \text{ ,} \forall i \in P \tag{59}$$

$$\sum_{i \in P} y_i + \sum_{l \in L} \hat{x}_{i,j} = \Delta \tag{60}$$

4.6.4. Dimensions Constraints

Equations (61), (62) and (63) forces the ship dimensions to be lower than the ports restrictions.

$$L_{ship} * y_i \leq L_i, \forall\ i \in P \tag{61}$$

$$B_{ship} * y_i \leq B_i, \forall\ i \in P \tag{62}$$

$$D_{ship} * y_i \leq D_i, \forall\ i \in P \tag{63}$$

4.6.5. Sub Route Constraint

The last constrain, given by equation (64) is used to eliminate sub tour solutions. This subtour constraint is an adaptation of the MTZ constraint, based on the idea given by Gouveia *et al.* (1999) and Yuan *et al.* (2020), for the case where the depot (homeport in this case) exists but is not known at the beginning.

$$u_i - u_j + (\Delta - 1) * \sum_{k \in S} x_{i,j,k} \leq \Delta - 2 + \Delta * \left(hp_i + hp_j\right), \forall i, j \in P : j \neq i \tag{64}$$

To see that this equation is a valid subtour constraint, assume x^1 a solution with at least one subtour. Without loss of generality, we can assume that the homeport is assigned to the first node, V_1. Therefore, there is a subset of size s, $V^s = \{n_1, n_2, \dots, n_s\}$, that forms a subtour of V and therefore and $V^s \cap V_1 = \emptyset$, assuming that the set is ordered in the sequence that the vehicle is traveling, then $x^1_{n_i, n_{i+1}} = 1\ \forall i \in V^s$, where the last term, $x^1_{n_s, n_{s+1}} = x^1_{n_s, n_1}$. Then, the formulation (64) returns:

$$\begin{cases} u_{n_1} - u_{n_2} + 1 \leq 0 \\ u_{n_2} - u_{n_3} + 1 \leq 0 \\ \qquad \vdots \\ u_{n_s} - u_{n_1} + 1 \leq 0 \end{cases} \tag{65}$$

Summing all these constraints, we obtain:

$$u_{n_1} - u_{n_1} + s \leq 0 \tag{66}$$

which is absurd. Therefore, these constraints guarantee that no subtour will appear on a feasible solution. Now rests to show that any solution with one simple cycle is satisfied by these constraints. Again, considering there is a subset of size s, where $s \leq \Delta$ and $V^s = \{n_1, n_2, \dots, n_s\}$ that forms a tour in V, $V_1 \in V^s$ and assuming that the set is ordered in the sequence that the vehicle is traveling, then $x_{n_i, n_{i+1}} = 1\ \forall i \in V^s$, where the last term, $x_{n_s, n_{s+1}} = x_{n_s, n_1}$ and $hp_{n_1} = 1$. The constraints for the cases where $x_{i,j} = 1$ gives:

$$\begin{cases} u_{n_1} - u_{n_2} + 1 \leq \Delta \\ u_{n_2} - u_{n_3} + 1 \leq 0 \\ \qquad \vdots \\ u_{n_{s-1}} - u_{n_s} + 1 \leq 0 \\ u_{n_s} - u_{n_1} + 1 \leq \Delta \end{cases} \tag{67}$$

A possible solution for these equations is: $u_{n_1} = 0, u_{n_2} = 0, u_{n_3} = 1, \dots, u_{n_s} = s - 2$. The last thing to be proven is that these constraints are also satisfied when one of the nodes considered are not in the solution. For these cases, they might end up in one of these cases:

1. The nodes V_i and V_j are not in the tour, then: $u_i - u_j \leq \Delta - 2$
2. The nodes V_i is in the tour and V_j is not in the tour, then: $u_i - u_j \leq \Delta - 2$
3. The nodes V_i and V_j are in the tour, then: $u_i - u_j \leq \Delta - 2$

All these 3 cases are always valid if we assume $u_i = 0 \ \forall i \notin V^s$. One additional note to be said is that the following equations are also valid subtour inequalities for this case, but not performed so good as the constraint (64) in the CPLEX.

$$u_i - u_j + \Delta * \sum_{k \in S} x_{i,j,k} \leq \Delta - 1 + \Delta * (hp_i + hp_j), \forall i, j \in P : j \neq i \tag{68}$$

$$u_i - u_j + \Delta * \sum_{k \in S} x_{i,j,k} \leq \Delta - 1 + \Delta * hp_j, \forall i, j \in P : j \neq i \tag{69}$$

$$u_i - u_j + (\Delta - 1) * \sum_{k \in S} x_{i,j,k} \leq \Delta - 2 + \Delta * hp_j, \forall i, j \in P : j \neq i \tag{70}$$

4.7. Implementation in CPLEX

This formulation is implemented in CPLEX 12.10 using the OPL language, divided in two files: a file containing the structure of the formulation (.mod file) and a file containing the parameters values used (.dat file). The structure of the model developed is shown in Figure 3. Moreover, the code lines can be found in Appendix 1. Because all the values related to the CPLEX solver are set as the default, the solver automatically selects the algorithm to be used, which in this case is a branch and cut algorithm. After solved, variables, expressions, and the objective function values for the optimum itinerary are displayed at the integrated development environment (IDE) and stored in an EXCEL file.

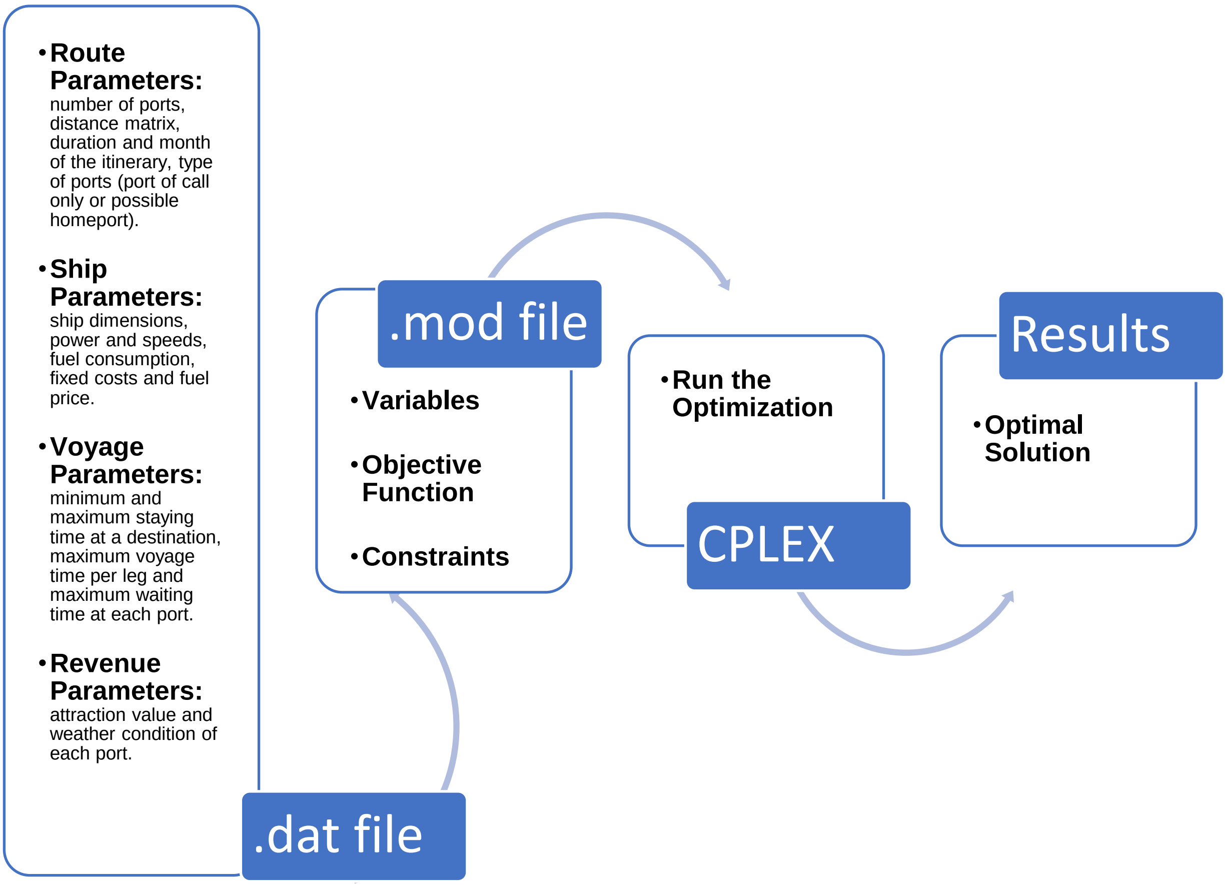

Figure 3: Flowchart of the optimization model.

5. NUMERICAL STUDIES

To analyze the developed model and investigate how it behaves in relation to existing itineraries, numerical studies are made for two different regions: an itinerary at the Atlantic coast of Iberian Peninsula and another one at the Brazilian coast. For each region, a specific ship is selected, and results for different scenarios are compared with existing itineraries of the region. The analysis is made always for weekly and fortnightly itineraries (8 days-7 nights, 14 days-13 nights). Moreover, the computational aspects of all analyses performed are presented at the end of this chapter. In both studies, values of parameters related to the time in port and maximum voyage time used, fuel prices and the daily administrative cost are equal, as shown by the following equations:

$$s_{min} = 7 \tag{71}$$

$$s_{max} = 11 \tag{72}$$

$$t_{leg}^{max} = 15 \tag{73}$$

$$t_{waiting} = 2 \tag{74}$$

$$c_a = 410 \tag{75}$$

5.1. Optimum Cruise Ship Itinerary for the Atlantic Coast of Iberian Peninsula

The first region to be studied is the Atlantic Coast of Iberian Peninsula, incorporating ports of Portugal, Spain, Gibraltar, and also Morocco, as shown in Figure 4 and Figure 5. Morocco, although not in the Iberian Peninsula, is included as it could provide suitable ports of call for cruise ships sailing from the Peninsula coastline to Madeira and the Canary Islands, located several hundreds of nautical miles away from the Peninsula. From these areas, it can be highlighted the following cities or regions as touristic areas: Galicia, Porto, Lisbon, Algarve, Madeira islands, Canary Islands, Morocco, Andaluzia and Gibraltar. A few ports within the Mediterranean Sea in the Spanish coast (Málaga, Motril) are included in the study, although not situated in the Atlantic Ocean, because of their interest for cruises and small distance to the Strait of Gibraltar.

Although the Atlantic Coast of Iberian Peninsula is located close to the Mediterranean Sea, there are not a lot of itineraries covering this region when compared to the Mediterranean and Adriatic Sea, despite of the enormous quantity of touristic cities, meaning that there is a growth potential of this region for the future. In the following sections is described the list of all ports considered for this study, the ship and fixed costs used, the analysis performed and a comparison with real itineraries for this region.

Figure 4: Main commercial ports in the Atlantic Coast of the Iberian Peninsula.

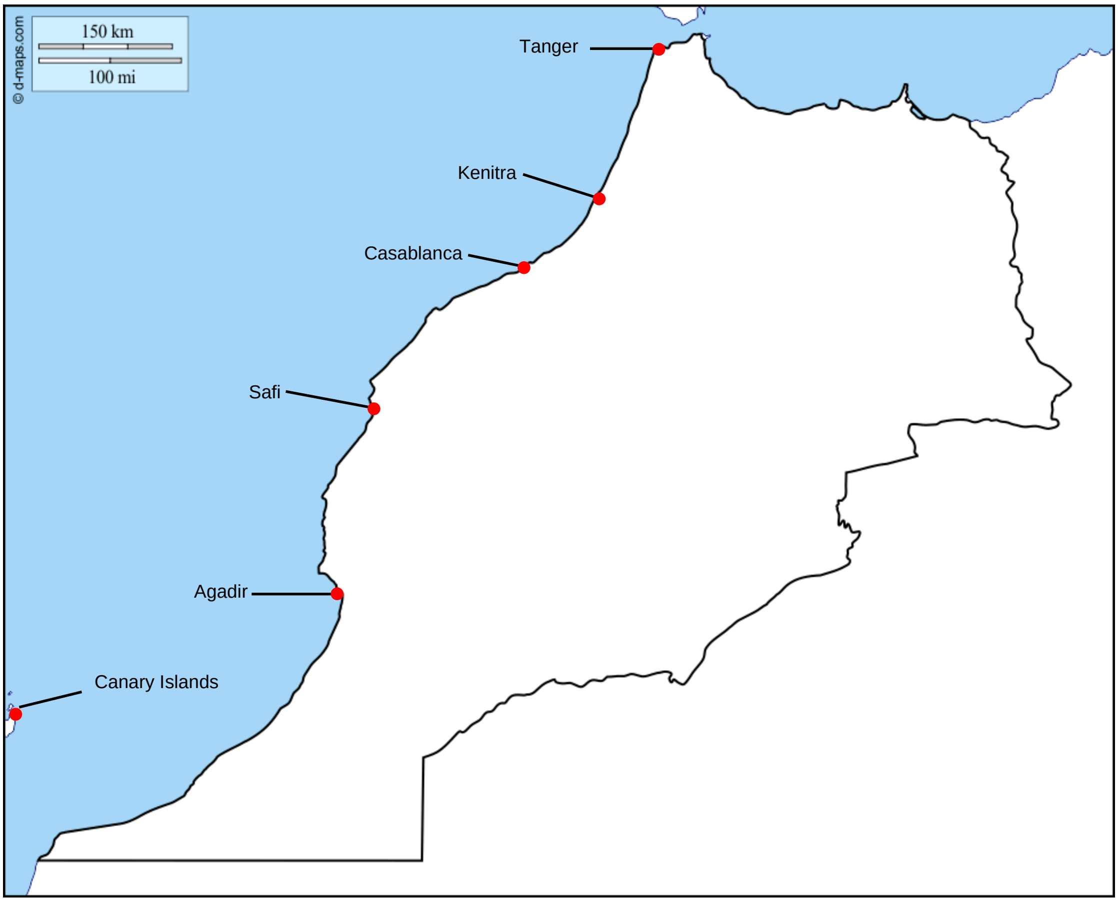

Figure 5: Main commercial ports in the Atlantic Coast of Morocco.

5.1.1. The Atlantic Coast of the Iberian Peninsula as a cruising region

Two sets of ports will be considered for the analysis made in this section, one set including the 19 most common cruise ports of this region, hereafter named as the as-is-situation, and another set with 30 ports, which includes all the ports of the as-is-situation and additional ports, named as improved situation. Table 2 and Table 3 contains the name and location of these ports, and also an indication whether each port can be or not a homeport.

Table 2: Set of ports included in the as-is-situation.

PORT NAME	COUNTRY	CAN BE A HOMEPORT?
Port of Leixões	Portugal	No
Port of Lisbon	Portugal	Yes
Port of Portimão	Portugal	No
Port of Funchal	Portugal (Autonomous Region of Madeira)	No
Port of A Coruña	Spain	No
Port of Vigo	Spain	No
Port of Cádiz Bay	Spain	No
Port of Málaga	Spain	Yes
Port of Arrecife	Spain (Canary Islands)	No
Port of Rosario	Spain (Canary Islands)	No
Las Palmas Port	Spain (Canary Islands)	Yes
Port of Santa Cruz de Tenerife	Spain (Canary Islands)	Yes
Port of Santa Cruz de La Palma	Spain (Canary Islands)	No
Port of San Sebastián de La Gomera	Spain (Canary Islands)	No
Port of Tanger Ville	Morocco	No
Port of Casablanca	Morocco	No
Port of Agadir	Morocco	No
Port of Gibraltar	United Kingdom (British overseas territory)	No

Table 3: Additional ports included in the improved situation.

PORT NAME	COUNTRY	CAN BE A HOMEPORT?
Port of Vilagarcia de Arousa	Spain	No
Port of Huelva	Spain	No
Port of Motril	Spain	No
Port of Ceuta	Spain (autonomous city)	No
Port of Viana do Castelo	Portugal	No
Port of Aveiro	Portugal	No
Port of Figueira da Foz	Portugal	No
Port of Setúbal	Portugal	No
Port of Faro	Portugal	No
Port of Kenitra	Morocco	No
Port of Safi	Morocco	No

Considering the same ports, values of port’s attractiveness and port’s dimension restrictions are shown in Table 4 and Table 5, respectively. Values of weather conditions (rain precipitation, average wave height, sunshine exposure, and average temperature) and the ports distance matrix can be found at the Appendix 2 and Appendix 3.

Table 4: Atlantic Coast of Iberian Peninsula port’s attractiveness, in USD per passenger.

PORTS	VALUE OF PORT	VALUE OF ATTRACTION NEARBY	DISTANCE TO ATTRACTION	TIME TO ATTRACTION
Port of A Coruña	29	0	0	0
Port of Vilagarcia de Arousa	26	50	54	0.75
Port of Vigo	27	0	0	0
Port of Viana do Castelo	27	0	0	0
Port of Leixões	30	65	14	0.5
Port of Aveiro	28	0	0	0
Port of Figueira da Foz	28	32	57	0.75
Port of Lisbon	98	0	0	0
Port of Setúbal	28	31	100	1.25
Port of Portimão	31	29	0	0
Port of Faro	30	0	0	0
Port of Huelva	26	59	95	1.25
Port of Cádiz	31	0	0	0
Port of Gibraltar	54	0	0	0
Port of Málaga	56	0	0	0
Port of Motril	26	54	71	1
Port of Ceuta	26	29	40	1.5
Port of Tanger Ville	37	0	0	0
Port of Kenitra	32	36	154	2
Port of Casablanca	46	32	90	1.25
Port of Safi	26	100	158	2.25
Port of Agadir	31	0	0	0
Port of Funchal	60	0	0	0
Port of Arrecife	53	0	0	0
Port of Puerto del Rosario	46	0	0	0
Las Palmas Port	45	0	0	0
Port of Santa Cruz de Tenerife	52	0	0	0
Port of Santa Cruz de la Palma	28	0	0	0
Port of San Sebastián de la Gomera	26	0	0	0

Table 5: Atlantic Coast of Iberian Peninsula port's dimension restrictions and tariffs.

PORTS	LENGTH [M]	BREADTH [M]	DRAUGHT [M]	PORT TARRIFS [USD]
Port of A Coruña	484	40	11	13,700
Port of Vilagarcia de Arousa	400	40	9	13,700
Port of Vigo	750	40	12	13,700
Port of Viana do Castelo	400	40	8	13,700
Port of Leixões	300	40	10	13,700
Port of Aveiro	150	40	9.5	13,700
Port of Figueira da Foz	150	40	6.5	13,700
Port of Lisbon	400	40	12	41,722
Port of Setúbal	365	40	12	13,700
Port of Portimão	215	35	8.5	13,700
Port of Faro	200	30.5	8	13,700
Port of Huelva	300	40	13	13,700
Port of Cádiz	324	40	10	13,700
Port of Gibraltar	300	50	9.6	13,700
Port of Málaga	400	40	17	41,722
Port of Motril	284	45	7.6	13,700
Port of Ceuta	330	50	10.2	13,700
Port of Tanger Ville	330	40	9.1	13,700
Port of Kenitra	400	50	10	13,700
Port of Casablanca	260	40	8	13,700
Port of Safi	255	40	8.5	13,700
Port of Agadir	320	40	15	13,700
Port of Funchal	425	40	10	13,700
Port of Arrecife	400	50	10	13,700
Port of Puerto del Rosario	400	50	10	13,700
Las Palmas Port	395	40	8	41,722
Port of Santa Cruz de Tenerife	424	40	12	41,722
Port of Santa Cruz de la Palma	315	40	12	13,700
Port of San Sebastián de la Gomera	341	40	12	13,700

Finally, the port tariffs are calculated using as basis the tariffs provided by the Port of Lisbon (equation 76) and the Port of Portimão (equation 77). Tariffs for ports that can be selected as the homeport are assumed to be equal as the tariffs charged by the Port of Lisbon, whereas tariffs for ports that cannot be selected as the homeport are assumed to be equal as the tariffs charged by the Port of Portimão. The value of tariffs are shown at Table 5.

$$0.0639GT + 2 * 2.7579\sqrt{GT} + 17 * n_{pax} + 1000 \tag{76}$$

$$0.0635GT + 2 * 7.9521\sqrt{GT} + 0.6 * 3.3264 * n_{pax} + 1000 \tag{77}$$

5.1.2. Cruise Ship Selected and Fixed Costs

The cruise ship selected for this numerical study is a mid-size cruise ship, called *AIDAbella*, with 1025 cabins and multiple cruise speeds. Main dimensions of the ship are described in Table 6 and propulsion power for all speeds the ship can have at each voyage leg, calculated accordingly with the equation (18), is shown at Table 7. Furthermore, to account for the reduction of electrical power consumption when the ship is docked at a port, is assumed that in this situation, the load factor is 0.48, representing 80% of the load factor value at open sea.

Table 6: AIDAbella technical characteristics.

Length	252.0 m
Breadth	32.3 m
Draught	7.3 m
Gross Tonnage (GT)	69,203
Number of Cabins	1025
Passenger Capacity	2500
Crew	646
Propulsion	Diesel-Electric, two shafts
Installed Power	4 x Cat Mak 9M43C, total power: 36,000 kW
Service speed	19.5 knots
S.F.O.C	210 g/kW.h
L.F.	0.6
L.F.P.	0.8
Electrical Power consumption	13,400 kW
Propulsion power	22,600 kW
Cost	$409 million

Table 7: *AIDAbella*'s propulsion power consumption and ship speeds.

SPEED [KNOTS]	MAIN ENGINE POWER [KW]
10	3,048
11	4,057
12	5,267
13	6,696
14	8,364
15	10,287
16	12,484
17	14,974
18	17,776
19.5	22,600
20	24,383
21	28,227

Capital cost is defined assuming a full loan for the ship, with a repayment period of 40 years, an interest rate of 1.2% yearly and constant payments of \$12.8 million per year (\$35,000 per day). Stores costs, regular maintenance and insurance are calculated by the following equation, respectively:

$$c_s = 4500 * n_{pax} + 4000 * \left(L_{ship} * B_{ship} * H_{ship}\right)^{0.25} + 250 * \left(p_{installed}\right)^{0.7} \tag{78}$$

$$c_{rm} = 0.0035 * c_{building} + \left(1.34 * p_{installed}\right)^{0.66} \tag{79}$$

$$c_i = 0.008 * c_{building} + 2.75 * GT \tag{80}$$

Crew composition is estimated proportionally to the crew composition of the P&O Cruiser's *Aurora*, and the total crew cost is calculated using the wages given at Table 8 as a basis, extracted from Deloitte (2013).

Table 8: AIDAbella crew composition and monthly wages.

CATEGORY	NUMBER	WAGE	TOTAL
Deck: Officers	8	\$4,000	\$32,000
Deck: Ratings	30	\$1,200	\$36,000
Engine: Officers	10	\$4,000	\$40,000
Engine: Ratings	32	\$1,800	\$57,600
Elctro-Technical: Officers	5	\$4,000	\$20,000
Electro-Technical: Ratings	5	\$1,800	\$9,000
Medical: Doctors	2	\$4,600	\$9,200
Medical: Nurses	3	\$1,800	\$5,400
Hotel: Officers	22	\$3,300	\$72,600
Hotel: Ratings	425	\$1,000	\$425,000
Entertainments: Officers	8	\$3,300	\$26,400
Entertainments: Ratings	22	\$1,000	\$22,000
Entertainments: Guests	26	\$1,000	\$26,000
Revenue (Shops/SPA)	37	\$1,000	\$37,000
	634		**\$818,200**

Moreover, administration cost is assumed to be \$150,000 per year, the periodic maintenance of the ship is assumed to be equal to 0.6% of its construction cost per year. Fuel price for this analysis are assumed constant to all situations studied and defined by a web search to bunker prices in ports of the Mediterranean region. Value for all the costs, in USD/day, and the fuel prices considered are shown at Table 9.

Table 9: Fuel and Fixed Costs for the Atlantic Coast of Iberian Peninsula Case.

Capital Cost (c_c)	\$35,000/day
Crew Cost (c_w)	\$27,000/day
Stores Cost (c_s)	\$33,000/day
Regular Maintenance Cost (c_{rm})	\$3,925/day
Insurance Cost (c_i)	\$9,485/day
Periodic Maintenance Cost (c_{pm})	\$6,723/day
Administration Cost (c_a)	\$410/day
IFO 180	\$320/ton

From these fixed costs, capital cost, stores cost, and crew cost accounts for more than 80% of the total, as presented in Figure 6. Moreover, administration cost and regular maintenance cost are practically irrelevant to the total fixed cost value. Crew cost and stores costs are greater for cruise ships when comparing it merchant ships because the quantity of persons onboard a cruise ship is considerably bigger than merchant ships, which may have a crew of about 30 persons and no passengers.

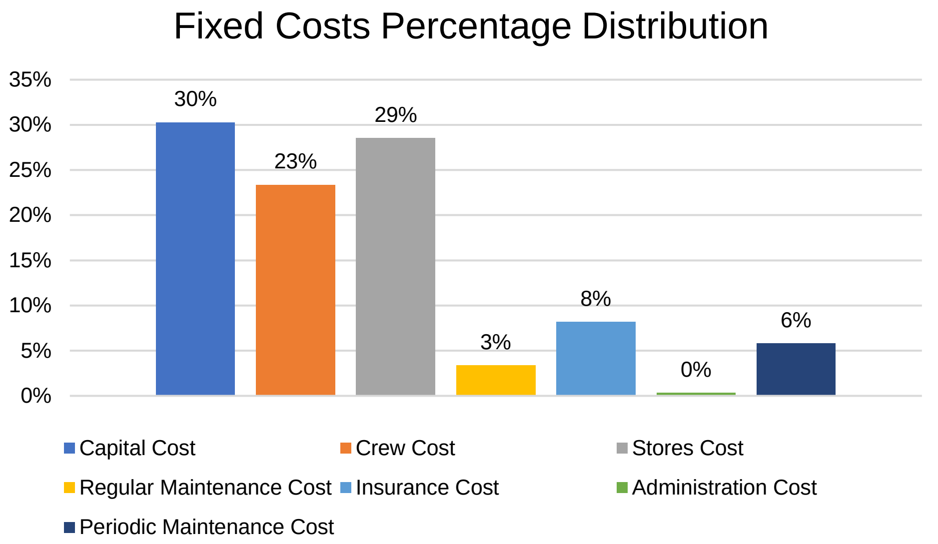

Figure 6: Fixed costs distribution, in percentage.

5.1.3. Optimum itinerary for a weekly cruise: as-is situation

This sub-section presents an analysis carried out for two seasons, Winter (January) and Summer (August), with the ports included only at the as-is-situation (19 ports, listed at Table 2). It will be shown the results of each decision variable and the costs calculated. These analyses are important to validate the model used in this thesis and understand how different it really is in comparison with real itineraries for the region studied. Moreover, the results obtained for this case are primordial to estimate quantitatively the profitability of the improved situation optimal itineraries, if any, and therefore to identify if there is an opportunity to improve the profitability of itineraries at this region.

5.1.3.1. Optimum itinerary for a weekly cruise in Winter

The as-is-situation port's attraction value at Winter is given at Table 10. From this table, it can be seen that the most attractive ports case are Lisbon, Leixões, Casablanca, Funchal, Arrecife, Santa Cruz de Tenerife and Málaga. Moreover, ports located at Galicia and north of Portugal suffers a significant negative impact due to the bad weather conditions of this region during Winter (lower average monthly sunshine hours, lower average daily temperature, and bigger average significant wave height). The only exception for this rule is the port of Leixões that despite of being located at the north of Portugal, because of the attractions nearby, still shows a good attraction value even during Winter.

Moving more to the south, the impact of bad weather becomes less expressive and, the south of Portugal, Morocco, Canary Islands, and Madeira Islands actually shows a positive magnification for its port's value because of the weather conditions at these regions. The average attraction value for this case is 41.5, with a standard deviation of 20.6.

Table 10: Port's attraction values for the as-is-situation of the Atlantic Coast of Iberian Peninsula at Winter.

PORT NAME	PORT ATTRACTION VALUE
Port of A Coruña	1.4
Port of Vigo	-1.4
Port of Leixões	64.2
Port of Lisbon	79.3
Port of Portimão	51.2
Port of Cádiz Bay	24.3
Port of Gibraltar	47.9
Port of Málaga	51.0
Port of Tanger Ville	31.1
Port of Casablanca	61.4
Port of Agadir	23.0
Port of Funchal	52.1
Port of Arrecife	56.0
Port of Puerto del Rosario	48.1
Las Palmas Port	47.5
Port of Santa Cruz de Tenerife	53.9
Port of Santa Cruz de La Palma	28.2
Port of San Sebastián de la Gomera	28.3

The ports obtained by the optimization for the Winter analysis of the as-is-situation are Málaga, Tanger, Lisbon, Leixões, Casablanca, and Gibraltar, resulting in a total attraction value of about 340 USD/pax, as shown by Table 11, detailing arrival and departure hours at each port.

The resulting route is composed by the four most valuable ports (Lisbon, Leixões, Málaga, and Casablanca) and by the ports of Gibraltar and Tanger, which although not having big attraction value, their location between Lisbon, Málaga, and Casablanca makes them a good solution to travel through these locations without having to increase the ship speed or requiring to stay one extra day at sea, since Lisbon is located more than one day of sea from Málaga or Casablanca. Table 12 shows the ship speed at each voyage leg, and Table 13 display major costs of this itinerary. Additionally, Figure 7 gives a visual representation of this itinerary.

Table 11: Optimum itinerary for a weekly cruise in Winter, as-is-situation of the Atlantic Coast of Iberian Peninsula.

DAY	PORT	ARRIVAL	DEPARTURE
DAY 1	Málaga	-	23:00
DAY 2	Tanger	7:00	18:00
DAY 3	Lisbon	9:00	20:00
DAY 4	Leixões	10:00	21:00
DAY 6	At Sea ...	-	-
DAY 6	Casablanca	10:00	21:00
DAY 7	Gibraltar	12:00	23:00
DAY 8	Málaga	7:00	-

Table 12: Speeds for each leg of the optimum itinerary for a weekly cruise in Winter, as-is-situation of the Atlantic Coast of Iberian Peninsula.

VOYAGE LEG	SPEED [KNOTS]
Málaga -> Tanger	11
Tanger -> Lisbon	19.5
Lisbon -> Leixões	13
Leixões -> Casablanca	13
Casablanca -> Gibraltar	13
Gibraltar -> Málaga	10

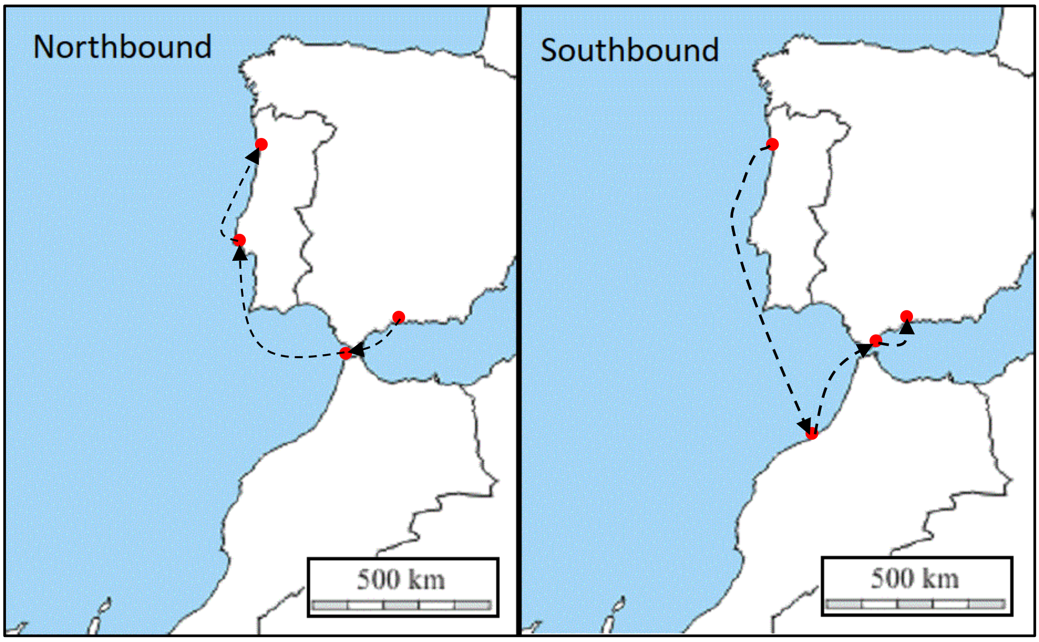

Figure 7: Optimum itinerary for a weekly cruise in Winter, as-is-situation of the Atlantic Coast of Iberian Peninsula.

Table 13: Optimum itinerary cost for a weekly cruise in Winter, as-is-situation of the Atlantic Coast of Iberian Peninsula.

	Main Propulsion Fuel Cost	- $55,403
	Auxiliary Fuel Cost	- $81,796
Total Fuel Costs		**- $137,199**
	Port Tariffs	- $138,123
	Fixed Costs	- $808,802
	Waiting Cost	- $4,933
Total Costs		**- $1,089,057**
	Gross Revenue	$1,393,002
Total Profit		**$303,946**

5.1.3.2. Optimum itinerary for a weekly cruise in Summer

Values of the as-is-situation port's attraction value at Summer are given at Table 14. From this table, it can be seen that the most attractive ports in this case are Lisbon, Leixões, Casablanca, Málaga, Gibraltar, Portimão, Las Palmas, Arrecife, Santa Cruz de Tenerife, Puerto del Rosario, and Funchal. During Summer, all ports suffered a positive increase of value because of the weather conditions, being that, again, the ports which received a bigger increase on its value are located at south of Portugal, Madeira Islands, Canary Islands and Morocco.

The average attractiveness value for the Summer is 79.0 points, with a standard deviation value of 21.4. In comparison with the average attractiveness value between Winter and Summer, an increase of 37.5 points happened during Summer, being that, in general, the ports located at Galicia and Portugal mainland have experienced a more expressive increase on its attractiveness value.

Table 14: Port's attraction values for the as-is-situation of the Atlantic Coast of Iberian Peninsula at Summer.

PORT NAME	PORT ATTRACTION VALUE
Port of A Coruña	42.2
Port of Vigo	45.6
Port of Leixões	108.8
Port of Lisbon	129.5
Port of Portimão	96.6
Port of Cádiz Bay	67.8
Port of Gibraltar	88.5
Port of Málaga	94.0
Port of Tanger Ville	72.2
Port of Casablanca	98.3
Port of Agadir	60.9
Port of Funchal	80.6
Port of Arrecife	83.1
Port of Puerto del Rosario	74.3
Las Palmas Port	74.6
Port of Santa Cruz de Tenerife	85.6
Port of Santa Cruz de La Palma	60.6
Port of San Sebastián de la Gomera	59.5

The ports chosen for the Summer analysis of the as-is-situation are Málaga, Gibraltar, Casablanca, Leixões, Lisboa, and Tanger. The itinerary of this case contains the same ports of the Winter route, but in a different order. Because of that, the total cost of both itineraries is equal however, the gross revenue is not, given that the total attraction value during Summer is higher. In fact, the total gross revenue is 75% bigger and the profit is 350% larger in comparison with Winter route.

Table 15 shows the optimum itinerary obtained, detailing arrival and departure hours at each port. Table 16 shows the ship speed at each voyage leg, and Table 17 display major costs of this itinerary. Finally, Figure 8 gives a visual representation of this itinerary.

Table 15: Optimum itinerary for a weekly cruise in Summer, as-is-situation of the Atlantic Coast of Iberian Peninsula.

DAY	PORT	ARRIVAL	DEPARTURE
DAY 1	Málaga	-	23:00
DAY 2	Gibraltar	7:00	18:00
DAY 3	Casablanca	9:00	20:00
DAY 4	At Sea ...	-	-
DAY 6	Leixões	9:00	20:00
DAY 6	Lisboa	10:00	21:00
DAY 7	Tanger	7:00	-
DAY 8	Málaga		

Table 16: Speeds for each leg of the optimum itinerary for a weekly cruise in Summer, as-is-situation of the Atlantic Coast of Iberian Peninsula.

VOYAGE LEG	SPEED [KNOTS]
Málaga -> Gibraltar	10
Gibraltar -> Casablanca	13
Casablanca -> Leixões	13
Leixões -> Lisboa	13
Lisboa -> Tanger	19.5
Tanger -> Málaga	11

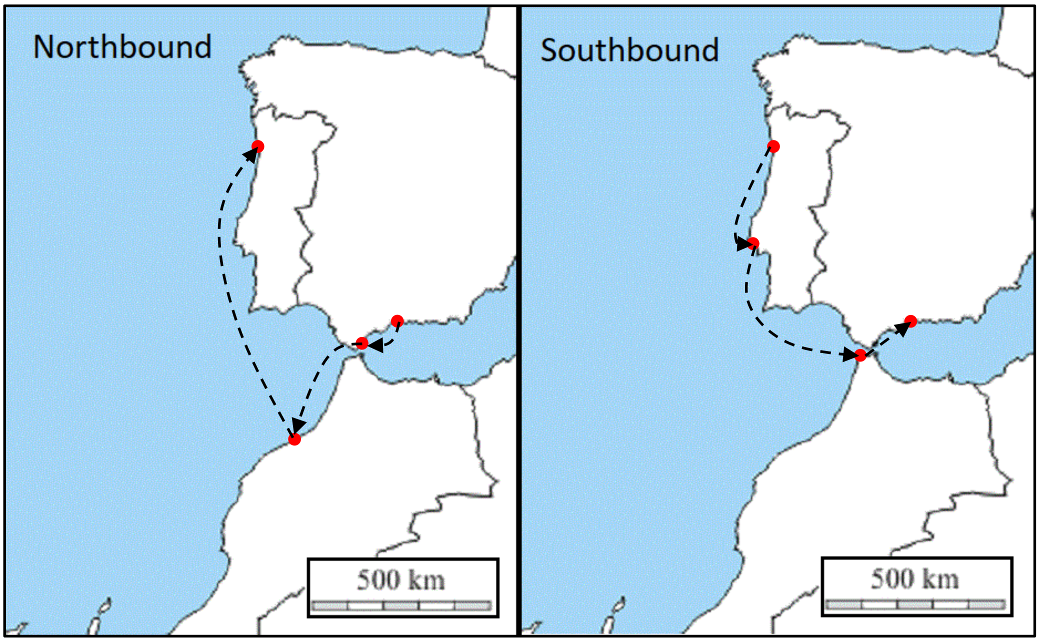

Figure 8: Optimum itinerary for a weekly cruise in Summer, as-is-situation of the Atlantic Coast of Iberian Peninsula.

Table 17: Optimum itinerary cost for a weekly cruise in Summer, as-is-situation of the Atlantic Coast of Iberian Peninsula.

	Main Propulsion Fuel Cost	- $55,403
	Auxiliary Fuel Cost	- $81,796
Total Fuel Costs		**- $137,199**
	Port Tariffs	- $138,123
	Fixed Costs	- $808,802
	Waiting Cost	- $4,933
Total Costs		**- $1,089,057**
	Gross Revenue	$2,444,652
Total Profit		**$1,355,596**

5.1.3.3. As-is-situation analysis and model validation

In this section, firstly a financial analysis is done, displaying a cost breakdown, assessing which are the major costs of the voyage, and how much profit are these routes generating. Then, the solutions obtained for the as-is-situation with the optimization model are compared with the solutions obtained with the Monte Carlo model presented in Santos (2020), and the data of the busiest cruise ports of the Iberian Peninsula region.

As mentioned in the as-is-situation Summer analysis, the cost values for both cases are exact the same, and Figure 9 shows the cost breakdown measured in percentage of the total cost. In contrast with other merchant ship operations, in cruise ships, fixed costs represents most of the costs, with crew, stores, and capital accounting for 60% of total cost. Reasons for this are the larger quantity of passengers and crew members, and the higher building cost, when comparing with other ship types with similar dimensions, such as liquid or dry bulk ships. Another consequence of this high fixed cost percentage is the impact of bigger revenues in to the profit, since fixed costs varies only with the number of days of the itinerary, and the fuel does not represent a significant proportion of the total cost, when comparing two itineraries with same duration.

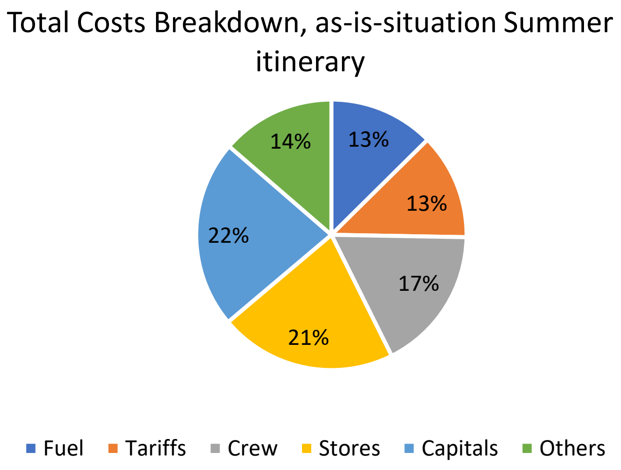

Figure 9: Cost breakdown for the Summer itinerary of the as-is-situation.

In terms of how much profit is made in each route, Table 18 shows the comparison of gross revenue, total profit, and two profit indicator(profit per passenger, and profit per passenger per day). With this table it can be seen the impact of the increase of total revenue into the itinerary. The two indicator values, although not important in this case, since both cases used the same ship and the same duration, allows comparisons of itineraries with different cruise ship capacities and duration, and therefore is desirable to have in mind when designing a cruise itinerary.

Table 18: Comparison between costs and revenue for the Winter and Summer study of the Atlantic Coast of Iberian Peninsula.

	WINTER	SUMMER	DIFFERENCE
Gross Revenue	$1,393,002	$2,444,652	$1,051,650
Total Profits	$303,946	$1,355,596	$1,051,650
Profit per Passenger	$148	$661	$513
Profit per Passenger per Night	$21	$94	$73

Continuing the analysis, it will be compared the solution of the Winter itinerary given by the CPLEX optimization model with a solution given by the Monte Carlo model. The reason of this comparison is because both models are using the same revenue expression, and the same fixed cost values to calculate the optimal itinerary meaning that the optimal solution of both models should yield similar itineraries.

In fact, using the same database for the month of January, both models find similar solutions, passing through the same ports as the CPLEX model, although in a different order. A comparison between these models are shown at the Table 19. The difference in total profit from both models can be attributed to the attraction value given by spending a day at sea of each model, and the inclusion of port tariffs into the CPLEX model.

Table 19: CPLEX and Monte Carlo models comparison of the Winter itinerary, as-is-situation.

	CPLEX	MONTE CARLO	DIFFERENCE
Total Cost	$1,089,057	$914,671	$174,386
Attraction Value	340	335	5
Revenue	$1,393,002	$1,372,502	$20,500
Total Profit	$303,946	$457,831	$153,885

Although this comparison in not conclusive enough to state that both models are giving a result applicable to the reality, knowing that both models are displaying similar itineraries indicates that route constraints of the CPLEX model is indeed working properly. The next step to validate this model is to compare it with real itineraries of the region. However, since there is not enough cyclical routes at this region, instead the solution given by this model is compared with a list of the busiest cruise ports at the region, extract of the MedCruise passenger statistics report of 2018.

The passenger traffic statistics of 2018 for the ports considered are shown at Table 20. Some ports are not included at this table (Aveiro, Figueira da Foz, Setúbal, Faro, Kenitra and Safi) because of lack of information about cruising activities. It can be seen that only 5 ports received more than 500,000 passengers in 2018 (Las Palmas, Santa Cruz de Tenerife, Lisbon, Funchal and Málaga) and 9 ports received between 100,000 and 500,000 (Cádiz, Arrecife, Gibraltar, Santa Cruz de La Palma, Puerto del Rosário, A Coruña, Vigo, Leixões and Agadir). Moreover, only four ports expressed a significant importance as turnaround ports: Las Palmas, Santa Cruz de Tenerife, Málaga and Lisbon. The itinerary duration might vary from 4 to 10 days for trips only at the Iberian Peninsula, Morocco, and Canary Islands region to 15 days or more for cruises coming to/from the Mediterranean Sea or Norther Europe.

Table 20: Passenger traffic statistics of 2018 for the ports at the Atlantic Coast of the Iberian Peninsula.

	TOTAL PASSENGERS	EMBARK / DISEMBARK	TRANSIT PASSENGERS	NUMBER OF CALLS
LAS PALMAS PORT	675,920	425,461	250,459	255
PORT OF SANTA CRUZ DE TENERIFE	617,986	137,552	480,434	298
PORT OF LISBON	577,603	62,089	515,514	339
PORT OF FUNCHAL	541,467	4,593	536,874	293
PORT OF MÁLAGA	507,360	107,887	399,473	298
PORT OF CÁDIZ	424,900	1,520	423,380	334
PORT OF ARRECIFE	423,116	1,833	421,283	217
PORT OF GIBRALTAR	406,998	0	406,998	243
PORT OF SANTA CRUZ DE LA PALMA	246,478	419	246,059	153
PORT OF PUERTO DEL ROSARIO	233,520	498	233,022	114
PORT OF A CORUÑA	178,965	696	178,269	94
PORT OF VIGO	158,449	1,689	156,760	70
PORT OF LEIXÕES	117,096	1,851	115,245	101
PORT OF AGADIR	105,767	-	-	-
PORT OF SAN SEBASTIÁN DE LA GOMERA	88,466	35	88,431	64
PORT OF CASABLANCA	69,853	-	-	-
PORT OF PORTIMÃO	36,786	960	35,826	66
PORT OF TANGER VILLE	31,250	0	31,250	46
PORT OF CEUTA	15,790	0	15,790	10
PORT OF HUELVA	11,691	0	11,691	16
PORT OF MOTRIL	5,313	0	5,313	28
PORT OF VILAGARCIA DE AROUSA	1,158	0	1,158	5

Comparing this data with the list of ports obtained from the as-is-situation, one may see that out from all ports included at the Winter or Summer itinerary (Lisbon, Málaga, Cádiz, Gibraltar, Leixões, Casablanca, and Tanger Ville), two of them are received more than 500,000 passengers in 2018, Lisbon and Málaga. Furthermore, three of the ports received between 100,000 and 500,000 passengers, Cádiz, Leixões and Gibraltar, and two of the ports received less than 100,000 passengers, Casablanca and Tanger. Another interesting point is that both itineraries selected the port of Málaga to be the homeport, which is one of the most important homeports of the region, after Las Palmas and Santa Cruz de Tenerife.

From this information, it can be seen that although the optimal itinerary obtained is consistent with the reality, it does not include the visited ports such as Las Palmas, Santa Cruz de Tenerife, Funchal, Cádiz, and Arrecife, which are on top of the list of total cruise passengers traffic. Moreover, Casablanca and Tanger, despite of included in the optimal solution are not attractive ports for cruising, having received only 69,000 and 31,000 passengers respectively in 2018.

Furthermore, when analyzing the database solution of the Monte Carlo model, it can be seen that the best valid itinerary passing through the Canary Islands and Madeira Islands has an attraction value of 315 points, and a total cost about 1% higher than the optimal solution.

Finally, is interesting to note despite Portimão is located close to Gibraltar and Cádiz, and having a slighter higher attraction value, its port infrastructure does not allow ships of the size of *AIDAbella*, and therefore it is not included in the optimal itinerary solution, neither is well ranked in the passenger traffic statistics. If Portimão had capabilities of receiving large cruise ships, it could have the potential to compete with Gibraltar and Cádiz.

5.1.4. Optimum itinerary for a weekly cruise: improved situation

This sub-section presents analysis for the same months as the as-is-situation analysis but considering the expanded list of ports (all ports in Tables 2 and 3). Firstly, the optimal solution for both cases are shown and then, comparisons are made with the as-is-situation solution. The idea of running this analysis is to observe how different would the result be if more ports are considered and to evaluate if there is an opportunity of itinerary not yet explored.

5.1.4.1. Optimum itinerary for a weekly cruise in Winter

Table 21 shows values of port's attractions for Winter considered in this analysis. It can be seen that on top of all ports mentioned for the as-is-situation, the ports of Safi, Motril, Huelva and Ceuta also show up as attractive ports during Winter, mainly because of its nearby attractions: Marrakesh, Granada, Sevilla, and Tanger respectively. Moreover, despite of Vilagarcia de Arousa being located in Galicia, it still shows a decent attraction value during Winter, given its proximity to Santiago de Compostela. Average attraction value for this study is 41.8, with a standard deviation of 22.0, an increase of 0.3 in comparison with the mean attraction value of the Winter as-is-situation.

Table 21: Port's attraction values for the improved situation of the Atlantic Coast of Iberian Peninsula at Winter.

PORTS	PORT ATTRACTION VALUE
Port of A Coruña	1.4
Port of Vilagarcia de Arousa	45.2
Port of Vigo	-1.4
Port of Viana do Castelo	6.0
Port of Leixões	64.2
Port of Aveiro	9.1
Port of Figueira da Foz	37.0
Port of Lisbon	79.3
Port of Setúbal	35.3
Port of Portimão	51.2
Port of Faro	24.5
Port of Huelva	61.2
Port of Cádiz	24.3
Port of Gibraltar	47.9
Port of Málaga	51.0
Port of Motril	70.9
Port of Ceuta	54.1
Port of Tanger Ville	31.1
Port of Kenitra	46.1
Port of Casablanca	61.4
Port of Safim	85.3
Port of Agadir	23.0
Port of Funchal	52.1
Port of Arrecife	56.0
Port of Puerto del Rosario	48.1
Las Palmas Port	47.5
Port of Santa Cruz de Tenerife	53.9
Port of Santa Cruz de la Palma	28.2
Port of San Sebastián de la Gomera	28.3

The itinerary chosen by the model contains the ports of Lisbon, Gibraltar, Motril, Ceuta, Safim, Casablanca, and Huelva, summing an itinerary attraction value of 460.1 USD/passenger. The possibility of selecting ports located close to the entrance of Mediterranean Sea, such as Safim, Motril, and Huelva, made the optimal itinerary shift to the South, not including Leixões into the route. Despite of that, no ports from the Canary or Madeira islands appears on this solution.

Table 22 shows the optimum itinerary obtained, detailing arrival and departure hours at each port, Table 23 shows the ship speed at each voyage leg, and Table 24 display major costs of this itinerary. Additionally, Figure 10 gives a visual representation of the route.

Table 22: Optimum itinerary for a weekly cruise in Winter, improved situation of the Atlantic Coast of Iberian Peninsula.

DAY	PORT	ARRIVAL	DEPARTURE
DAY 1	Lisbon	-	20:00
DAY 2	Gibraltar	11:00	22:00
DAY 3	Motril	9:00	20:00
DAY 4	Ceuta	7:00	18:00
DAY 6	Safim	9:00	20:00
DAY 6	Casablanca	10:00	19:00
DAY 7	Huelva	10:00	17:00
DAY 8	Lisbon	8:00	-

Table 23: Speeds for each leg of the optimum itinerary for a weekly cruise in Winter, improved situation of the Atlantic Coast of Iberian Peninsula.

VOYAGE LEG	SPEED [KNOTS]
Lisbon -> Gibraltar	21
Gibraltar -> Motril	10
Motril -> Ceuta	10
Ceuta -> Safim	21
Safim -> Casablanca	10
Casablanca -> Huelva	16
Huelva -> Lisbon	16

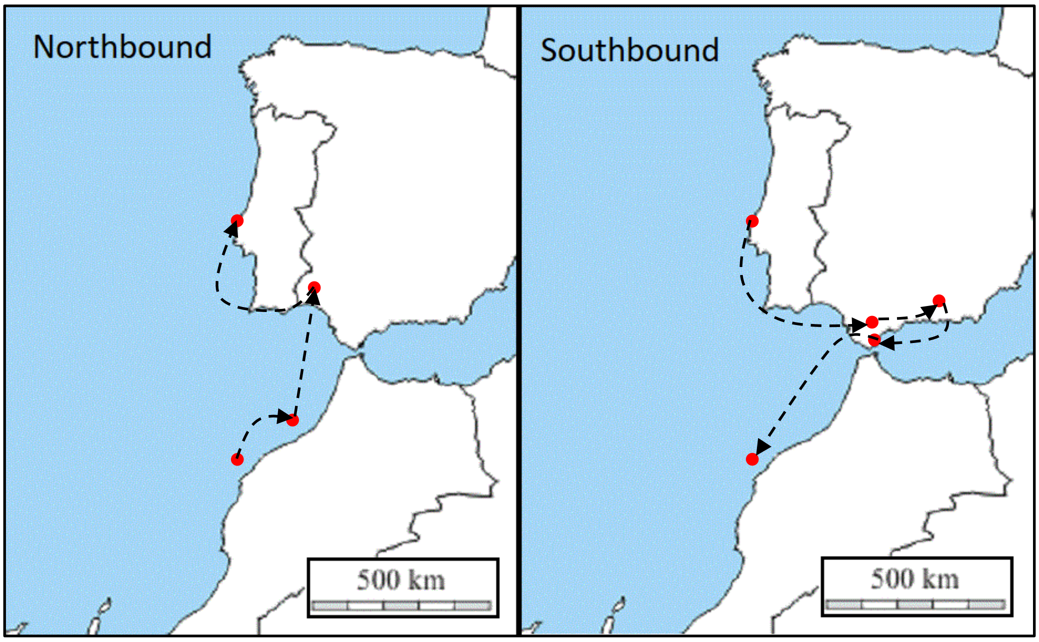

Figure 10: Optimum itinerary for a weekly cruise in Winter, improved situation of the Atlantic Coast of Iberian Peninsula.

Table 24: Optimum itinerary cost for a weekly cruise in Winter, improved situation of the Atlantic Coast of Iberian Peninsula.

	Main Propulsion Fuel Cost	- $86,871
	Auxiliary Fuel Cost	- $81,466
Total Fuel Costs		**- $168,337**
	Port Tariffs	- $123,739
	Fixed Costs	- $808,802
	Waiting Cost	- $5,779
Total Costs		**- $1,106,656**
	Gross Revenue	$1,885,433
Total Profit		**$778,777**

5.1.4.2. Optimum itinerary for a weekly cruise in Summer

Table 25 shows the values of port's attractions for Summer used in this analysis. From this, it can be highlighted the ports of Lisbon, Huelva, Leixões, Safim, and Motril. From these ports, only Lisbon and Leixões are included at the as-is-situation port's list. Average attraction value for this study is 81.0, with a standard deviation of 20.3, an increase of 2.0 points on the mean attraction value in comparison with the Summer as-is-situation analysis.

Table 25: Port's attraction values for the improved situation of the Atlantic Coast of Iberian Peninsula at Summer.

PORTS	PORT ATTRACTION VALUE
Port of A Coruña	42.2
Port of Vilagarcia de Arousa	91.5
Port of Vigo	45.6
Port of Viana do Castelo	56.8
Port of Leixões	108.8
Port of Aveiro	55.9
Port of Figueira da Foz	80.5
Port of Lisbon	129.5
Port of Setúbal	86.6
Port of Portimão	96.6
Port of Faro	68.6
Port of Huelva	111.8
Port of Cádiz	67.8
Port of Gibraltar	88.5
Port of Málaga	94.0
Port of Motril	102.0
Port of Ceuta	82.6
Port of Tanger Ville	72.2
Port of Kenitra	83.6
Port of Casablanca	98.3
Port of Safim	107.3
Port of Agadir	60.9
Port of Funchal	80.6
Port of Arrecife	83.1
Port of Puerto del Rosario	74.3
Las Palmas Port	74.6
Port of Santa Cruz de Tenerife	85.6
Port of Santa Cruz de la Palma	60.6
Port of San Sebastián de la Gomera	59.5

The itinerary chosen by the model contains the ports of Lisbon, Leixões, Setubal, Casablanca, Safim, Gibraltar and, Huelva, summing an itinerary attraction value of 731 USD/passenger. This itinerary has three ports included at the improved port's list: Setúbal, Safim, and Huelva. The port of Leixões returned to the optimal solution, highlighting the fact that although Leixões have a great attraction value, the cold weather during Winter provides a big negative impact to the city, reducing its attraction value in 40 points.

Moreover, the port of Setubal was not chosen because of its attraction value but rather because it is the only option for traveling from Leixões to the south of the Iberian Peninsula or Morocco and not having to stay one day at sea during the travel to other attractive ports. Table 26 shows the optimum itinerary obtained, detailing arrival and departure hours at each port, Table 27 shows the ship speed at each voyage leg, and Table 28 display major costs of this itinerary. Additionally, Figure 11 gives a visual representation of this itinerary.

Table 26: Optimum itinerary for a weekly cruise in Summer, improved situation of the Atlantic Coast of Iberian Peninsula.

DAY	PORT	ARRIVAL	DEPARTURE
DAY 1	Lisbon	-	17:00
DAY 2	Leixões	7:00	18:00
DAY 3	Setúbal	9:00	16:00
DAY 4	Casablanca	7:00	17:00
DAY 6	Safim	7:00	17:00
DAY 6	Gibraltar	8:00	19:00
DAY 7	Huelva	7:00	16:00
DAY 8	Lisbon	7:00	-

Table 27: Speeds for each leg of the optimum itinerary for a weekly cruise in Summer, improved situation of the Atlantic Coast of Iberian Peninsula.

VOYAGE LEG	SPEED [KNOTS]
Lisbon -> Leixões	13
Leixões -> Setúbal	14
Setúbal -> Casablanca	21
Casablanca -> Safim	10
Safim -> Gibraltar	21
Gibraltar -> Huelva	10
Huelva -> Lisbon	16

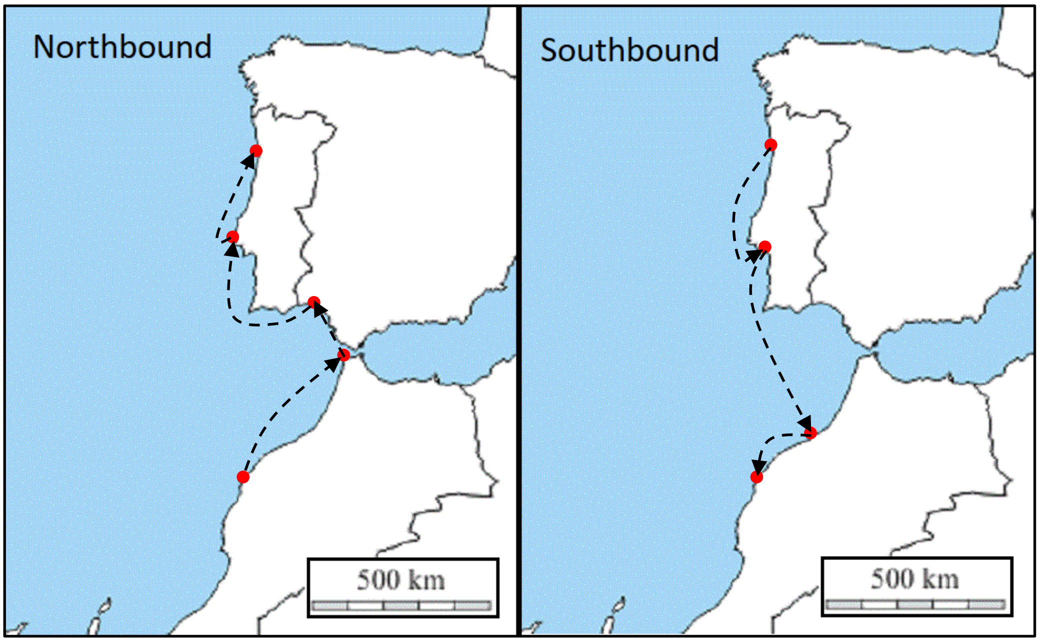

Figure 11: Optimum itinerary for a weekly cruise in Summer, improved situation of the Atlantic Coast of Iberian Peninsula.

Table 28: Optimum itinerary cost for a weekly cruise in Summer, improved situation of the Atlantic Coast of Iberian Peninsula.

	Main Propulsion Fuel Cost	- $88,784
	Auxiliary Fuel Cost	- $82,710
Total Fuel Costs		**- $171,493**
	Port Tariffs	- $123,739
	Fixed Costs	- $808,802
	Waiting Cost	- $2,698
Total Costs		**- $1,106,732**
	Gross Revenue	$2,996,389
Total Profit		**$1,889,658**

5.1.5. Itineraries Comparison

Finally, to evaluate and quantify if there are significant advantages on the Winter and Summer improved situation itineraries, a comparison between as-is-situation solution and improved solutions are made. These comparisons are going to take into consideration three aspects, the total attraction value, the port's selected, and the cost and revenues of the itinerary.

5.1.5.1. Winter itinerary

The Winter as-is-situation itinerary resulted in a total attraction value of 340 USD/passenger, passing through the ports of Málaga, Tanger, Lisbon, Leixões, Casablanca, and Gibraltar. For the improved situation, the solution returned an itinerary with attraction value of 460 USD/passenger, 35% higher than the as-is-situation, containing the ports of Lisbon, Gibraltar, Motril, Ceuta, Safim, Casablanca, and Huelva. Comparing both routes, only three ports are equal on both cases: Lisbon, Casablanca, and Gibraltar. The other ports of the as-is-situation were substituted for more attractive ports, closer to each other and in Morocco or South of Spain, regions situated closer to tropical zones. Costs and revenue comparison are shown at Table 29. From this table, it can be seen that the difference of costs from both itineraries are not so relevant as the increase of profits. The increase of profits from both cases is practically equal to the increase in gross revenue.

Table 29: Comparison between costs and revenue for the as-is-situation and improved situation study of the Atlantic Coast of Iberian Peninsula during Winter.

	AS-IS-SITUATION	**IMPROVED SITUATION**	**DIFFERENCE**	**PERCENTAGE DIFFERENCE**
Total Fuel Costs	$137,199	$168,337	$31,138	22.7%
Port Tariffs	$138,123	$123,739	-$14,384	-10.4%
Total Costs	$1,089,057	$1,106,656	$17,599	1.6%
Gross Revenue	$1,393,002	$1,885,433	$492,431	35.4%
Total Profits	$303,946	$778,777	$474,831	156.2%
Profit/Passenger	$148	$380	$232	156.2%

5.1.5.2. Summer itinerary

The Summer as-is-situation itinerary resulted in a total attraction value of 591 USD/passenger, passing through the ports of Málaga, Tanger, Lisbon, Leixões, Casablanca, and Gibraltar, the same ports as the Winter as-is-situation case. For the improved situation, the solution returned an itinerary with attraction value of 731 USD/passenger, 24% higher than the as-is-situation, containing the ports of Lisbon, Leixões, Setúbal, Casablanca, Safim, Gibraltar, and Huelva. Comparing these routes, the majority of the ports remain on both routes: Lisbon, Leixões, Casablanca, and Gibraltar. From the new ports included in the improved situation, Safim and Huelva are added because of its attraction value, and Setubal is added because it is the only option to connect Lisbon and Leixões to the rest of the itinerary without traveling a day at sea. Costs and revenue of this comparison are shown in Table 30. Again, as happened with the Winter analysis, the difference of cost from both itineraries are irrelevant in comparison with the increase of profits. The increase in gross revenue resulted in a practically equal increase of profits. Corroborating the analysis made for the other situations, that fixing a region and a duration of the itinerary, improvements of total profits are derived from improvements of gross revenue.

Table 30: Comparison between costs and revenue for the as-is-situation and improved situation study of the Atlantic Coast of Iberian Peninsula during Summer.

	AS-IS-SITUATION	IMPROVED SITUATION	DIFFERENCE	PERCENTAGE DIFFERENCE
Total Fuel Costs	$137,199	$171,493	$34,294	25.0%
Port Tariffs	$138,123	$123,739	-$14,384	-10.4%
Total Costs	$1,089,057	$1,106,732	$17,675	1.6%
Gross Revenue	$2,444,652	$2,996,389	$551,737	22.6%
Total Profits	$1,355,596	$1,889,658	$534,062	39.4%
Profit/Passenger	$661	$922	$261	39.4%

5.2. Optimum Cruise Ship Itinerary for the Brazilian coast

The next region to be studied is the Brazilian coast. For this study, the parameters for the optimization model are going to be the same as the ones used for the Iberian Peninsula region, changing only the ports and its characteristics, and the cruise ship considered. Ports used for cruising are mainly located in three different regions, the northeast region, the southeast region and the coast of Santa Catarina, as shown at Figure 12. The following sections will discuss about the current situation at the Brazilian coast region, including typical ports of call, currently itineraries and details about each port considered for this study. Furthermore, a new cruise ship is used, and its characteristics are to be provided below.

Figure 12: Cruise ports at the Brazilian coastline.

5.2.1. The Brazilian Coast as a cruising region

As mentioned at the introduction of this thesis, the Brazilian cruise market, alongside with Chinese and Australian market, are considered markets with plenty of growth potential. Despite of that, during the 2018/2019 season, about 462 thousand of tourists traveled in the Brazilian coast, which represents about half the number of passengers in the best Brazilian cruising season, 2011/2012, which carried 805 thousand of passengers. This downturn might be explained by the recent economic crisis that strike Brazil and the poor economic recovery experienced so far. The Brazilian market in 2018/2019 was serviced mainly by three companies: MSC, Costa and Pullmantur. Additionally, some special cruises and luxury cruises also travels to some Brazilian ports. Capacity of cruise ships servicing this region ranges between 3,000 and 5,500 passengers.

Regarding the itineraries, the main attractions of the ports at the Brazilian coastline are the beaches, natural landscape, and the local culture. The most desired destinations are located at the northeast and the state of Santa Catarina, but the majority of passengers comes from the southeast region (São Paulo and Rio de Janeiro). Therefore, there are two common itinerary routes: the ones traveling to the north, passing through Salvador and Maceio, and the ones traveling to the south, passing through Santa Catarina, Buenos Aires, and Montevideo. These routes duration ranges from 8 to 10 days. There are short itineraries as well, of 3 to 5 days, which goes until Santa Catarina coast or from São Paulo to Rio de Janeiro only. The set of ports included in this case study is shown at Table 31, values of port's attractiveness is shown at Table 32 and port's restriction and port's tariffs are included at Table 33.

Table 31: Set of ports included in the Brazilian coast situation.

PORT NAME	CAN BE A HOMEPORT?
Rio Grande	No
Porto Belo	No
Balneário Camburiú	No
Itajaí	Yes
Santos	Yes
Ilhabela	No
Ilha Grande	No
Rio de Janeiro	Yes
Cabo Frio	No
Búzios	No
Ilhéus	No
Salvador	Yes
Maceió	No
Recife	Yes
Natal	Yes
Fortaleza	Yes

As it can be seen, many ports have a nearby attraction, which are either a big city or a beach destination. Rio Grande is located close to Porto Alegre, a big city in the south of Brazil. Porto Belo and Itajaí nearby attraction is Balneário Camburiú, which is by itself also a port of call and a very famous touristic destination. Santos nearby attraction is the city of São Paulo, one of the main sources of cruise passengers. Ilhabela nearby attraction is São Sebastião, a beach destination at the mainland. Cabo Frio and Búzios are close to each other. Olinda is a famous historic city that is inside the metropolitan region of Recife, and finally Praia da Pipa is a famous beach destination close to Natal.

Moreover, values of weather conditions (rain precipitation, average wave height, sunshine exposure, and average temperature) and the ports distance matrix can be found at the Appendix 4 and Appendix 5. Values of port tariffs are calculated according to the equations (76) and (77).

Table 32: Brazilian Coast port’s attractiveness.

PORTS	VALUE OF PORT	VALUE OF ATTRACTION NEARBY	DISTANCE TO ATTRACTION	TIME TO ATTRACTION
Rio Grande	32.5	28.2	80	1.5
Porto Belo	26.0	31.6	11	0.5
Balneário Camburiú	43.7	0.0	-	-
Itajaí	27.1	43.7	20	0.5
Santos	37.9	175.0	80	1.5
Ilhabela	27.0	29.9	7	1
Ilha Grande	35.2	0.0	-	-
Rio de Janeiro	114.6	0.0	-	-
Cabo Frio	37.8	28.1	15	0.5
Búzios	35.1	0.0	-	-
Ilhéus	29.9	0.0	-	-
Salvador	71.6	0.0	-	-
Maceió	40.6	0.0	-	-
Recife	64.2	35.0	60	1.3
Natal	58.7	26.2	90	1.5
Fortaleza	69.1	0.0	-	-

Table 33: Brazilian Coast port's dimension restrictions and tariffs.

PORTS	LENGTH [M]	BREADTH [M]	DRAUGHT [M]	PORT TARRIFS [USD]
Rio Grande	-	-	9.4	$72,723
Porto Belo	-	-	-	$23,176
Balneário Camburiú	-	-	-	$23,176
Itajaí	306.0	48.5	14.0	$72,723
Santos	336.0	46.0	12.0	$72,723
Ilhabela	-	-	-	$23,176
Ilha Grande	-	-	-	$23,176
Rio de Janeiro	-	-	10.3	$72,723
Cabo Frio	-	-	-	$23,176
Búzios	-	-	-	$23,176
Ilhéus	261.0	-	9.3	$23,176
Salvador	384.0	-	9.0	$72,723
Maceió	330.0	40.0	10.5	$72,723
Recife	-	32.5	9.3	$72,723
Natal	240.0	-	12.4	$72,723
Fortaleza	-	-	10.5	$72,723

5.2.2. Cruise Ship Selected

The cruise ship selected is a mid-size cruise ship, called *Royal Princess*, with 1780 cabins and multiple cruise speeds. Main dimensions of the ship are described in Table 34 and the possible speeds that the ship can have at each voyage leg is shown at Table 35. Furthermore, it will be assumed that the electrical consumption of the ship is constant for the entire itinerary. The fixed cost for this ship is calculated using the same methodology used to calculate the *AIDAbella* costs. Furthermore, to account for the reduction of electrical power consumption when the ship is docked at a port, is assumed that in this situation, the load factor is 0.48, representing 80% of the load factor value at open sea.

Table 34: Royal Princess technical characteristics.

Length	330.0 m
Breadth	38.4 m
Draught	8.3 m
Gross Tonnage (GT)	142,714
Number of Cabins	1,780
Passenger Capacity	3,560
Crew	1,400
Propulsion	Diesel-electric, two shafts
Installed Power	DD-GG 2x 12V46F Wärtsilä (14,400 kW), DD-GG 2x 14V46F Wärtsilä (16,800 kW)
Service speed	22.0 knots
S.F.O.C	210 g/kW.h
L.F.	0.6
L.F.P.	0.8
Electrical Power consumption	26,400 kW
Propulsion power	36,000 kW
Cost	$735 million

Table 35: Royal Princess's power consumption and ship speed.

VELOCITY [KNOTS]	MAIN ENGINE POWER [KW]
10	3,381
11	4,500
12	5,842
13	7,428
14	9,277
15	11,411
16	13,848
17	16,610
18	19,718
19	23,190
20	27,047
22	36,000

Capital cost is defined assuming a full loan for the ship, with a repayment period of 40 years, an interest rate of 1.2% yearly and constant payments of $23.2 million per year ($63,560 per day). Stores costs, regular maintenance and insurance are calculated according to the equations (78), (79), and (80) respectively. Crew costs are estimated accordingly with Table 36, using as basis for the wages Deloitte (2013).

Table 36: Royal Princess crew composition and monthly wages.

CATEGORY	NUMBER	WAGE	TOTAL
Deck: Officers	18	$4,000	$72,000
Deck: Ratings	67	$1,200	$80,400
Engine: Officers	22	$4,000	$88,000
Engine: Ratings	71	$1,800	$127,800
Elctro-Technical: Officers	10	$4,000	$40,000
Electro-Technical: Ratings	12	$1,800	$21,600
Medical: Doctors	3	$4,600	$13,800
Medical: Nurses	7	$1,800	$12,600
Hotel: Officers	48	$3,300	$158,400
Hotel: Ratings	939	$1,000	$939,000
Entertainments: Officers	17	$3,300	$56,100
Entertainments: Ratings	48	$1,000	$48,000
Entertainments: Guests	57	$1,000	$57,000
Revenue (Shops/SPA)	81	$1,000	$81,000
	1400		**$1,795,700**

Moreover, administration cost is assumed to be $150,000 per year and the periodic maintenance of the ship is assumed to be equal to 0.6% of its construction cost per year. The value for all the costs, in USD/day, and the fuel prices considered are shown at Table 37.

Table 37: Fuel and fixed costs for the Brazilian coast.

Capital Cost (c_c)	$63,560/day
Crew Cost (c_w)	$59,856/day
Stores Cost (c_s)	$59,500/day
Regular Maintenance Cost (c_{rm})	$7,052/day
Insurance Cost (c_i)	$17,184/day
Periodic Maintenance Cost (c_{pm})	$12,082/day
Administration Cost (c_a)	$410/day
IFO 180	$320/ton
MGO	$350/ton

5.2.3. Brazilian coast itinerary study

Most common itinerary for the Brazilian coast region is a 7 days with a ship of dimensions described above, and it is optimized alongside with a 14 days route, using the same ship, and a 7 days route using the AIDAbella cruise ship, the same used for the Iberian Peninsula region analysis. The idea of these comparisons is to evaluate if different itinerary duration or ship's dimension can lead to an alternative route with better profits. These analyses are made for the month of January only, which is the peak of Summer season in Brazil.

5.2.3.1. Typical weekly itinerary

Values of the Brazilian port's attraction value are given at

Table 38. From this table, it can be seen that the most attractive ports in this case are Santos, Rio de Janeiro, Salvador, Recife, Fortaleza, and Natal. From these ports, only two of them are located outside the northeast region, being that, in the case of Santos, its attraction value arises mainly from the city of São Paulo. The ports obtained by the optimization for this situation are Santos, Ilha Grande, Cabo Frio, Rio de Janeiro, Ilhabela, Porto Belo, and Balneário Camburiú, summing a total attraction value of 638.8, as shown by Table 39, detailing arrival and departure hours at each port. It can be seen that despite of the northeast region having more attractive ports than the region of Santa Catarina, these cities are not included at the itinerary because of its port's restrictions, that do not allow for ships of this size to dock, and the distance to the southeast region, where is the main source of passengers, represented by the ports of Santos and Rio de Janeiro. Table 40 shows the ship speed at each voyage leg, and Table 41 display major costs of this itinerary. Additionally, Figure 13 gives a visual representation of this route.

Table 38: Port's attraction values for typical weekly itinerary of the Brazilian coast.

PORT NAME	PORT ATTRACTION VALUE
Rio Grande	73.70
Porto Belo	75.77
Balneário Camburiú	64.58
Itajaí	88.17
Santos	183.89
Ilhabela	59.46
Ilha Grande	43.60
Rio de Janeiro	138.35
Cabo Frio	72.98
Búzios	45.17
Ilhéus	55.48
Salvador	100.55
Maceió	69.23
Recife	118.81
Natal	106.84
Fortaleza	93.81

Table 39: Optimum itinerary for a weekly cruise, typical itinerary of the Brazilian coast.

DAY	PORT	ARRIVAL	DEPARTURE
DAY 1	Santos	-	23:00
DAY 2	Ilha Grande	14:00	21:00
DAY 3	Cabo Frio	12:00	22:00
DAY 4	Rio de Janeiro	8:00	19:00
DAY 6	Ilhabela	10:00	21:00
DAY 6	Porto Belo	12:00	23:00
DAY 7	Balneário Camburiú	7:00	18:00
DAY 8	Santos	9:00	-

Table 40: Speeds for each leg of the optimum itinerary for a weekly cruise, typical itinerary of the Brazilian coast.

VOYAGE LEG	SPEED [KNOTS]
Santos -> Ilha Grande	11
Ilha Grande -> Cabo Frio	14
Cabo Frio -> Rio de Janeiro	10
Rio de Janeiro -> Ilhabela	10
Ilhabela -> Porto Belo	20
Porto Belo -> Balneário Camburiú	10
Balneário Camburiú -> Santos	16

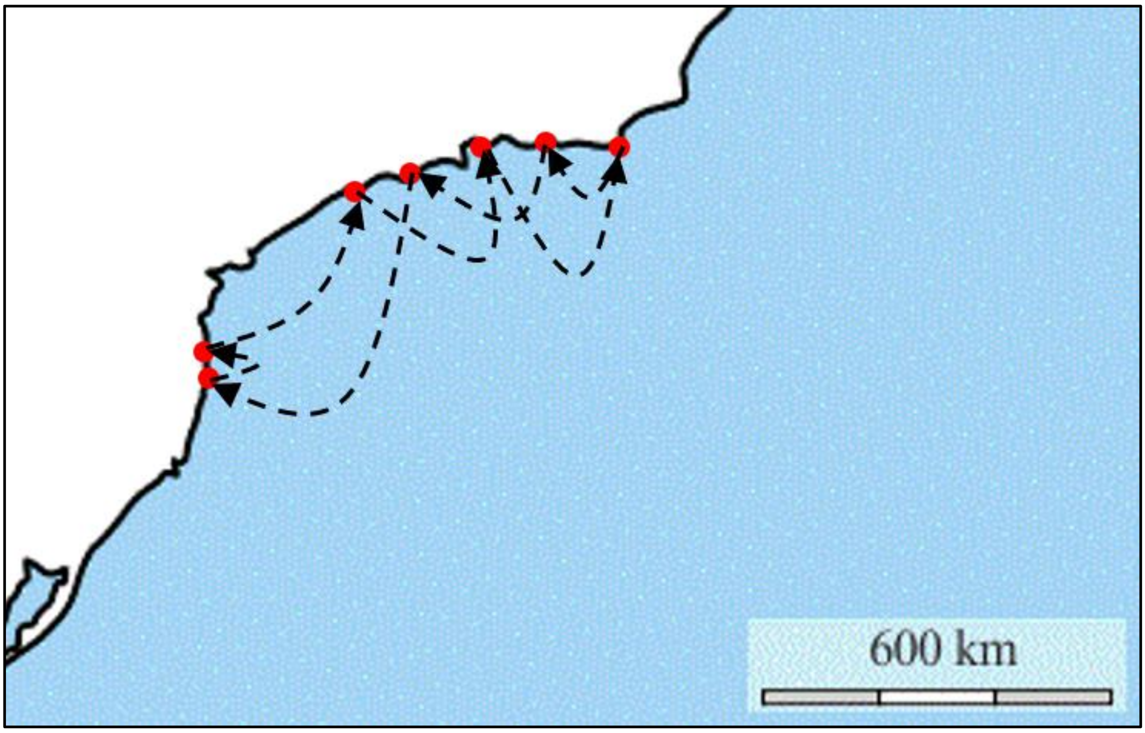

Figure 13: Optimum itinerary for a weekly cruise, typical itinerary of the Brazilian coast.

Table 41: Optimum itinerary cost for a typical weekly cruise of the Brazilian coast.

	Main Propulsion Fuel Cost	- $60,444
	Auxiliary Fuel Cost	- $155,364
Total Fuel Costs		**- $215,818**
	Port Tariffs	- $261,325
	Fixed Costs	- $1,537,508
	Waiting Cost	- $25,040
Total Costs		**- $2,039,691**
	Gross Revenue	$4,547,095
Total Profit		**$2,507,404**

5.2.3.2. Weekly cruise, smaller ship

A study with the ship *AIDAbella*, considerably smaller than the *Royal Princess*, is made to investigate the influence of port's restrictions to the optimum itinerary. Values for port's attractiveness are the same as the previous case study. Table 42 details arrival and departure hours at each port. Although the optimum itinerary is slightly different than the previous case investigated, it can be seen that it still passes through the southeast and Santa Catarina region, with the only difference being the addition of Itajaí instead of Ilha Grande, adding 44.8 points to the total itinerary attraction value. The reason for this increase is because Itajaí do not have enough dock length to receive a ship of the size of *Royal Princess* but can receive a ship such as *AIDAbella*. Table 43 shows the ship speed at each voyage leg, and Table 44 display major costs of this itinerary. Additionally, Figure 14 gives a visual representation of this itinerary.

Table 42: Optimum itinerary for a weekly cruise, smaller ship situation of the Brazilian coast.

DAY	PORT	ARRIVAL	DEPARTURE
DAY 1	Rio de Janeiro	-	23:00
DAY 2	Cabo Frio	9:00	20:00
DAY 3	Ilhabela	11:00	21:00
DAY 4	Itajaí	12:00	23:00
DAY 6	Porto Belo	7:00	18:00
DAY 6	Balneário Camburiú	7:00	16:00
DAY 7	Santos	7:00	18:00
DAY 8	Rio de Janeiro	9:00	-

Table 43: Speeds for each leg of the optimum itinerary for a weekly cruise, smaller ship situation of the Brazilian coast.

VOYAGE LEG	SPEED [KNOTS]
Rio de Janeiro -> Cabo Frio	10
Cabo Frio -> Ilhabela	17
Ilhabela -> Itajaí	18
Itajaí -> Porto Belo	10
Porto Belo -> Balneário Camburiú	10
Balneário Camburiú -> Santos	16
Santos -> Rio de Janeiro	15

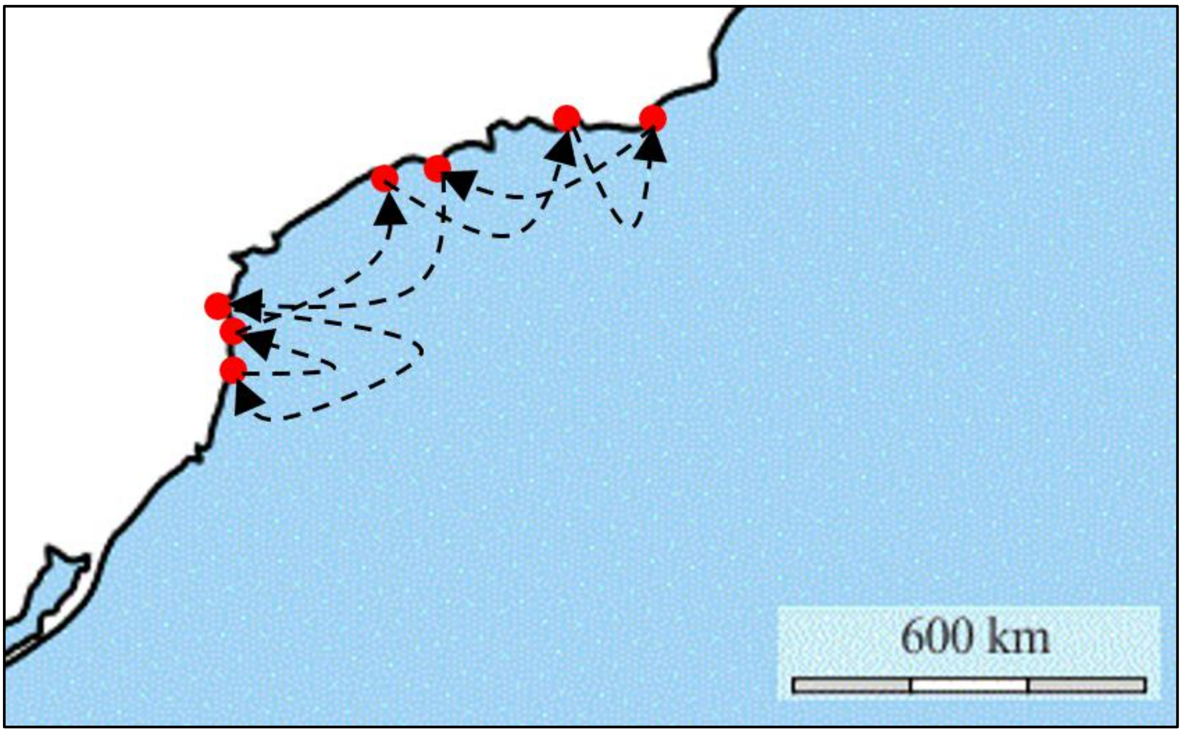

Figure 14: Optimum itinerary for a weekly cruise of the Brazilian coast with a smaller ship.

Table 44: Optimum itinerary cost for a weekly cruise, smaller ship situation of the Brazilian coast.

	MGO Fuel Cost	- $57,836
	IFO 180 Fuel Cost	- $73,203
Total Fuel Costs		**- $131,039**
	Port Tariffs	- $179,846
	Fixed Costs	- $808,801
	Waiting Cost	- $35,078
Total Costs		**- $1,154,764**
	Gross Revenue	$2,801,127
Total Profit		**$1,646,363**

5.2.3.3. Fortnight itinerary

Finally, for the last optimization for the Brazilian cost, an itinerary with a longer duration is studied. The idea of this case study is to investigate reasons why even though the ports of the northeast are more attractive, they do not appear on the optimum solution. One possible explanation for this is the distance between northeast and southeast region of about 600 nm, which makes itineraries of 7 days just not profitable. Again, the attraction value of the possible ports of call are shown at Table 38 since this optimization is considering the same month of the typical itinerary study.

The route of the fortnight itinerary, shown at Table 45, passes through the ports of Rio de Janeiro, Santos, Balneário Camburiú, Rio Grande, Porto Belo, Ilhabela, Cabo Frio, Salvador, Maceió, and Búzios, being that during the voyage the ship stays 4 days entirely on the sea, yielding a total attraction value of 904. This number represents an increase of about 40% in comparison with the attraction value of the weekly itinerary case. Table 46 shows the ship speed at each voyage leg, and Table 47 display major costs of this itinerary. Additionally, Figure 15 gives a visual representation of this itinerary.

Table 45: Optimum itinerary for a fortnight cruise in the Brazilian coast.

DAY	PORT	ARRIVAL	DEPARTURE
DAY 1	Rio de Janeiro	-	23:00
DAY 2	Santos	14:00	21:00
DAY 3	Balneário Camburiú	12:00	23:00
DAY 4	At sea ...	-	-
DAY 6	Rio Grande	12:00	20:00
DAY 6	At sea ...	-	-
DAY 7	Porto Belo	7:00	18:00
DAY 8	Ilhabela	9:00	16:00
DAY 9	Cabo Frio	7:00	18:00
DAY 10	At sea ...	-	-
DAY 11	Salvador	8:00	19:00
DAY 12	Maceió	10:00	21:00
DAY 13	At sea ...	-	-
DAY 14	Búzios	12:00	23:00
DAY 15	Rio de Janeiro	11:00	-

Table 46: Speeds for each leg of the fortnight optimum itinerary for the Brazilian coast.

VOYAGE LEG	SPEED [KNOTS]
Rio de Janeiro -> Santos	15
Santos -> Balneário Camburiú	16
Balneário Camburiú -> Rio Grande	10
Rio Grande -> Porto Belo	11
Porto Belo -> Ilhabela	20
Ilhabela -> Cabo Frio	17
Cabo Frio -> Salvador	17
Salvador -> Maceió	19
Maceió -> Búzios	22
Búzios -> Rio de Janeiro	10

Figure 15: Cruise route for the fortnight itinerary of the Brazilian coast.

Table 47: Fortnight Optimum itinerary cost for the Brazilian coast.

	MGO Fuel Cost	- $251,111
	IFO 180 Fuel Cost	- $334,496
Total Fuel Costs		**- $585,607**
	Port Tariffs	- $380,400
	Fixed Costs	- $3,075,015
	Waiting Cost	- $9,589
Total Costs		**- $4,050,611**
	Gross Revenue	$6,434,271
Total Profit		**$2,383,660**

5.2.4. Itineraries Comparison

The optimization result for both cases presented solutions departing from the southeast region and passing through Santa Catarina, in opposition to current cruise Brazilian itineraries, which usually starts in Santos or Rio de Janeiro and passes through the Northeast region. One possible explanation for this is the difficulty to properly estimate attractiveness value for small cities and islands destinations, where despite of the small influx of tourists in comparison to large cities such as Salvador and Rio de Janeiro, are still very attractive to cruise tourists. One interesting comment to be said is that those small cities and islands do not have proper infrastructure to dock large cruise ships, and therefore tendering is a common practice on those locations.

Table 48 shows the total profit, the profit per passenger, and profit per passenger day of all cases studied for the Brazilian coast region. From this table is concluded that no improvement is obtained with the alternative routes studied. The most profitable itinerary is the weekly typical itinerary solution. This shows a limit to increasing itineraries duration: in this case where there are 16 possible ports of call, a route with 14 days proved to be less profitable than a route with 7 days, because since the model forces passing at maximum one time in each port, even though the cities are not so attractive to visit, the ship is still forced travelling to different destinations, reducing the actual profit made for each passenger. One possibility in this case would be allowing staying more than one day in some very attractive ports, such as Rio de Janeiro and Salvador, to complete the duration desired without having to deliberately reduce total profits generated.

Table 48: Itinerary profitability comparison for the Brazilian coast region.

CASE STUDY	TOTAL PROFIT	PROFIT/PAX	PROFIT/PAX.DAY
Weekly route	$2,507,404	$704	$101
Weekly route, smaller ship	$1,646,363	$462	$66
Fortnightly route	$2,383,660	$670	$48

5.3. Computational Aspects

The CPU used to run these optimizations is a i5-8250U CPU. As expected, the time required to obtain the optimal solution grew exponentially with the number of possible ports of call.

Table 49 presents the relation between quantity of possible ports of call, quantity of variables in the optimization and time required. As it can be seen, the program runs in less than 6 minutes for all cases with less than 20 possible ports of call, whereas for the case of 29 ports of call the code takes more than 30 minutes to find the optimal solution. The only exception for these rules is the Brazilian coast fortnightly itinerary, which took more than 3:30 hours to run, because not only the number of possible ports is large but also the itineraries duration is twice as much as for the other cases.

Moreover, another parameter that influence in the optimization time is the possible speeds that the ship can have, despite of not affecting a specific optimization case in this thesis since all the studies used the same number of possible speeds.

Table 49: Computational aspects of the optimization runs.

CASE STUDY	NUMBER OF PORTS	NUMBER OF VARIABLES	TIME
Iberian Peninsula: as-is-situation	18	4,680	00:05:21
Iberian Peninsula: improved situation	29	12,325	00:40:32
Brazilian coast: typical weekly itinerary	16	3,680	00:02:09
Brazilian coast: weekly itinerary, smaller ship	16	3,680	00:01:51
Brazilian coast: fortnightly itinerary	16	3,680	03:39:56

6. CONCLUSIONS AND RECOMMENDATIONS

Cruise itineraries are a vacation option that has been gaining more and more attention since the 90's. This industry is currently undergoing a difficult situation due to the Covid pandemic, but once this situation is overcome, it is expected to recover and continue providing an interesting vacation option for customers worldwide as it offers a singular combination of traveling to many destinations without making cruisers tired of packing and unpacking their luggage every day.

Multiple companies are operating in this market, in one or more of several specific niches of the cruise market, either being luxury, exotic or contemporary cruises. Despite of that, because of the barriers to entry in this type of market, such as huge investment cost of leasing or buying a cruise ship, those companies are controlled by a very few number of large corporations, such as Carnival Corporation and Royal Caribbean Corporation, characterizing an oligopolistic market with strategy of brand diversification.

So far, major sources of passengers are North Americans and Europeans, travelling in itineraries usually located at the Caribbean or Mediterranean Sea. The growth of cruising activities during last decades caused a saturation of Caribbean and Mediterranean regions, creating the interest of the industry and the operation research literature for methods of selecting and creating new and optimized itineraries, the CSID problems.

This thesis presented an optimization model that returns the optimal itinerary route for a given set of ports. To do so, it takes as input information about possible ports of call and theirs attraction value, size of the ship and its cost, and the desired duration of the itinerary. The optimal itinerary is defined by the one which have the highest profit.

An application was carried out for two scenarios, one including ports from the Atlantic Coast of the Iberian Peninsula, Morroco and Canarian Islands, and another one considering the Brazilian coast. The analysis tried to identify whether there could be profit improvement for itineraries considering ports that are not traditionally served by cruise ships. Results for these case studies showed that given a fixed itinerary duration, any changes on the ports served by the itinerary, for good or bad, result in a approximated linear increase or decrease of profits, equals to the difference of values in the revenue function. This happens because given a fixed itinerary length, differences of fuel consumption of the ship are minimal in comparison with including more valuable attraction in the itinerary. This fact explains the seasonal characteristics of the cruise industry, rearranging the ships across the markets according with the seasons, focusing mainly on Summer seasons.

Moreover, the results showed that, in the case of the Iberian Peninsula, there are opportunities for new routes, with expected increase in profits of more than $400,000 both during Winter and Summer season. On both seasons, the improved itineraries focused on the coast of Portugal, Spain, and Morocco. For the Brazilian case, the results showed that the currently most common itinerary is in fact the most profitable.

Furthermore, for the Brazilian case, destinations which usually receives many cruise ships, such as the northeast region, ended up not being included in some solutions. The reason why results were better for the Portugal case than for the Brazilian case can be related to the development of the revenue function, which were designed taking in consideration the European cruise market, and the fact that the more attractive region for cruise ships in Brazil (northeast region) is far away from the centre of cruise passengers (southeast region), making it impossible to have short itineraries which covers that region.

Concluding, the optimization code developed in this thesis solves a simplified CSID in few minutes for most part of the time. Despite of that, it does not consider important factors for the cruise route such as the ports availability and the logistics of the food and the crews. Moreover, given that the number of passengers is assumed as a fixed capacity, regardless of the itinerary, and the fixed costs do not consider the region of the world that the ship is sailing, it is not intended to give precise values of expected profits or costs. Instead, it is a fast method that can give insights about which is the best route in certain region, when comparing it with different scenarios for the same region.

Finally, this model showed that when trying to select the optimum route of certain region, it might be a better strategy to go for the most attractive cities, maximizing the total revenue of the itinerary, than minimizing the itinerary total cost. Additionally, when focusing on reducing the total cost of an itinerary, it is the crew wage that accounts for the majority of the total cost, and not the fuel, suggesting that might be better to invest on automation than fuel efficiency of the hull, and explaining why cruise ships tend to stay sometimes more than 40 years in service.

For further works, improvements on the revenue and cost structure of the model should be made. The revenue function can be improved by considering the departure and arrival time when calculating the attraction value of each destination instead of forcing the optimization model to stay a minimum number of hours at each destination, and by using the list of destinations of the itinerary to calculate the numbers of expected passengers. For the cost structure, values of manning, fuel, and port tax should consider the region of the world where the itinerary is. Additionally, external costs such as environmental impact and social impact at the destinations could be included in the cost structure. Moreover, financial cost parameters should be revised, to use more realistic values. Finally, another parameter that could be considered is the availability of each port for receiving cruise ships at each day of the week, removing itineraries that are impossible due to local conditioning factors.

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APPENDIX 1 – CPLEX CODE

.mod file

```
/* DATA */

// set of ports
int n = ...;
range ports = 1..n;
int homeport[ports] = ...;

// set of possible speeds
int m = ...;
range speeds = 1..m;
float v[speeds] = ...;                        // [knots]

// set of all possible arcs i,j with different speeds k
tuple Edges {
  int i;
  int j;
  int k;
}
setof(Edges) edges = {<i,j,k> | i,j in ports, k in speeds : i!=j};

// set of all possible arcs i,j between ports
tuple Links {
  int i;
  int j;
}
setof(Links) links = {<i,j> | i,j in ports : i!=j};

// ship dimensions
float shipLength = ...;
float shipBreadth = ...;
float shipDraught = ...;
float lengthRestriction[ports] = ...;
float breadthRestriction[ports] = ...;
float draughtRestriction[ports] = ...;
int GT = ...;

//duration of the itinerary

int duration = ...;                           // [nights]
range months = 1..12;
int month = ...;                              // month of the itinerary
int minStay = ...;                            // minimum staying at port
int maxStay = ...;                            // maximum staying at port
//int homeportDeparture = ...;         // homeport minimum time departure
int maxWaitingTime = ...;              // maximum waiting time at each port
int maxSeaTime = ...;                         // maximum sea travel time per leg

// costs

int nPax = ...;                               // [USD/day]
float dailyCapCost = ...;                     // [USD/day]
float dailyCrewCost = ...;                    // [USD/day]
float dailyStoresCost = ...;           // [USD/day]
float dailyRegularMaintCost = ...;     // [USD/day]
float dailyInsuranceCost = ...;        // [USD/day]
```

```
float dailyAdminCost = ...;                  // [USD/day]
float dailyPeriodicMaintCost = ...;    // [USD/day]
float fixedVoyageCosts;                // [USD]
float Tarrif[ports];

// specif fuel consumption
float SFOC_Main[speeds] = ...;         // [Kg/kW.h]
float SFOC_Aux = ...;           // [Kg/kW.h]

// fuel price
float SFOC_MainPrice = ...;            // [USD/ton]
float SFOC_AuxPrice = ...;                   // [USD/ton]

// ship power [kW]
float mainPower[speeds] = ...;
float auxPower = ...;
float lf = ...;
float plf = ...;
float fuelMainCost[speeds];            // main machinery fuel cost [USD/hour]
float fuelAuxCost;              // auxiliary machinery fuel cost [USD/hour]

// itinerary attractiveness
float attractiveness[ports][1..4] = ...;
float meanTemperature[ports][months] = ...;
float meanPrecipitation[ports][months] = ...;
float meanSunshine[ports][months] = ...;
float meanWaveHeight[ports][months] = ...;
float portAttractiveness[ports];

// distance matrix between ports
float distance[ports][ports] = ...;    // [nm]
float d[links];

// time matrix for each possible speeds
float t[edges];                              // [h]


/* PRE PROCESSING */

execute {
  for (var l in links) {
    d[l] = distance[l.i][l.j];
  }

  for (var e in edges) {
    t[e] = distance[e.i][e.j] / v[e.k];
  }

  for (var i in ports) {
    portAttractiveness[i] = attractiveness[i][1] + attractiveness[i][2]*(12-
2*attractiveness[i][4])/12 + 2*(meanTemperature[i][month]-15) +
0.1*(meanSunshine[i][month]-200) - 5*(meanWaveHeight[i][month]-1.5);

    if (homeport[i] == 1) {
      Tarrif[i] = 0.0639*GT + 2*2.7579*Math.sqrt(GT) + 17*nPax + 1000;
    }  else {
      Tarrif[i] = 0.0635*GT + 2*7.9521*Math.sqrt(GT) + 1000 + 0.6*3.3264*nPax;
    }
  }
```

```
  fixedVoyageCosts = duration * (dailyCapCost + dailyCrewCost + dailyStoresCost +
dailyRegularMaintCost + dailyInsuranceCost + dailyAdminCost +
dailyPeriodicMaintCost);
  for (var k in speeds) {
    fuelMainCost[k] = mainPower[k] * SFOC_Main[k] * SFOC_MainPrice / 1000;
  }
  fuelAuxCost = lf * auxPower * SFOC_Aux * SFOC_AuxPrice / 1000;
}

/* DECISION VARIABLE */

// 1 if the ships travel at the arc (i,j) with speed k
dvar boolean x[e in edges];

// 1 if the port is the homeport
dvar boolean hp[i in ports];

// 1 if the port i is served
dvar boolean y[i in ports];

// 1 if the ship stays the day at sea
dvar boolean dayAtSea[l in links];

// Arrival time at port [h]
dvar int+ arrival[ports] in 7..14;

// Departure time at port [h]
dvar int+ departure[ports] in 16..23;

// subroute variable
dvar float+ u[ports]; //%!


/* EXPRESSIONS */

// time related expressions
dexpr float dwellTime[i in ports] = departure[i] - arrival[i];
dexpr float tSea[l in links] = sum(k in speeds) t[<l.i,l.j,k>] * x[<l.i,l.j,k>];
dexpr float totalSeaTime = sum(l in links) tSea[l];
dexpr float totalOnboardTime = sum(l in links, k in speeds) ((arrival[l.j] + (24 -
departure[l.i]) + 24*dayAtSea[l])*x[<l.i,l.j,k>]);
dexpr float totalWaitingTime = totalOnboardTime - totalSeaTime;

// cost related expressions
dexpr float fuelMainTotalCost = sum(e in edges) x[e] * t[e] * fuelMainCost[e.k];
dexpr float fuelCostPort =  plf * fuelAuxCost * sum(i in ports)
(y[i]*dwellTime[i]);
dexpr float fuelAuxTotalCost = sum(e in edges) x[e] * t[e] * fuelAuxCost;
dexpr float ifo = fuelMainTotalCost + fuelCostPort + fuelAuxTotalCost;
dexpr float tarrifPortCost = sum(i in ports) Tarrif[i]*y[i];
dexpr float waitingCost = totalWaitingTime*nPax;
             // [USD]
dexpr float totalCost = fuelMainTotalCost + fuelAuxTotalCost + fixedVoyageCosts +
fuelCostPort + tarrifPortCost + waitingCost;

// revenue related expressions
dexpr float grossRevenue = sum(i in ports) 2*portAttractiveness[i]*nPax*y[i] +
sum(l in links) 10*nPax*dayAtSea[l]; //[USD]
```

```
/* MODEL */

maximize grossRevenue - totalCost;
subject to {
  //FLOW CONSTRAINTS
  forall (i in ports)
    Flow_Out1:
    sum(k in speeds, j in ports : i!=j) x[<i,j,k>] == y[i];

  forall (j in ports)
    Flow_In1:
    sum(k in speeds, i in ports : i!=j) x[<i,j,k>] == y[j];

  forall(i in ports)
      Homeport1:
      hp[i] <= y[i];

  Homeport2:
  sum(i in ports) hp[i] == 1;

  forall(i in ports)
    Homeport3:
      hp[i] <= homeport[i];

  forall (l in links)
    Speed:
    sum(k in speeds) x[<l.i,l.j,k>] <= 1;

  //VOYAGE CONSTRAINTS
  forall(i in ports)
    Flow_Out2:
    sum(j in ports : j!=i) dayAtSea[<i,j>] <= 1;

  forall(j in ports)
    Flow_In2:
    sum(i in ports : i!=j) dayAtSea[<i,j>] <= 1;

  forall(l in links)
    Flow3: //
    (dayAtSea[l] == 1) => (sum(k in speeds)x[<l.i,l.j,k>] == 1);

  forall(l in links)
    Maximum_Sea_Time:
    tSea[l] <= maxSeaTime + dayAtSea[l] * 24;


  // TIME WINDOWs CONSTRAINTS
  forall (i in ports) {
    Dwell_Time1:
    dwellTime[i] >= minStay*(1 - hp[i]);
    Dwell_Time2:
      dwellTime[i] <= maxStay + (24 - maxStay)*hp[i];
  }

  forall (l in links)
    Time_Window:
    arrival[l.j] + (24 - departure[l.i]) + 24*dayAtSea[l] >= tSea[l];
```

```
  //ITINERARY DURATION CONSTRAINT
  Itinerary_Duration:
  sum(i in ports)(y[i]) + sum(l in links)dayAtSea[l] == duration;

  //DIMENSIONS CONTRAINTS
  Dimensions:
  forall(i in ports){
    Length_Constrain:
      shipLength*y[i]<=lengthRestriction[i];
      Breadth_Constrain:
      shipBreadth*y[i]<=breadthRestriction[i];
      Draught_Constrain:
      shipDraught*y[i]<=draughtRestriction[i];
  }

  //SUBROUTE CONSTRAINT
  forall (i,j in ports : j!=i) {
    Subtour:
    u[i] - u[j] + (duration - 1)*sum(k in speeds)x[<i,j,k>] <= duration - 2 +
(duration)*(hp[i] + hp[j]);
  }
}
```

.dat file

```
duration = 6;
month = 1;
// -----------------------------------------
minStay = 7;
maxStay = 11;
maxWaitingTime = 2;
maxSeaTime = 15;
// -----------------------------------------
SFOC_MainPrice = 320;
SFOC_AuxPrice = 320;
lf = 0.6;
plf = 0.8;
// -----------------------------------------
//Uncomment the Excel File you want to use
//SheetConnection my_sheet("DADOS2.xlsx");
//SheetConnection my_sheet("DADOS30.xlsx");
//SheetConnection my_sheet("BRAZIL.xlsx");


n from SheetRead(my_sheet,"nPorts");
homeport from SheetRead(my_sheet,"homeport");


// -----------------------------------------
m from SheetRead(my_sheet,"m");
shipLength from SheetRead(my_sheet,"L");
shipBreadth from SheetRead(my_sheet,"B");
shipDraught from SheetRead(my_sheet,"D");
nPax from SheetRead(my_sheet,"Pax");
GT from SheetRead(my_sheet,"GT");

dailyCapCost from SheetRead(my_sheet,"cap_C");
```

```
dailyCrewCost from SheetRead(my_sheet,"crew_C");
dailyStoresCost from SheetRead(my_sheet,"stores_C");
dailyRegularMaintCost from SheetRead(my_sheet,"reg_C");
dailyInsuranceCost from SheetRead(my_sheet,"ins_C");
dailyAdminCost from SheetRead(my_sheet,"adm_C");
dailyPeriodicMaintCost from SheetRead(my_sheet,"per_C");

v from SheetRead(my_sheet,"velocity");
SFOC_Main from SheetRead(my_sheet,"SFOC_Main");
SFOC_Aux from SheetRead(my_sheet,"SFOC_Aux");
mainPower from SheetRead(my_sheet,"Main_Power");
auxPower from SheetRead(my_sheet,"Aux_Power");
// ------------------------------------------
/*
// ------------------------------------------
//Used only for the brazilian coast case with a smaller ship!
SheetConnection AIDAbella("DADOS30.xlsx");

m from SheetRead(AIDAbella,"m");
shipLength from SheetRead(AIDAbella,"L");
shipBreadth from SheetRead(AIDAbella,"B");
shipDraught from SheetRead(AIDAbella,"D");
nPax from SheetRead(AIDAbella,"Pax");
GT from SheetRead(AIDAbella,"GT");

dailyCapCost from SheetRead(AIDAbella,"cap_C");
dailyCrewCost from SheetRead(AIDAbella,"crew_C");
dailyStoresCost from SheetRead(AIDAbella,"stores_C");
dailyRegularMaintCost from SheetRead(AIDAbella,"reg_C");
dailyInsuranceCost from SheetRead(AIDAbella,"ins_C");
dailyAdminCost from SheetRead(AIDAbella,"adm_C");
dailyPeriodicMaintCost from SheetRead(AIDAbella,"per_C");

v from SheetRead(AIDAbella,"velocity");
SFOC_Main from SheetRead(AIDAbella,"SFOC_Main");
SFOC_Aux from SheetRead(AIDAbella,"SFOC_Aux");
mainPower from SheetRead(AIDAbella,"Main_Power");
auxPower from SheetRead(AIDAbella,"Aux_Power");
// ------------------------------------------
*/
// ------------------------------------------
distance from SheetRead(my_sheet,"distance");

meanTemperature from SheetRead(my_sheet,"temperature");
meanPrecipitation from SheetRead(my_sheet,"precipitation");
meanSunshine from SheetRead(my_sheet,"sunshine");
meanWaveHeight from SheetRead(my_sheet,"wave_height");
attractiveness from SheetRead(my_sheet,"attractiveness");

lengthRestriction from SheetRead(my_sheet,"length");
breadthRestriction from SheetRead(my_sheet,"breadth");
draughtRestriction from SheetRead(my_sheet,"draught");
// ------------------------------------------
// ------------------------------------------
y to SheetWrite(my_sheet,"ports_solution");
arrival to SheetWrite(my_sheet,"arrival_solution");
departure to SheetWrite(my_sheet,"departure_solution");
hp to SheetWrite(my_sheet,"homeport_solution");
x to SheetWrite(my_sheet,"x_solution");
```

```
dayAtSea to SheetWrite(my_sheet,"dayAtSea_solution");
fuelAuxTotalCost to SheetWrite(my_sheet,"mgo_cost");
ifo to SheetWrite(my_sheet,"ifo_cost");
waitingCost to SheetWrite(my_sheet,"waiting_cost");
tarrifPortCost to SheetWrite(my_sheet,"tariff_cost");
totalCost to SheetWrite(my_sheet,"total_cost");
grossRevenue to SheetWrite(my_sheet,"gross_revenue");

// ------------------------------------------
```

APPENDIX 2 – PORT DISTANCES MATRIX FOR THE ATLANTIC COAST OF IBERIAN PENINSULA REGION

DISTANCE MATRIX – PART 1

	La Corunã	Arousa	Vigo	Viana do Castelo	Leixões	Aveiro
LA CORUNÃ	0	127	122	159	182	218
AROUSA	127	0	36	68	123	148
VIGO	122	36	0	42	74	110
VIANA DO CASTELO	159	68	42	0	36	69
LEIXÕES	182	123	74	36	0	38
AVEIRO	218	148	110	69	38	0
FIGUEIRA DA FOZ	245	169	139	100	70	54
LISBON	338	279	242	211	181	191
SETÚBAL	364	306	268	252	207	189
PORTIMÃO	476	398	379	334	302	308
FARO	481	419	388	367	327	323
HUELVA	538	475	445	418	384	375
CÁDIZ	558	536	465	443	404	399
GIBRALTAR	617	498	521	501	458	455
MÁLAGA	676	614	580	564	517	516
MOTRIL	722	660	626	610	563	562
CEUTA	617	552	521	503	458	456
TANGER	594	542	498	491	435	446
KENITRA	639	569	556	512	482	466
CASABLANCA	638	569	541	518	481	474
SAFI	703	636	606	575	546	535
AGADIR	828	782	629	737	568	659
FUNCHAL	783	721	704	671	655	632
ARRECIFE	935	858	838	810	778	762
ROSARIO	979	922	870	843	813	796
LAS PALMAS	998	932	912	923	854	837
TENERIFE	998	932	912	880	854	834
SANTA CRUZ DE LA PALMA	1015	946	927	897	855	856
SAN SEB. DE LA GOMERA	1035	966	948	915	891	873

DISTANCE MATRIX – PART 2

	Figueira da Foz	Lisbon	Setúbal	Portimão	Faro	Huelva
LA CORUNÃ	245	338	364	476	481	538
AROUSA	169	279	306	398	419	475
VIGO	139	242	268	379	388	445
VIANA DO CASTELO	100	211	252	334	367	418
LEIXÕES	70	181	207	302	327	384
AVEIRO	54	191	189	308	323	375
FIGUEIRA DA FOZ	0	136	156	269	301	353
LISBON	136	0	45	159	173	230
SETÚBAL	156	45	0	142	158	215
PORTIMÃO	269	159	142	0	40	94
FARO	301	173	158	40	0	68
HUELVA	353	230	215	94	68	0
CÁDIZ	377	250	235	118	87	73
GIBRALTAR	436	303	288	179	145	120
MÁLAGA	500	362	347	242	206	179
MOTRIL	546	408	393	288	252	225
CEUTA	439	303	288	178	147	120
TANGER	417	288	265	168	127	97
KENITRA	436	344	318	204	187	190
CASABLANCA	441	328	315	217	206	226
SAFI	506	393	378	296	294	326
AGADIR	632	514	518	439	420	459
FUNCHAL	601	538	536	497	521	578
ARRECIFE	733	632	624	553	563	598
ROSARIO	769	669	658	585	596	631
LAS PALMAS	807	710	718	644	663	702
TENERIFE	800	710	718	650	658	715
SANTA CRUZ DE LA PALMA	823	742	740	689	708	752
SAN SEB. DE LA GOMERA	840	757	752	697	714	755

DISTANCE MATRIX – PART 3

	Cádiz	Gibraltar	Málaga	Motril	Ceuta	Tanger
LA CORUNÃ	558	617	676	722	617	594
AROUSA	536	498	614	660	552	542
VIGO	465	521	580	626	521	498
VIANA DO CASTELO	443	501	564	610	503	491
LEIXÕES	404	458	517	563	458	435
AVEIRO	399	455	516	562	456	446
FIGUEIRA DA FOZ	377	436	500	546	439	417
LISBON	250	303	362	408	303	288
SETÚBAL	235	288	347	393	288	265
PORTIMÃO	118	179	242	288	178	168
FARO	87	145	206	252	147	127
HUELVA	73	120	179	225	120	97
CÁDIZ	0	73	132	178	73	50
GIBRALTAR	73	0	63	109	17	32
MÁLAGA	132	63	0	46	62	87
MOTRIL	178	109	46	0	108	133
CEUTA	73	17	62	108	0	31
TANGER	50	32	87	133	31	0
KENITRA	156	155	217	263	153	145
CASABLANCA	190	191	250	296	191	168
SAFI	306	315	374	420	314	293
AGADIR	429	437	496	568	437	414
FUNCHAL	576	612	671	717	612	589
ARRECIFE	590	624	682	728	600	588
ROSARIO	623	629	716	762	632	620
LAS PALMAS	687	701	760	806	701	679
TENERIFE	703	724	783	829	724	678
SANTA CR. DE LA PALMA	749	755	834	880	772	761
SAN SEB. DE LA GOMERA	751	777	835	881	771	760

DISTANCE MATRIX – PART 4

	Kenitra	Casablanca	Safi	Agadir	Funchal	Arrecife
LA CORUNÃ	639	638	703	828	783	935
AROUSA	569	569	636	782	721	858
VIGO	556	541	606	629	704	838
VIANA DO CASTELO	512	518	575	737	671	810
LEIXÕES	482	481	546	568	655	778
AVEIRO	466	474	535	659	632	762
FIGUEIRA DA FOZ	436	441	506	632	601	733
LISBON	344	328	393	514	538	632
SETÚBAL	318	315	378	518	536	624
PORTIMÃO	204	217	296	439	497	553
FARO	187	206	294	420	521	563
HUELVA	190	226	326	459	578	598
CÁDIZ	156	190	306	429	576	590
GIBRALTAR	155	191	315	437	612	624
MÁLAGA	217	250	374	496	671	682
MOTRIL	263	296	420	568	717	728
CEUTA	153	191	314	437	612	600
TANGER	145	168	293	414	589	588
KENITRA	0	51	189	372	513	488
CASABLANCA	51	0	136	257	472	452
SAFI	189	136	0	130	382	302
AGADIR	372	257	130	0	399	223
FUNCHAL	513	472	382	399	0	304
ARRECIFE	488	452	302	223	304	0
ROSARIO	521	472	334	250	336	34
LAS PALMAS	590	528	396	334	282	116
TENERIFE	604	551	419	372	264	148
SANTA CR. DE LA PALMA	658	617	492	450	244	228
SAN SEB. DE LA GOMERA	656	617	485	431	276	210

DISTANCE MATRIX – PART 5

	Rosário	Las Palmas	Tenerife	Santa Cr. de la Palma	San Seb. de la Gomera
LA CORUNÃ	979	998	998	1015	1035
AROUSA	922	932	932	946	966
VIGO	870	912	912	927	948
VIANA DO CASTELO	843	923	880	897	915
LEIXÕES	813	854	854	855	891
AVEIRO	796	837	834	856	873
FIGUEIRA DA FOZ	769	807	800	823	840
LISBON	669	710	710	742	757
SETÚBAL	658	718	718	740	752
PORTIMÃO	585	644	650	689	697
FARO	596	663	658	708	714
HUELVA	631	702	715	752	755
CÁDIZ	623	687	703	749	751
GIBRALTAR	629	701	724	755	777
MÁLAGA	716	760	783	834	835
MOTRIL	762	806	829	880	881
CEUTA	632	701	724	772	771
TANGER	620	679	678	761	760
KENITRA	521	590	604	658	656
CASABLANCA	472	528	551	617	617
SAFI	334	396	419	492	485
AGADIR	250	334	372	450	431
FUNCHAL	336	282	264	244	276
ARRECIFE	34	116	148	228	210
ROSARIO	0	108	151	231	214
LAS PALMAS	108	0	53	145	112
TENERIFE	151	53	0	99	66
SANTA CR. DE LA PALMA	231	145	99	0	54
SAN SEB. DE LA GOMERA	214	112	66	54	0

APPENDIX 3 – WEATHER CONDITIONS MATRIX FOR THE ATLANTIC COAST OF IBERIAN PENINSULA REGION

AVERAGE PRECIPITATION DAYS PER MONTH

Ports	J	F	M	A	M	J	J	A	S	O	N	D
Port of A Coruña	14	12	12	13	11	7	6	6	8	13	14	15
Port of Vilagarcia de Arousa	18	10	25	18	8	11	6	2	4	12	23	21
Port of Vigo	14	12	12	14	12	7	5	5	8	13	13	15
Port of Viana do Castelo	17	11	26	17	5	15	7	3	3	15	24	19
Port of Leixões	14	13	11	10	9	6	2	3	6	10	12	12
Port of Aveiro	12	10	24	16	6	15	6	1	2	10	22	13
Port of Figueira da Foz	12	11	8	11	7	7	3	1	4	8	10	11
Port of Lisbon	15	15	13	12	8	5	2	2	6	11	14	14
Port of Setúbal	5	7	18	21	6	7	4	1	1	13	21	7
Port of Portimão	4	3	20	18	2	3	2	0	0	15	20	4
Port of Faro	4	3	20	18	2	3	2	0	0	15	20	4
Port of Huelva	7	6	4	6	4	1	0	0	2	6	6	8
Port of Cádiz	6.9	6.4	4.8	5.6	3.2	1	0.1	0.2	2.5	5.6	7.2	8.1
Port of Gibraltar	7	7	6	7	4	1	0	0	2	6	8	9
Port of Málaga	6	5	4	5	3	1	0	1	2	4	6	7
Port of Motril	10	9	22	19	9	2	1	3	12	10	13	1
Port of Ceuta	7	8	6	5	3	1	0	1	2	5	7	9
Port of Tanger Ville	11.2	11.4	10.1	9.3	6	3.7	0.8	0.8	3.1	8	11.1	12
Port of Kenitra	9.9	9.8	9	8.7	5.7	2.4	0.3	0.4	2.4	6.4	10.2	10.4
Port of Casablanca	9	9	7	8	6	2	1	1	3	7	9	11
Port of Safi	5.4	5.6	5.1	3.7	1.4	1.3	0.2	0.4	1.6	4.1	5.3	5.3
Port of Agadir	12.4	10.1	9.8	9.5	5.1	1.6	0.4	0.4	1.8	6.5	10.1	12.3
Port of Funchal	12	10	9	8	6	3	1	2	6	9	10	13
Port of Arrecife	3	3	2	1	0	0	0	0	0	2	3	4
Port of Puerto del Rosario	3	2	2	1	0	0	0	0	1	2	2	3
Las Palmas Port	3.1	3	2.3	1.3	0.3	0.1	0	0.1	1.1	2.3	3.9	4.5
Port of Santa Cruz de Tenerife	4.2	3.8	3.8	2.4	0.9	0.2	0	0.3	0.9	3.1	4.7	5.4
Port of Santa Cruz de la Palma	4.2	3.8	3.8	2.4	0.9	0.2	0	0.3	0.9	3.1	4.7	5.4
Port of San Sebastián de la Gomera	4.2	3.8	3.8	2.4	0.9	0.2	0	0.3	0.9	3.1	4.7	5.4

MEAN SUNSHINE HOURS

Ports	J	F	M	A	M	J	J	A	S	O	N	D
Port of A Coruña	102	121	160	175	201	225	239	244	192	149	108	94
Port of Vilagarcia de Arousa	148.5	172.5	157.5	219.5	240	298.5	299	295.5	294	249.5	150	135.5
Port of Vigo	114	131	178	193	228	273	296	287	212	154	112	101
Port of Viana do Castelo	155.5	185	186	270.5	318.5	289	333.5	376.5	300	208	104.5	126.5
Port of Leixões	124	129	192	217	258	274	308	295	224	184	139	124
Port of Aveiro	171	196	207	267.5	318.5	269	322.5	372.5	294	217	125.5	145
Port of Figueira da Foz	176.5	204	217.5	271.5	323	276.5	326	363.5	294.5	211	110.5	145.5
Port of Lisbon	142.6	156.6	207.7	234	291.4	303	353.4	344.1	261	213.9	156	142.6
Port of Setúbal	179	218.5	217	262	338	309	349	370.5	285.5	222	141	173.5
Port of Portimão	208.5	232	223.5	267.5	368	338	381.5	371	293	206	178.5	204
Port of Faro	208.5	232	223.5	267.5	368	338	381.5	371	293	206	178.5	204
Port of Huelva	165	171	229	255	296	341	367	340	268	211	176	151
Port of Cádiz	184	197	228	255	307	331	354	335	252	228	187	166
Port of Gibraltar	147	143	204	233	289	319	326	309	240	197	135	134
Port of Málaga	181	180	222	244	292	329	347	316	255	215	172	160
Port of Motril	276	257	232	241	319	372.5	315	310	297.5	281	246	246
Port of Ceuta	269.5	243.5	231	235	304	300	310	302.5	276.5	200.5	225.5	266.5
Port of Tanger Ville	169.2	166.9	231.7	251.7	298.9	306.8	344	330.7	275.6	238.2	180.6	166.9
Port of Kenitra	179.9	182.3	232	254.5	290.5	287.6	314.7	307	261.1	235.1	190.5	180.9
Port of Casablanca	189.6	188.5	240.7	261.5	293.6	285	303.4	294.1	258.1	234.3	190.6	183.1
Port of Safi	230.5	223.6	269.5	281.8	295.7	269	269.8	253.9	242.4	245.6	218.7	228.5
Port of Agadir	205.5	208.5	258.7	277.8	314.4	298	325.8	316.5	263	243.6	204.1	198.7
Port of Funchal	141	150	181	182	202	162	228	240	200	184	155	140
Port of Arrecife	203	201	241	255	297	292	308	295	248	235	207	196
Port of Puerto del Rosario	190	190	233	242	280	285	294	289	246	227	203	186
Las Palmas Port	184	191	229	228	272	284	308	300	241	220	185	179
Port of Santa Cruz de Tenerife	178	186	221	237	282	306	337	319	253	222	178	168
Port of Santa Cruz de la Palma	178	186	221	237	282	306	337	319	253	222	178	168
Port of San Sebastián de la Gomera	178	186	221	237	282	306	337	319	253	222	178	168

DAILY MEAN TEMPERATURE

Ports	J	F	M	A	M	J	J	A	S	O	N	D
Port of A Coruña	10.8	11.1	12.4	13	15	17.4	19	19.6	18.6	16.1	13.3	11.5
Port of Vilagarcia de Arousa	9	7	8	11	14	16	18	21	19	17	12	12
Port of Vigo	8.6	9.6	11.5	12.4	14.6	17.9	19.6	19.8	18.3	15	11.5	9.3
Port of Viana do Castelo	9.8	10.5	12.7	13.7	15.9	19.2	20.8	20.8	19.2	16.1	12.8	10.8
Port of Leixões	9.3	10.1	11.5	12.9	15.1	18.1	19.9	19.8	19	16.2	12.3	9.9
Port of Aveiro	10.4	11.4	13.3	14.3	16.3	18.9	20.1	20.4	19.5	17.1	13.6	11.5
Port of Figueira da Foz	10.1	10.5	13.1	14.7	15.8	18	19	19.2	18.7	16.4	13.6	11.1
Port of Lisbon	11.6	12.7	14.9	15.9	18	21.2	23.1	23.5	22.1	18.8	15	12.4
Port of Setúbal	10.1	11.3	13.5	14.8	17.4	20.9	23.1	23.2	21.3	17.9	13.9	11.3
Port of Portimão	12	12.8	14.8	16.1	18.4	21.9	24.2	24.1	22.3	19.3	15.7	13.3
Port of Faro	12	12.8	14.8	16.1	18.4	21.9	24.2	24.1	22.3	19.3	15.7	13.3
Port of Huelva	11	12.4	14.7	16.1	19.2	22.8	25.8	25.8	23.4	19.5	14.9	12.3
Port of Cádiz	12.7	13.8	15.5	16.8	19.1	22.4	24.6	25	23.3	20.3	16.5	13.9
Port of Gibraltar	13.5	14.1	15.6	16.7	19	21.9	24.2	24.6	22.9	19.8	16.6	14.6
Port of Málaga	12.1	12.9	14.7	16.3	19.3	23	25.5	26	23.5	19.5	15.7	13.2
Port of Motril	10	8	10	13	15	19	22	23	21	20	17	16
Port of Ceuta	13.6	14.2	15	16.5	19.2	22.3	25	25.1	23	20.2	16.5	14.4
Port of Tanger Ville	12.5	13.1	14	15.2	17.7	20.6	23.5	23.9	22.8	19.7	15.9	13.3
Port of Kenitra	12.6	13.1	14.2	15.2	17.4	19.8	22.2	22.4	21.5	19	15.9	132
Port of Casablanca	12.6	13.7	15.3	16.5	18.5	20.9	22.7	23.2	22.3	19.8	16.5	14.2
Port of Safi	14.1	15.2	16.7	17	18.7	20.2	22	22.2	21.9	20.3	17.9	14.6
Port of Agadir	13	13.8	14.9	16	18.3	20.3	23.7	24.1	22.6	20	16.6	13.7
Port of Funchal	16.7	16.6	17.2	17.5	18.6	20.6	22.2	23.2	23.2	21.8	19.6	17.9
Port of Arrecife	17.4	17.9	19	19.6	20.8	22.6	24.3	25.2	24.7	23	20.7	18.6
Port of Puerto del Rosario	17.6	17.9	18.9	19.5	20.6	22.5	24	24.6	24.4	22.9	20.9	18.9
Las Palmas Port	18	18.4	19.3	19.5	20.5	22.2	23.8	24.6	24.3	23.1	21.2	19.3
Port of Santa Cruz de Tenerife	18.2	18.3	19	19.7	21	22.9	25	25.5	24.9	23.4	21.3	19.4
Port of Santa Cruz de la Palma	18.2	18.3	19	19.7	21	22.9	25	25.5	24.9	23.4	21.3	19.4
Port of San Sebastián de la Gomera	18.2	18.3	19	19.7	21	22.9	25	25.5	24.9	23.4	21.3	19.4

AVERAGE SIGNIFICANT WAVE HEIGHT

Ports	J	F	M	A	M	J	J	A	S	O	N	D
Port of A Coruña	3.38	3.25	2.89	2.44	1.91	1.65	1.51	1.59	1.98	2.51	2.88	3.19
Port of Vilagarcia de Arousa	2.98	2.86	2.54	2.18	1.77	1.54	1.41	1.46	1.73	2.23	2.54	2.81
Port of Vigo	2.9	2.79	2.48	2.13	1.75	1.53	1.42	1.45	1.7	2.18	2.49	2.75
Port of Viana do Castelo	2.74	2.64	2.35	2.03	1.68	1.47	1.37	1.4	1.61	2.07	2.35	2.59
Port of Leixões	2.77	2.66	2.39	2.08	1.73	1.53	1.45	1.47	1.66	2.11	2.39	2.62
Port of Aveiro	2.87	2.77	2.48	2.17	1.81	1.6	1.52	1.54	1.73	2.19	2.49	2.72
Port of Figueira da Foz	2.88	2.78	2.5	2.18	1.82	1.61	1.54	1.56	1.74	2.2	2.5	2.72
Port of Lisbon	2.74	2.65	2.4	2.1	1.75	1.54	1.48	1.49	1.65	2.09	2.38	2.62
Port of Setúbal	2.56	2.48	2.23	2	1.62	1.42	1.36	1.37	1.52	1.93	2.2	2.44
Port of Portimão	2.24	2.19	2.01	1.75	1.47	1.29	1.28	1.25	1.34	1.69	1.94	2.18
Port of Faro	1.58	1.56	1.45	1.27	1.05	0.92	0.88	0.84	0.92	1.19	1.37	1.58
Port of Huelva	1.5	1.5	1.41	1.25	1.03	0.9	0.84	0.8	0.89	1.14	1.3	1.51
Port of Cádiz	1.6	1.59	1.49	1.31	1.09	0.95	0.89	0.85	0.95	1.21	1.39	1.6
Port of Gibraltar	1.07	1.13	1.06	0.94	0.79	0.71	0.66	0.63	0.69	0.8	0.93	1.08
Port of Málaga	0.97	1.07	0.99	0.91	0.79	0.72	0.67	0.63	0.68	0.72	0.86	0.98
Port of Motril	1.05	1.16	1.08	1.03	0.9	0.81	0.74	0.7	0.75	0.79	0.94	1.05
Port of Ceuta	1.07	1.13	1.06	0.94	0.79	0.71	0.66	0.63	0.69	0.8	0.93	1.08
Port of Tanger Ville	1.07	1.13	1.06	0.94	0.79	0.71	0.66	0.63	0.69	0.8	0.93	1.08
Port of Kenitra	2.12	2.06	1.86	1.63	1.33	1.15	1.1	1.09	1.21	1.54	1.79	2
Port of Casablanca	2.32	2.25	2.06	1.8	1.49	1.29	1.28	1.26	1.37	1.72	2	2.2
Port of Safi	2.4	2.4	2.29	2.15	1.92	1.73	1.79	1.7	1.65	1.87	2.13	2.26
Port of Agadir	2.42	2.35	2.22	1.97	1.69	1.49	1.54	1.5	1.55	1.86	2.14	2.3
Port of Funchal	2.58	2.53	2.42	2.09	1.75	1.48	1.46	1.47	1.62	2.03	2.34	2.52
Port of Arrecife	1.93	1.94	1.88	1.74	1.54	1.41	1.55	1.46	1.35	1.5	1.74	1.84
Port of Puerto del Rosario	1.93	1.94	1.88	1.74	1.54	1.41	1.55	1.46	1.35	1.5	1.74	1.84
Las Palmas Port	1.88	1.87	1.82	1.66	1.46	1.35	1.51	1.42	1.31	1.46	1.68	1.8
Port of Santa Cruz de Tenerife	1.96	1.94	1.88	1.68	1.45	1.31	1.44	1.37	1.31	1.51	1.75	1.88
Port of Santa Cruz de la Palma	2.3	2.27	2.21	1.94	1.65	1.48	1.63	1.57	1.52	1.77	2.05	2.22
Port of San Sebastián de la Gomera	1.89	1.87	1.82	1.62	1.41	1.29	1.45	1.38	1.29	1.45	1.67	1.81

APPENDIX 4 – PORT DISTANCES MATRIX FOR THE BRAZILIAN COAST REGION

DISTANCE MATRIX – PART 1

	Rio Grande	Porto Belo	Balneário Camburiú	Itajaí	Santos	Ilha Bela
RIO GRANDE	0	381	404	411	606	642
PORTO BELO	381	0	23	30	256	298
BALNEÁRIO CAMBURIÚ	404	23	0	7	233	275
ITAJAÍ	411	30	7	0	226	268
SANTOS	606	256	233	226	0	70
ILHA BELA	642	298	275	268	70	0
ILHA GRANDE	717	375	352	345	163	86
RIO DE JANEIRO	755	419	396	389	220	146
CABO FRIO	855	519	496	489	320	246
BÚZIOS	870	534	511	504	335	261
ILHÉUS	1372	1036	1013	1006	837	763
SALVADOR	1478	1142	1119	1112	943	869
MACEIÓ	1705	1369	1346	1339	1170	1096
RECIFE	1819	1483	1460	1453	1284	1210
NATAL	1973	1637	1614	1607	1438	1364
FORTALEZA	2233	1897	1874	1867	1866	1624

DISTANCE MATRIX – PART 2

	Ilha Grande	Rio de Janeiro	Cabo Frio	Búzios	Ilhéus	Salvador
RIO GRANDE	717	755	855	870	1372	1478
PORTO BELO	375	419	519	534	1036	1142
BALNEÁRIO CAMBURIÚ	352	396	496	511	1013	1119
ITAJAÍ	345	389	489	504	1006	1112
SANTOS	163	220	320	335	837	943
ILHA BELA	86	146	246	261	763	869
ILHA GRANDE	0	107	207	222	724	830
RIO DE JANEIRO	107	0	100	115	639	745
CABO FRIO	207	100	0	10	539	645
BÚZIOS	222	115	10	0	524	630
ILHÉUS	724	639	539	524	0	117
SALVADOR	830	745	645	630	117	0
MACEIÓ	1057	972	872	857	297	284
RECIFE	1171	1086	986	971	483	400
NATAL	1325	1240	1140	1125	630	547
FORTALEZA	1585	1500	1400	1385	890	807

DISTANCE MATRIX – PART 3

	Maceió	Recife	Natal	Fortaleza
RIO GRANDE	1705	1819	1973	2233
PORTO BELO	1369	1483	1637	1897
BALNEÁRIO CAMBURIÚ	1346	1460	1614	1874
ITAJAÍ	1339	1453	1607	1867
SANTOS	1170	1284	1438	1866
ILHA BELA	1096	1210	1364	1624
ILHA GRANDE	1057	1171	1325	1585
RIO DE JANEIRO	972	1086	1240	1500
CABO FRIO	872	986	1140	1400
BÚZIOS	857	971	1125	1385
ILHÉUS	297	483	630	890
SALVADOR	284	400	547	807
MACEIÓ	0	198	432	701
RECIFE	198	0	159	432
NATAL	432	159	0	277
FORTALEZA	701	432	277	0

APPENDIX 5 – WEATHER CONDITIONS MATRIX FOR THE BRAZILIAN COAST REGION

AVERAGE PRECIPITATION DAYS PER MONTH

Ports	J	F	M	A	M	J	J	A	S	O	N	D
Rio Grande	10	8	9	10	11	11	10	11	11	10	9	9
Porto Belo	12	13	12	8	7	8	8	8	11	11	11	11
Balneário Camburiú	12	13	12	8	7	8	8	8	11	11	11	11
Itajaí	12	13	12	8	7	8	8	8	11	11	11	11
Santos	15	14	11	7	6	4	4	4	7	10	11	14
Ilha Bela	15	14	11	7	6	4	4	4	7	10	11	14
Ilha Grande	12	7	8	9	6	6	4	5	7	9	10	11
Rio de Janeiro	12	7	8	9	6	6	4	5	7	9	10	11
Cabo Frio	12	7	8	9	6	6	4	5	7	9	10	11
Búzios	12	7	8	9	6	6	4	5	7	9	10	11
Ilhéus	14	16	19	22	25	24	24	20	16	14	15	14
Salvador	14	16	19	22	25	24	24	20	16	14	15	14
Maceió	12	14	16	21	23	24	25	22	15	11	9	10
Recife	12	14	16	21	23	24	25	22	15	11	9	10
Natal	12	14	16	21	23	24	25	22	15	11	9	10
Fortaleza	12	14	16	21	23	24	25	22	15	11	9	10

MEAN SUNSHINE HOURS

Ports	J	F	M	A	M	J	J	A	S	O	N	D
Rio Grande	233	196	192	174	167	143	158	156	153	189	223	249
Porto Belo	201	185	194	195	185	163	169	152	129	159	173	188
Balneário Camburiú	201	185	194	195	185	163	169	152	129	159	173	188
Itajaí	201	185	194	195	185	163	169	152	129	159	173	188
Santos	170	162	167	165	182	172	187	175	152	153	163	150
Ilha Bela	105	106	106	102	109	106	110	104	78	73	83	92
Ilha Grande	105	106	106	102	109	106	110	104	78	73	83	92
Rio de Janeiro	196	207	196	166	171	157	183	178	137	159	169	179
Cabo Frio	153	137	157	133	159	132	149	166	139	97	109	144
Búzios	153	137	157	133	159	132	149	166	139	97	109	144
Ilhéus	221	216	236	203	200	191	198	211	199	200	190	220
Salvador	246	226	231	190	174	167	181	203	211	228	214	225
Maceió	254	226	203	179	192	179	176	205	205	252	275	264
Recife	246	211	204	185	187	168	170	108	217	247	266	255
Natal	255	206	199	174	194	178	193	236	248	253	280	263
Fortaleza	216	176	149	153	209	240	263	269	283	296	283	257

DAILY MEAN TEMPERATURE

Ports	J	F	M	A	M	J	J	A	S	O	N	D
Rio Grande	22.5	22	21	17.5	15.5	12	12.5	13	14.5	17	19	21.5
Porto Belo	24.5	24.5	23.5	23	19.5	17	16.5	17	18	20	22	23.5
Balneário Camburiú	24.5	24.5	23.5	23	19.5	17	16.5	17	18	20	22	23.5
Itajaí	24.5	24.5	23.5	21.5	19.5	17	16.5	17	18	20	22	23.5
Santos	23	23.5	22.5	20.5	18.5	17	17	18	19	20	21.5	22
Ilha Bela	23	23	22	20	17.5	16	15.5	16.5	18	19	20	22
Ilha Grande	23	23	22	20	17.5	16	15.5	16.5	18	19	20	22
Rio de Janeiro	26	26.5	26	24	23	21.5	21.5	21.5	22	23	24	25
Cabo Frio	22	22	21	19	16.5	15.5	15	16	17	18.5	19.5	20.5
Búzios	22	22	21	19	16.5	15.5	15	16	17	18.5	19.5	20.5
Ilhéus	25.5	25.5	25.5	24.5	23.5	22.5	21.5	22.5	23	23.5	24	25
Salvador	26	26.5	27	25	25	24	23.5	23.5	24	25	25	26
Maceió	26	26	26	25.5	25	24	23.5	23.5	23.5	25	25	26
Recife	26	26	26	25.5	24.5	24.5	24	23.5	24	25	25.5	26
Natal	26.5	26.5	26.5	26	25.5	24.5	24	24.5	24.5	25.5	26	26.5
Fortaleza	27	26.5	26	26	25.5	25	25.5	25.5	26	27	27	27

AVERAGE SIGNIFICANT WAVE HEIGHT

Ports	J	F	M	A	M	J	J	A	S	O	N	D
Rio Grande	1.14	1.14	1.19	1.21	1.23	1.19	1.22	1.24	1.37	1.29	1.26	1.17
Porto Belo	1.14	1.12	1.16	1.16	1.20	1.13	1.19	1.24	1.39	1.32	1.28	1.17
Balneário Camburiú	1.14	1.12	1.15	1.15	1.19	1.12	1.19	1.24	1.38	1.31	1.27	1.16
Itajaí	1.11	1.09	1.13	1.13	1.17	1.10	1.16	1.21	1.35	1.28	1.24	1.14
Santos	1.16	1.16	1.27	1.35	1.45	1.38	1.41	1.45	1.56	1.44	1.37	1.22
Ilha Bela	1.29	1.30	1.40	1.50	1.63	1.58	1.62	1.67	1.79	1.63	1.54	1.36
Ilha Grande	1.12	1.13	1.24	1.35	1.47	1.42	1.44	1.47	1.56	1.42	1.34	1.19
Rio de Janeiro	1.07	1.08	1.21	1.33	1.45	1.40	1.40	1.41	1.48	1.34	1.28	1.14
Cabo Frio	1.47	1.44	1.53	1.66	1.80	1.79	1.83	1.86	1.95	1.78	1.70	1.54
Búzios	1.35	1.31	1.40	1.50	1.62	1.61	1.65	1.69	1.77	1.63	1.56	1.42
Ilhéus	1.00	0.98	1.00	1.08	1.19	1.31	1.39	1.36	1.31	1.22	1.18	1.05
Salvador	1.02	1.01	1.05	1.16	1.29	1.40	1.47	1.44	1.37	1.26	1.21	1.06
Maceió	1.25	1.23	1.28	1.38	1.54	1.70	1.78	1.75	1.66	1.52	1.46	1.32
Recife	1.39	1.39	1.40	1.49	1.59	1.72	1.82	1.81	1.71	1.58	1.52	1.42
Natal	1.51	1.49	1.44	1.44	1.46	1.56	1.67	1.71	1.67	1.61	1.57	1.54
Fortaleza	1.68	1.65	1.54	1.48	1.46	1.55	1.68	1.83	1.85	1.82	1.78	1.73