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ARTICLES

OPTIMAL ALLOCATION OF FLEET OF HELICOPTERS AND AIRPORTS TO TRANSPORT PASSENGERS IN OFFSHORE MARITIME UNITS

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ABSTRACT. The choice and distribution of the optimal fleet mix of helicopters to service the offshore air operation is an important logistical problem that has a potential to reduce costs considered in the oil and gas industry. The variability of helicopter models and sizes, as well as the possible operational restrictions of airport bases and airspace, requires that adequate numerical techniques of Operational Research are applied. In this context, this work develops a model to determine the trajectories and distances traveled between airport bases and offshore maritime units and vice-versa, through an airspace modeled by a directed graph. Also develop a helicopter performance model to obtain the estimated payload and flight times for each specified mission and last but not least an integer linear programming model to allocate an optimal fleet and airport mix for passenger transport through the use of different helicopter sizes. The model was applied to offshore units operating in the Santos basin due to their strategic importance in the oil and gas industry. The results obtained included a map of preferred regions for two different helicopter sizes (large and medium), the weekly flight tables showing the allocation of helicopters and airport for different demand scenarios, additionally the impact of fuel prices on different airport bases and the concentration of movements on air routes are also evaluated in order to complement the analysis.

Keywords: optimization, offshore logistics, helicopters.

1 INTRODUCTION

The oil and gas exploration began with onshore operations. However with the growing demand for fuels and the depletion of onshore reserves, exploring the offshore basins has become fundamental in the oil and gas industry. The offshore operation brings several logistical challenges,

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as the supply of general cargos, diesel, and water for maritime units and the transport of workers to and from maritime installations. The transport of workers to and from maritime units are performed by two modes: ships and helicopters. This paper addresses the latter.

The resources involved in the offshore air activity are the helicopter, the airport bases onshore, helidecks aboard maritime units and the airspace between bases and installations. The physical characteristics of the helidecks (size, resistance) are also important for the definition/restrictions of which aircraft will be assigned to each voyage. This work focuses on the three most important resources in air operations: helicopters, airport bases, airspace as well as their interactions, in order to minimize the costs of transporting these workers to maritime units.

The assignment of a helicopter must consider the capabilities and characteristics of the airport bases and the design of the airspace to supply the demand. Although a simplistic criterion may point to the use of a cheaper helicopter considering a single trip, the number of hangars at the chosen airport may not be enough, or even the number of flights to be controlled in airspace may be incompatible with local control capability. Likewise, the assignment of the nearest airport may seem intuitively correct, it may not consider other important factors such as different fuel costs at airports or overload/air route conflicts. Local air traffic rules impose restrictions that need to be consider. The smallest geographic distance between airport and maritime unit cannot be feasible according to the air traffic rules.

To deal with all these particularities that involve the problem of transporting people by helicopters in the service of offshore oil exploration and production units, we developed an environment based on three models: the first serves to model the airspace, the second to calculate the performance of helicopters under different load and distance conditions and the last one aims to build a helicopter X airport X maritime unit allocation table to meet the demand of the latter.

The first model determine the shortest airspace route as a directed weighted graph, where the airports, maritime units and extreme points of the straight segments of the Air Traffic Services (ATS) routes were modeled as vertices of the graph and the straight segments as directed edges of same graph. The weight of the graph is the dimension of the edge, calculated using the geographic coordinates of the vertices. ATS routes are specific routes conduct the flow of air traffic in accordance with the provision of Air Traffic Services.

The second model develop a helicopter performance calculation model to obtain the estimated payload (sum of the weights of passengers, baggage and cargo that can be carried on the aircraft on a given flight), fuel consumption, and flight duration for each voyage. Lastly we propose an integer linear programming model to allocate an airport to a maritime units and select the type of aircraft required in order to minimize the logistical costs.

With this framework we are able to achieve the main objectives of the study, which are: (i) define a map of preferred regions for different helicopter sizes; (ii) construct a weekly flight tables showing the allocation of helicopters and airport for different demand scenarios; (iii) analyze the impact of fuel price on bases in the assignment of airport and unit, and (iv) analyses the concentration of movements on airspace.

1.1 Brief literature review

This article dealing with in offshore air transport is primarily related to the following main topics: flight schedules, selection/sizing of fleets and operational safety. Studies focused on the organization and impacts of air operations in the airspace focused on offshore aviation are rarer, but of paramount importance.

In the context of studies of flight schedules, it can be considered that the use of Operational Research techniques in the offshore air transport industry by helicopters to serve the oil and gas industry started more strongly in the mid-1990s through the works of Galvão & Guimarães (1990). In this work, a computerized system was designed and implemented in order to support flight scheduling decisions in the Campos basin, Brazil.

Later, Moreno et al. (2006) developed a heuristic algorithm based on column generation for the problem of planning helicopter flights to meet requests for transport between mainland airports and offshore platforms for the same region, Campos basin, but with a much higher number of units to be served. Menezes et al. (2010) enhanced the model proposed by Moreno et al. (2006) and developed a software based on the Mixed Integer Programming model whose objective was to prioritize the fleet that would be used to meet a certain demand for maritime units. The model, therefore, proposed to optimize the allocation of aircraft to meet demand. According to the authors, the program was used to schedule daily operations in the Campos basin with significant gains.

Rosa et al. (2016) proposed a mathematical model to solve the Capacitated Helicopter Routing Problem (CHRP) using a Clustering Search (CS) metaheuristics to plan the transportation of employees to oil and gas platforms in the Espírito Santo and Campos basins. The computational experiments indicated that CPLEX would not be able to optimally solve small instance of the problem, but CS metaheuristics would have presented good results.

Vieira et al. (2021) studied a real problem of short-term helicopter flight reprogramming that carry staff from and to maritime units in the context of a oil company and under real restrictions. In addition, they proposed two Mixed Integer Programming (MIP) formulations, based on different representations of Aircraft Recovery Problem (ARP) and developed customized heuristic approaches to find relatively good viable solutions within acceptable computational times.

Navarre (2021) develops an optimization model, which was tested in deep and ultra-deep water offshore units in the Gulf of Mexico, which solves the problem of assigning facilities, vehicles and passengers. Results show that the model effectively solves the complex transportation networks consisting of subject firms offshore nodes and eligible depots.

For the dimensioning of the helicopter fleet, in the Campos basin, Rocha (2001) carried out a case study using a model for dimensioning the helicopter fleet to serve maritime units in this region, based on a model proposed by Etezadi and Beasley (1983). According to the author, the model was able to present a result close to that obtained by the empirical method in force at the time. At the same time, Almeida (2002) proposed a helicopter selection model for the provision of offshore logistical support, based on the AHP (Analytic Hierarchy Process) method. The purpose would be to choose the best commercial proposals within the scope of a Petrobras tender to meet the demand for helicopters still focused on the Campos basin. The author concludes that the method would be valid due to the possibility of combining other criteria, in addition to the financial one (lower cost), guaranteeing, among others, the dimension of productivity and operational safety.

More focused on fleet sizing and allocation, Hermeto et al. (2014) developed a mixed integer optimization model to plan the logistics network in order to assist decision makers in choosing airport bases, distribution and fleet type. The results found indicated gains considered in the possible costs of air logistics. With a similar objective, Fernández-Cuesta et al. (2016) developed a heuristic model for the selection and allocation of fleets in airport bases. The tests were carried out in the Brazilian pre-salt region and in Norway, they also evaluated possible fuel supply hubs between airports and maritime units, and concluded that for the Brazilian case there would be no need for hubs at that stage of operation.

As the availability of the helicopter fleet is one of the main parameters for fleet sizing, Moreira (2015) proposed solutions to increase the availability of helicopter fleets for offshore air transport in the oil and gas industry. The multivariate technique chosen was the Multiple Regression Analysis, in order to verify the relative importance of factors such as fleet age, temperature, humidity, aircraft model, aircraft operator, among others, in the variability of the fleet availability index. The results showed that a greater concentration of the fleet in models with high availability is a more important factor than the choice of air transport companies, keeping the other conditions unchanged.

In addition to flight scheduling and selection/sizing of the helicopter fleet, operational safety is an important pillar in studies of offshore air operations. The works that stand out the most are those by Qian et al. (2011) that models the expected number of fatalities in offshore air operations at an operational planning level. In Qian et al. (2012) the authors evaluated the minimization of operational risk for pilots and passengers in the offshore air transport activity. Ways to increase safety through adequate routing were analyzed, whose objective is to minimize the aggregate operational risk of the occupants of the aircraft and finally, in the same line of studies, Qian et al. (2015) proposed approaches to create safer flight schedules.

Due to helicopter accidents that occurred in the area of the continental shelf of the United Kingdom, Downie & Gosling (2020) question whether what has been done so far has been enough to guarantee the safety of these workers, meeting legal and ethical standards. They analyzed from a legal point of view, the implementation of the recommendations made following these accidents and how the imbalance of power between oil and gas companies and helicopter operators influences safety in this area. They conclude that a public inquiry into the safety of helicopters in the continental shelf area of the United Kingdom would be necessary, showing how the issue of safety is widely discussed in this type of operation.

Some aspects regarding the mode of transport are taken into account in the work by Vilamea (2011) when the author discusses the alternative of operating part of the demand from vessels to a hub at about 160 nautical miles and from there it would complement each other transport from helicopters. However, the regulatory norm NR37, from the Ministry of Labor of Brazil, stipulates a limit of 35 nautical miles for the maximum displacement by vessels to serve maritime units on the Brazilian continental platform.

For an operational analysis of traffic in an airspace dedicated to offshore activities, Hermeto & Muller (2015) analyzed, through fast-time simulation, the impact of the use of ADS-B in the Campos basin. Aircraft use ADS-B technology to monitor their positioning via satellite, transmit their position to other spacecraft and also to a control station in real time. The authors concluded that its use had the potential to improve service level indicators regarding delays and flight time deviations.

In the scope of spatial modeling of any airspace (focused on airplanes), Pereira (2016) presented the problem of how to assess the vulnerability of air transport networks in the context of operational disruption in airports by modeling the Brazilian air system from of complex networks through graphs. The author concluded that the information found can contribute to support the decision-making of managers, especially in relation to the processes of planning the air network, risk management and protection of critical infrastructures.

1.2 Contribution of this work

This work seeks to develop a methodology for calculating helicopter performance aligned with a method of calculating the distance to be traveled by the aircraft in an airspace with well-defined traffic rules and then allocating flights to airports in an optimized way. It also contributes in graphically and expeditiously presenting initial parameters for choosing the type of fleet (medium or large) to be used depending on the distance from the maritime unit to the airport in order to assist in the planning stages of offshore logistics operations.

Only two regions of Brazilian airspace have airspace with specific traffic rules for helicopters in an offshore environment, namely: the Campos basin and more recently the Santos basin, with different rules. Regarding the modeling of this type of airspace, through graph theory techniques, there is no known literature since the topic is relatively new, so this work humbly fills this gap by being applied directly to the Santos basin.

The remainder of this paper is organized as follows: Section 2 defines the problem, Section 3 presents the mathematical models proposed and the experimental results. Conclusions and directions for future research are discussed in Section 4.

2 PROBLEM DEFINITION AND MODELING

The problem under study consists of putting a methodology to find an economically optimal way each maritime unit will have its demand for embarkation and disembarkation of onboard workers met in, considering the local operational and environmental characteristics. To achieve this objective it is necessaire obtain the trajectories and minimum distances between airport → maritime unit → airport, following the traffic rules stipulated in the region; to identify which airport will serve each unit using which type(s) of helicopter (s), and with how many weekly flights. The main aspects that must be considered are:

- Airport operational conditions (location, quantity, occupancy, yard restrictions, hangars etc.);
- Environmental conditions on land (airport opening hours, weather, noise, land access, accommodation, medical service etc.);
- Environmental conditions at sea (impacts from currents, wind, weather etc.);
- Type of marine units (fixed, floating, dimensions and strength of helidecks etc.);
- Air traffic rules that may vary from one region to another.

The methodology developed only considers passengers boarding the helicopter at the airport bound for maritime units. The same number of passengers is expected to disembark (return to airport) from the same maritime unit to the airport in the long term.

Therefore, air operation planning needs to consider all these aspects when maintaining an efficient and safe logistics network. Due to the location changes of some types of maritime units, planning must be carried out dynamically, that is, when any maritime unit changes location, its flight schedule must be reassessed, which may even impact other units due to capacity restrictions imposed by airports and the profile of the fleet in service.

Airports will have their theoretical capacity for daily flights defined, both in the total number of flights and by type of helicopter (large or medium-sized). Airport capacity restrictions do not necessarily mean physical restrictions, that is, that the airport cannot exceed them in contingency situations, for example, but rather an estimated desirable level of operation at each aerodrome. This capacity considers the airport infrastructure (yard, runway, terminal, hangars), possible environmental impacts that the operation may have on the surrounding community (noise etc.), as well as strategic issues regarding the concentration of operation in certain aerodromes and/or fleet available.

There will be no routing of the aircraft passing through more than one maritime unit per flight, that is, the helicopter will pass through a single maritime unit, with origin and final destination the same aerodrome (pendular model). Figure 1 illustrates the pendular model adopted. The following sections detail the airspace modeling, the calculation of helicopter performance, the allocation model of maritime units to airports, as well as a proposal for fleet sizing.

2.1 Airspace modeling

Modeling an airspace means creating the conditions for a computer program to understand the traffic rules stipulated in that region in order to trace the appropriate routes from a specified origin to a specified destination and with that calculate the total distances traveled. One way to model

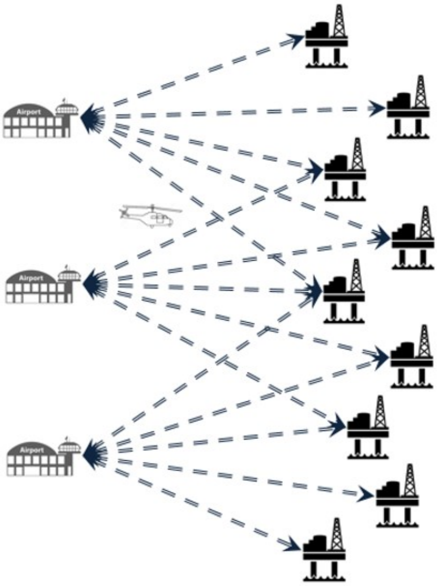

Figure 1 – Proposed operational model - pendular.

this airspace is through a directed graph, where each airport, maritime unit and waypoint in space corresponds to a vertice. The airspace must have connections between vertices that are directed, which we will call directed edges, that is, a connection between a vertices A to a vertices B may be allowed, but its inverse may not be allowed.

The airspace to be studied may have specific rules for departure from the airport to the first waypoint and for arrival and departure at maritime units that must be considered. Figure 2 presents a generic airspace modeled through a graph. There are gates that aircraft must follow in order to enter or leave the airspace, as well as mandatory entry and exit gates depending on which square the maritime unit is in. The maritime unit that is in a certain quadrant must have a single entry gate through which the aircraft must pass on the outbound flight before landing at the maritime unit and a single exit gate through which the aircraft must pass after takeoff from the unit sea on the return flight.

The edges that connect the entry and exit gates of the grids to the maritime units are not predefined in the airspace, since they depend on the geographic coordinates of each maritime unit at the time of flight. All other edges are fixed and immutable.

As part of the maritime units (rigs, special vessels, among others) are not stationary in the same place, it is initially necessary to find out in which grid all maritime units are located on that date of analysis, in order to determine by which gates input and output from that square shall be used on each flight path. With the definition of the entrance and exit grid gates for each maritime unit, the Graph initially modeled must be complemented with the gates and fixed waypoints with

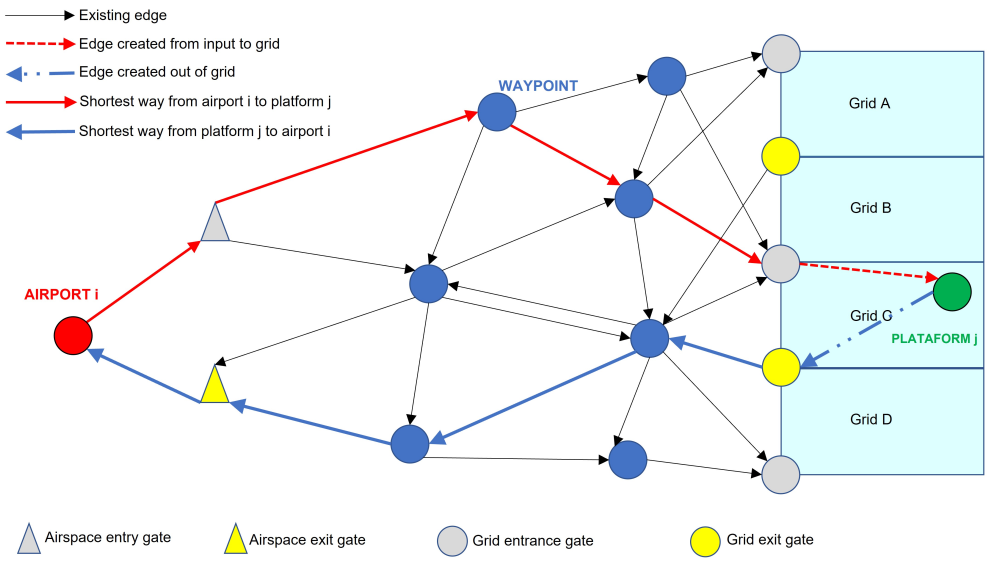

Figure 2 – Generic airspace modeled by a graph.

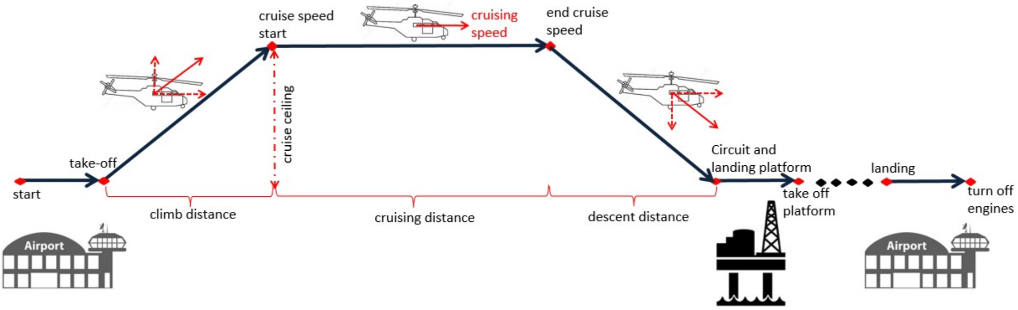

Figure 3 – Detailed proposed operating model.

complementary edges connecting the grid entrance gate to the platform and from this to the exit gate of the corresponding grid.

With the generated graph, taking into account each waypoint, airport and georeferenced maritime unit, the trajectory between the airport → maritime unit and the maritime unit → airport will be the shortest path covered in this graph using a shortest path algorithm, which in this work adopted the Dijsktra (1959) algorithm.

2.2 Performance helicopter model

The performance model aims to find the number of passengers, flight times, and amount of fuel consumed in each specified mission. Figure 3 indicates the main notable points of the operation considered in the model (departure, take-off at the airport, start of cruise flight, end of cruise flight, circuit and landing on the platform, take-off from the platform, start of cruise flight, end of cruise flight, airport landing and airport cut-off).

To calculate the number of possible passengers on board, it is necessary to know the payload for each mission, that is, the useful transport capacity on the aircraft, which includes passengers, cargo and baggage. The parameters are described in Table 1 whose proposed model consists of determining the number of passengers, flight times and amount of fuel consumed in the mission. Thus, the number of passengers possible to board the flight will be calculated according to Equation 1 to 4.

Table 1 – Performance model parameters.

Parameters	
cei^{cru}	Cruising ceiling
$fuelc^{f}$	In-flight fuel consumption
$fuelc^{g}$	On-ground fuel consumption (include helideck)
MTW	Maximum Takeoff Weight
OBW	Operating Basis Weight
r^{asc}	Rate of ascent
r^{des}	Descent rate
s	Number of seats available on the helicopter
spd^{cru}	Cruising speed
t^{dck}	Time on the ground (in helideck)
t^{g}	Time on the ground (in airport)
t^{pc}	Time on plataform circuit
w^{pax}	Standard weight of the passenger with their personal luggage
d^{tot}	Total distance traveled in the flight
$fuel^{mis}$	fuel from start to stop
$fuel^{res}$	Added fuel to ensure safe operation
t^{f}	Time in flight
pax	Number of passengers allowed to be boarded on the flight

$$pax = \begin{cases} min\left(s; \left\lfloor \frac{MTW - OBW - fuel^{mis} - fuel^{res}}{w^{pax}} \right\rfloor\right), & \text{if helicopter compatible helideck} \\ 0, & \text{if otherwise} \end{cases} \tag{1}$$

$$fuel^{mis} = t^{f} \times fuelc^{f} + (t^{g} + t^{dck}) \times fuelc^{g} \tag{2}$$

$$t_f = 2 \times \left(\frac{cei^{cru}}{r^{asc}} + \frac{\frac{d^{tot}}{2} - \frac{spd^{cru}}{2} \times \frac{cei^{cru}}{r^{asc}} - \frac{spd^{cru}}{2} \times \frac{cei^{cru}}{r^{des}}}{spd^{cru}} + \frac{cei^{cru}}{r^{des}} \right) + t^{pc} \tag{3}$$

$$fuel^{res} = max[1/2; (1/3 + 0,1 \times (t^{f} + t^{g} + t^{dck}))] \times fuelc^{f} \tag{4}$$

Function (1), which calculates the maximum number of passengers carried, is defined as the difference between the Maximum Takeoff Weight, the Operating Basic Weight, both defined by the aircraft manufacturer, and the total amount of fuel needed to fulfill the mission, including reserve fuel, divided by the standard average passenger weight. If the maritime unit's helideck is restricted to receive the specified type of aircraft, the number of passengers to be transported will be zero. The maximum number of passengers to be transported will be the number of seats available on the aircraft type.

The fuel needed to fulfill the mission, presented in Function (2), is calculated as a function of the flight time multiplied by the theoretical consumption of in-flight fuel and the time of the grounded aircraft times the theoretical consumption of the grounded aircraft. The flight time, presented in Function (3), is calculated taking into account that the cruise speed is reached at the same time the aircraft reaches the cruising altitude, leaving zero speed at the time of take-off at the airport and arriving again at zero on landing on the platform. With this, three time parcels are calculated, namely: ascent time, cruise time and descent time.

The ascent and descent times are calculated as the ratio between the cruise ceiling and the constant climb rate and the cruise ceiling and the constant descent rate, respectively. The time the helicopter is at cruising speed is half the total distance minus the ascent and descent distances divided by the cruising speed.

The flight time between the airport and the maritime unit will be considered equal to the return flight time, since the average distance was adopted, therefore they must be added to the total flight time composite. Added to this total time is included the circuit pattern time that the aircraft has to perform for identification and preparation for landing on the maritime unit.

For the calculation of the amount of reserve fuel required, presented in Function (4), it is defined as the maximum value between the fuel needed for 30 minutes of flight and the fuel needed for the aircraft to perform a flight lasting 20 minutes plus 10% of total mission time.

2.3 Flight Mix Allocation Model (FMAM)

In this section, an integer linear programming problem model will be presented, which seeks to find the optimal mix of service, using different aircraft, optimally allocating maritime units to airport bases, considering the capacity constraints of these facilities, aircraft and maritime units. The FMAM considers the logistical cost of flown hours and fuel consumption as the objective function of the problem.

It is intended to define how many and through which airports the flights will be served, in an optimized way, using what kind of helicopters. The sets, parameters and variables are described in Table 2 and the proposed model consists in minimizing the objective function (7) subject to constraints (8) to (11).

Each maritime unit has a specific need for the number of weekly shipments of workers depending on their size or the activity being carried out. Denotes by D_j the demand for passenger seats for weekly departures (equal to arrivals) for each maritime unit. The D_j demand is invariable in relation to the airport of service.

To meet the demand of D_j passengers, the weekly number of flights carried out by helicopters from an airport will be denoted by v_{ijk}. The number of passengers served (considering boarding only), per week in each maritime unit j from airport i using aircraft k, will be calculated according to Equation 5. Where v_{ijk} is the number of flights, from airport i to maritime unit j using aircraft k and pax_{ijk} is the maximum numbers of passengers served on each flight per helicopter size from each airport i for each maritime unit j in the aircraft k.

$$p_{ijk} = v_{ijk} \times pax_{ijk} \tag{5}$$

The cost of each flight departing from airport i to maritime unit j using aircraft k can be calculated by Equation 6.

$$c_{ijk} = f_k^p \times \left(t_{ijk}^f + t_k^{dck}\right) + fuel_i^p \times fuel_{ijk}^{mis} \tag{6}$$

For the purposes of accounting for the total flight time, the time landed on the platform is considered as the hour flown and must be added to the flight time, as the change of passengers (disembark and board the helicopter) takes place with the rotors rotating.

In order to optimally define the table of flights of each airport i for each maritime unit j, the mathematical formulation, adopting Integer Linear Programming, will have as Objective Function the minimization of the cost of expenditure with the air operation, focusing on operating costs derived from the hours flown (the cost already included with the consumption of fuel). The values corresponding to the fixed costs of the helicopters will be disregarded in this model, due to the premise that the fleet is already contracted and is available for the operation and will only be evaluated at the end when the verification of the fleet sizing is carried out.

The parameters and variables are described in Table 2 and the proposed model consists in minimizing the objective function (7) subject to constraints (8) to (11). The formulation for the proposed model is given by:

$$\mathbf{min} \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{q} \left(c_{ijk} \times v_{ijk}\right) \tag{7}$$

s.t.

$$\sum_{i=1}^{n} \sum_{k=1}^{q} p_{ijk} \geq D_j, \forall j \in J \tag{8}$$

$$\sum_{j=1}^{m} \sum_{k=1}^{q} v_{ijk} \leq \delta_i, \forall i \in I \tag{9}$$

$$\sum_{j=1}^{m} v_{ijk} \leq \varepsilon_{ik}, \forall i \in I, \forall k \in K \tag{10}$$

$$v_{ijk} \in \mathbb{Z}^+, \forall i \in I, \forall j \in J, \forall k \in K \tag{11}$$

Table 2 – Sets, parameters and variables FMAM.

	Sets
I(i)	set of airports
J(j)	set of maritime units
K(k)	set of types of aircrafts
	Parameters
n	Number of airports
m	Number of maritime units
q	Number of types of aircrafts
pax_{ijk}	Passengers transported on each flight
c_{ijk}	Cost of a flight
f^p	Flight hour price
$fuel^p$	Price per liter of fuel
δ_i	Total airport i flight capacity
ε_{ik}	Capacity of flights of aircraft k at airport i
D_j	Demand for seats
	Non-negative integer variables
v_{ijk}	Number of flights

The Objective Function (7) seeks to minimize the logistical cost. Constraints (8) state that all passenger demand must be met. The Constraints (9) state that the total capacity of flights at airport i will not be exceeded. Constraints (10) establish that the capacity for aircraft k flights at airport i will not be exceeded. Constraints (11) present the domain constraints of the variables.

2.4 Fleet sizing at each airport

Verification of the required fleet on each airport is important in order to make a comparison with the contracted fleet available on each airport (by type). Equation 12 gives the the necessary fleet in each aeroport i, by helicopter k.

$$fleet_{ik} = \frac{\left(\sum_{j=1}^{m} \frac{v_{ijk}}{7}\right) \times \left[1 + \frac{1}{Rf_{ik}}\right] \times \frac{1}{Av_{ik}^{average}}}{N_{ik}^{max}} \tag{12}$$

Where:

- Rf$_{ik}$: Recovery factor adopted as a function of closed aerodrome days. It is the number of days that demand will be fully serviced after 1 day of the airport being closed (for example: adverse weather conditions).

  The definition of the Recovery factor is intrinsically linked to the desired service level in the operation. The adoption of 4 days means that if you have an entire day without operation on the airport i (for weather reasons, for example), the demand will be fully met in the airport i in the next 4 days. In other words, the fleet available at the airport will be able to meet up to a 25% increase in the daily expected demand. This “slack” in the offer of helicopters can be used during the other days of operation to attend to unplanned (extraordinary) flights.

- $\text{Av}_{ik}^{average}$: Average availability in the aircraft k in the airport i. Percentage of aircraft time available for operation. It considers the downtime necessary to carry out the necessary maintenance/inspections (it is not considered in the “setup” time).
- N_{ik}^{max}: Maximum number of daily flights that an aircraft k can perform in the airport i.
- T_{ik}^{f}: Time between flights. Considered the ”setup” time, that is, it is the minimum time required for inspections/refueling between two consecutive flights of the same aircraft.
- Taverage_{ik}^{f}: Average flight time. Average total mission time (between turning the engines on and off) average in the basin.
- Window_{ik}^{op}: Operating window. Average viable operating time between sunrise and sunset or the availability limit defined in the aircraft charter contract, whichever is smaller.

Figure 4 presents these parameters in a daily service schedule.

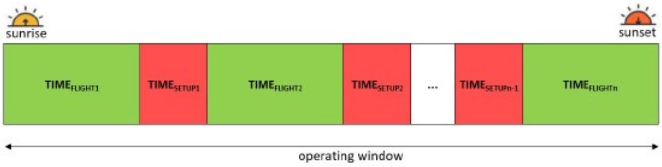

Figure 4 – Daily service schedule scheme.

Result:

$$N_{ik}^{max} \times Taverage_{ik}^{f} + (N_{ik}^{max} - 1) \times T_{ik}^{f} \leq Window_{ik}^{op} \tag{13}$$

$$N_{ik}^{max} \leq \left\lfloor \frac{Window_{ik}^{op} + T_{ik}^{f}}{Taverage_{ik}^{f} + T_{ik}^{f}} \right\rfloor \tag{14}$$

3 EXPERIMENTS AND RESULTS

This section defines the airport bases and maritime units considered, as well as their demands for passengers and operational restrictions. The results obtained through the proposed experiment are also presented. Initially, input data is presented with the location and demand of the maritime units, as well as the airport bases considered, with their respective capacity and location restrictions. Then, the scenarios that will be implemented in FMAM are defined.

With the airspace modeled, the Python package NetworX (2022) is implemented in the modeler and used to obtain the shortest path of the route airport → maritime unit → airport. For the implementation of the FMAM model and performance calculations, codes were developed in the Python programming language, using the PuLP (2022), a linear programming modeler, whose source codes and input data were hosted in a repository on the Github site github.com/hugolustosa/Gerador-de-Tabelas. A computer with Intel(R) Core(TM) i3-8130U CPU @ 2.20GHz 2.21GHz was used for processing the model. At the end, the analysis of the results for the various scenarios studied considering the FMAM is carried out.

3.1 Case study

In June 2021, the airports of Jacarepaguá and Cabo Frio, both in the state of Rio de Janeiro, served 42 maritime units in the service of Petrobras, the main Brazilian oil and gas operator, in the Santos basin. For this study, the maritime units were divided into the categories listed in Table 3. This categorization aims to define the weekly demand for passenger transport, as well as possible operational restrictions on landing on helideck.

Table 3 – Types of maritime units.

Type	Quantity	Change location?
Fixed production	2	no
FPSO	18	no
FPSO test	1	yes
Drilling (NS and SS)	9	yes
PLSV, DSV	8	yes
Maintenance and Security Unit	4	yes
	42	

The definition of the itinerary are made using the airspace modelling presents in section 2.1. The airspace of the Santos Basin needs to be modeled so that it can represent the provisions of the Circular of Aeronautical Information AIC 27/21, of the DECEA (Department of Air Space of Brazil), and guarantee that the trajectory of the aircraft follows as recommended in the legislation aeronautical, and not in a straight line (direct route), so that your distances traveled between airport maritime unit airport can be calculated correctly.

Figure 5 shows an example of an itinerary for a planned flight departing Jacarepaguá airport going to FPSO P-66 and returning to Jacarepaguá. On the way to the maritime unit (red line), the aircraft passes through a mandatory entrance gate into the basin and through 10 waypoints until arriving at the platform traveling 167.2 nautical miles. On the way back (blue line) to the continent, the aircraft passes through 10 waypoints and 1 obligatory exit gate from the basin, covering another 163.3 nautical miles.

It can be seen that the trajectories of the aircraft have to follow a specific path passing through the entrance and exit gates of the basin, in addition to specific routes and waypoints depending on the location of the maritime unit. The operational model adopted in this work consists of serving each maritime unit, with its location and demand for known passengers, through existing airports geographically located closer to these units and contiguous to the coast.

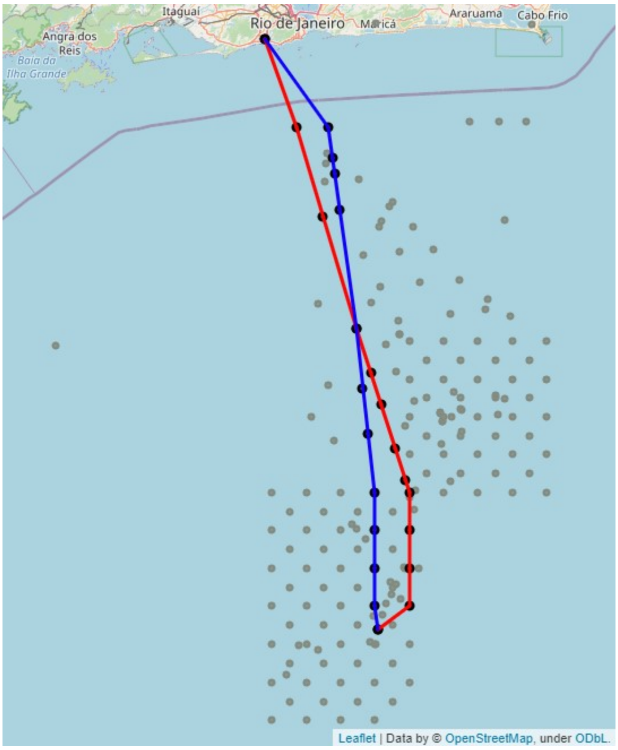

Figure 5 – Example itinerary SBJR → FPSO P-66 → SBJR.

3.2 Input data

The actual passenger demand for the operation of the 42 maritime units served at the Jacarepaguá and Cabo Frio airports in June 2021 was considered, with their appropriate georeferenced location on june/2021. The need to have a ”photograph” of the location of maritime units defined is necessary due to the constant movements, especially of special vessels. If the demand for any maritime unit was not known, it could be estimated according to Table 4, which lists the shipping demand by type of maritime unit.

Table 4 – Passenger demand estimate (weekly departures).

Type	P50	P75	P90
production	72	75	77
drill	85	87	89
special boat	25	30	35

Table 4 was built by analyzing passenger transport data throughout 2019 from the Jacarepaguá and Cabo Frio bases. The first column of the table presents the types of maritime units included in the study, with their respective demands for passenger boarding in the year 2019 with the percentiles of 50, 75 and 90%. Fixed units and MSU (Maintenance and Safety Units) were disregarded in the analysis due to the small sample analyzed, but the same demand was adopted for fixed units as production and for the MSU, weekly shipment demand was adopted in 250. In this work, the actual demand of each maritime unit was not used, but the weekly shipment demand calculated, with a percentile of 75%.

Figure 6 shows a heat map with the location of the units and their respective demand for passengers, highlighting the regions of the Búzios and Tupi blocks, which concentrate most of the demand in the Santos basin. The case study also considers that aerodromes will have their capacity limited in the number of daily flights, either by aircraft size or in the total quantity. Table 5 presents the aerodromes considered in the case study with their respective virtual capacity constrains.

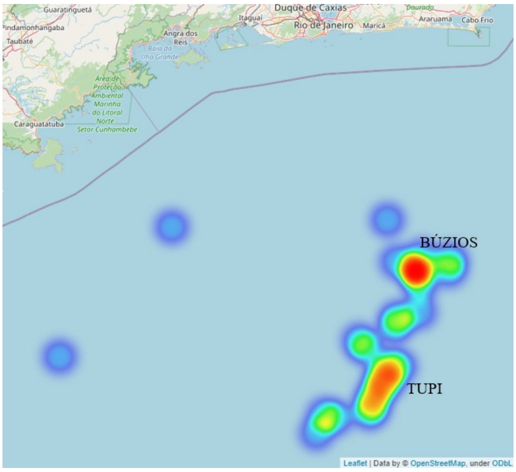

Figure 6 – Maritime units heat map - pax demand.

Table 5 – Aerodrome constrains.

Aerodrome	Daily flight constrains		
	Large size	Midsize	Total
SBJR (JACAREPAGUÁ)	15	20	26
SBMI (MARICÁ)	10	10	15
SBCB (CABO FRIO)	15	20	26
SBME (MACAÉ)	no constrains	no constrains	no constrains

3.3 Parameterization of flight times and mission payloads

With the Performance Helicopter Model, it was possible to parameterize the total flight times (from takeoff at the airport to the final landing at the airport) and capacities (payloads) for the two sizes of studied helicopters. Figure 7 shows the results of these parameterizations.

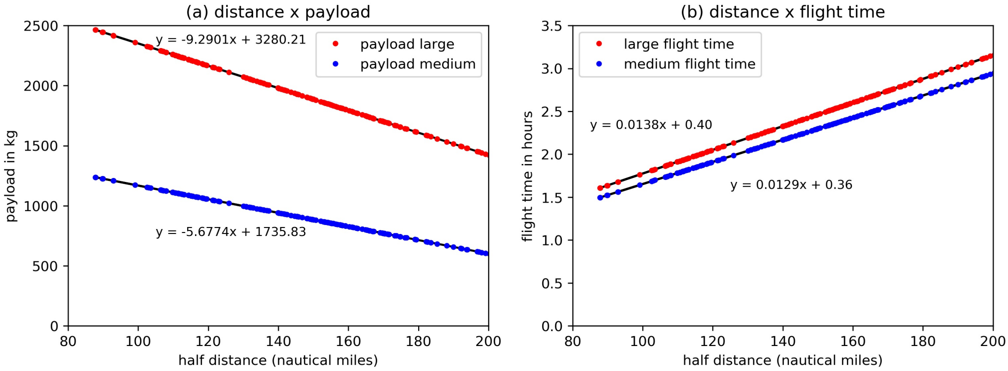

Figure 7 – Parameterizations (a) payload, (b) flight time.

Figure 7 (a) presents the parametric curves where the x axis is the half total distance of the airport → maritime unit → airport mission, in nautical miles, and the y axis is the payloud, in kg, for the two types of aircraft. And the figure 7 (b) presents the parametric curves where the x-axis is the half-total distance of the airport → maritime unit → airport mission, in nautical miles, and the y-axis is the flight time, in hours, for both types of aircraft. From these parameters, it is possible to preliminarily evaluate the most advantageous regions to operate with large and medium-sized aircraft, considering the relationship between the variable costs (price of hour flown and fuel) of the respective sizes of the helicopters.

Figure 8 shows the most advantageous regions to operate by aircraft type, taking the variable cost (including fuel) per transported passenger, considering that the aircraft have full occupancy of their seats within the limit of available for each mission with medium-sized aircraft considered in this 6.800 kg MTW study. It also shows the number of passengers that can be transported by the two types of helicopters. Note that the decrease in the number of passengers as a function of distance occurs in a staggered way, due to the integer condition of the number of passengers.

It can be seen in Figure 8 that maritime units that have around up to 99 nautical miles of half-way airport → platform → airport route tend to be operated by medium-sized helicopters, maritime units that have around from 118 nautical miles airport → platform → airport half-distance tend to be operated by large helicopters and the units that fall between these values are in a neutral region. In this region, the medium-sized aircraft has the capacity to carry 10 passengers and the large aircraft has a capacity of 18 passengers.

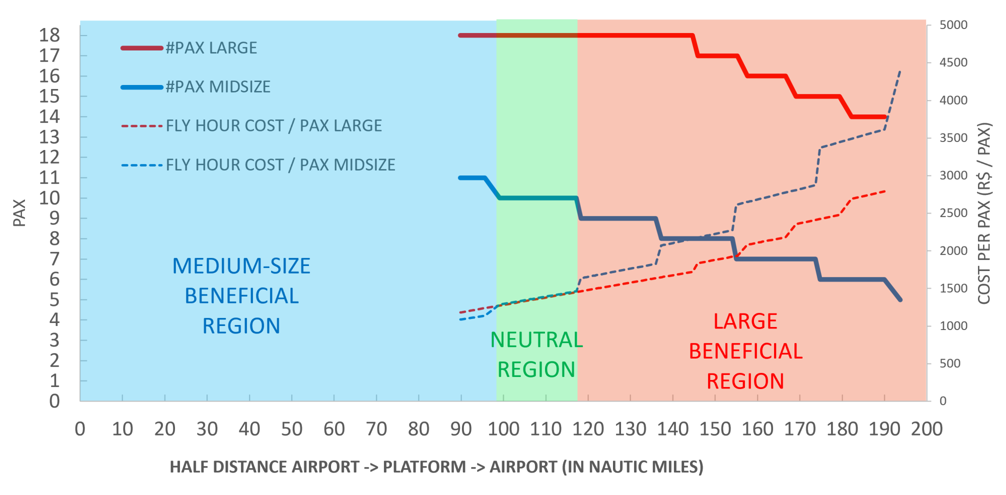

Figure 8 – Preferred region with MTW = 6.800 Kg.

When considering the mid-sized aircraft with MTW of 7.000 (possible structural improvement on the AW139) the large aircraft no longer clearly has a preferred region. Figure 9 shows the new region for this aircraft model.

This analysis can be interesting when you have uncertainty about the demand for shipments for unit(s) and if you want to use only one type of aircraft model. However, this is a preliminary assessment, as, by not taking into account the demand of each maritime unit specifically and using only one helicopter size, seat offers on certain flights may occur. With the possibility of adopting a mix of service, using both large and medium-sized helicopters to meet the schedule of flights from the same maritime unit, the possibility of spare seats is reduced, and with this it is more likely to find the best combination of service in which the lowest total variable cost is obtained. In this study, the possible impacts on the operations of maritime units were not considered due to a higher frequency of flights of medium-sized aircraft to the detriment of large flights.

3.4 Definitions of scenarios

Six scenarios were built, consolidated in Table 6, to assess the optimal service configuration, considering the various combinations of opening and closing of the aerodromes under analysis. Scenarios with a single open aerodrome were not considered due to the strategic premise of not concentrating all passenger demand in the Santos basin in a single service point. Scenarios 1.1 represents the fuel price sensitivity analysis.

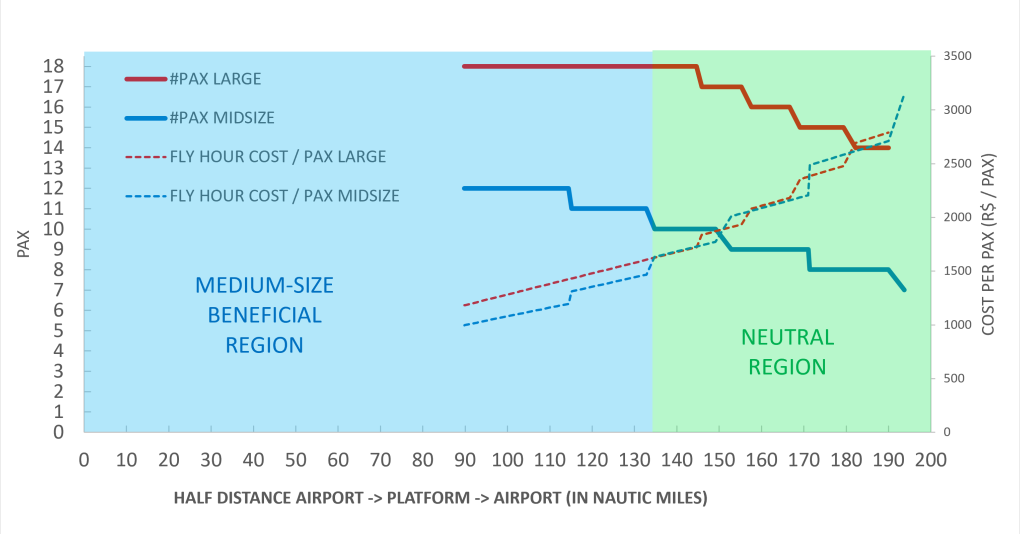

Figure 9 – Preferred region with MTW = 7.000 Kg.

Table 6 – Scenarios analyzed.

Sce.	SBJR	SBMI	SBCB	SBME
1	✓	✓	✓	X
2	✓	X	✓	X
3	✓	✓	X	X
4	X	✓	✓	X
5	✓	X	X	✓
1.1 (no capacity constrains)	✓	✓	✓	X

In the scenarios where Cabo Frio airport (SBCB) is open, opening Macaé airport (SBME) becomes innocuous because all units under analysis are closer to Cabo Frio when compared to Macaé. Table 7 show the parameters adopted for verifying the dimensioning of the fleet.

Table 7 – Aircraft parameters.

Item	Size	
	Large	Midsize
MTW	26.500 lb	6.800 kg (7.000 kg)
OBW	18.115 lb	4.680 kg
w^{pax}	235 lb	107 kg
$fuelc^{f}$	1.350 lb/h	400 kg/h
$fuelc^{g}$	675 lb/h	320 kg/h
t^{g}	17 min	17 min
t^{pc}	4 min	4 min

Table 7 - continued from previous page

Item	Size	
	Large	Midsize
t^{dck}	10 min	8 min
T^{f}	45 min	45 min
$Taverage^{f}$	2,75 h	2,75 h
r^{asc}	800 ft/min	800 ft/min
r^{des}	500 ft/min	500 ft/min
spd^{cru}	145 kt	155 kt
cei^{cru}	3.000 ft	3.000 ft
Rf	5 days	5 days
$Av^{average}$	92,5%	92,5%
f^{p} (R$/hours of flight)	R$ 9.000	R$ 5.000
$fuel^{p}$ (R$/liter)	R$ 5,00	R$ 5,00
s	18	12

3.5 Results of Optimal Allocations

Table 8 shows the result of passenger boarding capacities at each airport for all maritime unit. Not all combinations of origin and destination are feasible (example: SBME → PMLZ → SBME) due to the autonomy of the aircraft, however this restriction was not considered, as it is expected that in the model these combinations are rejected due to its high derivative cost.

Table 8 – Result of pax boarding capacities in each maritime unit.

un.	UM	SBJR		SBMI		SBCB		SBME	
		Large	Mid	Large	Mid	Large	Mid	Large	Mid
1	PMLZ	0	7	0	5	0	4	0	2
2	PMXL	0	10	0	9	0	7	0	5
3	FPAR	16	7	16	7	15	7	12	5
4	FPIB	15	7	15	6	14	6	11	4
5	FPIT	18	9	18	8	18	8	14	6
6	FPMA	18	8	18	8	17	8	14	6
7	FPMR	17	7	17	7	16	7	13	5
8	FPPA	17	8	17	8	16	7	13	5
9	FPPL	18	9	18	10	18	10	18	8
10	FPCS	18	11	18	11	18	11	18	9
11	FPSP	15	7	15	6	14	6	10	4
12	FPSA	16	7	16	7	16	7	13	5
13	NS31	18	10	18	10	18	10	18	8
14	NS33	18	10	18	10	18	10	17	8
15	NS38	18	9	18	9	18	10	17	8

Table 8 - continued from previous page

un.	UM	SBJR		SBMI		SBCB		SBME	
		Large	Mid	Large	Mid	Large	Mid	Large	Mid
16	NS39	18	9	18	10	18	10	18	8
17	NS40	18	9	18	10	18	10	18	8
18	NS42	18	9	18	8	18	8	15	6
19	NS43	18	9	18	8	18	8	14	6
20	NS44	18	9	18	9	18	9	15	7
21	P-66	16	7	16	7	15	7	12	5
22	P-67	17	8	17	8	17	8	13	6
23	P-68	18	9	18	9	18	8	15	6
24	P-69	16	7	15	7	15	6	12	4
25	P-70	18	9	18	9	18	9	16	7
26	P-74	18	10	18	10	18	10	17	8
27	P-75	18	9	18	9	18	9	16	7
28	P-76	18	10	18	10	18	10	17	8
29	P-77	18	10	18	10	18	10	18	8
30	SS75	15	7	15	6	14	6	11	4
31	UMMA	18	10	18	10	18	10	17	8
32	UMPA	16	7	16	7	15	7	12	5
33	UMTJ	18	10	18	10	18	10	17	8
34	UMVE	18	11	18	11	18	11	18	9
35	SRIO	0	10	0	10	0	10	0	8
36	SARU	0	8	0	7	0	7	0	5
37	SAJA	0	7	0	7	0	6	0	4
38	FASA	0	9	0	10	0	10	0	8
39	SECR	0	7	0	7	0	7	0	5
40	SAON	0	8	0	8	0	8	0	6
41	SKST	0	8	0	8	0	7	0	5
42	SKAU	0	7	0	7	0	7	0	5

Table 9 compares variable annual operating costs (hour flown and constant fuel price, not including the fixed cost of the fleet) for each of the 5 (five) analyzed scenarios.

Figure 10 and Figure 11 show the result of the weekly flight tables for Scenario 1 of the analysis, which considers the SBJR, SBMI and SBCB airports open to operation with their appropriate capacity restrictions met. Figure 10 (a) shows the verification of the fleet, by type of model at each aerodrome. It turns out that SBJR was the only base that needed more large aircraft than medium ones. In (b) the number of weekly flights in each base per aircraft size is presented. In (c) the number of hours flown per size at each base and finally in (d) the number of seats available for boarding per week at each aerodrome per aircraft size.

Table 9 – Comparison of Scenarios.

Sce.	Bases	Fleet		Variable cost R$	Annual diff. R$
		large	midsize		
1	SBJR, SBMI, SBCB	8,2	10,1	337.396.925	0
2	SBJR, SBCB	8,3	10,2	338.074.784	677.859
3	SBJR, SBMI	9,0	8,8	340.353.712	2.956.787
4	SBMI, SBCB	9,5	8,3	352.222.483	14.825.558
5	SBJR, SBME	11,0	5,5	372.055.979	34.659.054

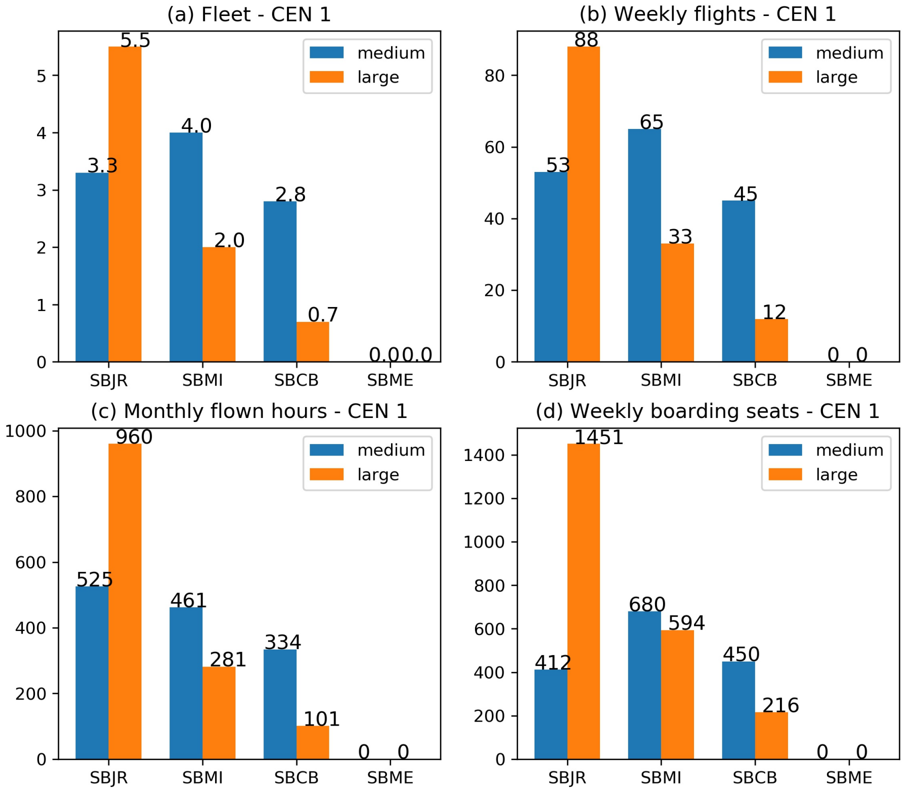

Figure 10 – Optimal distribution per base (a) fleet, (b) flights, (c) hours, (d) seats

There is a greater concentration of flights, hours flown and large seats at Jacarepaguá airport and medium-sized ones at Maricá and Cabo Frio airports. Figure 12 shows a map with the service allocation for Scenario 1. The thicker and darker the edge indicates greater air traffic in the stretch resulting from the optimization.

It appears that Scenario 1 presents the lowest annual cost considering only the hours flown and fuel costs. This is because the airport capacity limits for scenario 1 have not been reached. In Scenario 5, which presents the highest variable costs, the model indicated the need for fewer

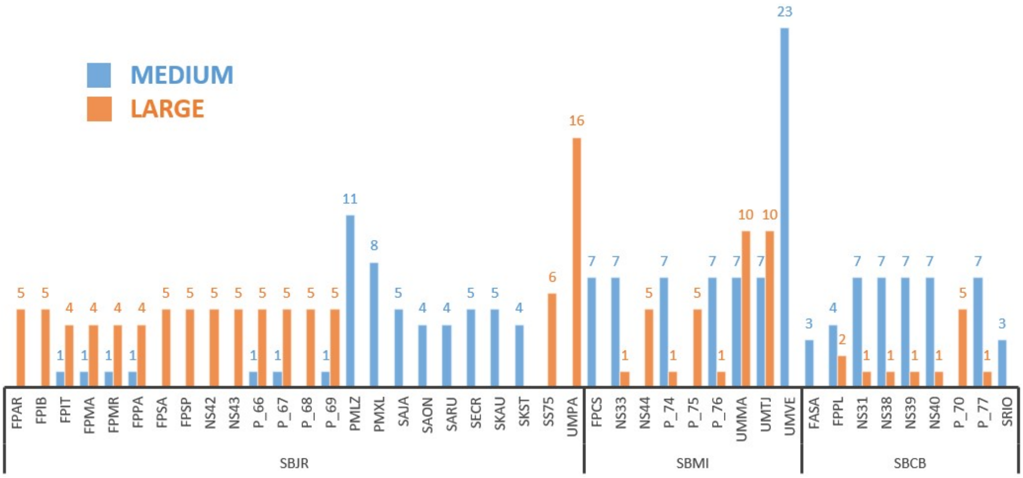

Figure 11 – Optimal distribution per maritime unit.

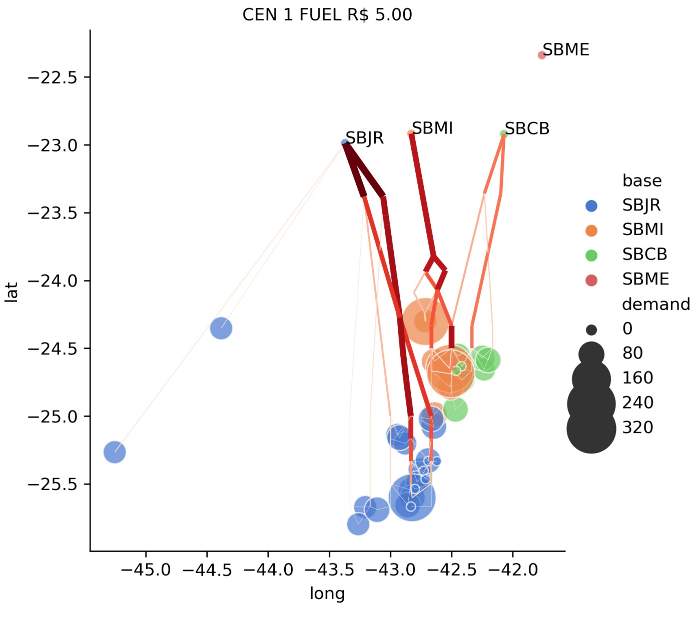

Figure 12 – Scenario 1: Optimal location map of maritime units.

aircraft, which can be explained by the greater concentration of demand at Jacarepaguá airport, which leads to greater economies of scale in the calculated fleet. This scenario still presents a larger aircraft fleet than the medium one, as well as Scenarios 3 and 4. For both scenarios 1 and 2, the ones that presented better results, the FMAM resulted a configuration creating two main service clusters in the studied area, which can be summarized as follows:

→ Tupi/Sapinhoá Cluster (closest marine units to P-66, P-67, P-69): Preferentially served by Jacarepaguá with greater use of large helicopters; and

→ Búzios/Libra Cluster (closest marine units to P-74, P-75, P-76, P-77): Preferentially served by Cabo Frio with greater use of medium-sized helicopters.

3.6 Fuel price sensitivity

For the scenarios analyzed so far (from 1 to 5), the fuel price constant at R$ 5.00 per liter was adopted in all bases. Due to the importance of this input also in rotary wing aviation, it is now intended to evaluate the influence of fuel prices on the allocation of units, not considering capacity restrictions at aerodromes. Figures 13, 14 and 15 show the spatial distribution of maritime units and their respective airport bases when the fuel price reduction for Scenarios 1.1 (no capacity restrictions at aerodromes) is 10% in SBJR, SBMI and SBCB respectively. The results indicate that a reduction from 10% in the price of fuel at SBMI makes this aerodrome attract a good part of the demand that was previously being served by SBJR.

One can also see the behavior of saturation of air routes when the operation is more concentrated in some airport due to the reduction in fuel prices. The scenarios that are most impacted are those in which the price is reduced in SBMI, largely due to the preference for using the edges connected to waypoint CS011 and Maricá airport. It should be noted, however, that the flight levels are different in the mainland → sea and sea → mainland path. For all scenarios initially analyzed (from 1 to 5), the fuel price constant at R$ 5.00 per liter was adopted. Now it is intended to evaluate the influence of fuel costs in Scenario 1.1 (no capacity restriction), considering different fuel prices per base.

Table 10 presents the analyzed scenario considering the impact on fuel price reduction by 10 and 20% at a time on each base, considering the other bases with the original price of R$ 5.00 per liter. The fuel prices of the bases could be changed in different ways, for example, reductions or increases in more than one base at the same time, however, in this work we chose to change one base at a time in order to individually evaluate these changes and thus better capture the impacts.

Table 10 – Fuel price sensitivity analysis.

Sce.	BASE	fuel R$/l	Variable Cost R$	%
1.1	ALL	5.00	337.396.925	0,0%
1.1	SBJR	4.50	329.626.170	-2,3%
1.1	SBMI	4.50	331.607.244	-1,7%
1.1	SBCB	4.50	333.407.095	-1,2%
1.1	SBJR	4.00	320.068.907	-5,1%
1.1	SBMI	4.00	321.979.020	-4,6%
1.1	SBCB	4.00	326.014.701	-3,4%

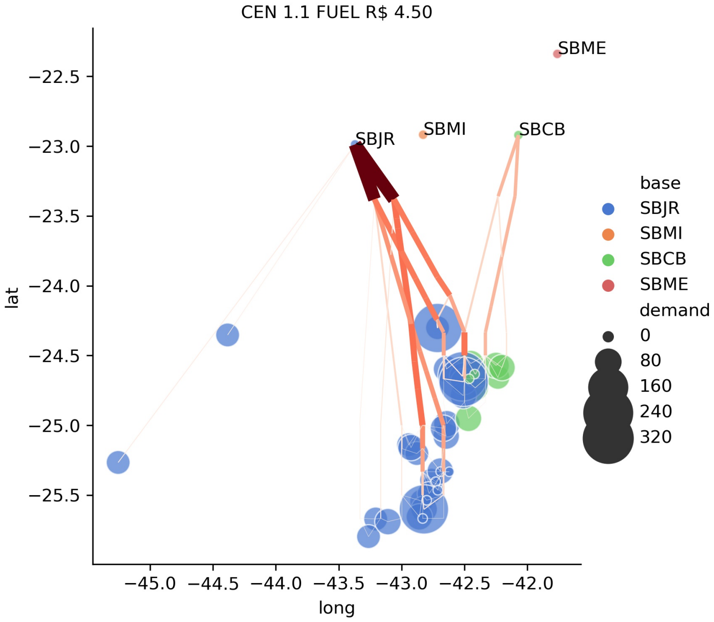

Figure 13 – Fuel price sensitivity -10% in SBJR.

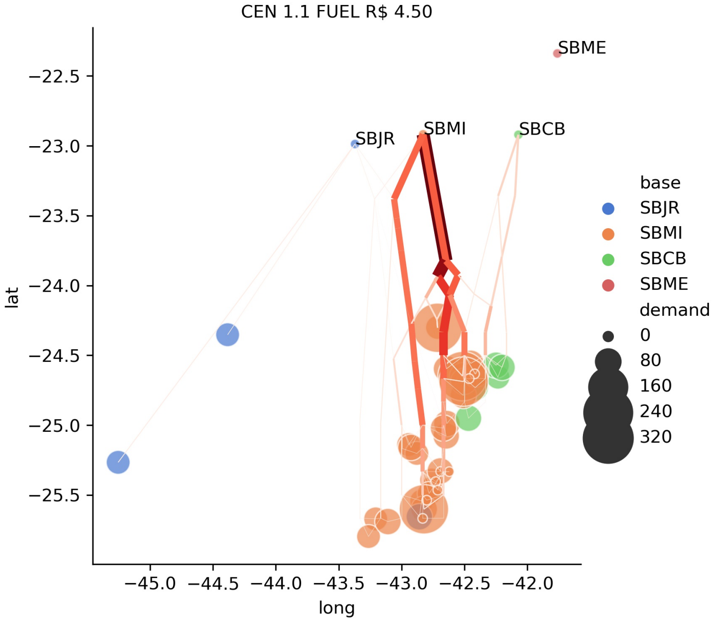

Figure 14 – Fuel price sensitivity -10% in SBMI.

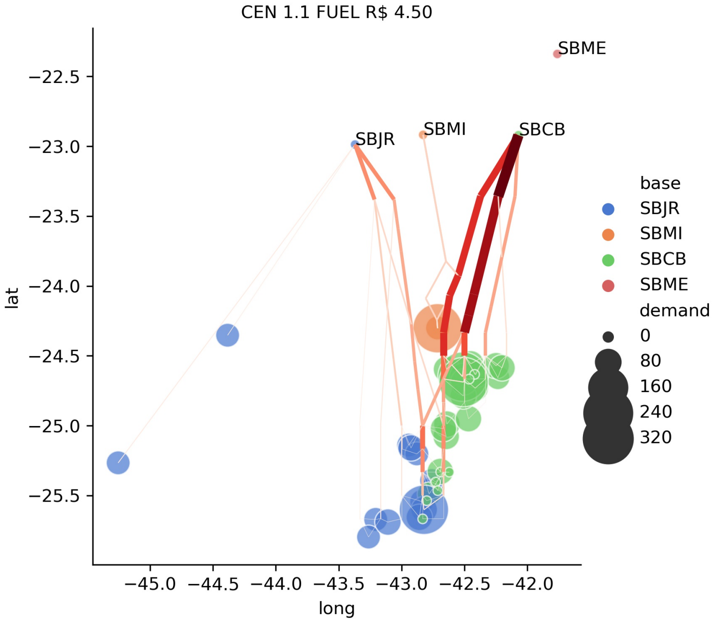

Figure 15 – Fuel price sensitivity -10% in SBCB.

It can be seen that fuel price reductions in the Jacarepaguá base (SBJR) have a greater impact on the logistics cost for the two percentage ranges (-10 and -20%), due to the greater demand that this base has. It is also observed that for the same reductions, whether of 10 or 20% in the price of fuel, the impacts are more felt in the SBMI than in the SBCB, denoting that the SBMI tends to gain more demand than the SBCB, due to the location of SBMI to be more central in the Santos basin.

3.7 Impact of AIC 27/21 (use of ATS Routs)

All the work developed so far considered the ATS Routes in accordance with AIC 27/21, the objective now is to quantify the increase in average distances covered, flight times, fuel consumption and logistical costs that this Circular brought when compared to the previous situation with the flights taking place directly. Here the objective is only to quantify the impact that the implementation of the ATS routes had on the operation, comparing with the previous situation when there was no obligation to follow these routes and it was possible to adopt the direct route between airport → maritime unit → airport.

For this, the airspace was again modeled as a graph, but this time with straight edges connecting each airport to each maritime unit in both directions. Thus, the minimum path chosen by the algorithm will be the direct connection for both going to the unit and returning to the continent, without the obligation to go through the entrance, exit and other waypoints gates.

Table 11 shows the comparison of the averages of all possible missions (airport → maritime unit → airport), considering the two types of aircraft size, except for the estimated missions originating from the Macaé airport for the basin of Santos and those whose impossibility to be performed due to the restriction of the helidecks.

Table 11 – Comparison of missions: AIC 27/21 and Direct Routes.

Item	Type of routes		%
	Direct	AIC 27/21	
half average distance (nm)	132,3	137,2	3,7%
average fuel consumption (kg)	1.115	1.148	2,9%
# average pax	12,4	12,2	-1,6%
average total cost R$	21.517	22.172	3,0%

It can be seen that the addition of routes according to AIC 27/21 increased, on average, about 3.7% of the average half distance traveled by aircraft, with an increase of around 2.9% in fuel consumption and a consequent decrease in capacity approximately 1.6% per mission, resulting in an increase of approximately 3% in the average total cost of the analyzed missions.

With the implementation of ATS Routes, it can be seen that the behavior is of increasing saturation of air routes when the operation is more concentrated in an airport in scenarios where there is a reduction in fuel prices. The most impacted scenarios are those where the price is reduced in the SBMI, largely due to the preference for the use of edges connected to waypoint CS011 and Maricá airport. It should be noted, however, that the flight altitudes are different on mainland → sea and sea → mainland path.

An analysis considering the overhead of these stretches of ATS Routes may be necessary. With the model proposed here, it is possible to identify the waypoints most subject to such restrictions in a deterministic way, indicating the amount of average movements in each point of the Graph for each analysis scenario, comparing their results. Table 12 presents the result of the comparison of the 3 (three) waypoints that demand more movements in each analysis scenario, including those that reduce the fuel price.

Table 12 – Concentration of movements on waypoints.

waypoint	Scenario	Mov./week	Mov./h	separation in minutes
CS011	cen1 5.00 reais	196	2.8	21.4
CS021	cen1 5.00 reais	186	2.7	22.6
CS017	cen1 5.00 reais	166	2.4	25.3
CS021	cen2 5.00 reais	186	2.7	22.6
DIBIL	cen2 5.00 reais	152	2.2	27.6
EGUDI	cen2 5.00 reais	152	2.2	27.6
CS011	cen3 5.00 reais	210	3.0	20.0

Table 12 continued from previous page

waypoint	Scenario	Mov./week	Mov./h	separation in minutes
CS021	cen3 5.00 reais	186	2.7	22.6
CS017	cen3 5.00 reais	178	2.5	23.6
CS017	cen4 5.00 reais	196	2.8	21.4
PAPIS	cen4 5.00 reais	182	2.6	23.1
BS082	cen4 5.00 reais	167	2.4	25.1
CS021	cen5 5.00 reais	166	2.4	25.3
DIBIL	cen5 5.00 reais	163	2.3	25.8
EGUDI	cen5 5.00 reais	163	2.3	25.8
DIBIL	cen1.1 4.50 reais SBJR	220	3.1	19.1
EGUDI	cen1.1 4.50 reais SBJR	220	3.1	19.1
BS009	cen1.1 4.50 reais SBJR	204	2.9	20.6
CS011	cen1.1 4.50 reais SBMI	343	4.9	12.2
CS017	cen1.1 4.50 reais SBMI	265	3.8	15.8
CS013	cen1.1 4.50 reais SBMI	203	2.9	20.7
PAPIS	cen1.1 4.50 reais SBCB	178	2.5	23.6
BS023	cen1.1 4.50 reais SBCB	156	2.2	26.9
CS018	cen1.1 4.50 reais SBCB	156	2.2	26.9
DIBIL	cen1.1 4.00 reais SBJR	259	3.7	16.2
EGUDI	cen1.1 4.00 reais SBJR	259	3.7	16.2
BS009	cen1.1 4.00 reais SBJR	220	3.1	19.1
CS011	cen1.1 4.00 reais SBMI	437	6.2	9.6
CS017	cen1.1 4.00 reais SBMI	308	4.4	13.6
CS013	cen1.1 4.00 reais SBMI	219	3.1	19.2
PAPIS	cen1.1 4.00 reais SBCB	247	3.5	17.0
CS014	cen1.1 4.00 reais SBCB	216	3.1	19.4
CS017	cen1.1 4.00 reais SBCB	216	3.1	19.4

It is verified that in scenarios 1 to 5, whose distribution is more uniform among the aerodromes, the number of movements/hour (considered 10 hours of operational window at each point) did not exceed 3 movements. When the sensitivity of fuel price reduction was made at some aerodromes, due to the concentration of operation, it presented waypoints with more than 4 movements per hour, as was the extreme case of CS011, which in the scenario price R$ 4.00/liter in Maricá attracted 6.2 mov/h, which corresponds to 9.6 minutes of longitudinal separation between aircraft in that position disregarding different flight levels, or 19.2 minutes if considering the level FL025 on the way and FL035 on the return.

4 CONCLUSIONS

With this work we were able, initially with the proposed performance model, to present maps of preferred regions using the distance from the airport to the maritime unit as a parameter in order to succinctly choose the best size of aircraft to be used. It was observed that when using medium-sized aircraft, with MTW of 7000 kg, the preferred region for using this size goes up to about 135 nautical miles and even from there this size is still quite competitive when compared to the large size. These maps can be very useful when you are in a logistical planning phase when the maturity of the projects is not yet fully defined, thus contributing to the choice of resources to become more assertive.

Using the performance model with the distances rigorously calculated through the shortest path methodology indicated by a graph previously modeled computationally and by the Flight Mix Allocation Model (FMAM), it was possible to determine the flight tables for different scenarios, indicating in a optimized by which airports each maritime unit and by which size of helicopter each flight should be carried out in order to meet the proposed demand. With this, it is possible to allocate resources properly in order to minimize the logistics costs of the activity. The FMAM indicated that there is potential for reducing logistics costs in the order of tens of millions of reais per year, depending on the scenario, when fully used.

In addition to the analysis that considered constant fuel prices by airport, a sensitivity analysis was carried out reducing fuel prices by 10 and 20%, due to their importance in the global costs of the activity. This analysis showed that from the 10% reduction onwards, the optimal distribution starts to be considerably altered, with demand being very attracted to the airport with a reduced price. Based on the analyzes carried out, the airports of Jacarepaguá and Maricá were the ones that most indicated that they could benefit from a possible reduction in fuel prices. As the scenario of differentiated prices by airports is relatively common, airport managers and logistical planners must always consider it in their decision making.

On the other hand, the concentration of operations in a given airport, either for geographic reasons or for benefits in the price of fuel, for example, can bring a side effect that is the concentration of movements in the airspace. That is why this verification was carried out where it can be seen that with the implementation of the ATS routes, originating from the AIC 27/21 and in the scenario of a 20% reduction in the price of fuel in Maricá, the waypoint CS011 would be close to saturation. Therefore, contingent traffic control actions could be necessary in this region.

For future work, a qualitative strategic assessment of the number of service bases can be carried out depending on the expected temporary variation in demand (new rounds of the ANP - National Petroleum Agency in Brazil, for example) and other associated risks that were not considered in this study.

For further complementary work, it is also suggested that a stochastic evaluation of air traffic can be carried out to evaluate the waypoint restrictions more completely and incorporated into the model, as well as through simulation to evaluate the capacity restrictions of the aerodromes.

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References

ALMEIDA PP. 2002. *Aplicação do método AHP – Processo Analítico Hierárquico – à seleção de helicópteros para apoio logístico à exploração e produção de petróleo "offshore"*. 101 f. Dissertação (Mestrado). Programa de Pós-graduação em Engenharia de Produção, Universidade Federal de Santa Catarina, Florianópolis.

DECEA DEPARTAMENTO DO CONTROLE DO ESPAÇO AÉREO. 2021. AIC 27/21 . Available at: http://https://publicacoes.decea.mil.br/publicacao/version/1717. Accessed on 2 Mai 2022.

DIJKSTRA EW. (1959). A Note on Two Problems in Connexion with Graphs. *Numerische Mathematik*, **1**, 269-271.

DOWNIE M& GOSLING, D. 2020. Offshore helicopter travel: is the UK oil and gas industry failing offshore workers? *New solutions: a journal of environmental and occupational health policy* [online], **29**(4), 504-518.

FEREIRRA FILHO VJM. 2016. Gestão de Operações e Logística na Produção de Petróleo. Rio de Janeiro, Brasil: Elsevier.

FERNÁNDEZ-CUESTA E, NORDAL ID, ANDERSON H & FAGERHOLD K. 2016. Base location and helicopter fleet composition in the oil industry. *INFOR: Information Systems and Operational Research*.

GALVÃO R, GUIMARÃES J. 1990. The control of helicopter operations in the Brazilian oil industry: Issues in the design and implementation of a computerized system. *European Journal of Operational Research*, **49**(2), 266-270.

HAMCHER S & FEREIRRA FILHO VJM. 2015. *Aplicações de pesquisa operacional na indústria internacional de petróleo e gás*. Rio de Janeiro, Brasil, Elsevier.

HERMETO NSS, FERREIRA FILHO VJM & BAHIENSE L. 2014. Logistics network planning for offshore air transport of oil rig crews. *Computers & Industrial Engineering*, **75**(2014), 41–54.

HERMETO TS & MULLER C. 2015. Analysis of offshore helicopter air traffic operations at the Campos Basin. *18th ATRS World Conference*.

MENEZES F, PORTO O & NASCIMENTO NC. 2010. Optimizing Helicopter Transport of Oil Rig Crews at Petrobras. *Interfaces*, **40**(5), 408-416.

MINISTÉRIO DO TRABALHO E PREVIDÊNCIA. 2018. Norma Regulamentadora No. 37 (NR-37). Available at: https://www.gov.br/trabalho-e-previdencia/pt-br/composicao/orgaos-especificos/secretaria-de-trabalho/inspecao/seguranca-e-saude-no-trabalho/normas-regulamentadoras/nr-37.pdf. Accessed on 2 Mai 2022.

MOLLER EB, VIANNA MFD & MEZA EBM. 2017. Definição de Nível de Serviço para Situação de Crise no Transporte Aéreo Offshore Utilizando o Método AHP – Analytic Hierarchic Process. *XLIX Simpósio Brasileiro de Pesquisa Operacional*, Blumenau, **49**(1), p.260-271.

MOREIRA DD. 2015. *Disponibilidade de frotas de transporte aéreo offshore por helicópteros*. Dissertação (Mestrado) – Instituto Militar de Engenharia, Rio de Janeiro.

MORENO L, ARAGÃO MP & UCHOA E . 2006. Column Generation Based Heuristic for a Helicopter Routing Problem. *Experimental Algorithms (WEA 2006)*, Vol. 4007. Springer, Heidelberg, Germany. 219-230.

NAVARRE JT. 2021. Randomized greedy algorithm for helicopter optimization in the energy industry: a practical approach to model development and solution deliverance. *International Journal of Energy Sector Management*, **161**, 149-170

NETWORKX NETWORK ANALYSIS IN PYTHON. 2022. Available at: https://networkx.org/. Accessed on 16 Jun 2022.

PEREIRA RRD. 2016. Método de Análise de Vulnerabilidade Utilizando Redes Complexas: Aplicação na Rede de Transporte Aéreo Brasileira. Dissertação de Mestrado em Transportes, Publicação PPGT/ENC. T.DM-008/2016, Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, Brasília, DF, 146 p.

PRESIDÊNCIA DA REPÚBLICA DO BRASIL. LEI Nº 13.475. 2017. Available at: http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/L13475.htm. Accessed on 2 Mai 2022.

PULP - OPTIMIZATION WITH PULP 2022. Available at: https://coin-or.github.io/pulp/index.html. Accessed on 16 Jun 2022.

QIAN F, GRIBKOVSKAIA I & HALSKAU SRØ. 2011. Helicopter routing in the Norwegian oil industry. Including safety concerns for passenger transport. *International Journal of Physical Distribution & Logistics Management*, **41**(Iss 4), 401–415.

QIAN F, GRIBKOVSKAIA I, LAPORTE G & HALSKAU SRØ. 2012. Passenger and pilot risk minimization in offshore helicopter transportation. *Omega*, **40**(5), 584–593.

QIAN F, STRUSEVICH V, GRIBKOVSKAIA I & HALSKAU SRØ. 2015. Minimization of passenger takeoff and landing risk in offshore helicopter transportation: Models, approaches and analysis. *Omega*, **51**, 93-106.

ROCHA PPF. 2001. *Modelo de dimensionamento de frota de helicópteros para um sistema de distribuição física de pessoas voltado às atividades offshore de exploração de produção de uma bacia petrolífera: estudo de caso*. Dissertação (Mestrado) - Programa de Pós-graduação em Engenharia de Produção, Universidade Federal de Santa Catarina, Florianópolis.

ROSA RA, MACHADO AM, RIBEIRO GM & MAURI GR. 2016. A mathematical model and a Clustering Search metaheuristic for planning the helicopter transportation of employees to the production platforms of oil and gas. *Computers & Industrial Engeneering*, **101**, 303-312.

VIEIRA T, DE LA VEGA J, TAVARES R, MUNARI P, MORABITO R, BASTOS Y & RIBAS PC. 2021. Exact and heuristic approaches to reschedule helicopter flights for personnel transportation in the oil industry. *Transportation Research Part E*, **151**, 102322.

VILAMEÁ E. 2011. Logistical Challenges for Crew Transportation in Brazilian Pre-Salt Province. *Proceedings of the RINA 9th Symposium on High Speed Marine Vehicles 2011*.

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