Logistics network planning for offshore air transport of oil rig crews

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ABSTRACT

Oil discoveries of recent years, especially in the pre-salt Santos Basin, reflect a large increase in petroleum exploration and production in Brazil. Accordingly, drilling rig and production platform crew transport demands will increase. This transport will also become more complex as average distance between fields and Brazil's coast increases. The helicopter, the modal most used for this purpose, is the most efficient means of transport in terms of speed and safety, but also entails high costs. Optimizing the crew transport logistics network thus becomes an economically significant issue. The study presents an optimization model for crew transport logistics network planning. That model aims to provide managers with accurate information to assist their decision making in logistics infrastructure planning. Such decisions involve airfield locations, distribution of demand among airfields and fleet profile. Since composing the fleet involves considerable expenditures, and once made, this composition is not easily changed, we built several scenarios varying in demand and fleet costs to evaluate the behavior of the model we are proposing as regards processing time and quality of the solution. We have obtained good results, despite the increasing complexity of the scenarios.

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1. Introduction

Oil discoveries of recent years, especially in the pre-salt of Santos Basin, reflect a large increase in petroleum exploration and production in Brazil. Accordingly, drilling rig and production platform crew transport demands will increase. This transport will also become more complex as average distance between fields and Brazil's coast increases.

The helicopter, the modal most used for this purpose, is the most efficient means of transport in terms of speed and safety, but also entails high costs. Optimizing the crew transport logistics network thus becomes an economically significant issue.

1.1. Motivation

Increasing distances, both from the coast and between marine units, hinder the formation of service routes because helicopter autonomy must be respected and available passenger capacity decreases with increasing fuel weight. Greater distances also lead to a greater need for air bases spread along the coast. In this context,

logistics costs tend to cause greater impact on oil extraction costs. It is thus of great importance to design an optimized logistics network that does not impede production from fields farther offshore. The challenges relate not only to costs, however, but also to helicopter flight autonomy and passenger safety. Therefore, use of operational research models is highly important to logistics network planning and fleet forecasting for the medium and long term.

1.2. Objective

The study presents an optimization model for planning a logistics network for offshore oil rig crew transport. That model aims to provide managers with accurate information to assist their decision making in logistics infrastructure design. Such decisions involve airfield locations, demand allocation and fleet size. The model also identifies the helicopter fleet composition affording lowest location costs for different demand and fleet rent rate scenarios. These decisions involve considerable expenditures, and once made are not easily changed, underlining the value of a decision support model.

1.3. Context

Passengers have always been transported to work in offshore oil exploration and production by air (helicopter) and sea (speedboat). The air mode predominates in this activity because of the speed,

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flexibility and comfort offered to passengers (Brittan & Douglas, 2009). Petrobras began its activities transporting passengers to work offshore in the mid-1970s, at the start of exploration of the Campos Basin. Initially, a mix of air and sea modes was used. This continued until the mid-1990s, when an internal study found that the air mode offers better flexibility and performance (time and cost) than maritime transport (Hermeto, 2009).

Studies have shown transport by boat to be safest (Spouge, Smith, & Lewis, 1994). Not only is maritime transport slower, however, it also entails problems in transferring passengers from vessel to platform, usually done in baskets lifted by platform crane. This overflow system has operational limitations according to sea conditions and wind speed, and the operating window is smaller than for helicopters. Currently, new technologies are available for offshore crew transport, including boats that are faster (up to 50 knots) and more stable. Transfer systems have also undergone safety-enhancing technological developments. Examples include the rigid basket, which provides greater safety than conventional baskets and has been in use since 2008 in West Africa (Brittan & Douglas, 2009), as well as models of ramp that are also at the development and/or trials stage. This study, however, is limited to transport by helicopter, the only means currently used in the area studied, which comprises the Campos and Santos basins.

The logistics network currently used for helicopter transport of crews comprises the airports of Vitoria, Macaé, Cabo Frio, Jacarepaguá, Itanhaém, Navegantes and the Sao Tomé heliport, as can be seen on the map in Fig. 1. The Sao Tomé heliport is owned by Petrobras; the others are partially leased by the company.

In 2010, Macaé airport was responsible for 45% of all related passenger movement. Taken together, Macaé airport, the Sao Tome heliport and Cabo Frio International Airport, which also serves transport to the Campos Basin, account for 77% of total movement. This is because oil-related activities are highly concentrated in the Campos Basin. However, growth forecast for the coming year is concentrated in the Santos Basin's pre-salt province, which is more distant from the coast and involves greater distances between rigs than the Campos Basin.

1.4. Paper organization

This paper is organized as follows. Introduction section addressed the motivation for studying this problem and its context. Section 2 presents related work. Section 3 describes the problem, assumptions involved and presents the mathematical formulation of the problem and the approaches used to solve it. Section 4 presents the experiments conducted in an instance based on real conditions. Section 5 presents obtained results and discussions. Lastly, Section 6 concludes the paper with the final remarks and suggestions for future work.

2. Brief literature review

The issue of logistics planning has been widely studied in its various aspects. Since the initial work that dealt with radical simplification of operational problems (e.g. problems of transport and allocation) to the most current studies that seek to model the richness of real-world conditions, considering different decision levels and planning horizons.

While the older approach consisted mainly of breaking the problem into smaller problems treated deterministically, the advancement of knowledge and computational power has allowed the most recent models include many features with the idea of reflecting some real cases or focusing on some particular aspects. Among the most widespread characteristics in the recent models are: a supply chain with multiple echelons and multiple products or families of products; stochastic where the data and variables are random variables; dynamic models where the data and variables may change at every period; complex product flows, with
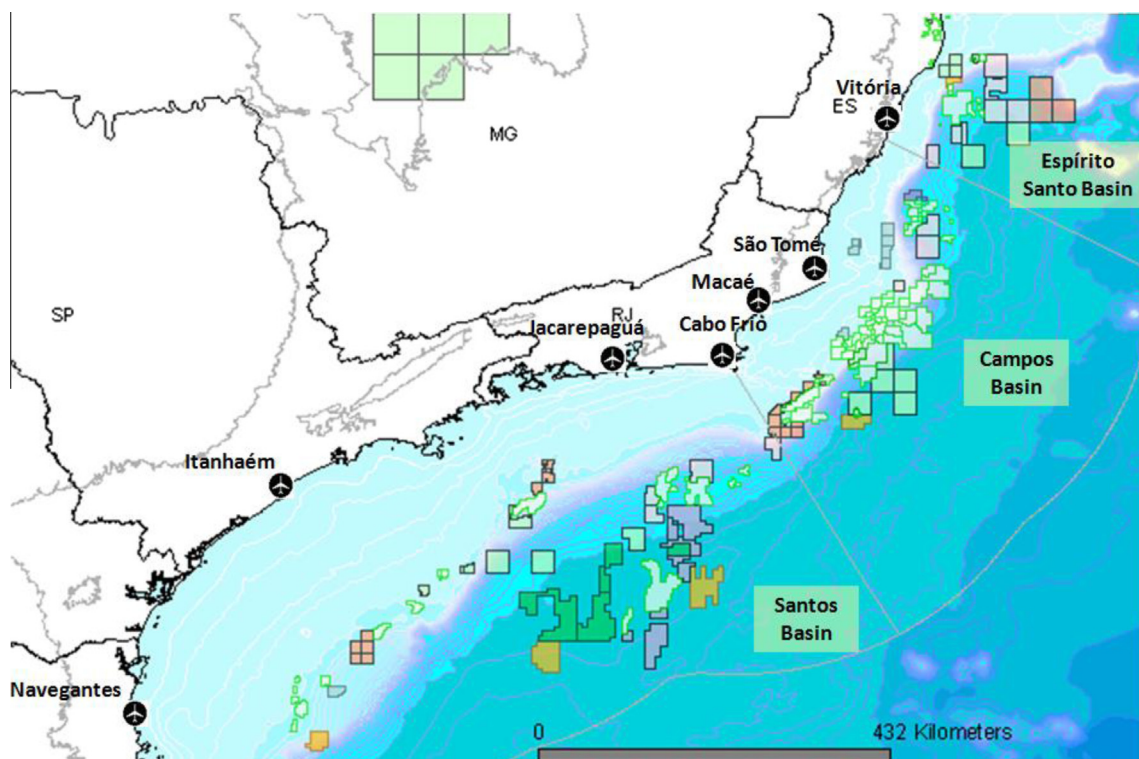

Fig. 1. Geographical distribution of airfields in the scope of the study.

Table 1
Levels of planning, activities and published references.

Planning Level	Activity	Period of Analysis	Update	Description	References
Operational	Routing	Day	In real time	Routing of transportation requests from maritime units	Qian et al. (2012), Menezes et al. (2010), Romero et al. (2007), Sierksma and Tijssen (1998), Galvão and Guimarães (1990)
Tactical	Flight Scheduling	Week	Reviewed annually and whenever an oil rig moves out of the service area of the initial airfield	Determine days of week, time intervals and air base where units may request transport, and number of places available at these times	Sherali et al. (2010), Tam et al. (2011), Yan and Tu (2002)
Tactical	Fleet Sizing	Bi-annual	Annual	Sizing of fleet to be hired for the coming year	Rocha (2001)
Strategic	Network Planning	20 years	Annual	Long-term planning. Location analysis and fleet profile analysis	Sena, Leite, Massuda, and Prallon (2010), Sena and Ferreira Filho (2010)

an exchange of products between plants or warehouses, direct deliveries to some customers, reverse logistics, re-manufacturing, etc.; a variety of constraints: competition or budget constraints, etc. – complex cost structures: fixed and variable costs, linear or non-linear costs; hybrid strategic/tactical models with inventories: average, safety or cyclic inventories.

The current literature is rich in reviews about different approaches to the problem of logistics planning. One of the reviews that dealt with routing and fleet size and composition are (Hoff, Andersson, Christiansen, Hasle, & Løkketangen, 2010) that reviews the literature of combined fleet composition and routing in maritime and road-based transportation while (Andersson, Hoff, Christiansen, Hasle, & Løkketangen, 2010) describes industrial aspects of combined inventory management and routing in maritime and road-based transportation, and gives a classification and comprehensive literature review of the current state of the research. Pantuso, Fagerholt, and Hvattum (2013) present a literature survey on the fleet size and mix problem in maritime transportation.

Facility location decisions play a critical role in the strategic design of supply chain networks. Melo, Nickel, and Saldanha da Gama (2009) present, a literature review of facility location models in the context of supply chain management. Meixell and Gargeya (2005) review decision support models for the design of global supply chains, and assess the fit between the research literature in this area and the practical issues of global supply chain design. Farahani and different coauthors have published a number of reviews considering specific location problem: Farahani, Steadieseifi, and Asgari (2010) provide a review on recent efforts and development in multi-criteria location problems in three categories including bi-objective, multi-objective and multi-attribute problems and their solution methods. In order to modify the current facility or develop a new facility, the dynamics of facility location problems (FLPs) ought to be taken into account so as to efficiently deal with changing parameters such as market demand, internal and external factors, populations, etc. Arabani and Farahani (2011) report on literature pointing out some aspects and characteristics of the dynamics of FLPs. Farahani, Hekmatfar, Fahimnia, and Kazemzadeh (2013) present a review of hierarchical facility location modeling.

In this work, we focus on the logistical planning of offshore passenger transport which may be organized into four macro-activities on three decision-making levels. The published references regarding each activity are summarized in Table 1.

2.1. Operational

The operational planning level includes daily helicopters routings, subject to review according to passenger weight, weather factors that influence fuel consumption (local temperature, wind direction and atmospheric pressure), weather conditions' affecting airfield and oil rig heliport availability, helicopter availability, and demand seasonality. Operational decision-making has been widely studied; there are a series of articles on this subject. Salient in the international literature is the study by Sierksma and Tijssen (1998), who used linear programming and heuristics to solve the routing problem to serve 51 North Sea platforms. Complementarily, Romero, Sheremetov, and Soriano (2007) combined heuristics with a genetic algorithm to solve the routing problem for offshore helicopter transport, applying the model to a real case of the Mexican Oil Company, PEMEX. Qian, Gribkovskaia, Laporte, and Halskau (2012) analyzed how to improve transport safety by solving the helicopter routing problem with a risk objective expressed in terms of expected number of fatalities. They proposed a mathematical model and applied a Tabu search heuristic to the problem. The results show that passenger transport risk can be reduced by increasing travel time at the expense of pilot risk. Their methodology can also be used to derive an equitable distribution of risk between passengers and pilots, considering that pilots fly much more frequently than passengers. In the Brazilian context, in particular at Petrobras, the studies by Galvão and Guimarães (1990) and Menezes et al. (2010) are to be noted. The former described the development of a computerized system based on a heuristic method for routing the transportation request to Petrobras maritime units in the Campos Basin. Menezes et al. (2010) formulated the problem using mixed integer programming, and arrived at a solution using an algorithm that combines column generation heuristic to exact methods.

2.2. Tactical

Tactical planning of air passenger traffic comprises fleet sizing and preparation of weekly flight tables, which are reset annually. The fleet sizing decision was studied by Rocha (2001), who adapted the model of Etezadi and Beasley (1983).

Currently, fleet sizing is performed to a 2-year horizon and updated annually. In this helicopter sizing model, market availability is considered a constraint. The flight table is prepared annually and revised whenever a rig changes location if, in its new location, it cannot be served by the same airfield. No references were found in the literature to drafting helicopter flight tables for crew transportation to offshore oil installations. However, aircraft[2] and crew scheduling and train scheduling have been extensively studied and can serve as a basis for developing optimization models for helicopter

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[2] An aircraft is a device that is used or intended to be used for flight in the air. (Federal Aviation Administration, 2013) Helicopters are aircraft with horizontal propellers that enable them to stabilize in the air or move in any direction. These features enable helicopters to land and take off without runways, and thus effect offshore crew transportation.

flight tables. Examples of studies in this area are Sherali, Bae, and Haouari (2010), Tam, Ehrgott, Ryan, and Zakeri (2011) and Yan and Tu (2002).

2.3. Strategic

Strategic planning provides a specification of the logistics network in the long term, by mapping new airfield needs and best locations, and pre-sizing fleets for hiring. Sena and Ferreira Filho (2010) describe a simplified model, which will be extended in this paper.

Quantifying airfield capacity involves three dimensions, as described below, with the most restrictive factor limiting the airfield capacity (Horonjeff & Mckelvey, 1993). These are, firstly, runway, aircraft parking, landing and takeoff capacity, given safe spacing between aircrafts, and number of parking positions; secondly, air traffic capacity, expressed as the maximum number of aircrafts that can enter an airspace sector in a given time period; and thirdly, passenger terminal capacity, i.e. the capacity of the waiting room, passenger boarding and disembarking, represented by the terminal area, for a given level of service.

Further, an extensive literature on location models, their many variations and solution methods can be found in Hale (2011), which features more than 3400 references on facility location and related matters. Recent books on the subject, such as Eiselt and Marianov (2011), Farahani and Hekmatfar (2009) and Drezner and Hamacher (2004), are also good sources.

3. Problem description and conceptualization

The decision-making process regarding transporting passengers to work in offshore oil operations takes into consideration not only the quantitative results of the optimization model. As represented by the chart in Fig. 2, decision makers also take account of qualitative issues, referred to externalities. These include environmental assessment, which is extremely important to airfield location, because environmental licensing can delay or even derail a project. Also analyzed are: ease of access to the site, soil characteristics, climate behavior, aeronautical charts, and others. Although such qualitative issues are important, the solutions to the quantitative model assist in choosing among qualitatively approved alternatives, in sizing each airfield to suit the optimum network configuration, and in showing managers the cost impact of each alternative.

3.1. The logistic system

The logistic system for offshore air transport of crew comprises onshore air bases and offshore maritime units (MUs). These nodes are connected by helicopter passenger transport. The logistics network planning problem involves each of these components, directly or indirectly, through the variables and constraints expressed in its formulation. Therefore, proper design necessitates knowing the related costs and main constraints.

3.1.1. Maritime units (MUs)

These are the offshore exploration and production facilities. The main types of MU currently in use by Petrobras are: Fixed Production Platform; Floating Production Platform; Floating, Production, Storage and Offloading/Floating, Storage and Offloading (FPSO/FSO) Vessels; Anchored and Dynamic Positioning Rigs; others (special boats, maintenance and safety units etc.). Each type of maritime unit has a different passenger demand profile relating to its maximum People on Board (POB) capacity, which is specified by the Brazilian navy. The number of permanent employees working aboard is related to the POB. There are fixed transport schedules for loading and unloading staff, coinciding with crew shift changes, and aircraft occupation rates are usually high. In addition, personnel often board sporadically to perform special activities, inspections, maintenance etc. These employees do not have a fixed schedule flight. For this type of passengers, it is necessary to provide places on flights with lower occupation than the crew shift flights. They may also visit a larger number of maritime units. Different types of maritime units display different demand distributions by passenger type. For example, there are more occasional flights to and from oil rigs than platforms, because they require more special services during the well drilling and completion stages, in addition to having more limited space and smaller POBs.

3.1.2. Helicopters

Transport capacity varies with the helicopter model considered. Each helicopter model has its own specifications in terms of number of seats, fuel tank capacity, and fuel consumption per kilometer, cruising speed, and carrying capacity. The weight that can be transported to a given destination – called the payload – is, in simplified form, the difference between the model's maximum takeoff weight (TOW) and the Basic Operating Weight (BOW). BOW
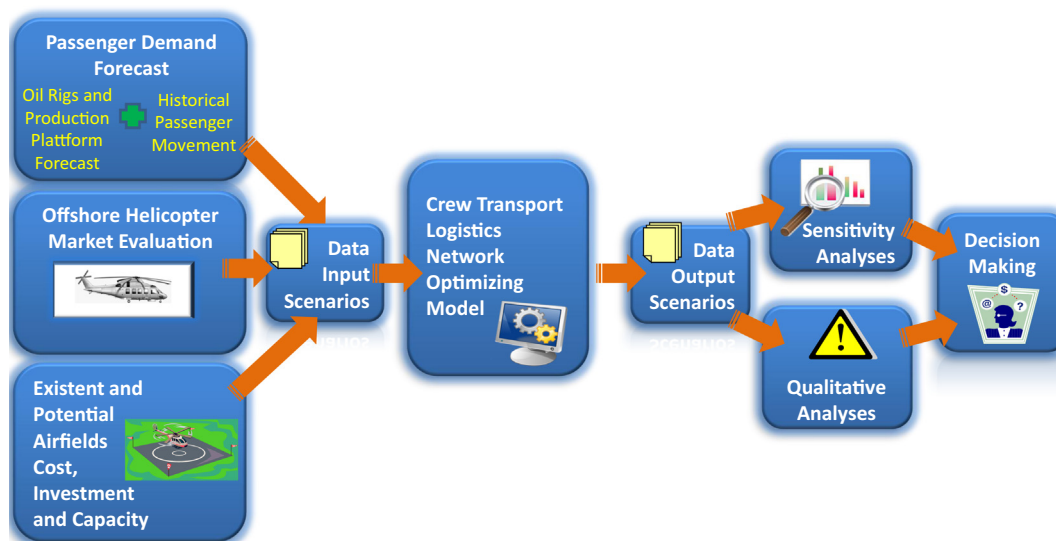

Fig. 2. Methodology for Logistics Network Planning.

is the sum of the aircraft's gross weight and the weights of the crew, equipment and fuel needed for the trip, and therefore varies depending on the distance to be traveled, i.e. it varies with the distance between the departure airfield and the maritime unit to be visited. In simplified form, the greater the distance to be traveled, the more fuel is needed, and the lower the weight capacity available for passengers and baggage (payload). Dividing this payload by average passenger-plus-baggage weight yields the average number of passengers likely to be transported in a particular helicopter model, considering the departure and destination pair set. Moreover, a helicopter load factor is also usually embedded to reflect the variability of demand and other operational factors that hinder full occupation of flights.

Aircraft autonomy, in kilometers, is an input parameter that acts as a maximum distance limit on an airfield's serving maritime units. In compliance with flight security requirements, an helicopter's mission can only be accomplished if it has enough fuel to: complete the path from the airfield to the maritime unit, return to the airfield of origin (or an alternative airfield), while retaining a technical reserve to fly usually an additional thirty or forty-five minutes, depending on the size of the aircraft.

Model input data for annual maritime unit passenger demand should be reported in number of seats available on flights. Each seat can handle up to two passengers; one embarking and the other disembarking. Also, the same occupation rate is assumed for the two legs of the round trip flight.

Given that the helicopters are rented, passenger carriage logistics costs comprise the fixed daily helicopter cost rate, the variable cost per hour flown by helicopters, and fuel costs. There are also contractual restrictions on the helicopters' use, such as maximum flight hours per month.

3.1.3. Aerodromes

According to International Civil Aviation Organization (ICAO) (1999), an aerodrome is "a defined area on land or water (including any buildings, installations, and equipment) intended to be used either wholly or in part for the arrival, departure and surface movement of aircraft". When used for helicopter arrivals, departures and movements, they are called heliports. The heliports used for carrying offshore passengers function as distribution centers, and their location strongly influences resource sizing and, consequently, oil extraction costs.

For this paper, aerodromes must be distinguished into two main types: helidecks and airfields. The helidecks situated on the maritime units serve only demand from the MU. There may be restrictions on the size of helicopter that can land on such helipoints. In the model discussed in this paper, the helideck location and size restrictions are considered as data input relating to the maritime unit they refer to.

Airfields, meanwhile, whose location is one of the objectives of this study to propose, serve a set of maritime units. The following text discusses aspects of their capacity and costs.

The maximum capacities (passengers/year) of the airfields to be used are limited by infrastructure, traffic control or expansion factors. Airfields are also subject to minimum capacities, i.e. the minimum demand that justifies the investment in building or hiring, or a contractual minimum flow, which is related to minimum flow contractual clauses at hired airfields.

The amount invested in an aerodrome is determined by the cost of land purchase or rental, earthworks, construction of passenger terminals, take-off and landing runways or heliports, hangars, aircraft parking, control tower, purchase of fire control systems, equipment, environmental licensing, and so on. For oil and gas companies using third-party airfields, these investments can be replaced by higher operating costs over the contract period. Accordingly, in order for the model to represent accurately the

reality, total investment in building or expanding an airfield and operating costs per passenger are model input parameters.

The investment required is strongly dependent on values of variables of the model, such as the number of passengers the helicopter located to an airfield. However, considering this dependency would make the model nonlinear. In order to represent cost differences between larger or smaller airfields, one alternative is to model more than one potential airfield at the same location, with different operating costs, maximum capacities and investment required.

3.1.4. Routes

As locations are given by their geographic coordinates, distances covered on a flight could be calculated in straight lines from airfield to maritime unit. However, for safety reasons, the national airspace control authority (DECEA) has stipulated that flights must obey a set of rules and use established routes (flight corridors passing through previously established gates according to flight origin and destination). Air gates are defined points with fixed coordinates. Helicopters must fly from the airfield of origin straight to one of these points, then after passing through the gate, follow the helicopter flight corridor until reaching a position perpendicular to the target platform, where the landing process should begin. These route changes have had significant impact on distances traveled by helicopter. They have also increased distances between airfield and maritime unit differentially among candidate airfields. These features can make one airfield more competitive than another for a particular unit, and thus change the logistics network.

3.2. Conceptual model

The problem of planning a logistics network for offshore air transport of oil rig crews is formulated in the next subsection. Schematically, it can be stated as it follows bellow.

Given the demand to be met (in terms of passengers per destination, group and year); the possible types of helicopter to be used; the possible airfields to be used; and the planning timeframe.

Obtain the number of passengers of group p to be transported from airfield a to maritime unit m by helicopter of type h in time t; the minimum number of helicopters of type h needed to transport passengers of group p from airfield a to maritime unit m in time t; the number helicopters of type h needed to meet demand allocated to airfield a in time t; and the decision to open airfield a in time t, if airfield a was opened in any year of the planning horizon.

At minimum (fixed and variable) cost of opening and operating the airfields, and using helicopters.

Subject to all demand must be met; helicopter constraints; and airfield constraints.

The solution of the model provides fleet sizing by airfield. However, this number should not be used for fleet planning as it disregards demand variability over the year, climate factors, and other factors that can influence fleet-related calculations. This number should only be regarded as a pre-sizing necessary to specify airfield location and infrastructure. Also, as the model operates to a strategic horizon and determines airfield locations', routing is not performed; instead, it is assumed that each flight will serve only one maritime unit. This approach is considered reasonable, given that, historically, approximately 70% of flights serve only one maritime unit each. However, it should be noted that the fleet estimates generated by the model should not be taken as a basis for fleet procurement, which requires models that perform routing.

3.3. Mathematical formulation

The proposed mathematical formulation has been stated in separate parts: Sets and Indices, Parameters (the model data),

Calculated Parameters (feasibility conditions calculated in advance – pre-processing to minimize the computational time required to execute the model), Variables (representing intermediate and final decisions), and Constraints.

3.3.1. Notation

The following notations, presented in Tables 2–7 are used to define the mathematical model.

3.3.2. Pre-processing

Due to the large number of maritime units, plus annual increases and reallocations, considering demand over 20 years, the scenarios involve very large numbers of variables and constraints. Therefore, in order to ensure a viable model, it is extremely important to use pre-processing techniques to reduce the number of variables and constraints to be considered. In this model, these techniques comprise primarily using suitably chosen sets of variables whose viability was tested prior to execution of the model.

Pre-processing starts with calculation of distance between airfields and maritime units. After that, the model tests flights feasibility, which involves a combination of factors. The first, of course, is that demand must exist, but capacity constraints on maritime unit helidecks and onshore airfields, as well as helicopter autonomy factors, must also be considered. These conditions are detailed and formulated in Appendix A.

3.3.3. The NOCT problem

The proposed mathematical program is as follows:

$$Min\left\{\sum_{h\in H}\sum_{(a,t)\in AO}RC_h fleet_{aht}\right.$$

$$+\sum_{(a,m,p,h,t)\in FF}\left(VC_h\frac{d_{am}}{(\rho_h HC_{amh})}k_{ampht}+OC_a k_{ampht}\right)$$

$$\left.+\sum_{a\in A}IO_a\delta AO_a+MaxQ\sum_{(a,t)\in AO}y_{at}\right\} \tag{1}$$

Subject to:

$$\sum_{(a,h)\in FF}k_{ampht}=Q_{mpt}\quad\forall(m,p,t)\in MPT \tag{2}$$

$$xfleet_{ampht}=\frac{k_{ampht}}{(\rho_h HC_{amh}MaxF_{amh})}\quad\forall(a,m,p,h,t)\in FF \tag{3}$$

$$fleet_{aht}\geqslant\sum_{m\in M}\sum_{p\in P}xfleet_{ampht}\quad\forall(a,t)\in AO,\quad\forall h\in H \tag{4}$$

Table 3
Parameters for maritime unit.

Parameters	Description
Q_{mpt}	Demand in year t of passengers of group p by maritime unit m;

$$\sum_{h\in H}fleet_{aht}\leqslant MaxH_{at}y_{at}\quad\forall(a,t)\in AO \tag{5}$$

$$\sum_{(m,h)\in MH}\sum_{p\in P}k_{ampht}\geqslant MinA_{at}y_{at}\quad\forall(a,t)\in AO \tag{6}$$

$$\sum_{(m,h)\in MH}\sum_{p\in P}k_{ampht}\leqslant MaxA_{at}y_{at}\quad\forall(a,t)\in AO \tag{7}$$

$$\sum_{a\in A}y_{at}\leqslant A_{max}\quad\forall t\in T \tag{8}$$

$$y_{at}\leqslant y_{at'}\quad\forall(a,t)\in AO,\quad t'>t,t,t'\in T \tag{9}$$

$$\delta AO_a\leqslant\sum_{t\in T}y_{at}\quad\forall a\in A \tag{10}$$

$$|T|\delta AO_a\geqslant\sum_{t\in T}y_{at}\quad\forall a\in A \tag{11}$$

$$\delta AO_a\in\{0,1\}\quad\forall a\in A \tag{12}$$

$$y_{at}\in\{0,1\}\quad\forall(a,t)\in AO \tag{13}$$

$$fleet_{aht}\in\mathbb{Z}\quad\forall(a,t)\in AO,\forall h\in H \tag{14}$$

$$k_{ampht}\in\mathbb{Z}\quad\forall(a,m,p,h,t)\in FF \tag{15}$$

$$xfleet_{ampht}\in\mathbb{R}\quad\forall(a,m,p,h,t)\in FF \tag{16}$$

The objective (1) is to minimize total cost over the planning horizon. Total cost is the sum of transportation costs, including the fleet fixed costs and the variable cost of the flights, plus the costs of opening and operating airfields. The last term in the objective function is a penalty implemented in order to conduct scenario studies where new airfields are undesirable. In this term, $MaxQ$ is used as a BigM parameter. Constraints (2) ensure demand from maritime units is met. Eq. (3) calculates the minimum fleet needed to meet demand, while constraints (4) calculate the required fleet by airfield and type of helicopter, considering that the fleet comprises a whole number of helicopters. Constraints (5) ensure that airfield maximum helicopter parking capacity is not exceeded,

Table 2
Indices and Sets.

Indices and Sets:	Description
$a\in A$	Set of potential airfields
$m\in M$	Set of maritime units
$p\in P$	Set of passenger groups (shift change and others)
$h\in H$	Set of helicopter models
$t\in T$	Set of time units (year)
$|T|$	Planning horizon (20 years)
$D=\{d_{am}\}$	Set of distances from airfield a to maritime unit m
$(a,t)\in AO$	Set of airfields a that can be opened in time t
$(m,h)\in MH$	Set of couples indicating which type of helicopter h can operate at maritime unit m
$(a,m,h)\in AMH$	Set of triples indicating which type of helicopter h has sufficient autonomy to serve maritime unit m from airfield a
$(m,p,t)\in MPT$	Set of triples indicating which maritime unit m has passengers of group p to be transported in time t
$(a,m,p,h,t)\in FF$	Set of tuples indicating feasible flights from airfield a to maritime unit m carrying passengers of group p using helicopter of type h in time t

Table 4
Parameters for airfield.

Parameters	Description
$MinA_{at}$	Minimum number of passengers that justifies opening the airfield a in year t (minimum capacity)
$MaxA_{at}$	Maximum number of passengers that can use airfield a in year t (maximum passenger capacity)
$MaxH_{at}$	Maximum number of helicopters that can use (park at) airfield a in year t (maximum helicopter capacity)
IO_a	Investment (fixed cost) to open airfield a
OC_a	Operating costs (per passenger) of airfield a
A_{max}	Maximum number of airfields that can be opened in any year

Table 5
Parameters by helicopter.

Parameters	Description
ρ_h	Utilization rate (seats occupied) per flight for helicopter of type h
RC_h	Annual fixed rental cost of one helicopter of type h
VC_h	Variable cost (in terms of distance) of flying helicopter of type h

while constraints (6) and (7) ensure, respectively, that airfield minimum and maximum capacity requirements are met while the airfield is open. Constraints (8) ensure that the limit of open airfields each year is not exceeded, which is complemented by constraints (9) establishing that an airfield, once open, remains in operation to the planning horizon. Constraints (10)–(12) guarantee that δAO_a of airfield a will be equal to 1 when this airfield is opened in any period of the planning horizon and equal to zero, otherwise. This variable is dependent on y_{at} and guarantees that if a potential airfield be opened in any time period, its investment value will be computed once in the objective function. Expressions (13)–(16) show, respectively, the binary nature of the decision to open an airfield, the integer nature of the variables "fleet" and "number of passengers transported", and the continuous nature of the fleet-related auxiliary variables.

4. Case study experiment

The proposed methodology was tested by conducting a case study based on a real situation of a Brazilian petroleum company. Considering information of exploration and production growth and the region of main growth, future demand projections had been made and a list of current and new airfields had been defined to be evaluated in this case study. Then, a set of scenarios was defined regarding managerial perspective.

The computational environment, the data involved (demands, potential airfield locations, and helicopter types) and the description of scenarios are presented in the next sessions and followed by the results, presented in Section 5.

4.1. Computational environment

This study was performed using a computer with the following configuration: CPU Intel Core™2 Duo CPU E6750 @ 2.66 GHz, 7.93 GB RAM, operating system Microsoft Windows Server 2003 R2 Enterprise ×64 Edition Service Pack 2. The modeling framework used was AIMMS 3.11 and the solver, GUROBI 2.0.

Using AIMMS and GUROBI makes the model easier to build and for end users to deploy, and for solver settings to be adjusted to suit the instance of the problem to be optimized. This flexibility allows results to be obtained more quickly and the model so developed is well received by end users.

We tested some internal settings of the software, and adopted the default settings, except for the MIP Relative Optimality Tolerance parameter, the default value for it is 10^{-13}, and which was also tested with the value 3×10^{-2}.

The value 3×10^{-2} was the smallest value for the MIP Relative Optimality Tolerance parameter that permitted running all scenarios without exceeding computer memory.

4.2. Demand

The demand input data for the optimization model is the number of passengers per platform, type of flight and year. This demand is forecasted based on historical medium flow by passenger type and MU per year, multiplied by projected MU start-ups in the next 20 years. Average annual growth in the number of passengers handled was projected to increase by 8% between 2011 and 2020. From then on, demand was considered constant, changing only in geographical distribution to represent the movement of rigs to each new well drilled. Fig. 3 illustrates both the growing demand and its geographic concentration in the Santos basin.

A total of 1098 demand points (w) were considered. Production units, once installed, remain always at the same location. Drilling

Table 6
Calculated Parameters.

Calculated parameters	Description
$MaxQ$	Number of passengers to be transported along the planning horizon
HC_{amh}	Passenger capacity of helicopter of type h when serving maritime unit m from airfield a
$MaxF_{amh}$	Maximum number of flights possible from airfield a to maritime unit m using helicopter of type h

Table 7
Variables.

| Variables	Description
k_{ampht}	Number of passengers of group p to be transported from airfield a to maritime unit m by helicopter of type h in time t; (Integer)
$xfleet_{ampht}$	Minimum number of helicopters of type h needed to transport passengers of group p from airfield a to maritime unit m in time t; (Continuous)
$fleet_{aht}$	Number of helicopters of type h needed to meet demand allocated to airfield a in time t (Integer)
y_{at}	Decision to open airfield a in time t (Binary)
δAO_a	If airfield a was opened in any year of the planning horizon (Binary)
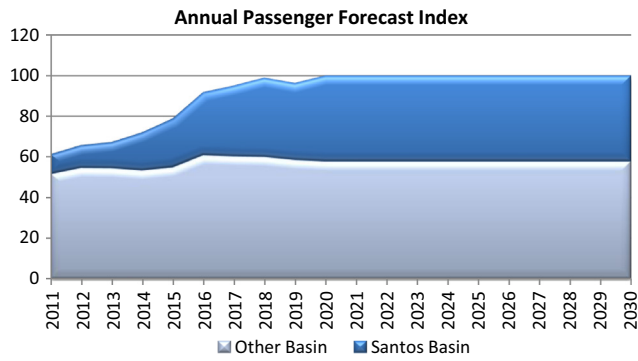
Fig. 3. Estimated passenger demand index used in the case study.

rigs move to each well location where they will be carrying out some activity. When doing so they represent a new demand point for each new location. This fact increases the number of variables and the difficulty of solving the model.

Demand of passenger transportation vary considerably according to exploration and production demands, which changes a lot year-by-year depending on many factors but especially exploration duration, exploration success index and new auctions of exploration blocks by ANP (National Petroleum Agency).

4.3. Airfields

The airfields considered in this case study were the 7 currently operated sites, besides another 7 potential points located on the south and southeast of Brazilian coast, totaling fourteen possible locations. The aim was to locate these new points close to where demand is expected to increase. In this study, the additional locations do not represent real alternatives, but they represent reasonable locations. Considering real alternatives would require

additional studies involving mapping of available areas and qualitative analysis. The map in Fig. 4 illustrates the airfields' locations considered.

4.4. Helicopters

Larger helicopters which a few years ago entailed much higher costs than the medium-sized, have now become financially competitive. These helicopters generally offer greater autonomy, allowing flights to units farther from the coast. Use of larger helicopters also yields important advantages in airfield management and transport capacity, because their use make possible to carry more passengers with fewer flights and thus require fewer parking spaces and helicopters at the aerodromes, while facilitate air traffic management processes.

Two models of helicopter were selected for this case study. They are among the most modern in the fleet currently in operation. The models of helicopter used and the related parameters are as follows:

(a) AW 139: a midsize twin-engine helicopter manufactured by AgustaWestland. It has cabin capacity for 12 to 15 passengers, limited to 12 passenger seats by client's internal health, safety and environment standards. Its maximum cruising speed is 306 km/h. This helicopter has autonomy of 584 km.

(b) EC225: a large helicopter manufactured by Eurocopter. It has cabin capacity for two pilots and 25 passengers, limited to 18 passenger seats by client's internal health, safety and environment standards. Its maximum cruising speed is 324 km/h. This helicopter has autonomy of 812 km.

Table 8 details the parameters considered in this study. For passenger capacity calculation to flights it was considered a medium weight for passengers based on historical data. $Wpax$ was considered to be 107 kg
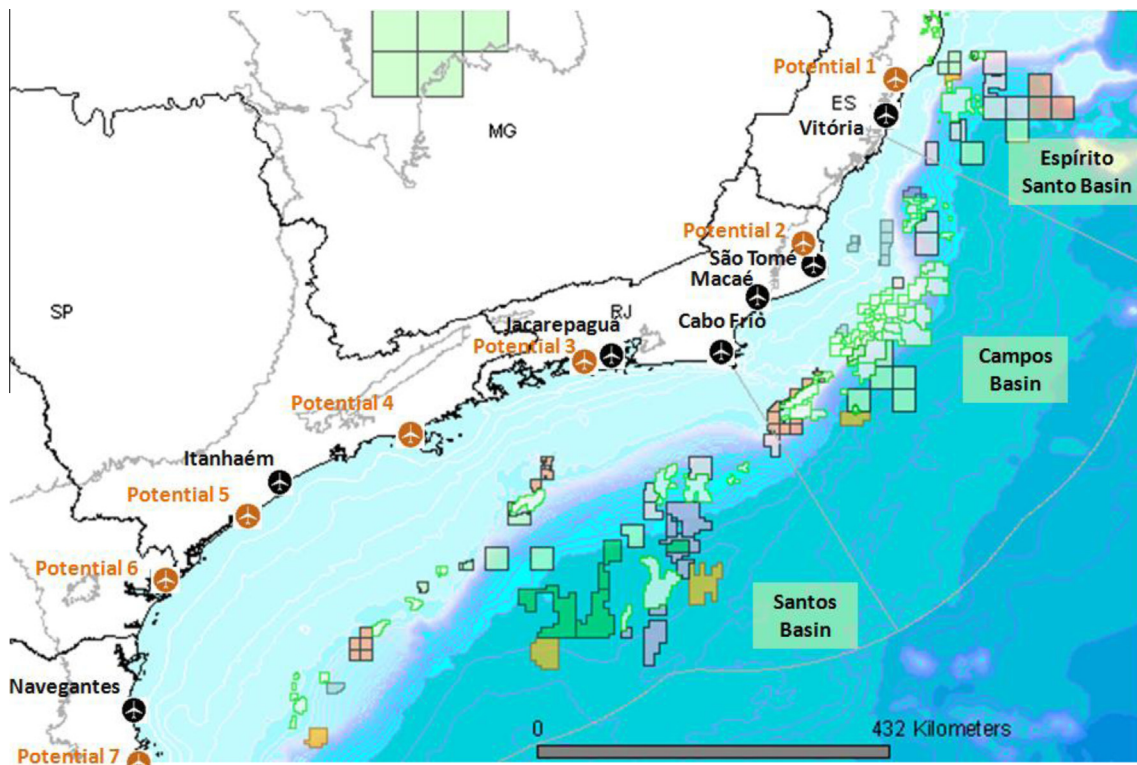

Fig. 4. Map illustrating airfields in operation and potential sites for new airfields.

Table 8
Helicopter parameters.

Parameter	AW 139	EC 225
ρ_h	75%	90%
$Speed_h$	152	140
RC_h	60.30	100.00
FC_h	0.000234	0.000345
$ExtraT_h$	1440	1440
Fh_h	0.75	0.87
$Seats_h$	12	18
$M\,Fuel_h$	1254	2742
TOW_h	6800	10520
BOW_h	4595	6997
$H\,Fuel_h$	528	797
$SafeT_h$	0.5	0.75

4.5. Scenarios

To test the efficiency of the model and understand their response to changes in demand six sets of scenarios were developed. The aim of scenarios' set defined is not only to support managers with deterministic optimal solutions but with sensitivity analyses covering the main uncertainties contained in this problem.

Available capacity of airports is difficult to calculate, in special when they are for mixed-use (offshore passenger transportation, executive aviation, regular civil aviation, skydiving, flying clubs, etc.). To be sure of these capabilities it would be necessary to forecast all this players' demand. Besides, in case of offshore passenger transportation, the capacity, in number of passengers will vary with fleet profile and distance of served fields. Therefore, as it is not a precise parameter, it's important to managerial decision making process to have a sensitivity analysis of this parameter.

With uncapacitated scenarios 1 and 3, it is possible to identify the ideal capacity of airfields, which minimizes costs.

Investments in construction or expansion of airfields are considerably difficult to calculate in some cases because they depend on market fluctuation and a range of other project configuration and economical and legal variables. According to this assertion, its important to managerial decision making process to have a sensitivity analysis on investment role in model results. In a real case, scenarios considering or not investment costs (scenarios 2 and 4) would be a starting point of values and risk analyses.

To finish scenario configuration, it was considered essential to analyze demand variation sensitivity. Thus, scenarios 5 and 6 where created, with a 25% variation on the base demand.

(1) Uncapacitated, with no investment costs (base scenario)

In this scenario all airfields have infinite maximum passenger and helicopter capacity, and minimum capacity set to zero so that they can be opened to accommodate any volume of demand that it is competitive for them to handle. Additionally, all airfield investment costs were annulled. The aim of this scenario is to ascertain the optimal service configuration assuming no differences in aerodrome cost or capacity limits. In this way it is possible to identify the potential use of each airport in terms of just location relative to demand. Comparing the results of this scenario with the others will show how the costs and capacity constraints influence the results.

(2) Capacitated, with no investment costs

The aim here is to determine to what extent capacity constraints raise operating costs. Very large cost differences between this scenario and scenario 1 should motivate studies to examine the possibility of expanding airfields that attract more demand.

(3) Uncapacitated, with investment costs

This scenario differs from scenario 1 in that it includes installation costs for existing airfields (e.g. related to the construction of a new terminal) not yet used by the company or as yet non-existing airfields, and also different operating costs for different airfields.

All values used were arbitrated to meet the criterion that operating cost per passenger must be less at company airfields than at contractors'. In contrast, where new airfields are to be constructed, investments will be considerably greater than those needed to fit an existing airfield for use. By comparing all possible airport options (existing and in use; existing and not yet used; and potential construction sites), it can be determined how installation and operating costs influence logistics network configuration, and how these costs and investments impact total operating costs.

(4) Capacitated, with investment costs

This is the complete scenario with full demand, aerodromes with capacity constraints, active investments in the opening of airfields, and operating costs all considered.

(5) Capacitated, with investment costs and 25% increased demand

This scenario differs from the previous ones by having passenger transport demand increased by 25%, distributed uniformly among the MUs. This is intended to check the sensitivity of the results (open airfields and operating cost) to increased demand. Scenarios of increasing demand are also useful to analyze the robustness of the solution, e.g. to determine what demand the solution could meet without exceeding airport capacity limits.

(6) Capacitated, with investment costs and 25% decreased demand

This scenario, like the previous one, aims to ascertain the sensitivity of the results (open airfields and operating costs) to demand fluctuations. In this case, the variation is downwards. Passenger demand is reduced by 25%, also distributed evenly among maritime units, i.e., maritime unit were not removed, but passenger volume per unit was reduced.

Scenarios are summarized in Table 9.

The dimensions of the studied case are illustrated in Table 10.

To demonstrate both the consistency of the results generated, and the convergence of the model for an optimal result in acceptable computational time, four runs were performed with different parameters, for each set of scenarios, as described below:

A. AIMMS default parameters and objective function with penalty for opening airfields.
B. AIMMS default parameters and objective function without penalty for opening airfields.
C. *MIP Relative Optimality Tolerance* = 3×10^{-2}; other AIMMS parameters set at default values and objective function with penalty for opening airfields, aiming to prevent the opening of an excessive number of airfields.
D. *MIP Relative Optimality Tolerance* = 3×10^{-2}; other AIMMS parameters set at default values and objective function without penalty for opening airfields.

5. Results and discussions

Results related to convergence of model are presented in Section 5.1. Next sections provide sensitivity analyses of most important and variable parameters of the problem to support managerial decision.

5.1. Proving the viability of the model

The main results are summarized in Table 11. In this table, "Gap%" column represents the percentage difference between the best integer solution found by model and its linear relaxation's lower bound. Column "Total Cost Index" represents the relative costs; they were obtained representing the highest cost found in the results of the model by 100 and then calculating the others as a percentage of it. Column "Penalty Index" represents the penalty for opening airfields; they were calculated. The penalty index

Table 9
Scenario description.

Scenario	Capacity	Investments costs	Demand
1	Uncapacitated	No	Base
2	Capacitated	No	Base
3	Uncapacitated	Yes	Base
4	Capacitated	Yes	Base
5	Capacitated	Yes	25% increase in base case
6	Capacitated	Yes	25% decrease in base case

Table 10
Dimensions of studied case.

Item	Value
Variables	2,324,241
Integer variables	1,162,540
Aerodrome	14
Aircraft types	2
Time unit (years)	20
Maritime units	1098

represents the proportion of the value obtained of the objective function that refers to the penalty for opening new airfields calculated by $MaxQ*\sum Y_{at}$. The "Real Cost Index" column represents the difference between the Total Cost Index and the Penalty Index. As it can be seen in Table 11, satisfactory results were obtained in all runs and processing times were all less than 2 h. This runtime is acceptable for the 20-year planning horizon. Even if the plan is reviewed annually, this processing time does not cause significant impact.

Considering runs A and B, in all sets of scenarios, every B round were ended due to lack of memory. However, all returned a feasible solution of good quality, with at most 2.46% difference compared to the linear relaxation of the lower bound, with software settings changed to 3% relative tolerance, rounds C and D were performed for each group of scenarios without the software encountering problems of lack of memory.

5.2. Assessment of fleet profile evolution

In all scenarios analyzed, there was gradual growth in the use of large helicopters as the demand from exploration blocks further from the coast increased. In the scenarios, the percentage of large helicopters in the fleet ranged from 8% to 19%.

For this case study, input parameters for large helicopters were arbitrated as follows: fixed cost 66% higher and variable costs 47% higher than for medium-size helicopters. Large helicopters offer maximum passenger capacity 50% greater than medium-sized helicopters. This cost-benefit, however, varies from maritime unit to maritime unit according to the change in their modal capabilities. Therefore, the ideal percentage of large helicopters in the fleet may be higher or lower in a real scenario, depending on the location of demand and the cost-benefit ratio of the helicopter type.

Interestingly, with the change in the distribution of demand, which moves away from the coast along the planning horizon, fleet occupation will gradually decrease, as can be seen in Fig. 5.

Fig. 6 shows the fleet projection in scenario 4B. Note the strong growth in total number of helicopters, which doubles by 2020 (peak demand). Part of this growth is due to increased demand, but some is due to a decrease in the average number of passengers carried per flight, as shown in Fig. 5.This is explained by the growth of demand in the Santos Basin, which comprises oilfields and exploration blocks farther from shore than in the Campos Basin and Espírito Santo Basin. To meet this demand, distance traveled by the helicopter will increase and there will be fewer flights per helicopter per day carrying fewer passengers per flight. The ratio between the two types of helicopters varies slightly over time, but averages seven AW139 for each EC225, with a small increase in the use of large helicopters in peak demand period.

5.3. Network configuration assessment

Table 12 shows the change in demand distribution among airfields in scenario 4B. In the first three years, around 80% of demand is met by the five airfields furthest north (Potential 1, Victoria,

Table 11
Summary of computational results.

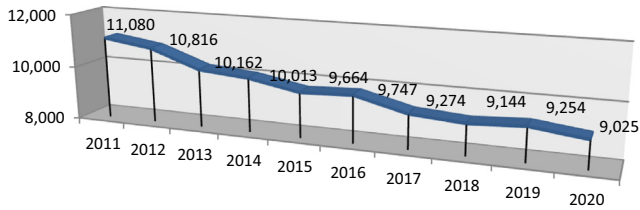| Scenario	Runs	Gap%	Iterations	Run time (h)	Total cost index	Penalty index	Real cost index
1	A	1.35	215,861	1.34	65.63	6.15	59.48
	B	0.94	181,624	1.12	58.62	–	58.62
	C	2.91	143,119	0.13	66.67	7.46	59.21
	D	2.67	73,248	0.01	59.50	–	59.50
2	A	1.75	556,543	0.97	73.44	9.44	64.01
	B	1.14	212,898	0.73	62.91	–	62.91
	C	2.37	234,154	0.14	73.91	9.58	64.33
	D	2.56	102,317	0.05	63.81	–	63.81
3	A	1.72	164,477	0.22	67.33	6.15	61.18
	B	1	205,32	1.25	60.25	–	60.25
	C	2.68	139,94	0.16	67.90	6.29	61.61
	D	2.97	73,145	0.05	61.30	–	61.30
4	A	2.36	522,598	1.42	76.00	9.67	66.32
	B	1.68	196,236	1.89	65.61	–	65.61
	C	2.75	226,967	0.09	76.30	9.58	66.72
	D	2.39	105,411	0.18	65.82	–	65.82
5	A	1.66	326,024	1.58	99.28	12.09	87.20
	B	1.84	251,128	0.59	86.23	–	86.23
	C	2.54	136,846	0.02	100.00	13.32	86.68
	D	2.18	136,485	0.08	86.54	–	86.54
6	A	2.46	527,494	1.51	55.34	5.88	49.46
	B	1.73	316,513	1.67	48.14	–	48.14
	C	2.83	546,616	1.65	55.64	5.88	49.76
	D	2.06	177,205	0.44	48.40	–	48.40

Fig. 5. Average number of passengers per helicopter to 2020 in scenario 4B.
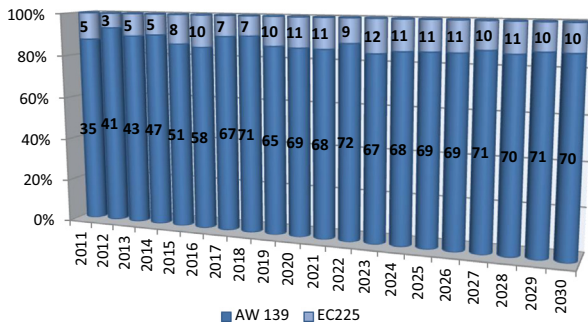

Fig. 6. Projected fleet by helicopter type in scenario 4B.

Potential 2, Sao Tome and Macae). As demand increases in the south, this proportion declines, stabilizing at just over 50%. Cabo Frio airport comes to account for a considerably larger percentage, reaching around 20%. Potential airfields 3 and 4, which in the model were only released for use after 2017, and represent potential areas in need of infrastructure construction, will together absorb around 10% of service provision.

5.4. Assessment of fleet productivity evolution

Table 13 shows fleet profile and productivity by airfield over the year of 2017 in scenario 4B. In this table, column "% of AW139 in fleet" represents the percentage of AW139 helicopter in the fleet. Column "Fleet Productivity Index" represents the comparative productivity index between airfields, where the productivity is measured by the number of passengers transported by helicopter. Table 13 shows that fleet productivity change dramatically by airfield. Analyzing this table, it becomes clear that this difference is not only related to fleet profile. Airfields serving basins with smaller distances between airfields and coast, as Potential 1 and São Tomé, tend to have bigger productivity. Airfields that attend remote areas with small demands, as Potential 7, tend to have

small productivity. Jacarepaguá aerodrome, even located in a highly demanding area and with a bigger percentage of EC225, that has more seats, has a small productivity. This is due to the fact that it is the best location to achieve most of Santos Basin fields and due to its capacity limitations is taking account of units further from the coast.

5.5. Sensitivity analyses on number of open airfields

Calculating operational costs and necessary investments to operate in new locations is a difficult activity with a lot of uncertainties involved. For instance, to manage a bigger number of airfields' contracts in operation there are some managing internal costs that can vary but are difficult to measure. Considering this, there were developed runs with and without penalization for opening new airfields. The runs with and without penalty are valid and can serve as a basis for management decisions.

If all direct and indirect costs of the passenger transport operation are considered in the model, it is not necessary to use the penalty.

To analyze the impact of the penalization of the objective function for opening an airfield on the results, we compare rounds A and B performed, respectively with and without penalty, for each scenario, and the results are shown in Table 14. In this table, column "Number of airfields" represents the total number of airfields used at some point during the period covered by the scenarios, and does not necessarily represent those operating throughout the analysis period; some potential aerodrome locations were considered null-capable in the first years of analysis, as not being immediately available given the prior need to build or adapt the aerodrome. Column "Total expenditures (costs + investments) Index" represents the relative expenditures; they were obtained representing the largest expenditure among all scenarios of all groups by 100 and then calculating the others as a percentage of it. As can be seen in Table 14, the penalty reduces the number of airfields (by up to 43%). However, the difference in total expenditure (cost + investment) is not significant in percentage terms (less than 3%). So, if there is any risk of having not estimated costs higher than 3% of the total expenditure managers, can decide to implement scenarios with penalty which presents a smaller number of opened airfields.

5.6. Sensitivity analyses of airport capacity, operational costs and investments

In scenarios with no cost and capacity constraints, each maritime unit is served by the closest airfield, representing less travel distance and consequently lower cost. In this case study, the free

Table 12
Passenger distribution index among airfields in scenario 4B.

Sites	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Potential 1	2.52	2.73	2.44	2.8	2.44	2.44	2.83	2.88	2.85	2.62
Vitoria	6.3	6.47	6.89	6.12	5.64	7.38	7.16	6.13	6.21	6.14
Potential 2	6.21	6.13	6.92	6.92	6.92	6.92	6.37	6.92	6.92	6.92
Sao Tome	15.23	15.23	15.23	15.23	15.23	15.23	15.23	15.23	15.23	15.23
Macae	19.68	20.88	20.97	19.68	21.87	24.24	24.24	24.24	22.96	22.75
Cabo Frio	4.48	2.29	2.83	7.92	13.34	20.27	21.04	21.97	20.71	21.92
Jacarepagua	3.54	6.73	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.68
Potential 3	0	0	0	0	0	0	2.11	4.65	3.69	5.38
Potential 4	0	0	0	0	0	0	4.02	4.64	5.42	7.11
Itanhaem	1.77	1.98	3.13	3.75	3.72	3.77	0.96	0.96	0.96	0.96
Navegantes	1.63	3.16	2.2	2.76	2.87	4.57	4.11	4.16	4.17	4.2
Potential 7	0	0.32	0.02	0	0	0.04	0.07	0.07	0.07	0.09
Total	61	66	68	72	79	92	95	99	96	100

Passenger distribution index = demand from each airfield is represented in this table as a percentage of the spike of total demand.

Table 13
Fleet profile and productivity by airfield in scenario 4B for 2017.

Airport	% of AW 139 in fleet	Fleet Productivity Index (%)
Potential 1	100	100.00
Vitoria	100	63.34
Potential 2	100	56.29
Sao Tome	100	76.99
Macae	100	57.16
Cabo Frio	95	37.21
Jacarepagua	40	24.50
Potential 3	100	24.83
Potential 4	100	35.52
Itanhaem	100	34.13
Potential 5	–	0.00
Potential 6	–	0.00
Navegantes	100	36.31
Potential 7	100	2.60

Table 14
Runs with and without penalty.

Scenario	Number of airfields			Total expenditures (costs + investments) index		
	A	B	% Difference in Number of airfields	A	B	% difference in expenditure
1	7	10	43	68.22	67.23	−1
2	12	13	8	73.95	72.15	−2
3	7	10	43	70.17	69.10	−2
4	11	12	9	76.07	75.24	−1
5	11	14	27	100.00	58.10	−1
6	10	12	20	56.72	55.21	−3

Table 15
Comparison of average costs by scenario group relative to scenario 1.

Scenario	Average% diff. as compared with scenario 1
2	8
3	3
4	12

Table 16
Sensitivity analysis of cost scenarios to changes in demand.

Scenario	Average% diff. as compared with scenario 4
5	31
6	−26

scenarios returned fewer opened aerodromes. The explanation is that marine units are in a roughly rectangular sea strip, while the coast has rounded shape, so that the most advanced sites over the sea present privileged position to meet demand, as can be seen at Fig. 4. Therefore, of the 14 potential airfield locations, only 10 seem to be closest to at least one MU. The other 4 can still be used if related cost or investment requirements are competitive or if needed to meet capacity limitations of closer aerodromes.

Table 15 shows the comparison between average scenario group costs. Scenario Group 1 was less restrictive, and thus showed lowest total costs. Group 2 was on average 8% more expensive than 1, representing increased costs due to capacity constraints at some airfields. Group 3 was 3% more expensive than 1, showing that, at least in this case study, the results are more sensitive to capacity limits than to airfield operating costs and investments in construction and adaptation. Group 4, which represents the baseline scenario with all restrictions, is on average 12% more expensive than the scenario without restrictions.

From these results managers could conclude, for this case study data that between the evaluated parameters what makes total expenditure increases more is the capacity restriction of airfields. So, there is one or more good locations with smaller capacity than desirable. So, if managers identify any possibility to increase capacity in these airfields they should try, and maybe run new scenarios with new capacity information.

5.7. Sensitivity analyses to demand variation

The results for demand variation sensitivity can be seen in Table 16, which compares the average cost of Group 4 to Groups 5 and 6, where the demand is adjusted by 25% upwards and downwards, respectively. It can be concluded that, in this case study, the

25% upward adjustment has more impact than the reduction in demand. This difference is because the increased demand scenario entails investment in new airfields. In Group 5 (increased demand), the total number of airfields ranges from 11 to 14, while varying from 11 to 12 in Group 4, and 10 to 12 in Group 6.

This type of evaluation can help managers to evaluate for example the maximum demand growth that the chosen scenario can attend helping then choosing more robust network configurations.

6. Conclusions and future directions

Oil discoveries of recent years indicate a large increase in oil exploration and production in Brazil. Consequently, there will be increasing demand for passenger transport, as well as increasing transport complexity due to longer average distances between oilfields and the coast. In this study a logistics network optimization model was applied to passenger air transportation for offshore activities. This model has great potential to help Petrobras and other oil companies as a decision support tool for planning the logistics of moving their employees to work offshore. This study is innovative: to the best of our knowledge there are no published studies that address this problem.

In this paper we describe the assumptions adopted in the model and their importance. The model was analyzed for consistency using a case study in meeting demand from offshore petroleum basins in southern and southeastern Brazil. The results were promising, particularly highlighting the importance of including the calculation of helicopters capacity vis-á-vis flight distance, which enabled the model also to choose the optimal fleet mix. Other benefits include: calculation of helicopters occupation rate; a more realistic representation of distances traveled in the Campos Basin, as required by the rules of the new Aeronautics Charter for the region; inclusion of airfields operating and investment costs; allocation of maritime units to aerodromes, taking into account helicopters capacity to suit the units' locations; accurate and optimum location of airfields, taking into account the aspects described above, all of which influence the calculation of the objective function of the problem.

Future work includes considering how investment cost varies with maximum number of helicopters allocated to an aerodrome, in order to represent the portion of investment that varies with the size of the infrastructure established. This refinement, however, makes the model nonlinear. Another possible extension would be to consider stochastic demand, as this is dependent on parameters with a high degree of uncertainty, such as the number and location of drilling rigs in operation in each time period. Finally, it is suggested the model be adapted to study other regions where helicopters are used for offshore passenger transport.

Appendix A. Pre-processing calculation

According to Section 3.3.2, the described problem involves a large amount of variables and constraints. Considering this, there were used pre-processing to reduce the quantity of variables and constraints and make the scenarios viable. The pre-processing equations consider some notations that are not presented in Section 3.3.1, this notations can be found in Tables 17–19. Below, there are described all the pre-processing calculations employed in this model.

A.1. Distance calculation

To calculate the geographical distance between points i and j, given by their geographical coordinates, we used Eq. (1) – Spherical Law of Cosines, proof of which can be found in Junkins and Shuster (1993). In this equation, *lat* and *long* refer to latitude and longitude (in radians), respectively, and R is the radius of Earth ($R \approx 6378$ km). Also, the Earth's shape is approximated to a sphere, ignoring ellipsoidal effects.

$$\check{d}_{ij} = R \arccos[\sin(lat_i)\sin(lat_j) + \cos(lat_i)\cos(lat_j)\cos(long_i - long_j)] \tag{17}$$

Using the notation defined above, the roundtrip distance from airfield a to maritime unit m and back to a, can be calculated using expressions (18) and (19), since there is only one gate for each leg of the flight.

$$d_{am} = 2\check{d}_{am} \quad \forall(a, m) \in \overline{AMG} \tag{18}$$

$$d_{am} = \sum_{g \in G}(\delta G_{amg}(\check{d}_{ag} + \check{d}_{gm})) + \sum_{g' \in G}(\delta G_{mag'}(\check{d}_{mg'} + \check{d}_{g'a}))$$
$$\forall(a, m) \in AMG \tag{19}$$

A.2. Feasible flights

A combination of factors is necessary for a flight to be feasible. The first, of course, is that demand must exist, but capacity constraints on maritime unit helidecks and onshore airfields, as well as helicopter autonomy factors, must also be considered. These conditions are detailed and formulated below.

(a) *Demand*: The set *MPT* is defined to enumerate all the triples (m, p, t) where there is demand, that is $Q_{mpt} > 0$, as indicated in expression (20). The parameter *MaxQ*, calculated by Equation (5), expresses all demand over the planning horizon.

$$MPT = \{(m, p, t)|Q_{mpt} > 0\} \tag{20}$$

Table 17
Pre-processing indices and sets.

Indices and Sets:	Description
$g \in G$	Set of air gates
$M_{ms} \subset M$	Subset of maritime units whose helideck handles only medium-sized helicopters
$AMG = \{amg_{am} = g, amg_{ma} = g'\}$	Set of tuples indicating that round trip from airfield a to maritime unit m uses the gate g and $\acute{g}$ on the outward and return legs, respectively
$(a, m) \in \overline{AMG}$	Set of couples indicating whether flights from airfield a to maritime unit m do not use an air gate (direct flights)

Table 18
Pre-processing parameter.

Parameters	Description
$Lat_m, Long_m$	Location (latitude and longitude) of maritime unit m
$Lat_g, Long_g$	Location (latitude and longitude) of air gate g
$Lat_a, Long_a$	Location (latitude and longitude) of airfield a
$Speed_h$	Average flight speed of helicopter of type h
$\check{d}_{ij}$	Geographical distance between points i and j
d_{am}	Geographical distance covered in one flight from airport a to maritime unit m and back to airport a, considering, when applicable passing by the air gate
Fh_h	Limit on hours flown per unit time (year) of helicopter of type h
$Seats_h$	Seats available on helicopter of type h
$MFuel_h$	Maximum fuel capacity of helicopter of type h
TOW_h	Max takeoff weight (TOW) of helicopter of type h
BOW_h	Basic operating weight (BOW) of helicopter of type h
$HFuel_h$	Average fuel consumption per hour flown of helicopter of type h
$ExtraT_h$	Additional time for each journey (takeoffs, landings, passenger embarkation and disembarkation at platform and helicopter taxiing at airfield on departure and return) by helicopter of type h
$SafeT_h$	Average flight time for which the helicopter must have spare fuel, in compliance with safety standards of helicopter of type h
$Wpax$	Average weight per passenger plus luggage

Table 19
Pre-processing calculated parameter.

Calculated parameters	Description
δG_{ijg}	If flights from local i to local j should use the air gate g
δMH_{mh}	If helicopter of type h can operate at maritime unit m
δAMH_{amh}	If helicopter of type h has sufficient autonomy to serve maritime unit m from airfield a
$\delta AMPHT_{ampht}$	If flight can be performed from airfield a to maritime unit m carrying passengers of group p using helicopter of type h in time t
$FFuel_{amh}$	Fuel consumption to serve maritime unit m from airfield a using helicopter of type h
WS_{amh}	Available passenger weight capacity when serving maritime unit m from airfield a using helicopter of type h

$$MaxQ = \sum_{mpt \in MPT} Q_{mpt} \qquad (21)$$

(b) *Feasibility of helicopter type and helideck port at maritime unit*: The parameter δMH_{mh} = 1 indicates feasible couples *(m, h)* of helicopter type and maritime unit helideck and the set *MH*, defined by expressions (22) inputs at the model only the feasible couples to avoid waste of computational time. Some helidecks support only mediun-sized helicopters, expressed by the subset $M_{ms} \subset M$. For any helicopter of this subset, δMH_{mh} = 1 only if m represents a medium-sized helicopter.

$$MH = \{(m, h)|\delta MH_{mh} = 1\} \qquad (22)$$

(c) *Helicopter autonomy*: to know if a helicopter has sufficient autonomy for a given flight its fuel consumption has to be calculated as in Eq. (23). Here, for greater rigor, fuel consumption should be a function of total weight of helicopter plus passengers, but including this consideration would make the model non-linear, and therefore more complex.

$$FFuel_{amh} = HFuel_h \times \left(\left(\frac{d_{am}}{Speed_h} \right) + ExtraT_h + SafeT_h \right) \qquad (23)$$

The helicopter with this amount of fuel must transport at least one passenger. This condition is expressed by constraint (24):

$$WS_{amh} = TOW_h - BOW_h - FFuel_{amh} \geqslant Wpax \qquad (24)$$

Parameter δAMH_{amh} consolidates helicopter autonomy. It is set according to expression (25) and (26):

$$\delta AMH_{amh} = \begin{cases} 1, \text{if } \delta MH_{mh} = 1 \text{ and } FFuel_{amh} \leqslant MFuel_h \text{ and } WS_{amh} \geqslant Wpax \\ 0, \text{otherwise} \end{cases} \qquad (25)$$

$$AMH = \{(a, m, h)|\delta AMH_{amh} = 1\} \qquad (26)$$

The number of passengers that helicopter type *h* can transport when serving maritime unit *m* from airfield *a* is given by expression (27), while expression (28) calculates the maximum number of flights that can be performed in those same conditions:

$$HC_{amh} = \begin{cases} \lfloor \frac{WS_{amh}}{Wpax} \rfloor & \textbf{if } \frac{WS_{amh}}{Wpax} \leqslant Seats_h \\ Seats_h, \text{otherwise} \end{cases} \qquad (27)$$

where $\lfloor x \rfloor$ indicates the largest integer less than or equal to *x*.

$$MaxF_{amh} = \frac{Fh_h}{\left(\left(\frac{d_{am}}{Speed_h} \right) + ExtraT_h + SafeT_h \right)} \qquad (28)$$

(d) *Airfield capacity:* is defined in terms of the parameter $MaxH_{at}$, which is the maximum number of helicopters that can use (park at) the airfield. *AO* is the set of all airfields that can be opened in each year defined by expression (29).

$$AO = \{(a, t)|MaxH_{at} > 0\} \qquad (29)$$

The set *FF* and the parameter $\delta AMPHT_{ampht}$ consolidate the conditions for a feasible flight, as indicated by expressions (30) and (31):

$$\delta AMPHT_{ampht} = \begin{cases} 1, \text{if } \delta AMH_{amh} = 1 \text{ and } Q_{mpt} > 0 \text{ and } MaxH_{at} > 0 \\ 0, \text{otherwise} \end{cases} \qquad (30)$$

$$FF = \{(a, m, p, h, t)|\delta AMPHT_{ampht} = 1\} \qquad (31)$$

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