A Study of Optimal Search and Rescue Operations Planning Problems

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Abstract

A Study of Optimal Search and Rescue Operations Planning Problems

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Search and Rescue (SAR) systems are vital to provide the quick response for saving lives in the first moments of natural and man-made calamities. In this dissertation, we present and discuss factors related to SAR operations planning and develop three SAR mathematical problems. In the first part we present an overview of SAR operations, highlighting questions affecting aerial search and rescue operations since it is the main object of our Thesis. In the second part, we consider an aerial fleet planning as a resource allocation problem and propose variations in the objective function of a binary integer programming (BIP) model according to different priorities related to area, time and type of the searching operation in high seas. We then study the problem for planning rescue missions in oceanic areas, modelled as a vehicle routing problem considering a heterogeneous fleet of vehicles and respective displacements during the operation. A BIP model is proposed and routing choices are assisted by probabilistic demands at each location that, when visited, may update previous decisions. In the fifth part, we consider the problem for planning a long-range mass rescue operation, modelled as an aircraft routing problem with pick-up and delivering, weight and endurance limits. A BIP model is proposed to minimize the flying time and feasible routes depend on factors such as aircraft endurance, fuel consumption rate, payload, take-off and landing weights, local demand and airfield capacities to operate different types of aircraft. The dissertation ends with conclusions and identified issues for future research.

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Chapter 1

Introduction

1.1 Overview

Passenger safety is the utmost goal for civilian air and maritime transportation. However, accidents, catastrophic or otherwise, still happen due to various known or undetermined reasons. Fortunately, a significant decreasing rate is noted in the past years, as represented by 10 years of aeronautical accidents in Figure 1.1 and maritime accidents in Figure 1.2. When a disaster happens, search and rescue operations (SAR) are used to find and transport people as well as to collect key components for investigation. All possible means are used to ensure assistance to persons in distress without regard to their locations, nationality, or circumstances. The availability of SAR resources are crucial to provide the initial response and relief vital for saving lives since first moments of natural and man-made calamities. SAR operations can be conducted by authorities of different countries or jurisdictions. According to the Convention on International Civil Aviation, the International Convention on Maritime Search and Rescue, and the International Convention for the Safety of Life at Sea, each participating country is responsible for certain specific search and rescue regions (SRR), where adequate communication infrastructure, efficient distress alert routine and proper operational coordination must be maintained. Each SRR has particular dimensions, climate, topographical and physical characteristics, presenting challenges for SAR operations and coordination.

Successful SAR operations provide positive image in emergency situations which normally are viewed negatively. Some tragedies, however, occur in remote regions posing additional difficulties

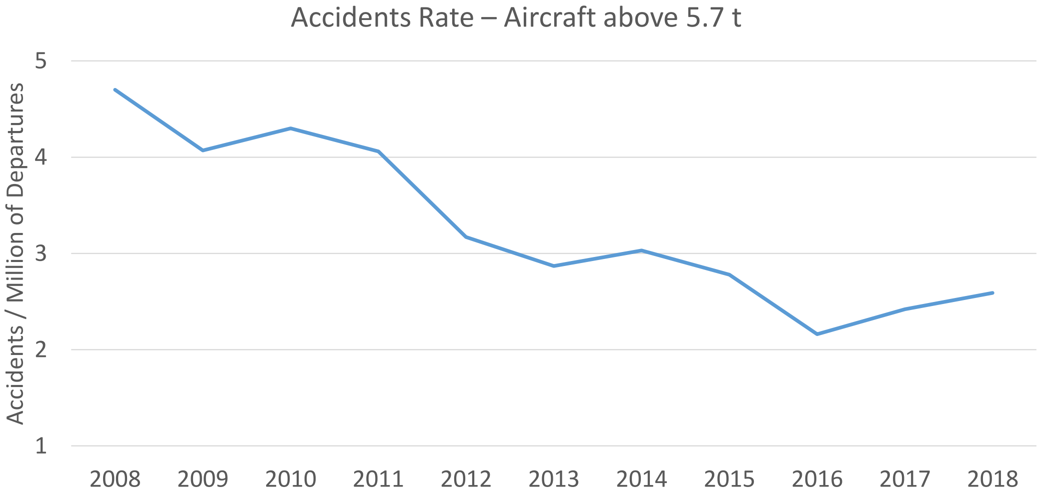


Figure 1.1: 10 years decreasing aeronautical accidents rate. Source: ICAO (2019)

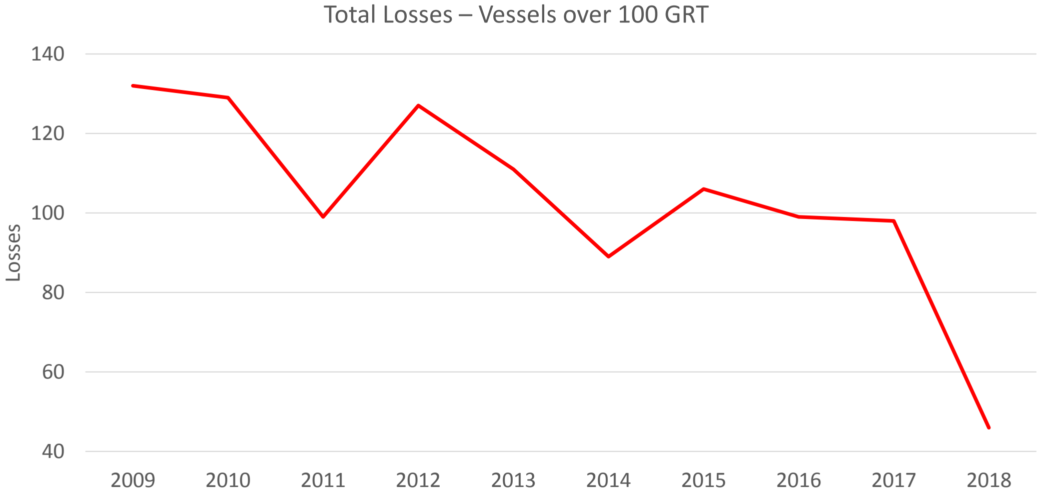


Figure 1.2: Nine years decreasing maritime accidents. Source: Allianz (2019)

to localize and save people in distress. In high seas, for example, the combination of sea currents, weather conditions and time contribute to disperse people and wreckage after an air or maritime accident creating vast areas to be searched. In many cases, even with the aid of electronic devices such as crash position indicators and remote sensing performed by aircraft and satellites, visual searching is still needed to confirm if a detected clue is a real target or not. Long-range aircraft are the vehicles mostly used in ocean SAR operations since they have the capacity to cover larger areas in shorter time. In such cases, a fleet of long-range aircraft is usually formed to execute a searching plan and dissolved when the operations are completed or terminated (a *had hoc* fleet). This fleet can be composed of multi-mission aircraft from government agencies or operated by private operators. The visual searching is highly dependent of visibility conditions, type of targets and aircraft speed and altitude. For example, in favorable weather conditions and sun position, a big target (i.e. a cargo ship) may be spotted in distances superior to 50km. On the other hand, small targets as a small life raft in the sea may require distances no bigger than one or two miles to be visualized. In fact, questions about detectability and others about SAR are well treated by the International Aeronautical and Maritime Search and Rescue Manual (IAMSAR) and related works, such as existing mission planning software.

As soon as a target is identified positively, rescue missions start. They are usually more risky once a rescue needs to enter in the same environment or conditions where survivors are, as well as some important material to obtain for posterior investigations. In high seas, the combination of ships and helicopters is very efficient for rescue operations since different characteristics of speed and cargo capacity generate a good synergy. Unmanned air vehicles (UAVs) may be also used, especially for a short-range searching to obtain details for rescue actions. When an accident occurs inland we have different conditions, especially related to the dispersion of targets and support points that may exist near to the area to be searched for posterior rescue. Searching in dense forest areas may be very demanding because targets are easily hidden by trees' coverage. The rescue inland can be needed by other reasons than accidents, such as disasters caused by flooding, fire, or even armed conflicts. The rescue in these cases has supplementary complications to reach and transport people since the infrastructure may be partial or totally affected by the local conditions and the number of people to assist may be large. In any case, given the urgency of actions and available assets, planning the optimal use of SAR resources presents challenges to the SAR officer once critical decisions must be made on vehicles, equipment and routes to be used. Such planning and decision-making processes may be supported by mathematical and numerical tools. As presented in this thesis, we analyze the dynamics of SAR operations due to air, maritime and land emergencies knowing that research in modeling SAR planning problems considering multiple practical aspects is limited in the literature.

1.2 The Study of Optimal SAR Operation Planning Problems

The main purpose of this thesis is to develop new mathematical models to solve multi-SAR vehicles planning problems based on real situations when searching, rescue and mass rescue operations are needed, contributing to scientific literature as well as supporting the decision-making in SAR operations planning and execution. The author of this thesis served in the Brazilian Air Force by 35 years as Aviator Officer (pilot) from which eight years in a maritime patrol squadron (1°/7° GAv, Salvador, BA) with missions directly related to surface searching and eventually SAR. Later he had opportunity to fly in airlift squadrons that, when solicited, were involved in supporting and rescuing people in remote regions. Thus, the idea to develop new mathematical models for optimizing SAR planning problems was born from these experiences. Although several SAR issues had been already studied and developed in the scientific literature, still there are numerous others that must receive attention, especially problems related optimal composition, dispatching and routing a fleet of vehicles to perform SAR operations. In this thesis we develop an overview and three different mathematical SAR planning problems as follows.

1.2.1 An Overview of Aerial Search and Rescue Operations Planning

An overview of questions affecting aerial search and rescue planning is presented highlighting current communication and location systems, the possible reduction of searching time by the use of space and airborne remote sensing to cover remote regions, the application of fixed-wing aircraft in doing visual and radar searching, and questions related to rescue operations, including mass rescue. This overview brings also main bibliography related to SAR operation, considering general and mathematical approaches.

1.2.2 A Mathematical Model for Tactical Aerial Search and Rescue Fleet and Operation Planning

A mathematical programming model is proposed for SAR operation planning considering a heterogeneous fleet of airplanes to be dispatched from available airports and allocated in specific searching areas. A model and four variants were developed according to different priorities related to area, time and costs.

1.2.3 Modeling and Solving a Search and Rescue Planning Problem for Emergencies in High Seas

A vehicle routing problem is presented considering heterogeneous fleet of helicopters and ships, displacements during the rescue operation and probabilities to find survivors at each location visited. Also, the rescue plan needs to be updated according to its execution in terms of alternative routes, times and courses dependent on the number of survivors found at each location visited.

1.2.4 An Aircraft Routing Problem for Long-Range Mass Rescue Operations Planning

The problem for planning aerial long-range mass rescuing missions inland is modelled as an aircraft routing problem with pick-up and delivering, weight and endurance limits. Given the characteristics of the available heterogeneous fleet of aircraft, we need to determine routes to minimize the flying time by considering aircraft endurance and weight dynamics that condition the feasibility of routes. Table 1.1 summarizes the characteristics of considered SAR planning problems.

1.3 Scope and Objectives

In this dissertation we develop new mathematical models for optimal searching, rescue and mass rescue operations considering multi-vehicles planning and execution. Specific objectives of this research are summarized as follows:

Table 1.1: A summary of considered SAR planning problems.

Issue	Chapter 3	Chapter 4	Chapter 5
Level of planning			
Tactical (days)	X		
Operational (a day)		X	X
Type of problem			
Resource allocation	X		
Dispatching	X		
Vehicle routing		X	X
Pick-up		X	X
Delivering			X
Stochastic demand		X	
Objective function			
Maximizing area	X		
Minimizing time	X	X	X
Minimizing costs	X		
Bi-objective	X	X	
Type of vehicles			
Fixed-wing aircraft	X		X
Helicopters		X	
Ships		X	
Constraints			
Endurance	X	X	X
Crew	X		
Weight			X
Transport capacity		X	X

- To develop a tactical SAR planning problem where an ad hoc fleet of long-range fixed-wing aircraft is needed for doing searching missions in high seas. We considered this situation as a resource allocation problem and proposed variations in the objective function of a binary integer programming model in response to diverse aspects of an aerial SAR operation, such as available information about targets, elapsed time from the declared emergency, as well as the type of the operation, real or simulated.
- To introduce the problem for planning rescuing missions in high seas by considering heterogeneous fleet of vehicles and their displacements during a considered time period as occurring in real life. Also, routing decisions are assisted by probabilistic rescuing demands, as eventually reported by searching missions.
- To develop an aerial long-range mass rescue operations planning by considering the weight dynamics of aircraft that cannot refuel during the mission but must deliver and rescue people in determined locations. This problem is modelled as an aircraft routing problem with pick-up and delivering, weight and endurance limits. Given the characteristics of the available heterogeneous fleet of long-range aircraft, we determine respective routes to minimize the flying time.

1.4 Contributions of this thesis

The presented thesis contributes to scientific literature as well as to support decision-making in SAR operations planning. We first present the contributions according to the chapters that form this dissertation, followed by their impact in the current state-of-art.

1.4.1 An Overview of Aerial Search and Rescue Operations Planning

- Questions affecting aerial search and rescue planning are highlighted.
- Communication and location systems currently in use, ground station and satellite based, are presented.

- The reduction of searching time by the use of space and airborne remote sensing to cover regions where is supposed to have an accident is discussed.
- Visual and radar searching performed by fixed-wing aircraft to cover extensive areas in remote regions are presented.
- Rescue operations are discussed, including an especial case where an expressive number of victims are involved and SAR systems capacities may be inadequate.
- Main bibliographic references are presented considering general and mathematical approaches.

1.4.2 A Mathematical Model for Tactical Aerial Search and Rescue Fleet and Operation Planning

- The approach considers tactical planning of an ad hoc fleet of aircraft and airports that can be used for but otherwise not dedicated to SAR operations.
- A multi-period resource allocation problem is considered.
- Practical considerations about air bases, aircraft, crew, time and area to be covered are used together to develop a new binary integer programming (BIP) model aiming at prompt response to emergencies.
- Four variations of this BIP model are also proposed representing different priorities related to area, time and costs, as well as combinations between them.

1.4.3 Modeling and Solving a Search and Rescue Planning Problem for Emergencies in High Seas

- A new model is developed considering important issues for rescue planning as they occur in real rescue operations in high seas, such as lack of support points, differences in vehicles performances and uncertain information from searching flights.
- There is fully cooperation between helicopters and ships where a helicopter can depart, intercept and land on a ship in movement in any point of its route, even on a different ship from

previous depart.

- Since we consider the transport capacity of all vehicles, the developed model can be viewed as a VRP variant aiming at prompt solutions in response to off-shore emergencies.
- The model also gives assistance for implementing the rescue plan, thus, we discuss the dynamics of executing a planned rescue when the number of survivors is uncertain and re-planning is needed according to the development of actions.

1.4.4 An Aircraft Routing Problem for Long-Range Mass Rescue Operations Planning

- We develop a new VRP variant considering a real problem where aircraft need to take-off with a certain amount of fuel and they are limited by endurance, payload and weight to take-off and land in certain locations to deliver and rescue people.
- We enumerate vehicle routes instead of the node-edge network for simpler computation and fast solution implementation, also avoiding the generation of subcircuits in the solution.
- We reduce the number of constraints by doing precalculations and generating indicators 0/1 to simplify computation and contribute to fast solution implementation.

The manuscript “A Mathematical Model for Tactical Aerial Search and Rescue Fleet and Operation Planning”, located in Chapter 3, was presented in the 2018 Optimization Days Conference and submitted to International Journal of Disaster Risk Reduction – IJDRR in Aug 2019. The manuscript “Modeling and Solving a Search and Rescue Planning Problem for Emergencies in High Seas”, located in Chapter 4, was submitted to Safety Science in September 2019.

1.4.5 Practical Contributions to SAR Systems

A given accident may have intersections in diverse areas such as prevention (actions to avoid or be prepared to mishaps), urban emergencies (i.e. a building on fire or traffic accidents), recovery (i.e. reopening ways and accesses in an area affected by an earthquake) and investigation (determining possible causes related to an accident) and SAR, as depicted by Figure 1.3. Although some

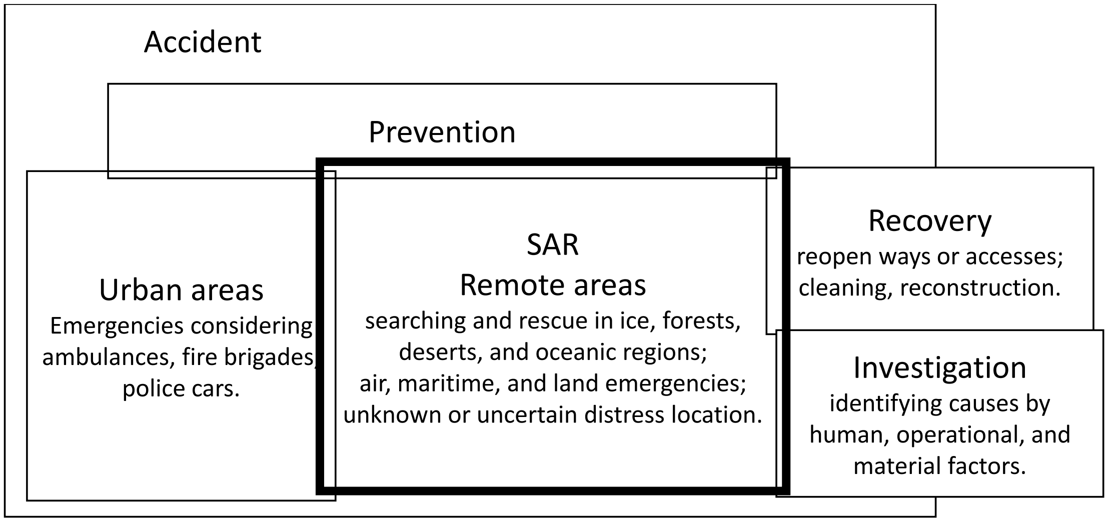


Figure 1.3: Main area related to the present thesis.

intersections may exists between these different areas, the present thesis mainly focus in emergencies that request air operations in ice, forest, mountains, desert and oceanic regions. These type of events are allied with incomplete or uncertain information about the accident, requesting specific actions, planning, equipment and training to locate and rescue people in the shorter possible time.

Given the subject of study, the IAMSAR (2016) has an important relationship with the present thesis. This Manual has three volumes in order to assist member states to meet their own SAR needs and the obligations accepted under the Convention on International Civil Aviation, the International Convention on Maritime Search and Rescue, and the International Convention for the Safety of Life at Sea (SOLAS). The IAMSAR has three volumes with specific objectives. The first volume discusses the global system concept, the establishment and improvement of national and regional SAR systems, and the international co-operation. The Volume II, to assist personnel in planning and coordinating SAR operations and exercises and Volume III, to be carried aboard rescue units, aircraft, and vessels to help with performance of a search, rescue, or on-scene coordinator functions, as well as regarding aspects of SAR that pertain to their own emergencies. The present thesis is related, not exclusively, to the Volume II, Chapter 7, “Multiple Aircraft SAR Operations – General Guidance” that provides principles and procedures for the management and conduct of multiple aircraft operations. The mathematical models developed, presented and discussed in this thesis go beyond of these principles and procedures, aiming specific questions about the optimization of a given set of available SAR vehicles in performing diverse missions, issues still not treated by the IAMSAR nor the available scientific literature. For example, in our thesis, the “Mathematical Model for Tactical Aerial Search and Rescue Fleet and Operation Planning” Chapter we are able to indicate which long-range fixed-wing aircraft should search in a specific location and in which time period, in order to obtain maximum results according to a set of priorities related to area, time and costs. Also, in the “Modeling and Solving a Search and Rescue Planning Problem for Emergencies in High Seas” Chapter we design the best combination of helicopters, ships and respective routes to perform a rescue operation in high seas given units’ characteristics, locations and probabilities to find survivors, in order to rescue a maximum number of persons in the shorter possible time. Our last model in the “An Aircraft Routing Problem for Long-Range Mass Rescue Operations Planning” Chapter aims to indicate the best combination of long-range fixed-wing aircraft and respective routes to perform a mass rescue operation in a remote region, given units’ performance, weight limits, distances, available airstrips and demand to pick-up and deliver. Typically SAR incidents pass through defined stages, as follows (IAMSAR, 2016).

(1) Awareness. Knowledge by any person or agency in the SAR system that an emergency situation exists or may exist.

(2) Initial action. Preliminary action taken to alert SAR facilities and obtain more information. This stage may include evaluation and classification of the information, alerting of SAR facilities, communication checks, and, in urgent situations, immediate performance of appropriate activities from other stages.

(3) Planning. The development of operational plans, including plans for search, rescue, and final delivery of survivors to medical facilities or other places of safety as appropriate.

(4) Operations. Dispatching SAR facilities to the scene, conducting searches, rescuing survivors, assisting distressed craft, providing necessary emergency care for survivors, and delivering casualties to medical facilities.

(5) Conclusion. Return of SAR units to a location where they are debriefed, refueled, replenished,

and prepared for other missions, return of other SAR facilities to their normal activities, and completion of all required documentation.

Thus, in a pragmatic sense, the presented thesis brings important contributions for SAR planning and operations stages, although chapter 3 also considers the return of aircraft in the presented model.

1.5 Organization of the Thesis

This thesis is organized as follows. Chapter 2 presents an overview of main factors related to SAR operations planning, highlighting issues related to aerial fleets. Communication and location systems, the use of remote sensing in support of searching missions, the use of visual and radar searching by long-range aircraft and posterior rescue missions, including mass rescue operations are discussed. Also, main bibliography related to SAR operations are presented, considering general and mathematical approaches. Chapter 3 presents a mathematical model for tactical aerial search and rescue fleet and operations planning. We consider a fleet of heterogeneous fixed-wing long-range aircraft to perform searching missions in high seas. We introduce a binary integer programming and four variations to represent different aspects of SAR tactical planning, such as area, time and costs. Related numerical examples are compared and discussed. Chapter 4 brings a model and a solution approach for a SAR planning problem in high seas. We discuss a VRP variant by considering a heterogeneous fleet of helicopters and ships, their displacements during the operation and probabilistic demands of each location to be visited. In this problem, a helicopter can depart and merge with the ship from any rescue location, given respective capacities and routes, and it is possible re-routing and re-planning. Chapter 5 introduces a VRP variant considering a problem where aircraft start their flights with a certain amount of fuel that will be consumed during the mission, since refueling is not possible. We present and discuss aircraft weight dynamics varying with distances, fuel consumption rate and the weight of the people to be delivered and rescued, to respect limits of payload, taking-off and landing. The thesis ends in Chapter 6 which summarizes the contents, reemphasizes the findings and also gives recommendations for future research direction. Figure 1.4 shows the relationship between the diverse Chapters in the Thesis.

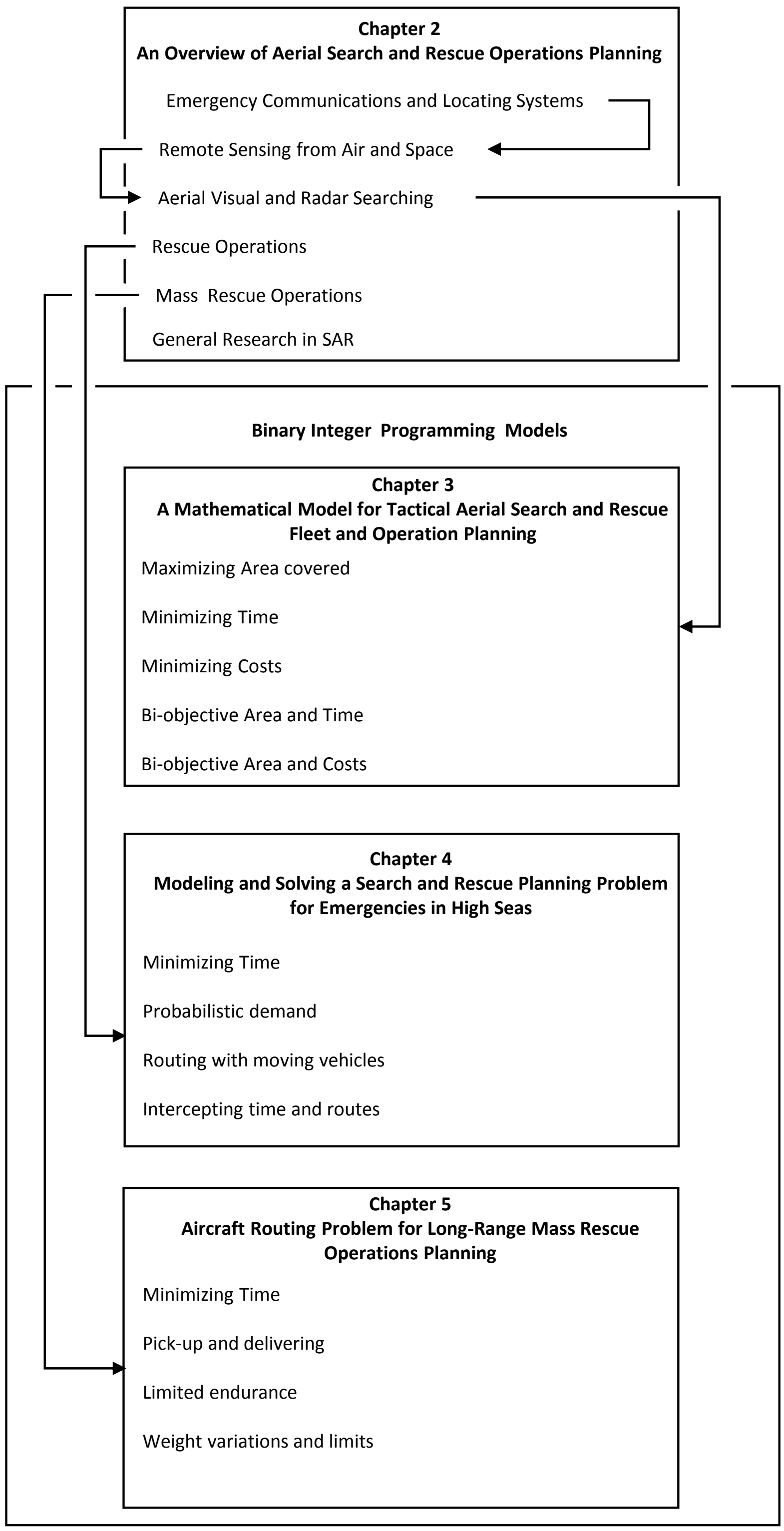


Figure 1.4: Relationship between chapters of the Thesis.

Chapter 2

An Overview of Aerial Search and Rescue Operations Planning

Search and Rescue systems must be ready to operate at any time since an emergency may occur in unexpected time and place. Time is always critical since the survivability increases with faster location and rescue operations. There are different emergency communication and location systems currently in use that, by known or uncertain reasons, may be insufficient to inform precisely where the emergency takes place. In such occasions, additional means are needed such as space and airborne remote sensing to cover regions where is supposed to have an accident, generating important information to reduce posterior searching time. Extensive areas in remote regions are usually covered by fixed-wing aircraft in performing visual and radar searching. Once targets are located, immediate rescue operations are done to transport the survivors to a safe place. When an expressive number of victims are involved, SAR systems capacities may be inadequate and a mass rescue operation is done, requesting especial procedures and planning. This Chapter presents and discusses these situations, highlighting questions affecting aerial search and rescue planning, the main object of the present thesis.

2.1 Introduction

Assisting any craft or person in distress serves national interests, is an established international practice based on traditional humanitarian obligations, translated in international agreements. Search and Rescue (SAR) goals are related to minimize loss of life, personal injury, and property loss or damage and minimize the time spent searching for persons in distress. Readiness is one of the most important characteristics of SAR systems since emergency alerts may come at any time and units must continuously be ready to receive them and respond as needed. Decisions must be made quickly and usually under pressure once time is critical factor to save people. Tragedies cause serious impact on people and business, receiving immediate attention by the media. Successful SAR operations provide positive image in emergency situations which normally are viewed negatively. Thus, the availability, training and well-planned search and rescue (SAR) resources are crucial to provide the initial response and relief capabilities in the first moments of natural and man-made calamities. SAR services may normally continue to be provided in times of armed conflict, in accordance with the Second Geneva Convention of 1949 (Geneva Convention for the Amelioration of the Condition of Wounded, Sick and Shipwrecked Members of the Armed Forces at Sea, of 12 August 1949) and Additional Protocol I to the Conventions (IAMSAR, 2016). The Geneva Conventions and their Additional Protocols are international treaties that contain the most important rules limiting the barbarity of war. They protect people who do not take part in the fighting (civilians, medics, aid workers) and those who can no longer fight (wounded, sick and shipwrecked troops, prisoners of war). The first Geneva Convention protects wounded and sick soldiers on land during war, the second protects wounded, sick and shipwrecked military personnel at sea during war, the third is applied to prisoners of war, and the fourth protects civilians, including those in occupied territory (ICRC, 2014).

SAR systems are based on the Convention on International Civil Aviation, the International Convention on Maritime Search and Rescue and the International Convention for the Safety of Life at Sea (SOLAS). Currently, there are 190 Contracting States in the Convention on International Civil Aviation, 162 in the SOLAS, and 107 in the International Convention on Maritime Search and Rescue. These conventions are managed by The International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO), specialized agencies of the United Nations responsible for regulating the international air and ship transportation. IMO's SAR Plan and ICAO's Regional Air Navigation Plans (RANPs) are the basis for creating and applying national and regional plans, manuals, agreements and other related SAR documents (IAMSAR, 2013), as shown by Table 2.1. Following IMO Global SAR Plan and ICAO RANP are regional SAR plans when applicable. Next are national SAR plans, and so forth down to the Rescue Co-ordination Centre (RCC) and local levels. ICAO and IMO also publish the International Aeronautical and Maritime Search and Rescue (IAMSAR) Manual that supports states to organize and provide SAR services.

Table 2.1: Basic SAR documents.

Administrative Structure	Implementing Guides
ICAO Regional Air Navigation Plans	ICAO-IMO SAR Manuals (IAMSAR)
IMO Global SAR Plan	Regional SAR Manuals
Regional Plans	National SAR Manuals
National SAR Plan	RCC/RSC Plans of Operations

The presented International Conventions guide the establishment of Search and Rescue Regions (SRR) to ensure the provision of adequate communication infrastructure, efficient distress alert routing and proper operational coordination to effectively support search and rescue services. The Convention on International Civil Aviation stablish that the SRR should, in so far as practicable, be coincident with corresponding Flight Information Regions and, with respect to those areas over the high seas, maritime search and rescue regions. Each SRR has unique characteristics such as dimensions, climate, type, posing specific challenges to SAR operations to be successful, as follows.

2.1.1 SAR Operation Environments

Mountain areas have strong winds associated to abrupt height variations. An aerial search in such conditions requires minimum visibility to avoid the terrain and enough aircraft maneuverability to allow flight control in turbulence. In some cases, obstacles such as power lines, towers, and ski lifts may be present. Helicopters may not be able to fly in high altitude regions, especially in presence of strong wind variations. The rescue capacity may be significantly improved using local services such as mountain guides, forest police, and ski resorts personnel. Targets in mountain regions targets are very difficult to detect as well as in forests, even in flat terrain.

Forests have specific difficulties for search and rescue operations. Trees canopy are the main obstacle for aerial searching while different types of terrain and vegetation create enormous difficulties to the advance and operation of ground crew. Locating a crash site in a forest by visual searching is very challenging since the trees' top may remain with few damage after an aircraft penetration. Also, depending on the time elapsing, smoke signs may not be present. On the other hand, when some objects of contrasting colors remain in open spaces, as a parachute in the top of a tree, it may be visualized in long distances. Survivors on land may move away from the distress scene to seek shelter, water, avoid or escape local dangers, creating more difficulties to be locating by SAR efforts.

In the sea, if smooth waters may be found, any object or disturbance of reasonable size can be seen easily. However, whitecaps, foam streaks, breaking seas, salt spray, and the reflection of the sun are usually present and tend to mask a search object or its signals. Distractions such as presence of seaweed, cloud shadows, or marine life may reduce the chance to visualize a small target such as a life raft. Also, wind and sea currents tend to scatter survivors and debris, being more difficult to detect them with the increasing elapsed time from the declared emergency. Targets of varied types and sizes are affected differently by wind and sea currents that increases the scatter effect. For example, a person with a life jacket is basically affected by sea current while a life raft is strongly affected by the wind.

The weather poses enormous influence on SAR operations. Bad weather reduces the visibility and may create turbulence that reduce the search efficiency of crew members. Rescue operations are affected by rain, wind and the possibility of land sliding. Usually SAR operations are paused during periods where additional lives are endangered. Low ceilings and reduced visibility usually impede aircraft operations, especially for fixed-wing aircraft. If some units in the fleet have enough training, equipment and adequate sensors, operations may be still conducted by them. In occasions where the weather changes in an unexpected way, crew leaders must be able to notice the evolution of conditions, evaluate risks, and decide what to do accordingly.

To improve the effectiveness of SAR services is important to reduce the elapsed time between the emergency and the rescue done. One possibility is reducing the transit time needed to arrive at the distress location, or in the search area if the actual location is not known, without delay. The mix of resources at SAR facilities must be reviewed to ensure they are correct for the environment, distances and type of emergency declared. It is especially important when the fleet of vehicles is heterogeneous, by the local availability of means or the international cooperation during the SAR campaign. The elapsed time may be also reduced by periodic training and exercises. In order to maintain proficiency and safety, skills, experience and judgement must be developed to handle typical SAR situations. However, in order to do that, the various SAR system components must be used simultaneously, also for verifying their performance. Although the monetary cost of a SAR operation is not in a critical factor during real emergencies, they may be restrictive for exercises, especial when real units are involved, such as aircraft and respective crew members. For example, the cost of a single hour of a Lockheed P-3C Orion (a typical long-range fixed-wing maritime patrol aircraft) reaches US$ 9,015 (USDoD, 2018). By simply multiplication, considering a 12 h flight (although its endurance reaches 16 h), this mission would cost US$ 108,180. For planning purposes of the aerial part, additional costs may be also considered such as meals and lodging for crew and maintenance teams, support equipment (i.e. for compressor and turbine desalination washes, start power units), consumable items (i.e. lubricants), expendable items (i.e. light, smoke, dye sea markers), as well as for eventual ground transportation. In summary, training and exercises must be done but they may be very expensive. They need to be planned carefully to guarantee frequency in order to reach and maintain a high level of competence for SAR personnel and to verify systems components (i.e. communications network). In real situations, as in (IAMSAR, 2016), the State providing aeronautical and maritime SAR services fund those services, even if the assistance is provided at the request of another entity (i.e. an RCC of another State). Requests for reimbursement are not normally made, therefore, to the State requesting or receiving the services.

Readiness is vital for SAR systems. Distress alerts may be received at any time and the system must be always ready to receive and respond to them once the survivability increases as the time to locate and rescue people decreases. It is very important to minimize the transit, localizing and rescuing time since time is critical in SAR operations. Some existing systems may abbreviate the time to receive an emergency communication and to locate people in distress, as presented in the next Section. When these systems are not enough to inform or locate the incident, remote sensing may be used to reduce the searching time, as discussed in Section 3. Section 4 presents aerial SAR missions that are performed concomitant to remote sensing, in order to locate and rescue people in distress. Section 5 discuss mass rescue operations, when an expressive number of people need to be rescued and special measures must be done. Conclusion remarks are presented in Section 6.

2.2 Emergency Communications and Location Systems

SAR procedures should be initiated if an aircraft or vessel becomes overdue or fails to make a report. For aircraft, this is usually accomplished through an air traffic service or the flight plan system. The frequency 121.5 MHz is the aeronautical emergency frequency and, where required, the frequency 123.1 MHz is the auxiliary frequency (ICAO, 2018). Especially long-range and high altitude flights are surveilled by radars present in many air traffic control (ATC) systems. Usually these radars are composed by a primary radar (i.e. based on the detection of the energy reflected by the aircraft surface) and a secondary surveillance radar (SSR) that depends on aircraft transponders, equipment that understand different signals emitted from the SSR and transmit specific codes to be received and interpreted by the secondary radar. These radars can measure distance and bearing of aircraft and request automated information such as altitude and identity. There are specific codes to be used in transponders to indicate problems without the need of voice communication between the aircraft and the ATC system. Introducing especial codes, they produce alert signs in the radar console that can start specific monitoring or emergency measures. The emergency transponder codes recognized by both ICAO and FAA are (FAA, 2012):

- 7500 – unlawful interference
- 7600 – radio communication failure
- 7700 – emergency

Aircraft, especially commercial airliners, may use also the Aircraft Communication Addressing and Reporting System (ACARS) and the Automatic Dependent Surveillance – Broadcast (ADS-B). The first is a datalink for short messages between the aircraft and ground stations. For example, automated messages from the ACARS indicated the presence of smoke in toilets and in the avionics bay in the EgyptAir Flight 804 that had an accident in the Mediterranean Sea in May 2016, helping to locate the mishap and to understand some conditions related to the event (FSF, 2018). The ADS-B uses Global Positioning System (GPS) technology to generate specific aircraft information that is broadcast directly to a network of ground stations, the air traffic controllers and also to other aircraft. The ADS-B can be used to supplement existing surveillance systems or as the principal source of surveillance data in providing more frequent position update-rates than radar, deliver more precise location and velocity information for the aircraft, and offer critical in-cockpit traffic and weather information (ICAO, 2014, 2017). In any case, however, if radar or communications are unexpectedly lost, SAR procedures may be started.

People and vehicles in distress may be also located by automated or intentionally transmitted information using satellite, maritime and terrestrial technology. Three main of the currently used systems are presented, as the Global Maritime Distress and Safety System (GMDSS), the AMVER system and the COSPAS-SARSAT, as follows.

2.2.1 Global Maritime Distress and Safety System

The Global Maritime Distress and Safety System (GMDSS) is an international safety system to prevent accidents from happening and to automatically alert the rescue authorities and nearby vessels quickly in an emergency (Inmarsat, 2019). Under the Safety of Life at Sea (SOLAS) convention, cargo ships of 300 gross register tonnage (GRT) and upwards and all passenger ships on international voyages must be equipped with satellite and radio equipment that conforms to international standards. For aviation, Inmarsat allow a global coverage for multi-channel voice and data services.

2.2.2 AMVER System

The United States Coast Guard operates the AMVER system, a maritime mutual assistance program for the development and co-ordination of search and rescue (SAR) efforts in the oceans. Sail plans and periodic position reports to the Amver Centre may be sent by merchant vessels making offshore passages. The system uses radio messages through marine communications and traffic services (MCTS). Information from these messages is entered into a computer that generates and maintains dead reckoning positions (i.e. estimating the direction and distance travelled) for participating vessels throughout their voyages. The predicted locations and SAR characteristics of all vessels known to be within a given area are furnished upon request to recognized SAR agencies of any nation for use during an emergency (CCG, 2019). Also, MCTS centers in certain parts of Canada are connected to the cellular telephone network system where cellular telephone users can, in an emergency situation only, dial *16 on their cellular telephone to access a MCTS Centre in order to obtain assistance.

2.2.3 COSPAS-SARSAT System

The Cospas-Sarsat System is designed to locate activated distress beacons operating in 406MHz. These beacons can also be integrated with global navigation satellite systems (GNSS), such as GPS, GLONASS or GALILEO, generating a distress message transmitted from the beacon. GNSS-equipped beacons provide helpful redundancy in determining the beacon location and in certain circumstances can reduce the time needed for Cospas-Sarsat to locate the beacon. There are different types of beacons according to the mainly use. For example, Emergency Locator Transmitters (ELT) are designed for aircraft use. Emergency Position-Indicating Radio Beacons (EPIRB) are designed for use aboard a marine vessel. Personal Locator Beacons (PLB) are designed to be carried by a person (while hiking, for example). Each type has specific features such as automated response by strong acceleration, presence of water or intentionally activated by an individual in distress (Cospas-Sarsat, 2019). Although the Cospas-Sarsat system operates only with 406 MHz signals, some beacon models also transmit a lower powered signal on 121.5 MHz for local search teams to follow (homing) this frequency near the beacon location. In some countries, the misuse of rescue services may have serious consequences. For example, in the United States, knowingly and willfully transmitting a hoax distress call is a felony punishable by up to six years in prison, a US$ 250,000 fine, and restitution to the rescue agency for all costs incurred responding to the distress (NOAA, 2019).

Unfortunately, in some occasions distress beacons may not work as expected by reasons such as antenna disconnected from the transmitter during the accident, fire damage, incorrect installation, water submersion, antenna shielded by post-crash environment, and others, as analyzed in Stimson, Littell, Mazzuca, Foster, and Theodorakos (2017). They conducted a comprehensive study of ELTs performance over a three year period, considering informed performance, analysis of contemporary aviation crashes reports, as well as a series of tests including crash safety (vertical drop tower), vibration, antenna cable system strength, and antenna cable fire survivability. The investigation of ELT failures generated recommendations for improvements in the system performance, aiming the reduction of loss of human life as well as risk, time and costs for SAR operations.

2.3 Remote Sensing

Remote sensing can significantly improve the chances to locate the vehicle or wreckage in question. For example, a remote sensing aircraft was the first platform to detect metallic and non-metallic objects from the AF447 flight floating in the oceanic Brazilian SRR. In that period, weather conditions were not favorable to visual searching, still related to the conditions that contributed to the accident. The detections were passed to two other searching aircraft that confirmed visually that the objects were from the missed aircraft Meyer (2017). This procedure saved important means, especially time, critical in these situations. In another situation, during the search of the MH370 flight, an analysis of radar data and subsequent satellite communication (SATCOM) system signaling messages placed the aircraft in the Australian search and rescue zone on an arc in the southern part of the Indian Ocean. This arc was considered to be the location close to where the aircraft's fuel was exhausted ATSB (2014). Because of these information, the search zone was moved from Malaysia to South Indian Ocean region after the five first days of search. Satellites imagery may be also used to help in the search for missing aircraft or vessels but it needs an indication of where to search for the missing craft since it would be impossible to find a lone craft in a vast area. In a general sense, remote sensing refers to the means related to the objective to obtain information about a given target by collecting and processing data without physical contact with the target as in Moser and Zerubia (2018) and Khorram, Van Der Wiele, Koch, Nelson, and Potts (2016).

Remote sensing sensors may be located in aircraft, including remotely piloted aircraft (such as drones or UAVs), balloons, and satellites. Sensors are based in electromagnetic emissions collected by instruments mounted on aircraft or Earth-orbiting spacecraft, making it possible to collect information about large geographic areas with a single observation. Airborne remote sensing offers some advantages such as to capture information in shorter distances than satellites and the possibility to change or upgrade sensors in an easier way. Satellites, on the other hand, can revisit an area of interest on a regular cycle, from days to hours, facilitating the acquisition of data to reveal changing conditions over time. Remote sensing has a particular role in SAR operations since they may reduce SAR efforts, especially related to the searching phase.

As it can be seen in Figure 2.1, a satellite or aircraft (A) with an electro optic (EO) sensor is following direction (B). The area imaged on the surface (D) is related to the (C) instantaneous field-of-view (IFOV), producing a strip covered by the sensor of width (E), referred as swath width. Considering the distance between the sensor and the scene, imaging swaths for spaceborne sensors generally vary between tens to hundreds of kilometers wide. For aircraft, some kilometers to hundreds of meters only. In this sense, airborne platforms are not suited to capturing large geographic areas (e.g., 10,000 km^2) at once, thus satellites do the broad-scale remote sensing. One common definition of resolution is the ability to identify objects or features in a captured image. Using a concept related to cartography where a large-scale map shows more details than a small-scale map, a large resolution image shows more details than a small resolution. Thus, if the image (D) is composed by a large number of pixels, we have a large resolution. In fact, there are four basic types of resolution for remote sensing: spatial, spectral, temporal, and radiometric. Spatial resolution, is a measure of the clarity or fineness of detail of an image, related to sensor's pixel size. The size of a pixel determines its spatial resolution which in turn determines the degree of recognizable detail in an image. It is also related to the IFOV and the distance between the sensor and the surface. If this area viewed is divided by a big number of pixels, a large resolution image is obtained. For SAR applications, a broad view of a region affected by an earthquake or tsunami before and after the tragedy may be very useful for planning purposes, even if the image obtained by the satellite does not allow the identification of smaller targets such as houses or cars. In these cases, larger swath widths and spatial resolution of tens to hundreds of meters should not be a problem. However, if target recognition is intended, i.e. for identifying wreckage of an accidented vehicle, bigger spatial resolutions are required and smaller swath width are used. In fact, it poses some difficulties for using remote sensing images for SAR planning. Larger swaths are interesting for covering larger areas, the resolution obtained may be sufficient for discriminating large events, such as flooding or earthquakes, but for small targets (i.e. a crash site or floating debris) it may be not possible. Smaller swaths, in its turn, may allow larger resolution but targets may be outside the strip covered by the sensor and remain undetectable. In past searches such as about the MH370 flight, may be noted that, first, to consider all information to reduce the area where targets may be contained to direct the sensors to that specific region. Second, the use of images of varied resolutions (including type of sensors) to verify from a small to bigger resolution (or scale) detected clues.

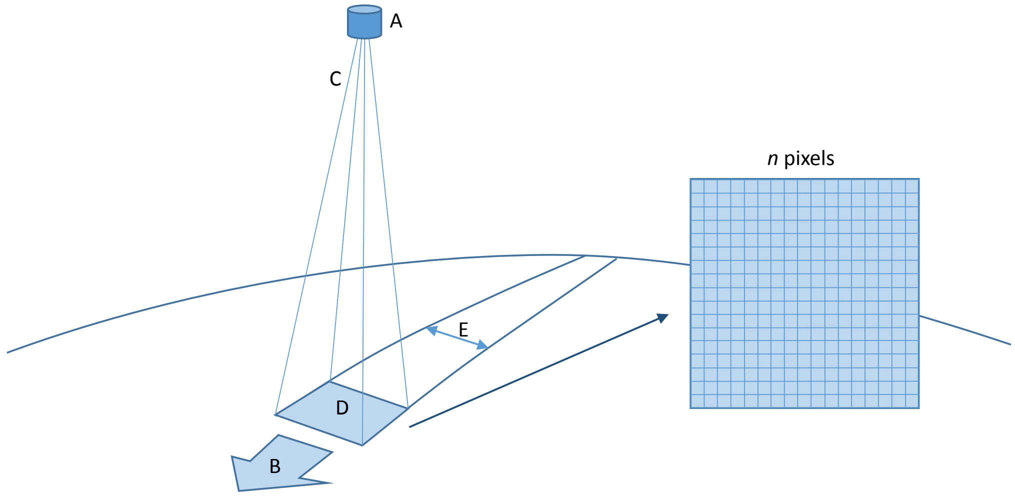


Figure 2.1: Image resolution basic components.

Spectral resolution represents the sensor's ability to discriminate different wavelengths between objects in a scene of interest. For example, a missing green painted aircraft may be very difficult to be detected visually in a similar color background, but if the paint reflect different wavelengths (a different spectral signature), a multi spectral sensor (MSS) evidence these differences, allowing us to separate the target from the background. Temporal resolution is the amount of time it takes for a sensor to revisit or reimage a particular geographic location. For an Earth observation satellite, this time may be about four to five days, however, having the ability to steer the sensor to the area of interest, this time may be reduced to daily. It is important to verify changes in specific areas, where is supposed or known to have a SAR target. Radiometric resolution is the sensitivity of a sensor to incoming electromagnetic energy (i.e., the smallest differences in intensity that the sensor can detect).

2.3.1 Electro-Optic and Radar Imagery

Satellite imagery was extensively used during the search of the flight MH370. As related in ATSB (2017), during the initial stages of the search for MH370 there was a concerted effort to identify MH370, or a possible condensation trail from the aircraft, in any available satellite imagery captured over the Malay Peninsula and the Strait of Malacca. Available satellite imagery for the Indian Ocean was also later analyzed for the time of the flight and some hours after. The aircraft was not identified in any of this imagery although some possible condensation trails were identified and analyzed. During the subsequent surface search in the Indian Ocean, AMSA, with the assistance of the Australian Geospatial-Intelligence Organisation, made requests of foreign governments including France, Italy, Germany, Thailand, the People's Republic of China and the United States to capture imagery (in various electromagnetic spectra including radar, optical and infrared) using their low earth orbiting satellites in the region of the MH370 search area. The intent was to cover as wide an area as possible with the satellites in the hope that aircraft debris floating on the ocean surface. A summary of analyzed satellite imagery data can be found in Minchin, Tran, Byrne, Lewis, and Mueller (2017) which concluded that the four satellite images contain at least 70 identifiable objects, with twelve being assessed as probably man-made and a further 28 objects assessed as possibly man-made. The resolution of the images at 0.5m, however, was insufficient to conclude with certainty that any of the objects were debris from MH370 although some objects show geometric shapes that do not conform with wave patterns or other expected natural phenomena.

Satellite imagery may be used to help in the search for missing ocean-going vessels or aircraft, but is needed an indication of where to start the search for the missing craft. Main contributions are provided by the international charter 'Space and Major Disasters'. It is a worldwide collaboration among space agencies to provide satellite data for disaster management authorities during the response phase of an emergency. The Charter operates since November 2000, covering natural and technological disasters such as floods, hurricanes, tsunamis, earthquakes, landslides, forest fires, volcanic eruptions, ice jams, oil spills, and missing vehicles such as vessels, aircraft and submarines. The system has been activated in response to over 626 major disasters in more than125 countries, including the 2004 Asian tsunami, the 2008 cyclone Nargis in Myanmar, the 2010 earthquake in Haiti, the 2010 flooding in Pakistan, the 2011 earthquake and tsunami in Japan, the 2012 cyclone Bopha and the 2013 super Typhoon Haiyan in the Philippine (ICSMD, 2019). Other types of disasters such as a train or aircraft crash, an accident at a factory, power plant or other large scale impact accident may also benefit from satellite observations that can be used to map the extent of the disaster area. For example, the Charter was activated for covering areas related to a missing South Korean cargo ship (April, 2017), an Argentinian submarine (February, 2017), an aircraft crash in Iran (February, 2018) and a dam collapse in Brazil (January, 2019).

At time of writing this thesis, there were 17 Charter Members with 61 contributing satellites, as listed in Figure 2.2. These satellites have different types of sensors, swath width, spectral range and bands, and revisiting time. A more detailed information about satellite characteristics, as well other contributing organizations may be found in the “disasterscharter.org” site. In most cases, participating satellites are based on electro-optic (EO) systems that provide panchromatic (PAN) and multi spectral (MS) images that increases the possibility to discriminate a target from the background if compared to PAN only. Spatial resolution, revisiting time and swath width depends on the sensor on board of the satellites but also the orbit adopted. In a general sense, Geo-synchronous orbits (GEO) allow bigger swath, up to the Earth disk, a daily observation, but the spatial resolution is restricted to observe large events such as floods, earthquakes or tsunamis. Medium Earth orbit (MEO), especially using polar and sun-synchronous orbits, are used for observation satellites, where are many of the Chapter’s satellites. EO sensor are usually multi-spectral (MSS) with a resolution from some meters up to 30 cm. Revisiting time are from some days (i.e. five days at nadir) to daily (off-nadir). Revisiting time is also abbreviated by the use of constellations of satellites, such as Disaster Monitoring Constellation-3 (DMC-3) that uses three satellites separated by 120° in the same orbit, as well as the RapidEye constellation (DLR) that uses five satellites. Also, the capacity to move the field-of-view (FOV) of sensors to some predefined location (off-nadir) at each passage near a zone of interest allows daily observation (instead some days at nadir). Other sensors than EO have been also implemented using space and airborne platforms, as active remote sensing systems. They differ from passive remote sensing systems (the vast majority of sensors) since they generate and send their own “pulses” of electromagnetic energy and record the strength of the signals returned

Table 2.2: Summary of International Charter satellites' characteristics.

Member	Data available from satellite	Type	Spatial Resolution (m)	Swath (km)
ABAE	VRSS-1	EO	2.5 - 16	29 - 180
Venezuela	VRSS-2	EO	1 - 60	30
CSA	RADARSAT-1	RADAR	Archive only	
Canada	RADARSAT-2	RADAR	1 - 100	18x8 500X500
INPE	CBERS-1/2/2B	EO	Archive only	
Brazil	CBERS-4	EO	5 - 64	60 - 886
Planet (USA)	PlanetScope	EO	3.9	24
CNES	Pléiades-1A/1B	EO	0.5 - 2	20
France	SPOT 6/7	EO	1.5 – 6	60
DLR	TerraSAR-X, TanDEM-X (SAR)	RADAR	1 - 40	10x5 270x200
Germany	RapidEye constellation (5 satellites)	EO	6.5	77
DMC	UK-DMC2	EO	22	660
UK	Deimos-1	EO	22	660
JAXA	Daichi-2	RADAR	1 - 100	25 - 490
Japan	Kibo	EO	15 - 260	26x15 500x290
UAESA/MBRSC	DubaiSat-2	EO	1 - 4	12
UAE	DubaiSat-1	EO	Archive only	
ISRO	IRSP5	EO	2.5	27.5
India	Cartosat-2/2A/2B	EO	1	9.8 - 18
	Resourcesat-2	EO	5.8 – 56	23 – 740
ROSCOSMOS	Kanopus-V 1/3/4/5/6	EO	2.5 – 10.5	20 – 23
Russia	Kanopus-V-IK	EO	2.5 – 200	20 – 2,000
	Meteor-M	EO	60	450 – 900
	Resurs-P 1/2/3	EO	1 – 3	38
	Resurs-DK	EO	Archive only	
CNSA	FengYun-3C	EO	250 – 1,100	2,600
China	Gaofen-1	EO	2 - 16	70 – 800
	Gaofen-2	EO	0.8 – 3.2	45
	Gaofen-3	RADAR	1 – 500	650
	Gaofen-4	EO	50 – 400	650
	SJ-9A	EO	Archive only	
ESA	Sentinel-1A/1B	RADAR	5x20 20x40	20 - 400
Europe	Sentinel-2A/2B	EO	10 – 60	290
	Proba-V	EO	100 - 333	517 – 2,285
KARI	KOMPSAT-2	EO	1 - 4	15
South	KOMPSAT-3	EO	0.7 – 2.8	16
Korea	KOMPSAT-3A	EO	0.55 – 2.2	12
	KOMPSAT-5	RADAR	1 - 20	5 - 100
USGS	Landsat-8	EO	15 – 100	185
United	Landsat-7	EO	15 – 60	185
States	WorldView-1	EO	0.5	17
	WorldView-2	EO	0.5 – 2	17
	WorldView-3	EO	0.31 – 30	13
	GeoEye-1	EO	0.4 – 1.65	15.2
	IKONOS,	EO	Archive only	
	Landsat – 5,	EO	Archive only	
	QuikBird	EO	Archive only	
CONAE (Argentina)	SAC-C	EO	Archive only	
EUMETSAT	Metop-A/B/C	EO	1,110	2,048
Europe	Meteosat 2nd Gen	EO	1,000 – 3,000	Earth Disc
NOAA	NOAA-15/18/19	EO	1,100 – 2,048	2,048
United	NOAA-20	EO	400 – 800	3,000
States	GOES-15	EO	1,000 – 8,000	Earth Disc
	GOES-16/17	EO	500 – 2,000	Earth Disc
	GOES-8 to 14	EO	Archive only	

from the features. Although in our case active systems refer to radar and laser systems, we will focus on radars only, since they have some interesting characteristics in helping SAR. EO observations from both aircraft and satellites are affected by weather conditions, especially clouds. For radar detection, however, weather effects are significantly reduced and the eventual possibility to vary transmitted frequency and polarization can improve detection of metallic parts. Recognizing objects, however, maybe more difficult than EO sensors, especially when natural colors are somehow important. Aperture synthetic radars (SAR) are used with some interesting advantages such as not be affected by weather factors such as clouds, haze, or Sun illumination. The capacity of some radars to operate in submetric modes provides details about background and targets similar of optical sensors. For example, features of vehicles and planes begin to differ at resolutions below 50 cm, as in Lacomme, Marchais, Hardange, and Normant (2001), that brings also examples of different missions, summarized in Table 2.3.

Table 2.3: Summary of reconnaissance modes for synthetic aperture radars.

Mission	Resolution (m)	Swath (km)
Search of objectives / cartography	≈ 3	> 10
Search of objectives + activity assessment	≈ 3	10
Ground- installation analysis	≈ 0.50	5
Target classification	≈ 0.30	> 2
Target identification	≈ 0.15	> 1
Surveillance / large area cartography	≈ 20	> 30

Depending on the frequency used, some capacity of tree canopy penetration is obtained, as described in Imhoff, Story, Vermillion, Khan, and Polcyn (1986) and M. E. Davis (2016). This capacity, when possible, may be useful to detect wreckage in a forest region since metallic parts are expected and their reflections are usually stronger than other materials, facilitating the discrimination from the background. Also, the possibility to vary the polarization of the radar waves (transmitting and receiving) in a SAR can improve the detection of targets. For example, the wreckage tends to assume horizontal position in the ground, thus, horizontal polarization for transmitting and receiving may be the one that promote bigger radar returns.

2.4 Aerial Searching

Searching is the most prolonged phase of the SAR operations especially in oceans, where the combination of uncertainty about the distress incident location and the displacement of survivors and debris creates large areas to be investigated. Even using the best resources for minimizing the searching time, SAR operations may last from few days to many weeks and be very expensive. The searching for the accidents involving Air France AF447 and the Malaysian Airlines MH370 flights in 2009 and 2013 respectively show how difficult are SAR operations in high seas. The Airbus A330 of flight AF447 crashed about 600 nautical miles (NM) away from Brazilian coast while in route from Rio de Janeiro airport bound for Paris Charles de Gaulle. The fleet for surface searching was composed by 15 aircraft, including one for remote sensing. Participating with Brazil in the SAR efforts were United States and France. The EMB R99-A for remote sensing detected the first debris of the AF447 in the second day after the accident. Oil and a floating seat were confirmed visually by other two searching aircraft in the third day of operation. According to (da Silva, 2006) and reproduced in Figure 2.2, 185,349 km^2 were covered in four days but the aerial searching still lasted for more 21 days. Larger green rectangles represent the area covered by aerial remote sensing. Only two years later, the main wreckage was found at a depth of 3,900 meters. The final official report about this accident was done by the Bureau d'Enquêtes et d'Analyses - BEA (2014).

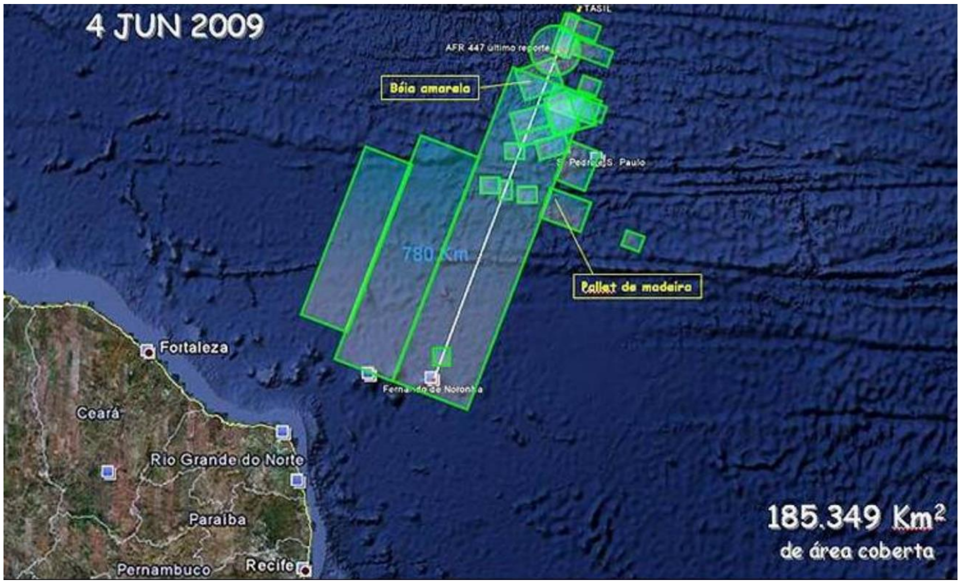


Figure 2.2: Area covered in four days of AF447 searching. Source (da Silva, 2006).

The Malaysia Airlines flight MH370 disappeared on March 8, 2014 and only a piece of the wing was recovered until the end of the underwater searching in January 2017. The aerial search lasted for 52 days and used about 50 aircraft in the in Southeast Asia and 29 aircraft in the South Indian Ocean. Joint efforts in this second phase by Australia, United Kingdom, United States, China, Japan, New Zealand, and South Korea covered about 2.4 million NM^2 (4.5 million km^2) using 334 searching missions (about 8 flights per day) for a total of over 3,000 flight hours. Figure 2.3 from ATSB (2017) shows searching areas between days 18 and 27 March, 2014. Such distances involved required long aircraft endurance. For example, the distance of 1,970 km shown between the coast and the nearest area would require about six hours (i.e. considering 335 kt of cruise speed) only to do the way between the SAR base and the searching area.

Some points may be highlighted about these two SAR operations. Although airborne remote sensing had been very helpful in the start of the AF447 operation and satellite information in the MH370 search, in both cases, however, large areas were still demanded to be covered, especially in the search of the MH370 flight. In general, the uncertainty about the impact and debris locations create significant difficulties to determine the optimal use of the fleet by the SAR planner, allied to different characteristics of vehicle performances, usual in international cooperation.

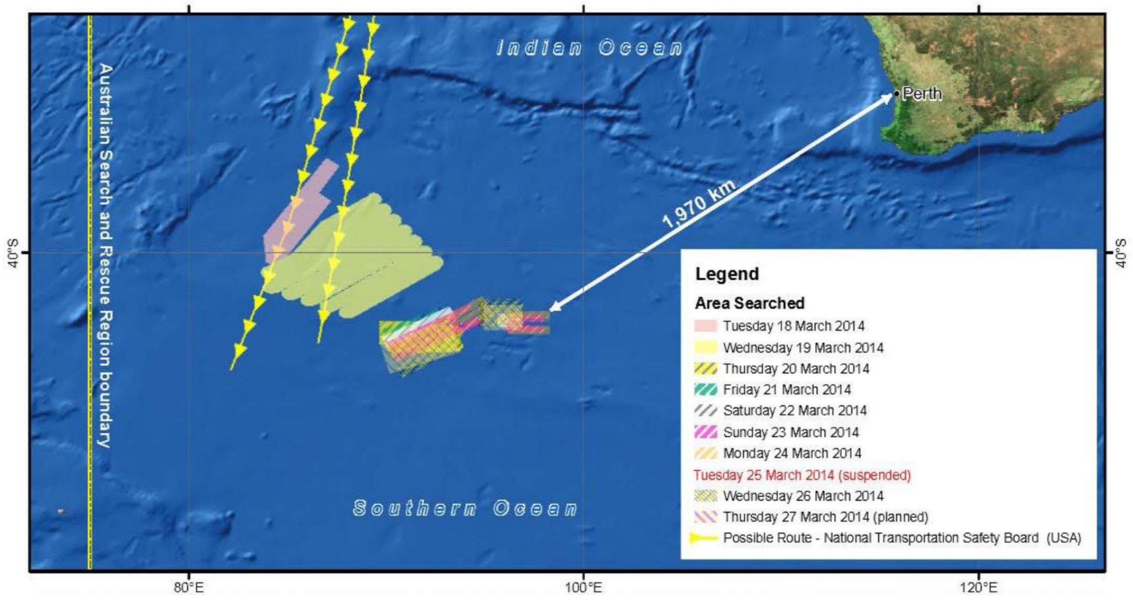


Figure 2.3: MH370 searching areas 18 - 27 March, 2014. Source ATSB (2017).

Aerial searching is usually performed by visual and radar means. One important factor to be considered in the aerial searching planning is about the sweep width. Following the (IAMSAR, 2016), the sweep width is a measure of the effectiveness with which a specific sensor can detect a particular target under local environmental conditions. Sweep width values combines characteristics of sensor, search object and environmental conditions and can be found in specific tables (based on many years of experience and testing). For example, sweep width values from 0 NM (no flight search due to weather) to 5 MN were considered for visual searching during the operation about the MH370 in March, 2014 (ATSB, 2017). Although optimal sweep width values does not guarantee that the targets will be located in that space, the important factor to be considered in the search planning is the area effectively swept by a search vehicle (the search effort), as the product of search speed, search endurance, and sweep width.

Other accident that requested international efforts for search and rescue operations in sea areas was the AirAsia's flight QZ 8501. According to ICAO (2015) the AirAsia's 8501 departed from Surabaya to Singapore with 162 persons onboard and disappeared from the radar monitor in early morning on 28th December 2014. SAR assets deployed in the operation comprised of 17 fixed wing aircraft, 24 rotary winged aircraft, and 70 vessels. The bad weather on projected sites that challenged the air units, vessels, as well as the divers to be dispatched to evacuate the black boxes and main wreckage. At the most areas and time of searching the tide were 3-4 m and the visibility underwater was barely zero due to muddy sea-bed condition. The SAR operation was led by Basarnas (the National Search and Rescue Agency of Indonesia) with the support of Indonesia Armed Forces, furthermore neighboring countries namely Singapore, Malaysia, Australia, Japan, South Korea, USA, Russia and PRC rendered assistance. First debris were located in the second day after the accident.

As illustrated by the previous cases, heterogeneous fleet of aircraft are usually employed for sea searching in air crashes. The optimal use of these assets, however, presents challenges for SAR planners, since different questions related to performance, distances, weather conditions and availability of vehicles and crew members, for example, must be considered.

2.4.1 Visual Searching

Visual searching is usually done by its simplicity. It does not need especial equipment and with few training, people are able to interpret and recognize targets in real time. Main limitations are related to visibility conditions, target type and daylight availability. According to (IAMSAR, 2016), search height of 150 m (500 ft) is the maximum recommended for detecting small targets (i.e. a small life raft). It can be suitable for a helicopter or a slow fixed-wing aircraft but may be impracticable for most jet aircraft. Also, the maximum recommended speed is 150 kt. The best time for visual searching during daylight is from mid-morning to mid-afternoon, when the sun is at a relatively high elevation. However, depending on the available sunlight and distances involved, a searching aircraft may depart still during the night to reach the search area with the local sunrise to initiate the searching. Something especially simple and useful in helping the detection of survivors are mirrors. Reflections produced by mirrors or other reflective surfaces may be spotted in greater distances than people in a life raft or in the woods, for example. A problem, evidently, occurs during periods without sunlight, at night or with heavy clouds. In these cases, emergency flares are very important items to be available in emergency kits. Visual searching can be complemented by infrared (IR) devices and night vision googles (NVG).

Available in emergency kits, different types of aids can help searching and rescuing operations in facilitating the location of people in distress. Table 2.4 summarizes the approximated visual detection range according to Gradwell and Rainford (2016). Rocket flares go higher than mini flares and burn for approximately six seconds. Smoke flares produce light and smoke, usually orange that may be spotted in a clear day at distances of 10 NM. Strobe lights in life rafts are very strong and may last by many hours. Some strobes may emit in the infrared band, allowing discrete signals, perceived by IR devices such as NVG. They may be used by military or security forces to operate covertly but detectable by friendly forces. Water activated sea lights are part of most emergency kits and they provide a small light source by approximately eight hours. A heliograph is a mirror with a sighting system that allow people to point easily the sun reflex to a desired direction, such as an aircraft, being simple and very effective. In addition, bright colors such as orange and yellow of life rafts and parachutes facilitate their visual detection in a forest, ice, desert, and especially at the sea.

Table 2.4: Approximate detecting range of different types of visual aids.

Type	Day (NM)	Night (NM)	Remarks
Mini flares	1 – 2	5	200 ft high
Rocket flares	4 – 5	8	800 ft high
Smoke flares	10	—	
Strobe lights	—	7	Standard
Strobe lights (IR)	—	—	Military use
Sea lights	—	3	8h battery life
Heliograph	20	—	Mirror

Infrared (IR) devices have good performance during the night. The IAMSAR (2016) recommends search height from 70 m to 150 m (200 ft to 500 ft) for an aircraft searching small search objects such as persons in the water and up to a maximum of approximately 450 m (1,500 ft) for larger search objects or those having a stronger heat signature. The sweep width, however, depends on characteristics of the sensor, provided by the manufacturer. Use of night vision goggles (NVGs) can be effective in searches carried out by helicopters, fixed-wing aircraft, rescue vessels, utility boats, and ground search parties. This type of sensor, however, depends on some (although weak) luminosity in the scene such as stars or moon light, since NVG amplifies light. Also, internal and external lights of the vehicle may interfere in observations using NVG. Thus, some especial measures must be taken to avoid this problem, such as creating areas without lights in the vehicle, turning off, using filters or the minimum intensity as possible.

2.4.2 Radar Searching

Radar searches allow bigger sweep width than considered for visual searching since radars are not affected by visibility conditions, clouds, period of the sunlight, etc. The sweep width to employ in computing the optimal search area will depend on the type of radar, height of the antenna, environmental clutter, radar cross-section of the search object, radar beam refraction due to atmospheric layers, and operator ability. Surface searching radars usually present in SAR operations are able to detect small targets, comparable to a periscope. However, if waves height increase to above one to two meters, it starts to interfere in the detection of small targets and the sweep width must be adjusted. Nowadays, many radars used on board of maritime patrol aircraft are synthetic aperture radars, making possible very good target discrimination, sometimes with imaging capacity. The radar horizon is affected by the height of the antenna. Considering normal refraction atmospheric conditions, the equation $d_{NM} = 1.23 \times \sqrt{h_{ft}}$ gives us the radar horizon, where d is given in nautical miles and the radar height h is in feet (Skolnik et al., 2001). However, significant variations in the atmospheric refraction index create sub or superrefraction layers, respectively reducing or increasing the radar horizon, as well as forming atmospheric ducts. For example, in some conditions when the radar antenna and the target are inside the same duct, such as a floating target and a vessel preforming tha radar search, detections may be significantly increased in the presence of a evaporation duct. Abnormal refraction conditions, however, may occur in varied height and may, in fact, prejudice the radar detection. Details about effects of atmospheric layers in airborne radars may be found in Ferrari (2003), including considerations related to passive detection. The detection of EPIRB or ELT signals can be viewed as passive detection. The radar cross-section refers to the target capacity to reflect the energy back to the radar. It depends on many factors such as size, shape and material. In summary, the reflected radar energy is proportional to the size of the target, although variations occur according to the relation between target size and wavelength. The shape is important because it determines how the energy is scattered and how much is reflected back to the radar. For example, a metallic plane surface act as a mirror; if a face is towards to the radar antenna, it facilitates the detection. However, if the plane is pointed to a direction other than the radar, most of the incident energy is deviated and the detection is prejudiced. A more complete list of scattering shapes are found in Brookner (1988). Radar reflectors formed by a square trihedral corner planes are frequently used in life rafts to facilitate the radar reflection. They tend to reflect the energy back to the radar in any position that they are, facilitating the location. IAMSAR (2016) recommends aircraft altitude between 2,400 ft and 4,000 ft when searching for small targets and a maximum of 8,000 ft for bigger targets. Initial searching of MH370 in the South Indian Ocean used radar searching considering 40 NM of sweep width (track spacing), as in ATSB (2017), that gives us an search altitude about 2,000 ft. In fact, to combine visual and radar searching is interesting especially when targets detected by radar can be verified visually by the same vehicle that saves time for the eventual rescue.

Inland, expecting that most of metallic wreckage from an accident remains in the horizontal position, the use of horizontal polarization may be the one that promotes better returns. Also, depending on the wreckage sizes and the radar frequency used, resonance effects may be obtained, generating also better returns to be received by the radar. In the sea, however, a different approach may be considered since non-metallic materials (i.e. fiberglass and plastic) tends to float and parts with metal to sink, prejudicing the radar detection.

2.4.3 Rescue Operations

When the search target has been located, the SAR coordinator must decide on the method of rescue to be followed and the facilities to be used. In some occasions, the rescue may be done by the same searching vehicle such as a boat or a helicopter. However, rescue operations are more risky than searching missions and the crew must be prepared since errors made by rescuers in removing victims from perils can produce worse consequences. As noted in IAMSAR (2013), rescue operations are often carried out under circumstances of extreme stress, hazards, and crisis where quick decisions and choices must be made which will not always be the same if they could be made with more time and information. Also, the time is crucial since chances for survival of injured persons decrease by as much as 80% during the first 24h, and that those for uninjured persons diminish rapidly after the first three days. Following an accident, even uninjured persons who are apparently able-bodied and capable of rational thought are often unable to accomplish simple tasks, and are known to have hindered, delayed or even prevented their own rescue. Helicopters are the most efficient vehicle to perform rescuing given the capacity of hovering and enter in confined areas. They may operate from helidecks in ships and oil rigs, increasing the flexibility to perform rescue in the sea. However, helicopters have limited capacity to transport people, as well as endurance is relatively shorter when compared to fixed-wing aircraft. Some rescue operations request the transport of large number of persons and usual platforms, as helicopters, may not be sufficient to atend the rescue demand, as discussed in the next Section.

2.5 Mass Rescue Operations - MRO

When a large number of persons in distress need assistance, SAR systems capacities are usually inadequate and a different approach is adopted. Thus, a mass rescue operation (MRO) must be specific planned, since hundreds or thousands of persons may be rescued from remote and hostile regions. Causes are varied, such as large aircraft or ship disasters, flooding, release of hazardous material in the environment, earthquakes as well as armed conflicts. MROs usually require extensive preparation once they may need extra actions related to pollution control, large-scale logistics and medical assistance, hazards mitigation, as well as intense public and political attention. Situations requiring MROs generate high visibility, thus, providing information to the media is very important for shaping of public opinion. Information must be delivered to the media without delays and freely exchanged to obtain good public and media relations. On the other hand, keeping contact with the media may be very demanding and it is appropriate to design a specific person to do so, releasing planners and decision makers to do their activities. MRO efforts must often start immediately at an intense level and be sustainable for days or weeks. Although not an exhaustive list, accidents that had or could require mass rescue efforts are enumerated in Table 2.5.

Available rescue time is severely limit by environment-related factors. The use of life jackets, immersion suits, clothing conditions, the clothing's wetness, person activity, physical and psychological condition, hunger and will to live affects the survivor life expectancy. MROs at sea request immediate actions since, allied to natural danger of drowning, persons are strongly affected by water temperature. Figure 2.4 and Figure 2.5 show respectively a realistic upper limit of survival time for people in the water wearing normal clothing, and the effects of various wind speed and air temperature combinations, indicating the equivalent temperature on dry skin in still air. It shows the need to shelter survivors in a shorter possible time. Hypothermia causing death is over four times more often in water than on land.

Other important question is about where the situation takes place, requesting additional care to conduct the rescue. At sea, the distance associated is very important since that operation of helicopters may be restricted by endurance, as support points in the route may not be available (i.e. a helideck in an oil rig or a ship), and they are important vehicles in these situations. The weather associated is also critical since waves too high may prevent the deployment of rescue boats, as happened during the Viking Sky rescue in 2019. Also, rescue equipment such as cables, pulleys, nets, may be frozen by cold weather, as occurred during the oil rig Ocean Ranger rescue in 1982. Inland, in short distances, helicopters are preferred vehicles since they may operate in small spaces

Table 2.5: Emergencies involving a large number of persons.

Vehicle	Name	Persons affected	Date	Place	Claimed cause
Oil rig	Ocean Ranger	84	Feb 1982	Grand Banks of Newfoundland, Canada	Severe storm
Oil and gas rig	Piper Alpha	228	Jul 1988	North-east of Aberdeen, Scotland	Explosion and fire on board
		5,000,000	Dec 2004	Indian Ocean coast	Tsunami
		3,000,000	Jan 2010	Port-au-Prince, Haiti	Earthquake
Ship	MS Costa Concordia	4,229	Jan 2012	Isola del Giglio, Italy	Reef collision
Ship	Sewol	476	Apr 2014	Incheon to Jeju, South Korea	Improperly secured cargo
Ship	MS Norman Atlantic	478	Dec 2014	Strait of Otranto, Italy, Albany	Fire on the car deck
Ship	Eastern Star	450	Jun 2015	Yangtze River, China	Capsized by a tornado
Boats	Refugees	10,000	Oct 2016	Mediterranean Sea, Italy	Unsafe conditions
		1,000,000	Sep 2018	Palu, Indonesia	Earthquake and tsunami
		700	Jan 2019	Brumadinho, Brazil	Collapsed mining dam
Kayaks, outriggers, Stand up	Manaku Harbour Race	110	Feb 2019	Manaku Harbour, New Zealand	Sudden weather change
Ship	Viking Sky	1,373	Mar 2019	Tromso to Stavanger, Norway	Engine failure

while maintaining a constant position over the ground, allowing to hoist people from varied places (i.e. people trapped on rooftops during an inundation) and taking them to a safe place. In remote and distant places, fixed-wing aircraft may be used if airfields nearby offer conditions for landing and taking-off operations. Refueling, however, may be restricted and aircraft endurance will be a critical factor to consider when planning MROs. Depending on the type of the problem, if the operation takes place in a region near big cities, the local infrastructure may be seriously affected

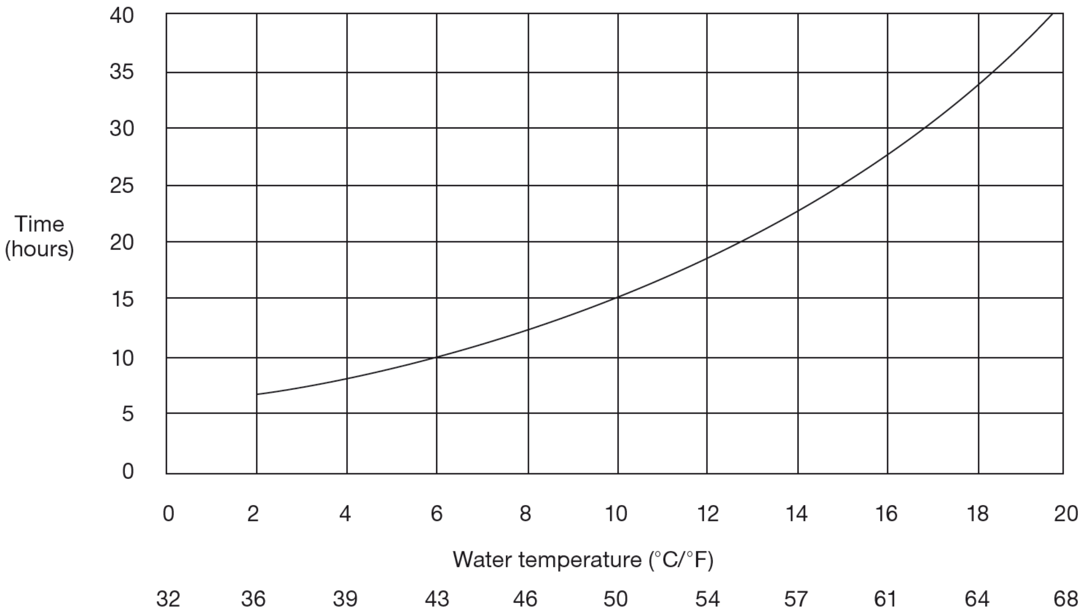


Figure 2.4: Water survival time. Source IAMSAR (2016)

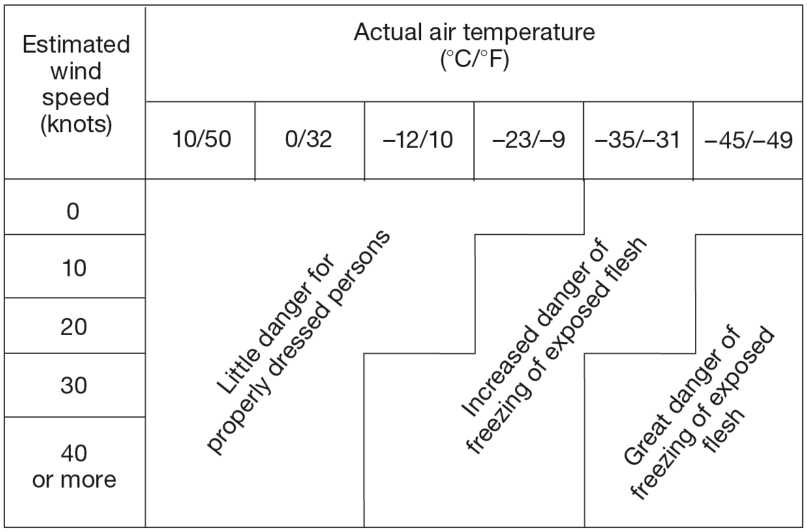


Figure 2.5: Wind chill and frostbite. Source IAMSAR (2016)

by the disaster and, more important, the number of casualties tend to be very high. For example, the earthquake in Haiti in 2010 affected about 3 million of people and the main infrastructure in the region.

2.6 Research in SAR

2.6.1 General Approaches

Kyne, Lomeli, Donner, and Zuloaga (2018) developed a study to understand the evacuation decision-making behavior of residents in the event of a hurricane. M. Davis, Proctor, and Shageer (2016) proposed a conceptual model for integrating live, virtual, and constructive models with nuclear disaster and mitigation models utilizing a system-of-systems approach. Rubin (2015) provided reflections on how researchers and practitioners have evolved over the last four decades about emergency management. Woo et al. (2019) analyzed the difference between the results of using long and short term seasonal data in the production of simulated Landsat image. Arikawa et al. (2018) investigated traces of subsidence and the characteristics of tsunami incidents in a bay far from the epicenter of an earthquake. Takahashi and Kimura (2019) analyzed the Hokkaido Eastern Iburi Earthquake in 2018 and its consequences to the region. Usuda, Hanashima, Sato, and Sano (2017) developed a platform for disaster management based on shared information. Fujiwara et al. (2019) described a developed real-time earthquake damage estimation system including the distribution of seismic ground motion, structural damage, and casualties based on data obtained immediately after a major earthquake. Hall et al. (2017) described the development of a methodology by the European Union to enable the rapid risk assessment (RRA) of environmental emergencies based on a network of risk assessors in providing back-office support to deployed experts, enabling them to have rapid access to information and expertise. Paige and Painho (2015) described search and detection methods for exogenous floating marine debris using remote sensing techniques. Okamoto and Kawashima (2002) presented satellite-remote-sensing-based approaches to monitor environmental disasters caused by surplus or deficient water resources, highlighting methods to detect events and evaluate the damage caused by them. Pilnick and Landa (2005) developed detection rate model to analyze the effectiveness of airborne radar search for a diesel submarine, assuming intermittent periscopes or masts exposure. One example of SAR exercise to identify and explore the gaps between the functionality of approved safety equipment and the functionality required by the Polar Code may be found in Solberg, Gudmestad, and Kvamme (2016). Teo, Chong, Liow, and Tang (2016) evaluated the conditions for the medical support of a SAR operation in an event of a large-scale aircraft disaster at sea considering challenges posed by the maritime environment. Chen et al. (2019) analyzed data about total-loss marine accidents involving 16 ship types and 13 main navigation sea regions between 1998 and 2018 and results showed that the main influential factors are foundering, stranding and fires or explosions. A study conducted by Carter, Williams, and Roberts (2019) about passenger and crew deaths on UK seagoing passenger ships considering long-term trends since 1900 showed that over the course of the 20th century, there has been a continuous fall in the number of incidents and in their severity. At the start of the 1990s the fatal accident rate was about 0.65 per million flights. When comparing it with the five-year period 2010–2015, there is a decrease to an average of one per 2.75 million flights according to Ekman and DeBacker (2018). Their study also showed that the survivability was lower and the casualty rate and the rate of seriously and fatally injured was higher in accidents occurring during the approach phase, involving smaller aircrafts and with destruction of the vehicle. Also, two-thirds of the accidents occurs at the airport or in its immediate vicinity. Claesson et al. (2017) and Amukele, Ness, Tobian, Boyd, and Street (2017) discussed drones for delivering medical supplies or other articles in disaster areas. Liaropoulos, Sapountzaki, and Nivolianitou (2016) analyzed operational procedures and existing conditions for maritime search and rescue for endangered offshore platforms. Frost and Stone (2001) discussed and compared different software packages used by coast guard forces of US, UK, and Canada. Vettor and Soares (2015) discussed functions in information system required to support SAR operation planning. A methodology to generate optimal grid pattern model for search and rescue operations forest was proposed by Alsagoff (2011). A geographic decision support system for assisting Canadian SAR operations to maximize the likelihood of SAR successes was presented by Abi-Zeid and Frost (2005) and Siljander, Venäläinen, Goerlandt, and Pellikka (2015) discussed the applicability and various features of geographic information systems for strategic maritime SAR planning. Rahman, Ansary, and Islam (2015) presented the support of geographic information system (GIS) for mapping vulnerabilities to earthquakes and fire hazards. The search and rescue planning system used by US Coast Guard for maritime searches was discussed in Kratzke, Stone, and Frost (2010). A graphical method for improved system reliability for UK Coastguard SAR coordination in maritime rescue operations was presented in Norrington, Quigley, Russell, and Van der Meer (2008).

2.6.2 Mathematical Approaches

Morse (1982) described numerical methods developed and utilized to search and destroy enemy submarines in World War II in the 1940s that can be considered as early development of the theories related to SAR. The importance of using mathematical models in emergency planning including facility locations, evacuation planning and humanitarian logistics was presented by Dhamala, Adhikari, Nath, and Pyakurel (2018). Anaya-Arenas, Renaud, and Ruiz (2014) presented a review of studies on relief distribution networks in response to disasters. Reviews on models and optimization techniques for emergency response facility location can be found in Li, Zhao, Zhu, and Wyatt (2011) and Simpson and Hancock (2009). Karagiannis and Synolakis (2017) identified components of incident planning process such as information gathering from the field, estimating the situation, response-generated demands, resource capabilities and time for mobilization, development and analysis of the course of action adopted, and decision-making under uncertainty. Polimeni (2012) presented a review on path and route optimization for rescue vehicles. Pitman, Wright, and Hocken (2019) conducted a study that showed that the use of lifejacket is significantly correlated with lower fatality rates of drowning and the survivability among those casualties verified wearing life jackets was 94%. Morin, Abi-Zeid, Quimper, and Nilo (2017) considered various operational conditions and non-overlapping rectangular areas in a mathematical model to assign aircraft in order to maximize the probability of search success. A model that determines the yearly boat assignment plan to minimize the total number of required vessels and total cost was developed by Nakamura et al. (2015). They developed a mixed integer programming (MIP) model in considering the vehicle type and mission requirements for individual stations, mission hours, and limitations for sharing resources. A math model and a solution methodology to assign sea rescue boats to ports along a segment of ocean coast was developed by Azofra, Pérez-Labajos, Blanco, and Achutegui (2007). Chauhan, Unnikrishnan, and Figliozzi (2019) developed a facility location model aiming at locating capacitated facilities and assigning drones for distributing supplies. A multi objective MIP for faster response to incidents while minimizing costs and mismatch between workload and annual operation fleet capacity was developed by Razi and Karatas (2016) for determining optimal placement of SAR boats. Brachner, Stien, and Hvattum (2019) developed a multi-objective mathematical programming model to optimize both average and maximum response time in offshore emergencies. Acar (n.d.) considered set covering, maximal covering and P-median models to define optimum locations for SAR units. A mathematical programming model for maritime SAR operations using search and rescue vessels was proposed by Pelot, Akbari, and Li (2015). A model to determine the optimal yearly deployment, operational levels and aircraft allocation for US Coast Guard Air Stations was proposed by Nelson et al. (2014). Integer programming models to optimally match supplies of various types of boats with demands of U.S. Coast Guard stations were developed by Wagner and Radovilsky (2012) and Radovilsky and Wagner (2014). A solution method to optimally locate US Coast Guard air stations for responding to emergency calls from uncertain ocean locations was developed by Afshartous, Guan, and Mehrotra (2009). An optimization model to allocate aircraft among various potential bases considering estimated occurrences of air and marine emergencies was proposed in Armstrong and Cook (1979). A mathematical model considering potential crash nodes and paths for optimal aeromedical base locations was proposed in Erdemir et al. (2008). A solution approach by combining optimization and simulation to allocate helicopters in SAR bases was proposed by Karatas, Razi, and Gunal (2017). Bezgodov and Esin (2014) also used simulation to develop a model to investigate problems related to maritime SAR operations including different SAR strategies to locate floating objects from air crash on ocean waves.

Traveling salesman problems (TSP) have been studied for solving a variety of SAR related problems. The possibility of using autonomous or semi-autonomous vehicles in emergency situations was discussed in Calisi, Farinelli, Iocchi, and Nardi (2007) that developed a strategy for a rescue robot considering autonomous exploration, mapping, victim detection and localization and Karma et al. (2015) in considering search and rescue in forest fires. Also, Forsmo, Gr, Fossen, Johansen, et al. (2013) developed a mixed integer linear programming model for planning search missions using cameras or other sensors in drones. For example, Yu, Wang, Liu, and Bian (2015) used a TSP model to determine the route through hexagonal regions with different probabilities that the debris of an air crash could be dispersed. Murray and Chu (2015), Kitjacharoenchai et al. (2019), Ha, Deville, Pham, and Ha (2018), and Agatz, Bouman, and Schmidt (2018) developed TSP problems considering UAVs collaborating with delivery trucks to distribute parcels. Vehicles routing problems (VRP) have also similarities in the problems developed in this Thesis, as in Mancini (2016) that considered a multi-depot and multi-period VRP with a heterogeneous fleet. The problem of planning mass rescue operations in maritime areas using helicopters and vessels was studied by Deus (2018). VRP problems considering drones were developed by Rabta, Wankmüller, and Reiner (2018) that utilized short-range distribution in disaster relief operations. A capacitated helicopter routing problem for off-shore oil companies transporting employees was developed by de Alvarenga Rosa, Machado, Ribeiro, and Mauri (2016). Gendreau, Jabali, and Rei (2016) discussed three classes of stochastic VRPs considering uncertainties in demands, customers and travel or service times. Gianessi (2014) proposed a VRP model with intermediate replenishment facilities and Vitetta, Quattrone, and Polimeni (2009) the path design for emergency vehicles rescuing handicap persons during calamities. Kek, Cheu, and Meng (2008) a distance constrained VRP with flexible assignment of start and end depots. A large-scale linear programming model for optimizing strategic airlift through a transcontinental network was presented by Baker, Morton, Rosenthal, and Williams (2002). A VRP variant to minimize the total distance traveled of a single vehicle with limited capacity with uncertain demands at given locations was studied by Bertsimas (1992).

2.7 Discussion

Although nowadays are available important and sophisticated communication and locating systems such as GMDSS, AMVER and COSPAS-SARSAT, some emergencies still request searching missions by SAR units and posterior rescue operations. Searching time may be reduced by the aid of remote sensing from air and space, however, there are important questions about the spatial resolution and area covered by the sensor. In general, wide swaths capture large areas but the spatial resolution does not allow the recognition of small objects. On the other hand, narrow swaths may have higher spatial resolution but the area of interest may escape from the sensor's FOV. For SAR applications, smaller spatial resolutions and wide swaths are interesting to observe the evolution of larger disasters such as floods and earthquakes. The availability of images from smaller to bigger resolutions are useful to compare different results in a same area in search of targets. Higher resolutions such as sub-metric may allow target recognition but they need a good approximation where targets are since they need narrow swaths. Also, MSS capacities are very useful to separate targets from the background by discriminating the difference between wavelengths emitted. Comparing space and airborne platforms, aerial remote sensing presents some advantages for SAR, especially related to spatial resolution and the capacity to revisit the scene.

Aerial search have good efficiency in SAR operations especially when large and distant areas need to be covered in a short time. Long-range fixed wing aircraft may be needed and the area covered depends basically on the search endurance, search speed and the sweep width. Usually SAR aircraft are multi-mission platforms, performing different missions when not involved in searching operations. It produces heterogeneous fleets, especially when international efforts are present. One important question derived from this situation is how to combine aircraft different capacities to obtain an optimized search effort. Radar and visual search are usually applied together producing an important synergy for detecting and recognizing targets by the same unit. Visual searching is does not request especial equipment and people may be trained in short time. Radars have important characteristics especially related to weather, range and daylight time, although a visual recognition of targets may be additionally needed. During the night, IR and NVG devices may aid the search. NVGs are usually equipment more simple than IR and they are very sensitive to light sources, even weak. Both types, however, are also affected by weather conditions.

Rescue operations are riskier than searching once rescue members need to enter in the same environment where persons in distress are. According to IAMSAR (2013), past incidents with fatalities indicates that two hours is generally the average critical time within which persons in distress must be rescued in order to survive, thus, response time is crucial in rescue operations. Helicopters are the best platforms to perform rescue given their flying characteristics. In the sea, the combination of helicopters and ships produces an important synergy given their complimentary transport capacities, speed and endurance. Operations involving a large number of persons need especial procedures since standard SAR means, such as helicopters, may not be capable to attend the transport demand. For long distances, fixed wing aircraft may be best option since a minimum infrastructure (i.e. airfields) exists.

2.8 Conclusions

In the first part, general questions related to aerial searching and rescue operations planning were presented and discussed once it is the main object of this thesis. Aerial searching and rescue operations are needed even in the present days where air and maritime transportation can count with a well-structured system of emergency communications based on terrestrial and space stations, able to receive emergency calls from barely any part of the globe. Also, air traffic control systems using secondary surveillance radars can receive alert from aircraft transponders by selecting specific codes, without the need of voice communication. Thus, as soon as one vehicle such as an aircraft or a ship reports some distress situation, search and rescue procedures are started to follow and help the vehicle, being important actions for saving time in any result that the emergency can take. However, in some situations the communication system may not be accessible or available, and the vehicle cannot report its position and conditions. In these cases, additional means such as distress beacons are very important to transmit electronic signals from the crash site, if it the accident occurs. These emissions may be detected by specialized satellites as well as equipment on board of aerial, maritime or ground units, locating the vehicle and people in question and abbreviating the rescuing time. Distress beacons, however, they may not be present in the vehicle or, even existing, they may not work properly. In consequence, without a precise location of the vehicle in distress, searching missions are started.

Even with the support of remote sensing by aerial and spatial platforms, fixed-wing aircraft are the vehicles most used when large areas must be covered in a short time. Different types of aircraft and sensors may be used and as soon as a target is located, rescue missions are started. Helicopters are the vehicles more adapted to rescue operations given their flying characteristics, especially in the sea, where the combination of helicopters and ships creates a good synergy for operating in such environment. Some especial situations, however, request the rescue of a large quantity of people that can be still done by helicopters, but the distances involved must be relatively short. In long distances, fixed-wing aircraft may be used, but questions about available airfields, refueling and coordination must be carefully evaluated. In the following chapters of this thesis, we attempt to develop scientific solution methods using optimization tools to address some of the important issues discussed in this chapter. The development of such modeling and solution methods is based on practical issues facing operation planner and managers in various SAR situations.

Chapter 3

A Mathematical Model for Tactical Aerial Search and Rescue Fleet and Operation Planning

Public safety in air and ocean transportation is the utmost important consideration for national and international transportation authorities. When accidents occur, however, it normally requires joint civil and military efforts to perform search and rescue operations to locate the geographic locations of the disaster in searching for lives, the aircraft or the vessel in question. This research considers the problem for planning an ad hoc fleet for doing searching missions in high seas as a resource allocation problem. Variations in the objective function of a binary integer programming model are proposed in response to diverse aspects of an aerial SAR operation, such as available information about targets, elapsed time from the declared emergency, as well as the type of the operation, real or simulated. A numerical example based in practical considerations including available airports, heterogeneous fleet, aircraft and crew availability is used to test and illustrate the developed model. The results show that an air search operation may be optimized according to different priorities related to area to be covered, time flown and costs for flying and supporting the operation.

3.1 Introduction

Passenger safety is the paramount goal for today's civilian air and maritime transportation. However, accidents, catastrophic or otherwise, still happen due to various known or undetermined reasons, although with significant decreasing rate in the last decade according to ICAO (2019) and Allianz (2019). When an accident happens, search and rescue operations (SAR) will be launched for searching and rescuing survivors as well as to collect key components for investigation. Saving life, reducing personal injury and minimizing property damage are the main objectives of most operations.

SAR operations can be conducted by authorities of different countries or jurisdictions. According to the Convention on International Civil Aviation, the International Convention on Maritime Search and Rescue, and the International Convention for the Safety of Life at Sea, each participating country is responsible for certain specific search and rescue regions (SRR), where adequate communication infrastructure, efficient distress alert routine and proper operational coordination must be maintained. Each SRR has unique dimensions, climate, topographical and physical characteristics, presenting challenges for SAR operations and coordination. Comparing to inland operations, ocean SAR operations require additional efforts related to very long distances and continuous displacement of targets by wind and sea currents. Long-range aircraft are mostly used in ocean SAR operations since they have the capacity to cover larger areas in shorter time. In such cases, a fleet of long-range aircraft is usually formed to execute a searching plan and dissolved when the operations are completed or terminated. This fleet can be composed of multi-mission aircraft from government agencies or operated by private operators with varying performances, required number of crews, ranges, costs, etc. For example, the ocean surface search for Air France flight AF447 crashed in 2009 employed 10 aircraft from Brazil, France and US. The search for Malaysian Airlines MH370 flight in 2014 used 34 aircraft in the region around Malaysia. It later involved 50 aircraft in the search in South Indian Ocean where more than 1.3 million square nautical miles were covered by 334 flights with over 3,000 flight hours (JACC, 2014). Such operations certainly require tremendous amount of efforts and expenses. For example, according to Agency Reuters (2014), the sum of US$ 44 million were spent in the first month of MH370 search on the deployment of military ships and aircraft in the Indian Ocean and South China Sea by Australia, China, the United States and Vietnam. The above mentioned cost does not include defense assets sent by other countries and additional costs for using civilian aircraft, accommodations for large number of personnel involved, as well as expenses for intelligence analysts worldwide. Typically, SAR operations of such magnitude require SAR managers to promptly make critical decisions on:

- assets and equipment needed to cover farthest areas in the search and rescue region;
- available airports to utilize;
- time horizon for the planned SAR operations;
- composition of the national or multinational, if necessary, fleet of SAR aircraft; and
- amount of funds required to support SAR operations.

Various mathematical and numerical tools have been developed for assisting SAR management and decision making processes at strategic, tactical and operational levels. Numerical methods developed and utilized to search and destroy enemy submarines in World War II in the 1940s can be considered as early development in this area (Morse, 1982). Since then, many advances have been made with more sophisticated and computerized solution methods developed for SAR planning and executions. Advanced information technologies have been utilized for SAR operations. For example, different software packages used by coast guard forces of US, UK, and Canada were discussed and compared in Frost and Stone (2001). Abi-Zeid and Frost (2005) presented a geographic decision support system for assisting Canadian SAR operations to maximize the likelihood of SAR successes. Vettor and Soares (2015) presented information system functions required to support SAR operation planning. Applicability and various features of geographic information systems for strategic maritime SAR planning were discussed in Siljander et al. (2015). In addition, various mathematical models were related to SAR planning. Baker et al. (2002) developed a large-scale linear programming model for optimizing strategic airlift through a transcontinental network. Breivik and Allen (2008) developed a stochastic trajectory model to calculate the net motions of the SAR targets. The search and rescue planning system discussed in Kratzke et al. (2010) was used by US

Coast Guard for maritime searches. Morin et al. (2017) proposed a mathematical model to assign aircraft to non-overlapping rectangular search areas in maximizing the probability of search success and considering various operational conditions. Norrington et al. (2008) presented a graphical method for improved system reliability for UK Coastguard SAR coordination in maritime rescue operations.

Location models have been investigated by many researchers in solving SAR problems involving short-range vehicles such as ambulances, boats and helicopters. These include Erdemir et al. (2008) that proposed a mathematical model considering potential crash nodes and paths for optimal aeromedical base locations in New Mexico. Nelson et al. (2014) developed a model to determine the optimal yearly deployment, operational levels and aircraft allocation for US Coast Guard Air Stations. Bezgodov and Esin (2014) presented a simulation model to investigate problems related to maritime SAR operations. The model investigating different SAR strategies to efficiently locate floating objects from air crash on irregular ocean waves. Azofra et al. (2007) developed a math model and a solution methodology to assign sea rescue boats to ports along a segment of ocean coast. Armstrong and Cook (1979) proposed an optimization model to allocate aircraft among various potential bases considering estimated occurrences of air and marine emergencies.

Mathematical models based on traveling salesperson problems (TSP) and vehicle routing problems (VRP) have been also developed for optimal SAR operations. Yu et al. (2015) developed a TSP model to determine the route through sub-regions partitioned in hexagonal shape where debris from an air crash may be dispersed. Kek et al. (2008) proposed a distance constrained VRP model with flexible assignment of start and end depots, Gianessi (2014) with intermediate replenishment facilities, Schneider, Stenger, and Goeke (2014) using electric vehicles with time windows and intermediate stops, and Mancini (2016) considering multi-depot and multi-period VRP with a heterogeneous fleet. Karma et al. (2015) presented the use of drones for search and rescue in forest fires and Rabta et al. (2018) developed a VRP considering drones for delivering small items in short-range disaster locations.

Nakamura et al. (2015) developed a mixed integer programming (MIP) model considering the vehicle type and mission requirements for individual stations, mission hours, and limitations for sharing resources. This model determines the yearly boat assignment plan to minimize the total number of required vessels and total cost. Various MIP models have been developed for tactical level of SAR planning. Wagner and Radovilsky (2012) and Radovilsky and Wagner (2014) developed integer programming models to optimally match supplies of various types of boats with demands of U.S. Coast Guard stations. Razi and Karatas (2016) presented an incident-based boat allocation model, developed for determining optimal placement of SAR boats. The model uses a multi objective MIP for quick response to incidents while minimizing costs and mismatch between workload and annual operation fleet capacity. Pelot et al. (2015) proposed mathematical programming models for maritime SAR operations using search and rescue vessels. Forsmo et al. (2013) proposed a mixed integer linear programming model for planning search missions using unmanned aerial vehicles equipped with cameras or other sensors for specified field-of-view. Chan, Mahan, Chrissis, Drake, and Wang (2008) used a variant of location covering model for SAR planning. Afshartous et al. (2009) developed a solution method to optimally locate US Coast Guard air stations for responding to emergency calls from uncertain ocean locations. Karatas et al. (2017) proposed a solution approach combining optimization and simulation to allocate helicopters in SAR bases. Reviews on models and optimization techniques for emergency response facility location can be found in Li et al. (2011) and Simpson and Hancock (2009). More recently, Bell and Griffis (2015) discussed different location problems in military applications and Acar (n.d.) used set covering, maximal covering and P-median models to determine minimum response time locations for Turkish Air Force SAR units.

For SAR operation planning, we noticed that the research on resource allocation was mainly focused on strategic level of decisions considering existing Coast Guard infrastructure. The results can support yearly planning while the decisions are limited to a predefined fleet of vehicles and locations. As main contributions of this research, (i) our approach considers tactical planning of an ad hoc fleet of aircraft and airports that can be used for but otherwise not dedicated to SAR operations; (ii) practical considerations about air bases, aircraft, crew, time and area to be covered are used together to develop a new binary integer programming (BIP) model aiming at prompt solution in response to emergencies; and (iii) four variations of this BIP model are also proposed representing different priorities related to area, time and costs, as well as combinations between them. Details of our research problem, the proposed model and respective variations are presented in Section 2. A numeric example with compared variants' solutions are presented and discussed in Section 3. Concluding remarks are in Section 4 and acknowledgements in Section 5.

3.2 Problem Description and Modeling

In this section, we first present specific features of the considered SAR planning problem followed by the proposed optimization model for solving the considered SAR problem. Several variants of the developed model will be presented for SAR operations for different search and rescue applications.

3.2.1 Tactical SAR Planning

In the considered SAR operation planning problem, the decisions are related to optimal composition and dispatching of a fleet of aircraft to take SAR operations over the sea to cover a large area with given information related to distances, environment, and time. The given conditions will affect the decisions in composing the fleet of aircraft, equipment and crew. A graphical illustration of the considered SAR planning problem is depicted in Figure 3.1. The search area's location and size, as well as subareas, are defined by the SAR manager in response to situations such as an accident, a simulated emergency or for general planning. The IAMSAR (2016) provide guidelines, tables and graphs to define search area and subareas, as well as done by related software. In response to a real accident, it requires a prompt decision in selecting and scheduling one or several aircraft to cover the area of interest as fast as possible. A simulated emergency is used for exercises which is important for training personnel and verifying SAR system capabilities. Planning is also important as a well-developed plan allows the SAR system to be ready for faster and orderly responses in case of real emergencies. In all considered cases, however, if the coast guard services, a main component of SAR systems, do not have sufficient equipment or personnel to perform the required tasks, other resources must be considered, such as military squadrons, government and private segments from the home country or abroad. When such resources are utilized, much variability in aircraft in the SAR fleet, their capabilities, performances and costs must be considered in decision making. In certain cases, available long-range aircraft dispersed in air bases inland need to be moved to an airport near

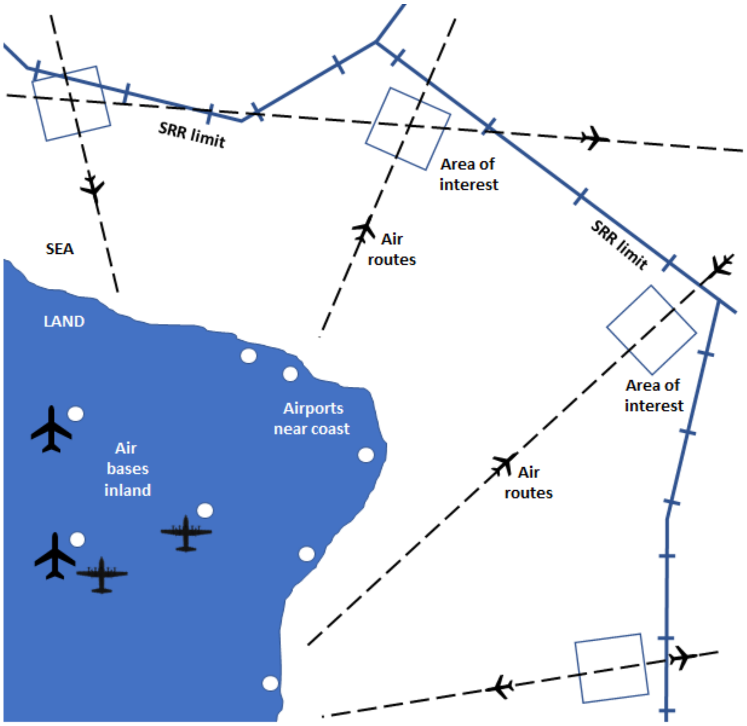


Figure 3.1: Location of areas of interest in high seas.

the search area, which becomes a SAR base. These airports will be used to launch and receive the fleet since there are no nearest support stations in the path to and from the search area. Depending on the local infrastructure, parking and refueling may also be restricted. As shown in Figure 3.2, the SAR decision making processes need to consider (1) the demand arising from a defined area and subareas, (2) the near coast airports that aircraft should be moved to; and (3) the use of maximum searching capacity of each unit. The SAR planning process also needs to estimate the searching capacity of each aircraft to have the areas and subareas effectively covered in terms of aircraft performance, maximum distance, time for maneuvering, and investigating sights. Additional factors such as weather conditions, type of targets, aircraft and crew availability are also considered by the planner in deciding the number of daily search flights. Monetary cost may be associated with the use of each aircraft in each flight as well as for supporting the operation. In general, the objective of SAR planning is to form a fleet of aircraft from all available sources to cover the identified oceanic region as quickly as possible with certain level of cost control. When the SAR tasks are completed or considered to be completed by the authority, all aircraft, personnel and support equipment will return to their original bases.

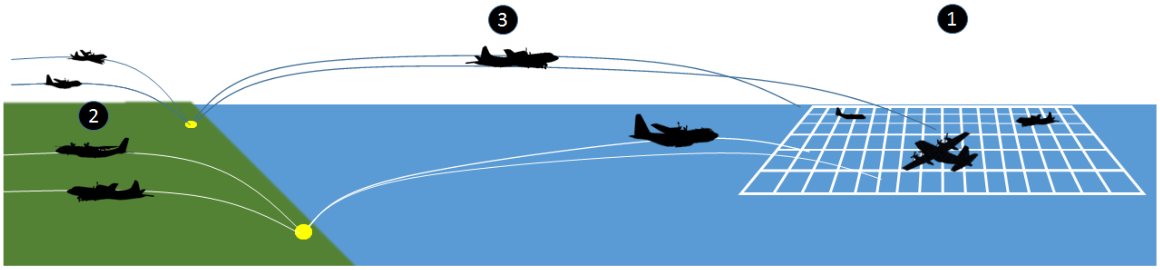


Figure 3.2: Basic tactical planning.

3.2.2 Mathematical Model P1: Maximizing Area Covered

To identify optimal solutions in tactical SAR planning, we propose a BIP model for solving the considered problem. The solutions of the BIP model will select and schedule a fleet of aircraft with varied performances and costs to meet search demand. We consider, among other factors, subareas demand, heterogeneous fleet, multiples airports with limited parking, aircraft and crew flight time, as well as crew qualification, availability and rest periods. Such SAR planning problems arise when the SAR operations are required to cover an extensive area with a limited fleet. The main purpose is to cover the largest area with available aircraft and information is not sufficient to narrow down the target locations. Such situations, for example, occurred during the second phase of search for Malaysia Airlines MH370 flight, where the time after the accident and target estimations based on satellite communications and imagery created wide areas in the Southern Indian Ocean.

The search operations are typically limited by certain factors. For example, subarea demands defined by the SAR manager must be met resulting in various time periods of operations. An aircraft with shorter flight hours after each inspection may have limited availability. Additional units will be required to complete the same mission. Crew availability and qualification are also important because the specialization requested by each aircraft type usually does not allow interchanges. Also, crew may not be always available since rest periods are needed for safety reasons. The number of daily flights is also related to the type of search and locations of the search area. For example, if the search area is far away from SAR airports and visual searching is required, daylight time may allow only one flight per day for each aircraft. The locations of available airports on shore also affects the capability of the SAR fleet as the aircraft uses farther bases for refueling or parking, it will decrease its available time for searching. The mathematical programming model presented next is to determine optimal solutions maximizing the search area covered by the SAR fleet, subject to several conditions such as subarea demands, search capability of the fleet, flight time, crew availability and qualification, number of daily flights, airport parking limits and other conditions. We first present the notations used in the model.

Sets and Indices

K	Set of aircraft, indexed by $k \in K$.
A	Set of airports, indexed by $a \in A$.
M	Set of subareas, indexed by $m \in M$.
M'	Subset of subareas, indexed by $m' \in M'$.
D	Set of time periods, indexed by $d \in D$.
D'	Subset of time periods, indexed by $d' \in D'$.
R	Set of crew, indexed by $r \in R$.

Parameters

N	A large number.
σ	A conversion parameter.
SN	Minimum searching time.
γ_{kr}	0/1 indicator; 1 if crew type *r* is qualified to fly aircraft *k*; 0 otherwise.
SE_{kma}	Search effort of each aircraft *k* in subarea *m* from airport *a*.
ST_{kma}	Searching time for each aircraft *k* in subarea *m* from airport *a*.
VT_k	Moving time for each aircraft *k*.
MT_k	Mission time for each aircraft *k*.
IC_k	Initial value (capacity) of flight hours for each aircraft *k*.
CH_r	Available flight hours for each crew *r*.
DF_{kd}	Number of daily flights allowable for each aircraft *k* in time period *d*.
AD_m	Searching demand at subarea *m*.

MC_k	Mission cost for each aircraft *k*.
PC_k	Personnel daily cost for each aircraft *k*.
MSC_k	Moving and support cost for each aircraft *k*.
DP_{da}	Daily parking capacity in each airport *a* in time period *d*.

<u>Decision variables</u>

$$w_{kamdr} = \begin{cases} 1 & \text{if crew } r \text{ is assigned to aircraft } k \text{ flying from airport } a \text{ to subarea } m \text{ in time period } d; \\ 0 & \text{otherwise.} \end{cases}$$

$$x_{kamd} = \begin{cases} 1 & \text{if aircraft } k \text{ is assigned to airport } a \text{ to investigate subarea } m \text{ in time period } d; \\ 0 & \text{otherwise.} \end{cases}$$

$$y_{kd} = \begin{cases} 1 & \text{if aircraft } k \text{ is assigned in time period } d; \\ 0 & \text{otherwise.} \end{cases}$$

$$u_k = \begin{cases} 1 & \text{if aircraft } k \text{ is assigned to the SAR operation;} \\ 0 & \text{otherwise.} \end{cases}$$

With the given notations, the binary integer programming model to maximize the area searched (P1) is presented as follows.

P1

$$\text{Maximize:} \qquad \sum_{k \in K} \sum_{a \in A} \sum_{m \in M} \sum_{d \in D} SE_{kam} \times x_{kamd} \tag{1}$$

Subject to:

$$\sum_{k\in K}\sum_{a\in A}\sum_{d\in D} x_{kamd} \geq 1 \qquad \forall\, m \in M \tag{2}$$

$$I_{kd} = IC_k - VT_k \qquad \forall\, k \in K, d \in D \tag{3}$$

$$I_{kd} - \sum_{a\in A}\sum_{m\in M} MT_k \times x_{kamd} = I_{k(d+1)} \quad \forall\, k \in K, d \in D \tag{4}$$

$$I_{kd} - \sum_{a\in A}\sum_{m\in M} MT_k \times x_{kamd} \geq 0 \quad \forall\, k \in K, d \in D \tag{5}$$

$$\sum_{r\in R} \gamma_{kr} \times w_{rkamd} = x_{kamd} \qquad \forall\, k \in K, a \in A, m \in M, d \in D \tag{6}$$

$$\sum_{k\in K}\sum_{a\in A}\sum_{m\in M}\sum_{d\in D} MT_k \times \gamma_{kr} \times w_{rkamd} \leq CH_r \qquad \forall\, r \in R \tag{7}$$

$$\sum_{k\in K}\sum_{a\in A}\sum_{m\in M} w_{rkamd} + w_{rkam(d+1)} \leq 1 \quad \forall\, r \in R, d \in D \tag{8}$$

$$\sum_{k\in K}\sum_{a\in A}\sum_{d\in D} SE_{mka} \times x_{kamd} \geq AD_m \qquad \forall\, m \in M \tag{9}$$

$$\sum_{k\in K}\sum_{a\in A} x_{kam'd'} = 1 \qquad \forall\, m' \in M', d' \in D' \tag{10}$$

$$ST_{kam} \geq SN \qquad \forall\, m \in M, a \in A, k \in K \tag{11}$$

$$\sum_{a\in A}\sum_{m\in M} x_{kamd} \leq DF_{kd} \qquad \forall\, k \in K, d \in D \tag{12}$$

$$\sum_{m\in M} x_{kamd} \leq y_{kd} \times N \qquad \forall\, k \in K, a \in A, d \in D \tag{13}$$

$$\sum_{d\in D} y_{kd} \leq u_k \times N \qquad \forall\, k \in K \tag{14}$$

$$\sum_{k\in K}\sum_{m\in M} x_{kamd} \leq DP_{da} \qquad \forall\, d \in D, a \in A \tag{15}$$

$$w_{kamdr} \in \{0,1\} \qquad \forall\, k \in K, a \in A, m \in M, d \in D, r \in R \tag{16}$$

$$x_{kamd} \in \{0,1\} \qquad \forall\, k \in K, a \in A, m \in M, d \in D \tag{17}$$

$$y_{kd} \in \{0,1\} \qquad \forall\, k \in K, d \in D \tag{18}$$

$$u_k \in \{0,1\} \qquad \forall\, k \in K \tag{19}$$

In the above presented model P1, the objective function Eq(1) represents the area to be covered by the fleet. Eq(2) states that each subarea m must be visited at least once during the considered planning horizon. Eq(3) specifies initial values for inventory of flight hours for each aircraft. Eq(4) presents the amount of flight hours available for the next time period and Eq(5) prevents flying more than available time in inventory. Eq(6) ensures that each mission must have one qualified crew. Eq(7) limits the crew flight time during the entire operation. Eq(8) ensures one time period of rest after each flight performed by a crew. Eq(9) states the area demand at each subarea. Eq(10) allow the model to assign aircraft k to subareas m' in specific time periods d'. Eq(11) limits the search time to a minimum value. Eq(12) specifies the maximum number of flights in the same time period. Eq(13) computes the use of aircraft k time period d for calculating daily costs. Eq(14) calculates the use of airplane k in the SAR operation, the costs for moving and support, as well as the time for moving. Eq(15) limits parking capacity for each airport *a* in time period *d*. Eqs(16)-(19) states as binaries decision variables w_{rkamd}, x_{kamd}, y_{kd} and u_k. The above model was tested using several example problems to be discussed later in Section 3.

3.2.3 Model Variant P2: Minimizing Time Flown

As discussed earlier, SAR planning at times may have different focuses in various applications. The proposed math model P1 can be used for some of those applications with slight modifications. For example, in some occasions the SAR manager needs to cover an area as fast as possible. It occurs in situations right after an accident when time is crucial to find survivors, as well as more information about the emergency. There are good evidences about time and position of the distress, making possible precise initial areas to investigate. A similar situation may be seen during the search of AF447 flight, since the disappearance occurred in an air route and automated communication systems were able to inform the time of the accident with good accuracy. In these cases, to find a fleet that minimizes the time to investigate the area of interest is more important than maximizing the amount covered. Thus, the goal of P2 problem is to calculate the best fleet combination to meet the area demand by reducing the time flown during the operation. This time is composed by the mission time MT_k and the moving time VT_k. The first parameter includes the time consumed inside the searching area and the transit between there and the SAR base, computed at each mission. The moving time is related to the displacement between the original location of the aircraft and the SAR base. This will occur only once, if the aircraft have been chosen. Previous conditions related to area demand, flight time, aircraft characteristics, crew availability and qualification as well as airport parking limitation, expressed by Eqs(2)-(19), are considered.

P2

$$\text{minimize:} \qquad \sum_{k\in K}\sum_{a\in A}\sum_{m\in M}\sum_{d\in D} MT_k \times x_{kamd} + \sum_{k\in K} VT_k \times u_k \tag{20}$$

subject to: Eqs(2)-(19).

3.2.4 Model Variant P3: Maximizing the Difference Between Area Covered and Time Flown

Sometimes, immediately after a declared accident, there is no precision about the last knowing position of the target. Analogous situation occurred in the first phase of the MH370 flight searching. During the first week, searching efforts were done in oceanic regions around Malaysia, in the North (Gulf of Thailand and South China Sea) and South (Andaman Sea and Strait of Malacca), following radar tracking clues. For similar cases, it should be interesting to combine the maximum search effort of the fleet in a faster operation, or, in our approach, the maximization of the search effort with the minimization of the time flown. We merged the objective functions of P1 and P2 in a new equation, shown as follows.

P3

$$\begin{aligned}\text{maximize:}\quad & \sum_{k\in K}\sum_{a\in A}\sum_{m\in M}\sum_{d\in D} SE_{kam}\times x_{kamd} \\ & -\sigma\times(\sum_{k\in K}\sum_{a\in A}\sum_{m\in M}\sum_{d\in D} MT_k\times x_{kamd}+\sum_{k\in K} VT_k\times u_k)\end{aligned} \tag{21}$$

subject to: Eqs(2)-(19).

As expressed by Eq(21), the first part is the search effort and the second is the time flown in the operation. Once the area to be maximized must be numerically comparable with time values, a negative conversion parameter σ is used. All previous considerations expressed by constraints in Eqs(2)-(19) remain.

3.2.5 Model Variant P4: Minimizing Costs

Our model may have different applications than provide responses to accidents. It may be used for planning exercises, important for training personnel and verifying system components, such as communication, navigation and traffic controlling. In these cases, the budget may have significant influence. Thus, we consider an objective function to minimize costs for flying each mission (MC_k), personnel costs (PC_k) and expenses for moving aircraft and support equipment (MSC_k). The first one is proportional to the time used in each searching mission and the cost of each flight hour of respective aircraft. Personnel costs are related to daily expenses of crew and maintenance teams, usually for meals and lodging. Moving and support costs are computed once if the airplane is selected. They are expenses for the transit between the original location of the aircraft and the SAR base as well as for some special equipment needed on ground or in flight.

P4

$$\begin{aligned}\text{minimize:}\quad & \sum_{k\in K}\sum_{a\in A}\sum_{m\in M}\sum_{d\in D} MC_k\times x_{kamd} \\ & +\sum_{k\in K}\sum_{d\in D} PC_k\times y_{kd}+\sum_{k\in K} MSC_k\times u_k)\end{aligned} \tag{22}$$

subject to: Eqs(2)-(19).

Table 3.1: Summary of the objective functions of the BIP model and respective variants.

Variant	Equation	Objective function
P1	Eq(1)	Maximize area covered
P2	Eq(20)	Minimize time flown
P3	Eq(21)	Maximize the difference between area covered and time flown
P4	Eq(22)	Minimize costs
P5	Eq(23)	Maximize the difference between area covered and costs

We rewrite the objective function as in Eq(22) and consider all constraints already presented.

3.2.6 Model Variant P5: Maximizing the Difference Between Area Covered and Costs

We may also consider planning exercises in the farthest sites of the SRR, where more difficulties are expected, given the distances involved and environmental conditions present in open seas. Thus, since the area demand is met, maximizing the search effort with a lower costs fleet is one additional option. We use a weighted sum of the objective functions in P1 and P4 to maximize the difference between area covered and costs incurred by the SAR operation.

P5

$$\text{maximize:} \quad \sum_{k\in K}\sum_{a\in A}\sum_{m\in M}\sum_{d\in D} SE_{kam}\times x_{kamd} - \sigma \times (\sum_{k\in K}\sum_{a\in A}\sum_{m\in M}\sum_{d\in D} MC_k \times x_{kamd} + \sum_{k\in K}\sum_{d\in D} PC_k \times y_{kd} + \sum_{k\in K} MSC_k \times u_k) \tag{23}$$

subject to: Eqs(2)-(19).

As shown in Eq(23), the first part of the objective function is the search effort to be maximized and the second, the costs associated with the aerial SAR operation (i.e. expenses of flights, personnel, moving and support) that need to be minimized, subject to Eqs(2)-(18).

Table 3.1 summarizes the objective functions used in our BIP model and respective variants. In the next section, they will be used to solve a SAR planning problem and to compare different results.

3.3 Numerical Example and Analysis

In this section, we use a numerical example to verify results of proposed BIP model with respective variations. This instance is based in a simplified SAR problem, starting with one officer that needs to plan a SAR operation in a region 1,600 nautical miles (NM) far from two airports separated by 140 NM, as shown in Figure 3.3. Total area is a square of 176,400 NM^2 divided by nine subareas with equal demand of 19,600 NM^2. For simplicity, subareas also have same priority to be covered.

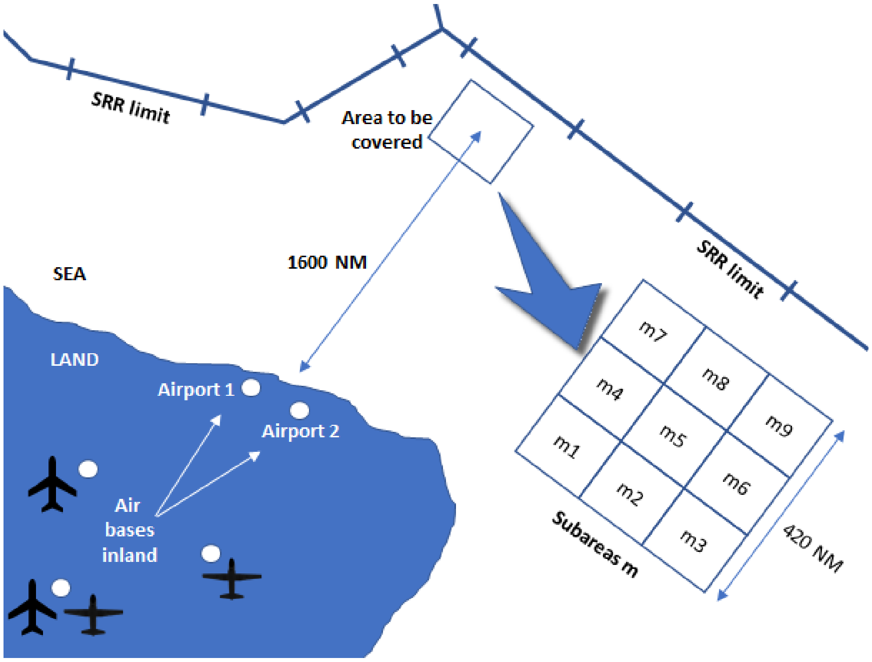


Figure 3.3: Area and subareas location and sizes.

There are 12 available long-range aircraft k, as shown in Table 3.2, divided in two types of jets and two types of turboprops with respective performances and costs. Flight hour costs (FHC) are based in real values utilized by USDoD (2018). The mission cost (MC) is the result of the mission time (MT) and FHC. All aircraft are located inland, 600 NM from the two airports. In this example, we assume no penalties for changing airfields during operation and no parking or refuelling limitations. Each aircraft has two crews for flying in alternate days to allow a rest of one day between flights for safety rules. Each crew and aircraft receive 120 h of available time to fly.

Table 3.2: Available aircraft performances and costs

Aircraft k	Type	Cruise speed (kt)	MT (h)	FHC (\$)	MC (\$)
k1, k2, k3	Jet	440	11.5	8,700	100,050
k4, k5, k6	Jet	445	14	11,000	154,000
k7, k8, k9	Turboprop	330	15	7,000	105,000
k10, k11, k12	Turboprop	335	15	6,000	90,000

Table 3.3: Performance metrics and indexes for comparing formulations results.

Formulation	FS (un)	TM (un)	TAC (MN^2)	TTF (h)	TC (\$)	TC/TAC (\$/NM^2)	TAC/TTF (NM^2/h)	TAC/acft (NM^2)
P1	12	60	204,559.70	870.43	7,936,761.83	38.80	235.01	17,046.64
P2	12	51	179,585.81	735.43	6,956,761.83	38.74	244.19	14,965.48
P3	11	51	180,278.25	735.29	6,891,257.29	38.23	245.18	16,388.93
P4	12	50	181,064.57	752.93	6,832,311.83	37.73	240.48	15,088.71
P5	11	50	181,064.92	750.20	6,758,584.56	37.33	241.36	16,460.45

SAR missions will be planned considering visual searching during daylight, that allows a single flight per day. The plan also considers 150 kt as search speed for all aircraft and charts of IAMSAR indicate 5 NM of sweep width at 500 ft of altitude. These values combined with distance to subareas, endurance, holding fuel, cruise speed and time for maneuvering and investigating sights, about 15% of the available time for searching, give the effective area covered, or the search effort, of each aircraft. Operation costs consider mission costs and, for simplicity, \$5,000 per day for crew and maintenance teams and \$50,000 of support equipment for each aircraft selected, such as auxiliary power units, desalination kits, as well sea markers, life rafts or other goods launched by aircraft.

The comparison of results, as shown in Table 3.3 and Figure 3.4, is done by five performance metrics: fleet size (FS), total missions (TM), total area covered (TAC), total time flown (TTF) and total costs (TC), as well as three indexes based on relationships between these performance metrics. The TC/TAC index represents the cost for covering a single squared nautical mile; the relation TAC/TTF shows how much area can be covered by a single flight hour and the amount of area covered by each aircraft (acft) is given by the TAC/acft index. Our instance can be solved by commercial solvers with insignificant computing time.

When compared to the other variants, P1 finds the maximum area covered value, including for TAC/acft index, as expected. This maximum is interesting in situations such as described about having an area relatively extensive to the number of available aircraft. We have also the highest values in the others performance metrics. It occurs because the model uses the maximum 60 possible missions during the five days and, in consequence, time flown and costs are more elevated.

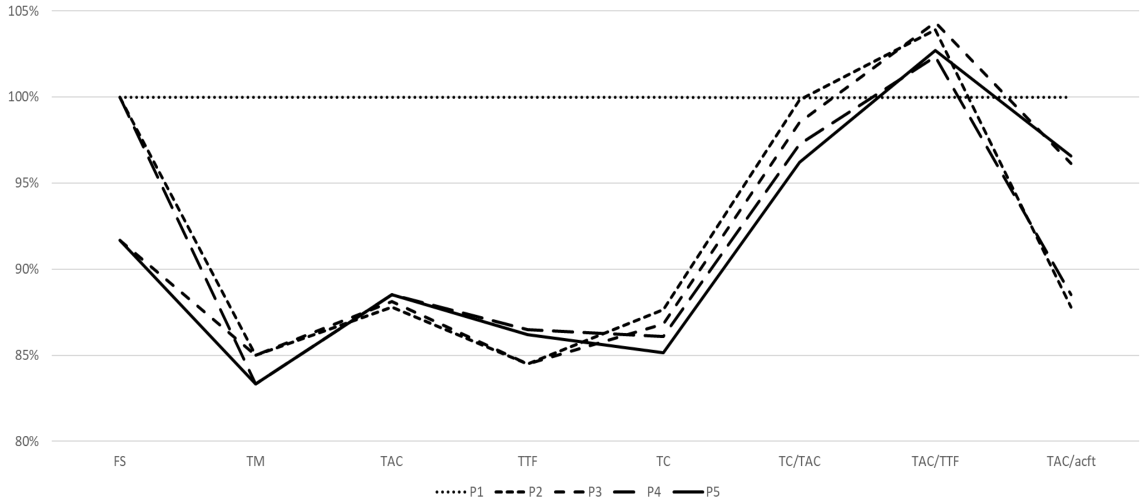
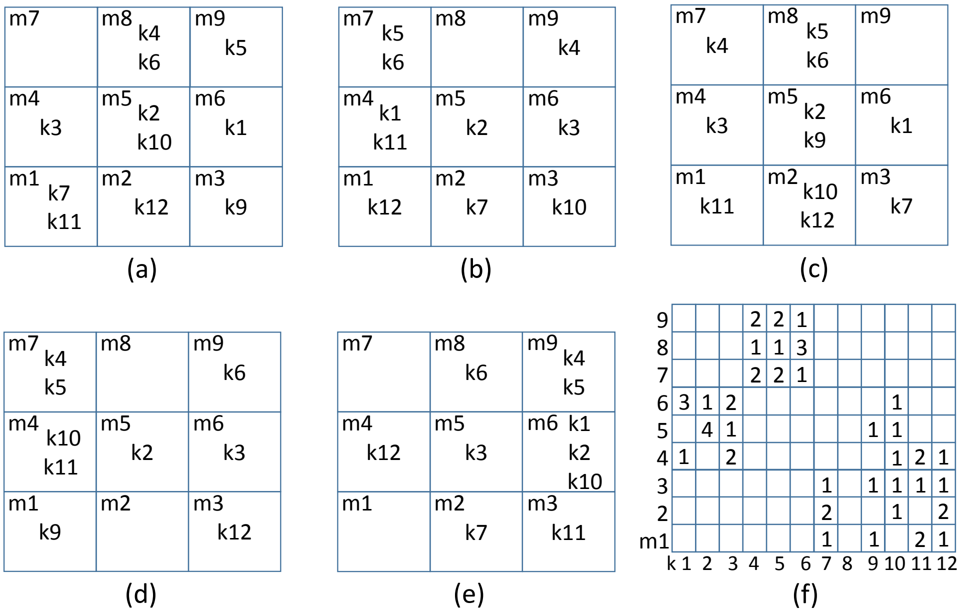


Figure 3.4: Normalized performance metrics and indexes results.

The area covered, as well as time flown and costs, are reduced when using P2 to P5 formulations. It happens because P1 tend to exceed subareas demand while P2 to P5 aim the inverse. In other words, the lower limit for area covered in each subarea, given by Eq(9), is important in P1 to determine the minimum feasible amount of time periods, and, from there, the model will find the maximum area covered as possible. Problems from P2 to P5 also uses Eq(9) to determine the minimum feasible amount of time periods and, when minimizing time or costs, the area calculated to cover each subarea is as near as possible to respective demand.

Results of P2 and P3 show lower values for total time flown than P1, P4 and P5, as foreseeable. When comparing P2 and P3, although no significant difference exists in the TTF, P3, that uses a bi-objective function for maximizing the difference between area and time flown, can reach a lower total cost and a better relation TAC/acft, especially because this formulation considers only 11 aircraft in the fleet. Also, in P3 the fleet can cover a bigger area as shown by TAC and TAC/TTF values. The distribution of aircraft k for P3 in the nine subareas m is shown by time periods in Figure 3.5. The sequence of days is according to order of letters (a) to (e). In (f) we have a graph that summarizes the previous letters. For example, in letter (a), the first day of operation, we have the visit of $k4$, $k5$ and $k6$, the fastest aircraft, in the farthest subareas $m7$ to $m9$, that saves time. Nearest areas, $m1$ to $m3$, are visited by relatively slower turboprops $k7$, $k9$, $k11$ and $k12$. In (f) we have the columns showing the amount of areas visited by each aircraft; in the rows, how many aircraft visited each area during the five days of operation.



m7	m8 k4 k6	m9 k5
m4 k3	m5 k2 k10	m6 k1
m1 k7 k11	m2 k12	m3 k9

(a)

m7 k5 k6	m8	m9 k4
m4 k1 k11	m5 k2	m6 k3
m1 k12	m2 k7	m3 k10

(b)

m7 k4	m8 k5 k6	m9
m4 k3	m5 k2 k9	m6 k1
m1 k11	m2 k10 k12	m3 k7

(c)

m7 k4 k5	m8	m9 k6
m4 k10 k11	m5 k2	m6 k3
m1 k9	m2	m3 k12

(d)

m7	m8 k6	m9 k4 k5
m4 k12	m5 k3	m6 k1 k2 k10
m1	m2 k7	m3 k11

(e)

9				2	2	1						
8				1	1	3						
7				2	2	1						
6	3	1	2							1		
5		4	1						1	1		
4	1		2							1	2	1
3							1		1	1	1	1
2							2			1		2
m1							1		1		2	1
k	1	2	3	4	5	6	7	8	9	10	11	12

(f)

Figure 3.5: Aircraft distribution by area during five days of operations for P3.

Although P2 and P3 are both useful in situations when time is crucial, as described in items 3.2.3 and 3.2.4, in a practical sense, P3 formulation may have some advantages for the planner, since it requests less airplanes in the fleet and it is desirable to count with some spare aircraft to make substitutions in case of scheduled or unscheduled maintenance. Based on our experiments, the value of the conversion factor σ used in P3 was 300.

P4 and P5 show lower total cost than P1, P2 and P3, as also expected. When comparing P4 and P5, although there is no significant difference in TAC, results show that P5 utilizes less means, as indicated by FS, TC, TTF and the three indexes. As P5 may leave one aircraft as reserve, such as in P3, it is useful in real situations. The σ value used in P5 calculation was 3.

3.3.1 Discussion

The considered problem was modeled as an extended Assignment Problem (AP) with binary integer variables. All presented formulations (P1 to P5) behaved as expected and the two bi-objective formulations tend to be more interesting for some practical uses. For example, the P3 bi-objective formulation maximizes the area covered while minimizing the searching time, being important in initial actions where is expected to obtain information quickly. Thus, P3 formulation allows to obtain more information (by maximizing the area covered) and using the shorter possible time (quickly). As shown by the instance results, when P3 is compared with P1 that maximizes the area covered only, we save 135h of flying time. The other bi-objective formulation is P5 that considers maximizing the area covered while minimizing costs. When compared to P1, P5 results show savings about US$1.2 million, which is important for planning exercises.

Although we considered in our instances a big area composed by nine subareas located besides each other, we could have other configurations, as requested by the emergency scenario. For example, suppose that we had received additional information by remote sensing (i.e. satellite photos) showing clues in specific locations, thus, we could consider subareas with different sizes, shapes and positions that could abbreviate the searching phase. Following the same supposition, since we have no significant variations in different mission profiles (i.e. basically the mission time is used in some activity in a specific area and then returning to air base), we could extend the model to support simultaneously multi-mission planning such as SAR, maritime patrol, anti-submarine warfare (ASW) and electronic surveillance, as depicted by Figure 3.6, for example. It could be done by adding specific constraints to select aircraft according to different subareas (and missions), similarly to Eq(10) that can determine subareas to be covered in specific time periods (i.e. subareas with higher priorities are covered in the first days).

3.4 Conclusion

Different types of long-range aircraft may be used together in performing searching missions in high seas. They are very important vehicles for SAR operations given their capability to cover large areas in short time. While the combination of different performances creates important operational

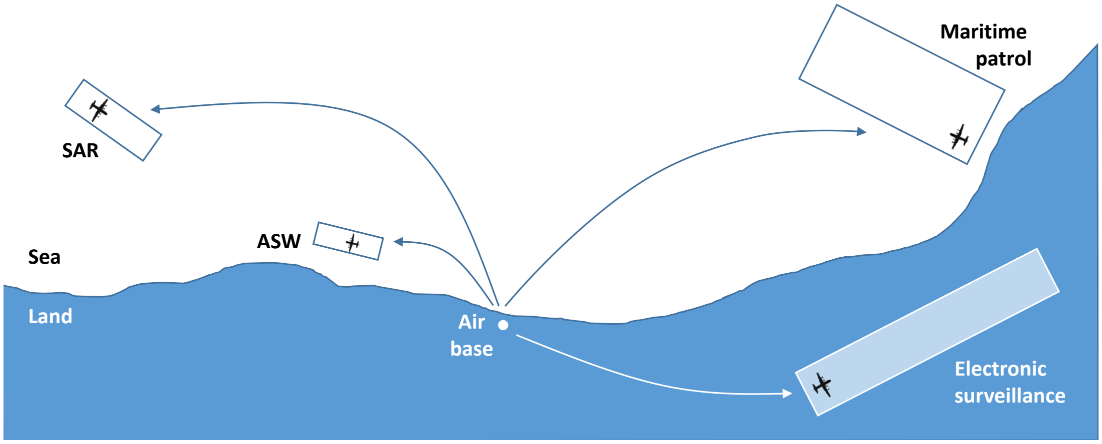


Figure 3.6: Possible model extension to consider multi-mission operations planning.

advantages, on the other hand, it poses challenges in achieving the optimal level of search effort and efficiency. In this Chapter, a mathematical programming model was proposed for SAR operation planning considering a heterogeneous fleet of airplanes to be dispatched from available airports and allocated in specific searching areas. The model and respective four variants were developed according to different priorities related to area, time and costs and solved for practical applications. Numerical examples tested the developments and compared results showed that (i) P1 calculated the maximum value for area covered, which is interesting in circumstances such as having an area relatively extensive to the number of available aircraft; (ii) P2 and P3 showed lower values for total time flown, important in emergency situations, and, between them, P3 could determine a lower total cost and a better relation total area covered by aircraft; and (iii) P4 and P5 calculated lowest total costs of all variations, that is interesting in situations such as planning exercises, and P5 utilized less means, as indicated by various indexes. In summary, all formulations behaved as expected and the two bi-objective formulations, P3 and P5, tended to be more efficient for some practical uses.

This study contributed to add scientific support for planning an efficient aerial fleet for SAR operations in high seas and, in future research, we planned to extend the model to optimize multi-mission operations planning and develop efficient and effective solution methods for solving larger size SAR problems with short computing time.

Chapter 4

Modeling and Solving a Search and Rescue Planning Problem for Emergencies in High Seas

The importance of saving lives is globally recognized, as well as the need to render aeronautical and maritime search and rescue (SAR) services to persons in distress. In high seas, the combination of different types of air and maritime vehicles used to perform rescue operations produces important operational advantages while, on the other hand, poses challenges for planning their use. In this Chapter, the problem for planning rescue missions in high seas is modelled as a vehicle routing problem (VRP) by considering heterogeneous fleet of vehicles and their displacements during a considered time period. Routing decisions are assisted by probabilistic demands at each node, as eventually reported by searching missions. Given characteristics of available ships and helicopters, we determine a rescue plan with respective routes to maximize an expected number of survivors in the shortest time. Feasible routes depend on factors such as helicopters' endurance for intercepting a ship in movement and ships' capacities to receive helicopters. A binary integer programming (BIP) model is proposed and results of numerical examples show the validity of the model in choosing the best routes when urgency of actions, vehicles of different performances and respective displacements, as well as uncertainty about number of survivors are involved. Also, we discuss how our model could support immediate updates in the rescue plan during its execution. In addition, for practical reasons, courses for helicopters intercepting a ship are also calculated by considering a geographic orientation.

4.1 Introduction

Safety is the paramount goal for today's civilian air and maritime transportation, aiming to prevent and reduce the effects of disasters, generating a safer environment for aerial and maritime activities such as commerce, recreation, and travelling. However, although significant decreasing rate in terms of total air and maritime transportation accidents in the last decade (Allianz, 2019; ICAO, 2019), mishaps, catastrophic or otherwise, still happen due to various known or undetermined reasons. In such cases, SAR systems provide the response and assistance needed from early stages, crucial for saving lives. SAR operations usually start with a searching phase and, once people, accidented vehicles, wreckage or significant clues are found, rescue missions are planned and executed. Long-range fixed wing aircraft are the vehicles mostly used for searching in high seas, complemented by satellites, given their capacity to cover large amount of area in short time. However, a combination of factors such as weather conditions, type of sensors, sun position and distance of detection, affect the collection of data by searching flights, and, in consequence, available information for planning upcoming searching or rescuing missions. For example, the analysis of four PLEIADES 1A images of March 23, 2014 in Minchin et al. (2017) classified 12 objects as "probably man-made" from a total of 70 detected objects but could not determine whether they were aircraft debris.

Helicopters and ships are the vehicles generally used in sea rescue. Their different performances such as endurance, capacity to transport people and speed are complementary, creating an efficient combination of vehicles for operating in high seas. For example, while in transit, ships can save precious time sending helicopters in advance to confirm and rescue survivors in determined locations. Some tasks, such as short range searching and delivering supplies to survivors, may be done by drones or unmanned air vehicles (UAVs) instead of piloted helicopters, as shown by Figure 4.1. Planning the optimal use of air and maritime vehicles, however, presents challenges to the SAR manager since critical decisions must be made on performances, rescue equipment, locations to be visited, distances and courses to be followed, as well as available helidecks on vessels or in other structures in the region. Such SAR planning and decision-making processes may be assisted by mathematical and numerical tools, as shown by the following referred bibliography.

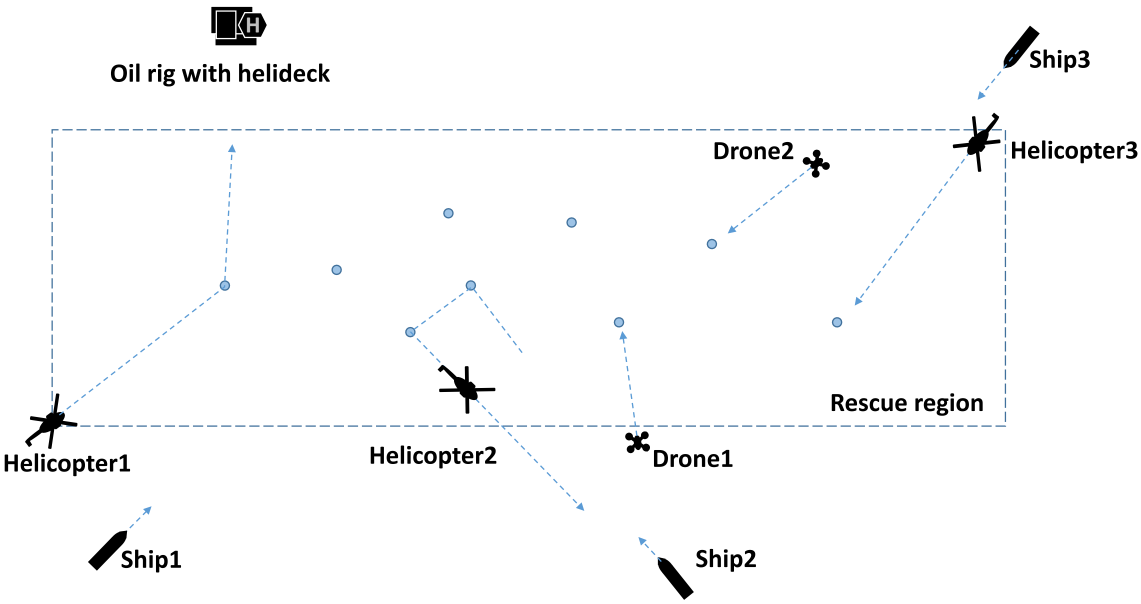


Figure 4.1: Rescue operation using ships, helicopters and drones.

Norrington et al. (2008) developed a methodology to model the reliability of SAR operations. Dhamala et al. (2018) highlighted the importance of using mathematical models in emergency planning including facility locations, evacuation planning and humanitarian logistics. Anaya-Arenas et al. (2014) presented a review of studies on relief distribution networks in response to disasters. Bezgodov and Esin (2014) studied problems of efficiency of maritime search and rescue operations at sea using simulation for floating objects movements on irregular waves. The support of geographic information system (GIS) in SAR operations was discussed in Rahman et al. (2015) for mapping vulnerabilities to earthquakes and fire hazards and in Siljander et al. (2015) for maritime SAR planning. Liaropoulos et al. (2016) analyzed operational procedures and existing conditions for maritime search and rescue for endangered offshore platforms.

Location models are especially useful to define the position of a SAR base for launching vehicles such as ambulances, boats, helicopters and drones. Brachner et al. (2019) developed a multi-objective mathematical programming model to optimize both average and maximum response time in offshore emergencies, especially in response to a helicopter ditching during a personnel transport to or from offshore facilities. Azofra et al. (2007) developed a general methodology to define individual and zonal distribution models to assign sea rescue resources. Pelot et al. (2015) developed a vessel location model for maritime SAR. Also, Bell and Griffis (2015) discussed location problems in military applications. The possibility of using drones in emergency situations was discussed in Karma et al. (2015) that considered search and rescue in forest fires and in Forsmo et al. (2013) that proposed a mixed integer linear programming model for planning search missions using drones with cameras or other sensors. Claesson et al. (2017) and Amukele et al. (2017) discussed drones for delivering medical supplies or other articles in disaster areas. Chowdhury, Emelogu, Marufuzzaman, Nurre, and Bian (2017) developed a model to determine optimal distribution center locations, their corresponding service regions and ordering quantities, to minimize the overall distribution cost for disaster-relief operations. Chauhan et al. (2019) developed a facility location model aiming at locating capacitated facilities and assigning drones for distributing supplies. Modeling and solution methods for solving traveling salesman problems (TSP) have been adopted for solving a variety of SAR related problems. For example, Yu et al. (2015) used a TSP model to determine the route through hexagonal regions with different probabilities that the debris of an air crash could be dispersed. The decision making process in rescuing operations using vessels and helicopters has similarities with that of using UAVs collaborating with delivery trucks to distribute parcels as studied in Murray and Chu (2015) and in Kitjacharoenchai et al. (2019). Agatz et al. (2018) discussed a last-mile delivery problem in which a truck collaborates with a drone to make deliveries as a traveling salesman problem with drone (TSPD). Ha et al. (2018) considered a variant of the TSPD with the objective to minimize operational costs, including total transportation cost and the time wasted by vehicles that must wait

Certain problems of planning SAR operations have similarities to the well-researched vehicles routing problems (VRP) which are closely related to the problems studied in our work. Deus (2018) considered a problem of planning mass rescue operations in maritime areas using helicopters and vessels. de Alvarenga Rosa et al. (2016) studied the capacitated helicopter routing problem for off-shore oil companies transporting employees between onshore basins, airports and platforms under certain operational conditions. Bertsimas (1992) developed a VRP variant to minimize the total distance traveled of a single vehicle with limited capacity with uncertain demands at given locations. Ghiani, Laporte, and Musmanno (2004) presented the node routing problem set partitioning in which costs are minimized considering a set of feasible routes and a certain number of vehicles. Özdamar, Ekinci, and Küçükyazici (2004) developed a model that indicates the optimal quantities and mix of loads to be picked up and delivered for decision support in natural disaster logistics systems, able to regenerate plans by incorporating new requests for materials, supplies and transportation that become available during the planned time horizon. Their plan generated is time dependent and re-planning occurs repeatedly during the operation. Rabta et al. (2018) consider a VRP for the use of drones in short-range distribution in disaster relief operations. Peng (2018) developed a VRP considering the risk of drones experiencing shocks during the mission such as caused by bad weather. Gendreau et al. (2016) discussed three classes of stochastic VRPs considering uncertainties in demands, customers and travel or service times and Gianessi (2014) that considered intermediate replenishment facilities.

In this Chapter, we analyze the dynamics of rescue operations due to air or maritime emergencies since research in modeling SAR planning problems considering multiple practical aspects is limited in the literature. In our study we consider a heterogeneous fleet of helicopters and ships where the number and type of vehicles are part of the decision variables to define the best routes in order to minimize the rescue time and maximize the probability to find survivors. Also, our model allows re-routing at each location visited where the situation is evaluated. While previous traveling salesman problems developed in the literature considered that drones and trucks can only merge at a customer node, in our study, we have full cooperation between helicopters and ships in which a helicopter can depart, intercept and land on a ship in movement in any point of its route, even on a different ship from previous depart. In addition, real issues for rescue planning in high seas are considered such as lack of support points, differences in vehicles performances and uncertain information from searching reports. In summary, we provide scientific support for rescue planning and assistance for implementing respective actions when the number of survivors is uncertain and all vehicles are moving.

4.2 Problem Description and Modeling

In this section, we present specific characteristics of the considered rescue planning problem and propose a mathematical model for solving the considered problem.

SAR operations in high seas usually start with searching flights to locate survivors in distress as other floating objects. Long-range fixed wing aircraft and satellites are the vehicles mostly used for these tasks, given their capacities to cover large areas in short time. However, the information generated in this searching phase can be affected by factors such as weather conditions, type of sensors, time of the day, distances, and hence can often be vague and distorted in describing emergency situations. Thus, searching results may be expressed in terms of probabilities to be considered in rescue planning and operations.

4.2.1 SAR Rescue Planning

A typical rescue operation uses a combination of helicopters and ships, given the synergy obtained by their different capacities of mobility, cargo, speed and endurance. Helicopters may be launched in advance by one or more vessels while approaching the rescue region, returning to the ships thereafter. This procedure saves critical time in rescue operations. In the considered SAR planning problem, the decisions are related to optimal routing of a heterogeneous fleet of helicopters and ships to perform rescue operations with given information related to distances, vehicle performances and searching results. The given conditions will affect the decisions in helicopter and ship routing, as well as the points in the sea where helicopters intercept and land on a ship after completing a mission, since all vehicles may be moving during the operation. Also, the occasionally vague and uncertain information indicated in probability in identifying the number of people in each visited location affects the choice of the type of helicopters to dispatch as well as their routes, as depicted in Figure 4.2.

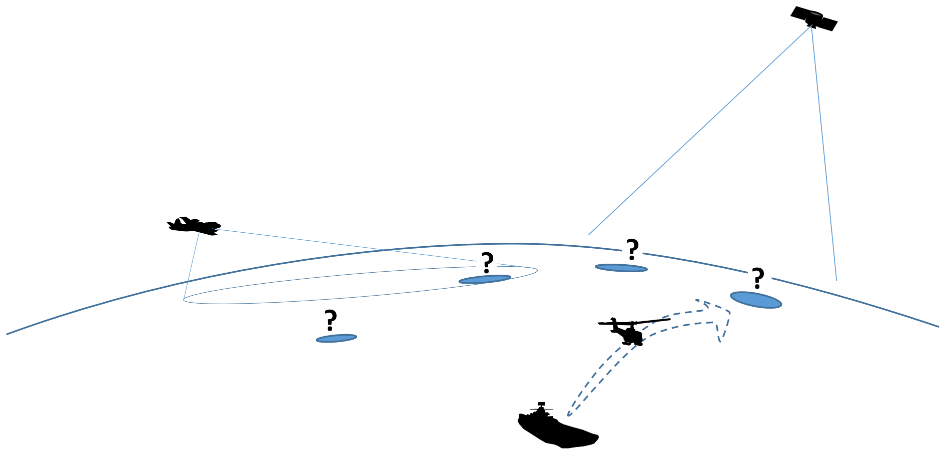


Figure 4.2: A rescue with uncertain information about number of survivors.

Rescue operations are typically limited by certain factors. Helicopters are faster, but their endurance and internal space are very small comparing to vessels. Depending on the situation, helicopters must do many flights to the same area to rescue all people in distress. The rescuing time spent at each location affects negatively how far a helicopter can go in a route. Some ships may not be equipped with landing areas for helicopters, such as helidecks, or these areas are very limited, reducing the options for returning helicopters. Also, when the ships with helidecks are moving during the period that helicopters are flying, returning helicopters must find the new position of the ship for landing. If the planned route with corresponding interception point exceeds the helicopter's endurance, that route becomes infeasible to the helicopter.

In our problem, however, we must consider re-planning at each location visited because the number of survivors is updated and the situation is re-evaluated. For example, if a helicopter did a rescue but still has capacity (i.e. endurance and internal space) to go to an additional location, it can be done. However, we also must consider survivors' conditions. If the helicopter has enough capacity and rescued survivors do not need immediate medical assistance, the helicopter can go to an additional location to rescue more persons. Otherwise, the helicopter without capacity or carrying survivors in critical conditions must go to the planned destination. In fact, our model gives to the helicopter good flexibility to re-route as the operation is being developed. The ship, however, cannot change its course once it has been defined by the plan because:

- all information of helicopters' feasible routes are linked with ships' routes;
- ships have limited capacity to receive helicopters, thus, if a helicopter returns to a different place, it may cause conflicts or accidents; and
- loss of communication, navigation and radar systems are possible and may produce serious consequences if units change their actions without necessary evaluation and coordination, especially if bad weather conditions are present.

The goal in our problem should be to produce a plan to be on board of all units. This plan should contain all possibilities for helicopters' re-routing according to the information that is updated at each location and the conditions to be followed to return to a helideck (i.e. time and bearing from a specific place), especially in the event of loss of communications, navigation or radar systems. These factors are considered in developing the mathematical model to determine the optimal rescue plans. Details of the model development are presented below.

4.2.2 Mathematical Modeling

As discussed above, a binary integer programming (BIP) model to solve the considered SAR planning problem is proposed. The BIP solutions will select routes for a fleet of helicopters and ships to rescue survivors of an accident in high seas. The main purpose is to rescue the maximum number of survivors in the shortest possible time period with limited aircraft and ships. We also consider that the available information may be vague in identifying exact numbers of survivors at each location. First we present the notation used in the mathematical model.

Sets and Indices

H	Set of helicopters, indexed by $h \in H$.
R	Set of routes for helicopters, indexed by $r \in R$.
S	Set of ships, indexed by $s \in S$.
D	Set of routes for ships, indexed by $d \in D$.
I	Set of nodes, indexed by $i \in I$.

Parameters

M	A large number.
$p(n)_{lr}$	Probability to find n survivors in location l along route *r*.
HV_h	Maximum number of survivors transported by helicopter *h*.
HE_h	Maximum endurance of helicopter *h*.
SH_s	Maximum number of helicopters transported by ship *s*.
λ_{ri}	0/1 indicator; 1 if node *i* exists in route *r*; 0 otherwise.
FT_{rhsd}	Flight time of helicopter *h* that follows route *r* and arrives in ship *s* that uses ship path d.

Decision variables

$$x_{rhsd} = \begin{cases} 1 & \text{if helicopter } h \text{ follows route } r \text{ and arrives in ship } s \text{ that uses ship path } d; \\ 0 & \text{otherwise.} \end{cases}$$

$$y_{sd} = \begin{cases} 1 & \text{if ship } s \text{ uses ship path } d; \\ 0 & \text{otherwise.} \end{cases}$$

With the given notations, the following mathematical model is formulated for solving the considered SAR operation planning problem. The goal of solving the SAR problem are to minimize total flight time and to maximize the total expected survivors based on the probability information from the cruise airplane. The expected number of survivors at location l on route r and the total expected number of survivors along route r will be, respectively:

$$\mu_{lr} = \sum_{n=0}^{C} n \times p(n)_{lr}$$

and

$$\mu_r = \sum_{l=1}^{L} \mu_{lr},$$

where C is the maximum possible number of survivors at location l on route r and and L is the maximum number of locations to visit along route r. The mathematical model given below.

$$\text{Maximize:} \qquad \sum_{r\in R} \sum_{h\in H} \sum_{s\in S} \sum_{d\in D} (\mu_r - \gamma \times FT_{rhsd}) \times x_{rhsd} \tag{24}$$

Subject to:

$$\sum_{r\in R} x_{rhsd} \leq M \times y_{sd} \qquad \forall\, h \in H; s \in S; d \in D \tag{25}$$

$$\sum_{r\in R}\sum_{s\in S}\sum_{d\in D} x_{rhsd} \leq 1 \qquad \forall\, h \in H \tag{26}$$

$$\sum_{r\in R}\sum_{h\in H}\sum_{s\in S}\sum_{d\in D} \lambda_{ri} \times x_{rhsd} \leq 1 \qquad \forall\, i \in I \tag{27}$$

$$\sum_{d\in D} y_{sd} \leq 1 \qquad \forall\, s \in S \tag{28}$$

$$\sum_{r\in R}\sum_{s\in S}\sum_{d\in D} \mu_r \times x_{rhsd} \leq HV_h \qquad \forall\, h \in H \tag{29}$$

$$\sum_{r\in R}\sum_{s\in S}\sum_{d\in D} FT_{hrsd} \times x_{rhsd} \leq HE_h \qquad \forall\, h \in H \tag{30}$$

$$\sum_{r\in R}\sum_{h\in H}\sum_{d\in D} x_{rhsd} \leq SH_s \qquad \forall\, s \in S \tag{31}$$

$$x_{rhsd} \in \{0,1\} \qquad \forall\, r \in R, h \in H, s \in S, d \in D \tag{32}$$

$$y_{sd} \in \{0,1\} \qquad \forall\, s \in S, d \in D \tag{33}$$

The objective function Eq(24) represents the probability to rescue a certain number of survivors and related flying time. A conversion factor γ may be utilised for the difference of dimensions between μ_r and FT_{rhsd}. Eq(25) defines the relationship between x_{rhsd} and y_{sd}. Eq(26) limits each helicopter to a single route *r*, a ship *s*, and a route *d*. Eq(27) states that a node *i* is visited at most once. Eq(28) prevents a ship *s* to follow more than one route *d*. Eq(29) defines the capacity to be used by each helicopter *h* to transport survivors. Eq(30) limits the flight time to helicopters endurance. Eq(31) specifies the capacity of each ship *s* to receive helicopters. Eqs(32)-(33) limit to binary values decision variables x_{rhsd} and y_{sd}.

As can be seen from the problem description, the considered SAR operation planning problem is composed of several vehicle routing problems with stochastic demand (VRPSD) as discussed in Chepuri and Homem-De-Mello (2005), while the problem sizes of these VRPSD subproblems are quite small due to capacity limit of the vehicles employed in SAR operations. The above presented mathematical model is, therefore, modeled based on enumerated vehicle routes instead of the node-edge network for simpler computation and fast solution implementation. In this research, we propose a dynamic solution approach to repeatedly solving the optimization model when the information based on probability becomes certainty during the SAR operations. We first elaborate the calculations on the parameters used in the model and then further explain the dynamic solution method.

4.2.3 Route Generation and Parameter Calculations

Some parameters used in our model are given directly by vehicles' characteristics such as maximum number of survivors transported by a helicopter (HV_h), maximum endurance of helicopters (HE_h) and maximum number of helicopters transported by a ship (SH_s), others require certain calculations from the input information in solving the above presented optimization model. In solving the considered problem, we first generate a list of all possible helicopter routes, from the departing point up to the last node visited. A tree diagram is built by considering the options available to helicopter pilots and the number of survivors with respective probabilities at each locations based on the probabilistic information provided by the surveillance airplane pilot. In addition, we also generate all possible paths for the ship to move from its origin towards all possible rescue locations. A route will be generated covering one or more locations if the possible number of survivors to be rescued is within the helicopter space capacity as well as helicopter endurance determined by remaining fuel and the distance to intercept the docking ship. The optimal ship path and helicopter route will be selected in maximizing the objective function value as given in Eq(24) in the model. The total helicopters' flight time FT_{rhsd} is composed by the time flown from the departing point to the point intercepting the docking ship and the time spent to do the rescue at each location it visits along the given route. The intercepting points are calculated based on the distances the ship will travel during the time period of the helicopter flying and performing rescue operations. The distances and angles involved in these calculations can be visualized in the Figure 4.3. For example, to determine FTG_{rh}, we use the distances of each route DL_r, helicopters cruise speed HS_h and the rescue time at each node RT_i. These relationships are seen in equation Eq(34) that includes λ_{ri}, a parameter that indicates 1 if the node i is in route r, 0 otherwise.

$$DL_r/HS_h + \sum_{i \in I} RT_i \times \lambda_{ri} = FTG_{rh} \qquad \forall\, r \in R; h \in H \tag{34}$$

FTG_{rh} also determines DHS_{sd}, the distance between the helicopter last node and the ship that

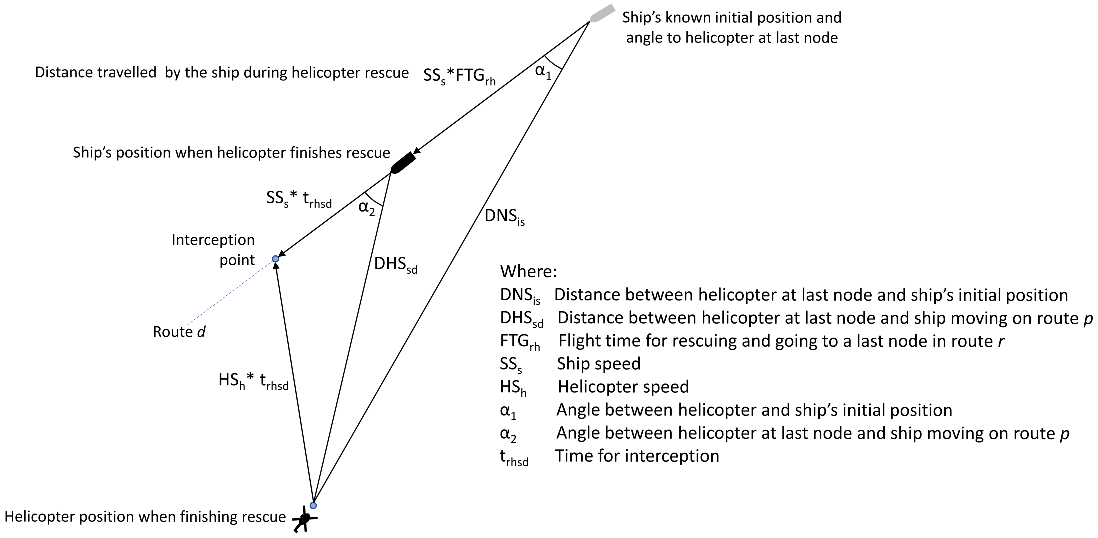


Figure 4.3: Distances and angles involved in the flight time calculations.

moved with speed SS_s. We calculate DHS_{sd} using the cosine rule as expressed in Eq(35), where α_1 is the angle and DNS_{is} the distance between the helicopter in the last node and the ship's initial position in route d. Basic calculations about cosine rule and interception points can be found in a note at the end of this Chapter.

$$DHS_{sd}^2 = (SS_s \times FTG_{rh})^2 + DNS_{is}^2 – 2 \times SS_s \times FTG_{rh} \times DNS_{is} \times cos(\alpha_1)$$
$$\forall\, r \in R; h \in H; s \in S; d \in D; i \in I \tag{35}$$

Once we know DHS_{sd}, we use Eq(36) to calculate α_2, needed to determine the time for interception, as follows.

$$\alpha_2 = 180 – arccos(((SS_s \times FTG_{rh})^2 + DHS_{sd}^2 – DNS_{is}^2)/2 \times SS_s \times FTG_{rh} \times DHS_{sd})$$
$$\forall\, r \in R; h \in H; s \in S; d \in D; i \in I \tag{36}$$

Given α_2 and DHS_{sd} we calculate the last two sides of the triangles on Figure 2 by using the ship and helicopter speeds (SS_s and HS_h) and the time to interception, common for both vehicles. The relationship between them is also given by the cosine rule as in Eq(37), that may be also expressed in a quadratic equation in Eq(38). The interception time is then determined by the positive result of t_{hrsd} in the quadratic formula of Eq(39).

$$
\begin{aligned}
&(HS_h \times t_{rhsd})^2 = (SS_s \times t_{rhsd})^2 + DHS_{sd}^2 – 2 \times SS_s \times t_{rhsd} \times DHS_{sd} \times cos(\alpha_2) \\
&\forall\, r \in R; h \in H; s \in S; d \in D \qquad (37)
\end{aligned}
$$

$$
\begin{aligned}
&(HS_h^2 - SS_s^2) \times t_{rhsd}^2 + 2 \times SS_s \times DHS_{sd} \times cos(\alpha_2) \times t_{rhsd} - DHS_{sd}^2 = 0 \\
&\forall\, h \in H; s \in S; d \in D \qquad (38)
\end{aligned}
$$

$$
\begin{aligned}
&t_{rhsd} = (-2 \times SS_s \times DHS_{sd} \times cos(\alpha_2) \pm ((2 \times SS_s \times DHS_{sd} \times cos(\alpha_2))^2 \\
&-4 \times HS_h^2 - SS_s^2 \times DHS_{sd}^2)^{\frac{1}{2}})/2 \times HS_h^2 - SS_s^2 \\
&\forall\, h \in H; s \in S; d \in D \qquad (39)
\end{aligned}
$$

Given the time to go to a last node FTG_{rh} and the time for interception t_{hrsd} we determine the parameter FT_{rhsd}, as in Eq(40), that means the total flight time for each helicopter h that follows a route r and arrives in a ship s moving in a route d. In some cases, routes become infeasible to helicopters without enough endurance. When it happens, respective flight time goes to a large number M to prevent respective route from being chosen by the model.

$$
FTG_{rh} + t_{rhsd} = FT_{rhsd} \qquad \forall\, r \in R; h \in H; s \in S; d \in D \qquad (40)
$$

The interception point calculation is also related to the course that helicopters must follow to reach a ship. Once we have the interception time t_{hrsd}, we find all sides and internal angles of the triangle on the left side of Figure 4.3. When these angles are related to some geographic reference, as the true north, we determine the true course for a helicopter intercepting a ship. Although this information is not used directly by our optimization model, it is important for calculate this value accurately in the planning. The knowledge of distances, times and courses allows pilots to complete their missions even if navigation and communication systems present failures during a flight. Also, alternative courses and times are important when unexpected situations arise and helicopters need to go to a different destination than previously planned. Details about intercepting point calculations may be found in the Appendix A, including VBA code for Excel examples.

4.2.4 Problem Solving with Updated Information

For practical applications, a dynamic solution procedure based on real-time information in planning and directing SAR operations is proposed in this research. Since SAR helicopters' space and fly-time capacities are very limited, the sizes of corresponding vehicle routing problems with stochastic demand (VRPSD) requires minimum computational time to determine the optimal solution. On the other hand, SAR operations are associated with real-time communications between pilots of the rescuing helicopters and commanding officers. The optimal SAR plan should and can be updated and revised when new information is available, especially when a probable situation becomes a certain case as a helicopter reaches the rescuing locations. For simplifying intercepting points calculations, however, it is assumed that once a ship starts following a certain course, it will not change its direction and speed during the period that helicopters are flying.

4.3 Numerical Examples and Results

In this section, we use numerical examples to illustrate the use of the proposed BIP model. Our study focus in modelling once considered past accidents show a relatively small number of helicopters operating simultaneously in a rescue, from one to six helicopters adapted to SAR, such as in the accident involving the oil rig Ocean Ranger in 1982 (Hickman, 1984), the platform Piper Alpha in 1988 (Cullen, 1988), the Air France flight AF447 in 2009 (CECOMSAER, 2009), and more recently, the MV Viking Sky cruise ship that had an engine failure in 2019 (TBO, 2019). In considering such cases, it is expected that a commercial solver is able to solve our model in a reasonable computing time without the need of developing a specific solution methodology. The first instance is based in a simplified SAR problem, in which a SAR officer needs to plan and execute a rescue to be done in high seas. We start with a report from a searching aircraft that describes three locations that may contain survivors. It is not possible to know with certainty how many people are in each site as the report uses only probabilities related to the number and locations of survivors, as shown in Table 4.1.

The ship s_1, carrying the helicopter h_1, are approaching the area and will be considered to do the operation, shown in Figure 4.4. Vehicles parameters are in Table 4.2. From that initial position

Table 4.1: Number and probabilities of survivors at each node i.

	$p(n)_i$		
μ_i	i_1	i_2	i_3
0	0.22	0.1	0.05
1	0.23	0.2	0.15
2	0.27	0.3	0.35
3	0.28	0.4	0.45

Table 4.2: Parameters for s_1 and h_1.

Vehicle	Code	Speed (kt)	Endurance (h)	Transport capacity
Ship	s_1	18	...	1 helicopter
Helicopter	h_1	180	02:00	6 survivors

h_1 will be launched and s_1 will follow a direct route d to one of the three survivor's locations i, as determined by the SAR plan. Considering Figure 4.4 oriented to the true north as indicated, respective ship's true courses d are in Table 4.3. Given these initial parameters, the SAR officer faces a problem to choose the best routes for the ship and the helicopter to maximize the probability to rescue a limited number of survivors in a shorter possible flying time.

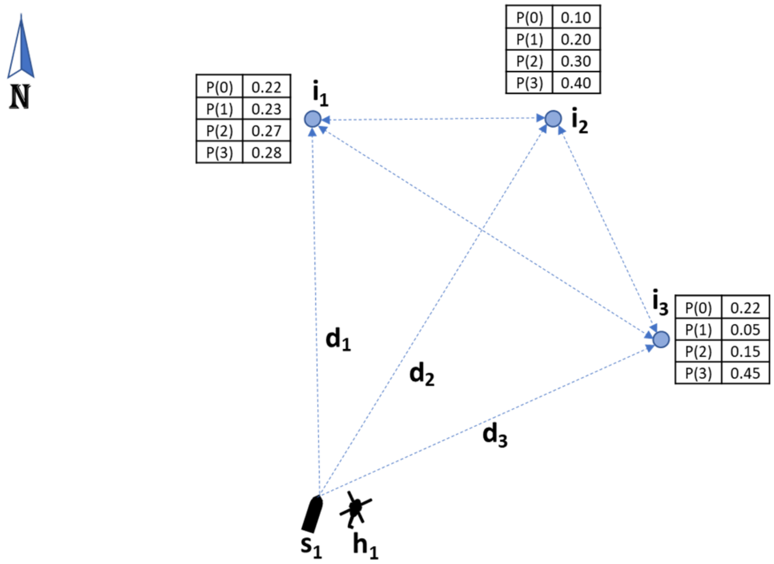


Figure 4.4: General view.

First we define all possible helicopter routes considering that it will depart from ship s_1 and the options are going to one or more survivors' locations i before to initiate an intercepting course to return to s_1. Given four possibilities of number of survivors at each location, a tree diagram

Table 4.3: True courses of routes d for ship s_1.

True course	d_1	d_2	d_3
s_1	000°	030°	060°

Table 4.4: Distances between nodes and initial position of ship s_1.

Distances (NM)	s_1	i_1	i_2	i_3
s_1	0	80	92	81
i_1	80	0	45	81
i_2	92	45	0	47
i_3	81	81	47	0

generated an initial list of 492 possible routes. This list is then reduced to 144 routes by considering only the highest probability for each number of survivors and sequence of nodes. All parameters are calculated and organized in spreadsheets. To calculate FTG_{rh}, the time that the helicopter h needs to go to the last node of a given route r, we consider the distances shown in Table 4.4, helicopter's cruise speed HS_h in Table 4.2 and a rescue time at each node RT_i, assumed 15 minutes for our planning. The interception time t_{rhsd} is then calculated by Eqs(34)-(39) and added to FTG_{rh} for finding the total flight time FT_{rhsd}, as in Eq(40). This first instance can be solved using the parameters already in spreadsheets, following the developed mathematical model. For while, we consider a simple rescue plan in which the helicopter departs from s_1 and goes first to node i_3, where we have the highest probability to find tree people, and later to i_2 aiming also three survivors, then returning to s_1 that follows route d_2, as in Figure 4.5(a). Thus, if the helicopter rescue a total of six persons in that route, it follows true course 210° from i_2 to return to s_1 with 01:34h of flying time. However, especially considering uncertain the number of survivors at each location, the plan may request prompt updates according to development of events.

When executing the rescue plan, we do not know how many survivors are in the first visited node before we reach there. Suppose that only two survivors were found in i_3, as in Figure 4.5(b). In this condition, we may prompt review the plan to consider the helicopter's remaining capacity of four survivors because when the parameters are calculated and organized in spreadsheets, it is also done for all possible routes, including number of survivors, respective probabilities, intercepting times and courses, as shown in Table 4.5. When FT_{rhsd} is above the helicopter's endurance, the respective value shows M, assumed 10,000 in our calculations. We verify that h_1 has enough endurance to do

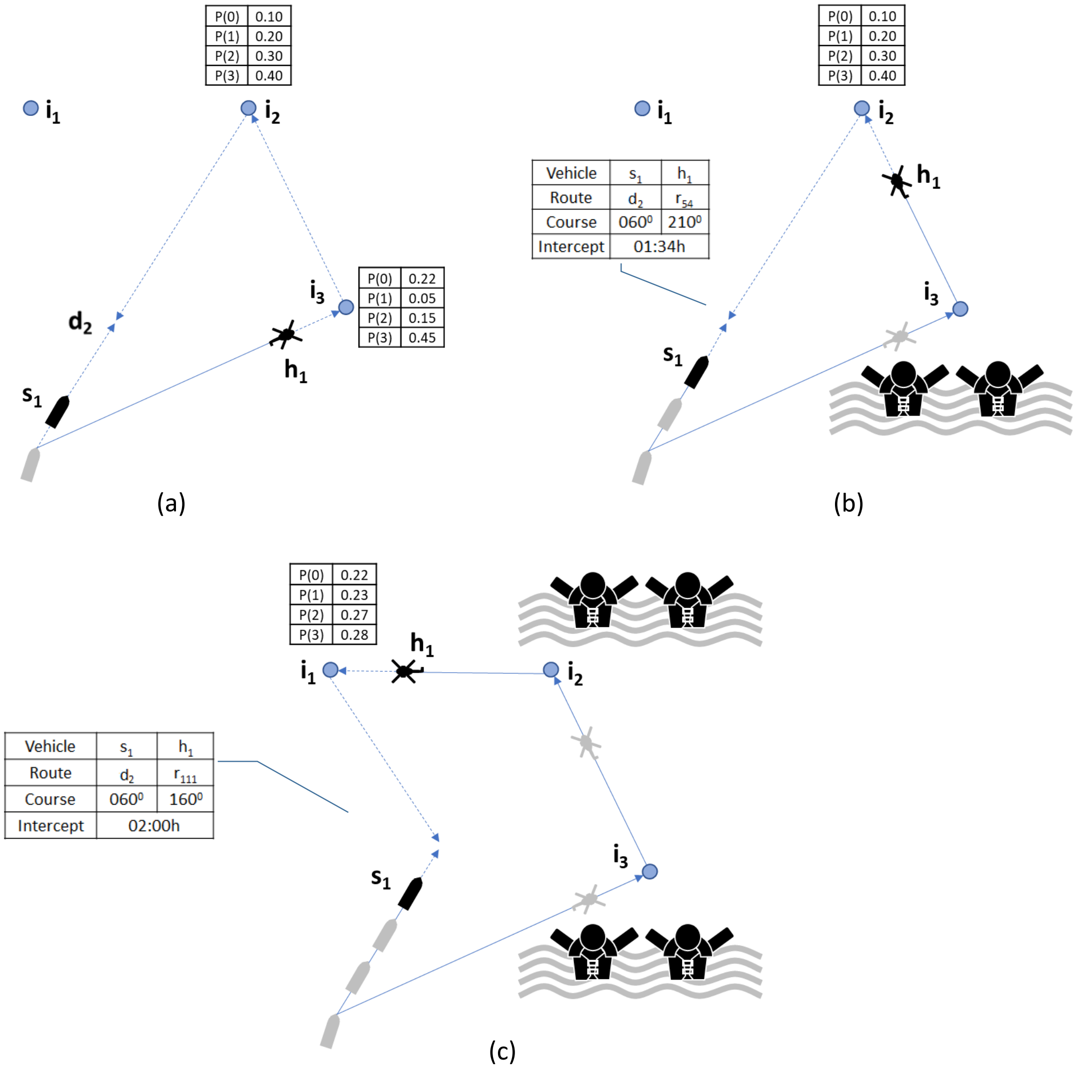


Figure 4.5: Updating the rescue plan according to its execution.

a rescue at i_2 and i_1 when s_1 keep following route d_2. Otherwise, for example, the helicopter could not intercept s_1 in route d_3 because it would be beyond its endurance. Supposing that again only two survivors are found in i_2, as in Figure 4.5(c), the remaining helicopter's capacity for transporting survivors in i_1 will be two. From there, the helicopter follows course 160° to intercept ship s_1 with 02:00 h of flying time, the limit of its endurance. A flowchart with the basic steps for the presented decision making is shown in the Figure 4.6.

For verifying model results when more units are considered, we add one extra ship and one extra helicopter in a scenario similar as in previous instance, as shown in Figure 4.7 (a). Vehicles

Table 4.5: Partial list of FT_{rhsd} and intercepting courses for h_1 .

				s_1		
r	μ_r	PV_r	i	p_1	p_2	p_3
r_1	0	0.22	1	01:02 180°	01:03 171°	01:06 166°
r_2	1	0.23	1	01:02 180°	01:03 171°	01:06 166°
r_3	2	0.27	1	01:02 180°	01:03 171°	01:06 166°
r_4	3	0.28	1	01:02 180°	01:03 171°	01:06 166°
r_5	0	0.10	2	01:10 218°	01:09 210°	01:10 202°
r_6	1	0.20	2	01:10 218°	01:09 210°	01:10 202°
r_7	2	0.30	2	01:10 218°	01:09 210°	01:10 202°
r_8	3	0.40	2	01:10 218°	01:09 210°	01:10 202°
r_9	0	0.05	3	01:06 224°	01:04 218°	01:02 210°
r_{10}	1	0.15	3	01:06 224°	01:04 218°	01:02 210°
r_{11}	2	0.35	3	01:06 224°	01:04 218°	01:02 210°
r_{12}	3	0.45	3	01:06 224°	01:04 218°	01:02 210°
…	…	…	…	…	…	…
r_{48}	0	0.005	3-2	01:35 222°	01:34 210°	01:35 197°
r_{49}	1	0.015	3-2	01:35 222°	01:34 210°	01:35 197°
r_{50}	2	0.035	3-2	01:35 222°	01:34 210°	01:35 197°
r_{51}	3	0.070	3-2	01:35 222°	01:34 210°	01:35 197°
r_{52}	4	0.105	3-2	01:35 222°	01:34 210°	01:35 197°
r_{53}	5	0.140	3-2	01:35 222°	01:34 210°	01:35 197°
r_{54}	6	0.180	3-2	01:35 222°	01:34 210°	01:35 197°
…	…	…	…	…	…	…
r_{105}	0	0.0011	3-2-1	01:58 180°	02:00 160°	M
r_{106}	1	0.0033	3-2-1	01:58 180°	02:00 160°	M
r_{107}	2	0.0077	3-2-1	01:58 180°	02:00 160°	M
r_{108}	3	0.0154	3-2-1	01:58 180°	02:00 160°	M
r_{109}	4	0.0231	3-2-1	01:58 180°	02:00 160°	M
r_{110}	5	0.0308	3-2-1	01:58 180°	02:00 160°	M
r_{111}	6	0.0396	3-2-1	01:58 180°	02:00 160°	M
r_{112}	7	0.0414	3-2-1	01:58 180°	02:00 160°	M
r_{113}	8	0.0486	3-2-1	01:58 180°	02:00 160°	M
r_{114}	9	0.0504	3-2-1	01:58 180°	02:00 160°	M

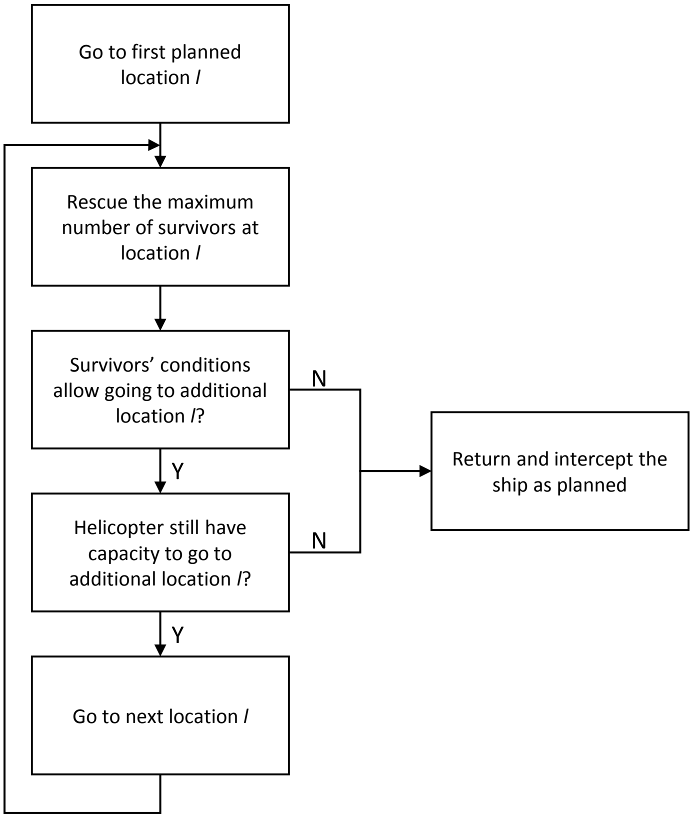


Figure 4.6: Flowchart for decision making when executing the rescue plan.

performances are in Table 4.7 and distances in Table 4.7. True courses of routes d for each ship s are in Table 4.8. Possible routes are the same as previously calculated, the difference is the intercepting time t_{rhsd} that varies with new ship's speed and courses, as well as new helicopter's speed and endurance, reflecting in the total flight time FT_{rhsd} and helicopters' routes feasibility. This second instance may be solved as already discussed in the first instance or using commercial solvers with insignificant computational time. The optimized rescue plan given by the exact solution is summarized in Table 4.9 and Figure 4.7(b). In this plan, h_1 flies 01:28 h in route r_{12}, that goes from ship s_1 to node i_3 and it is expected to find 3 survivors with 0.45 of probability there. The true course for a helicopter intercepting a ship is calculated considering same reference of Table 4.2. Thus, from i_3, h_1 follows true course 240° to intercept s_1 that will be maintaining route d_3. Helicopter h_2 flies 01:32 h in route r_{19} where is expected to find 6 survivors with 0.112 of probability. From i_2 the helicopter follows course 029° to intercept s_2 in route d_2. If some update

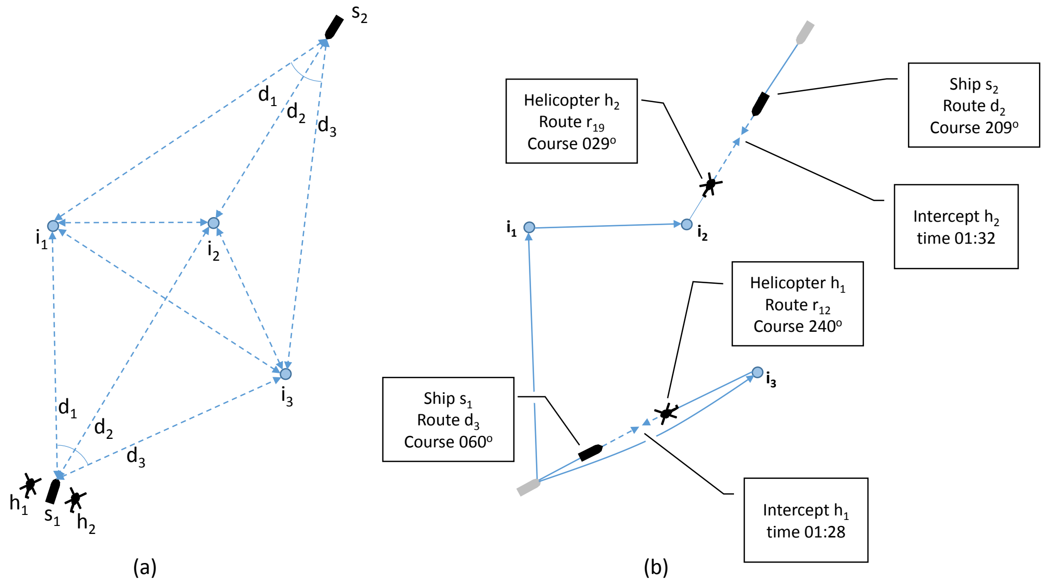
Table 4.6: Parameters for ships s_1 and s_2 and helicopters h_1 and h_2.

Vehicle	Code	Speed (kt)	Endurance (h)	Transport capacity
Ship	s_1	18	...	2 helicopters
Ship	s_2	12	...	1 helicopter
Helicopter	h_1	110	02:15	3 survivors
Helicopter	h_2	180	02:00	6 survivors

Table 4.7: Distances between nodes and initial positions of ships.

Distances (NM)	s_1	i_1	i_2	i_3	s_2
s_1	0	80	92	81	172
i_1	80	0	45	81	110
i_2	92	45	0	47	81
i_3	81	81	47	0	111
s_2	172	110	81	111	0

should be needed (i.e. one helicopter must return immediately from the first point visited because one survivor is in critical state), the same procedure as discussed before should be used.



(a) (b)

Figure 4.7: Rescue plan considering additional vehicles.

Table 4.8: True courses of routes d for each ship s.

True course	d_1	d_2	d_3
s_1	000°	030°	060°
s_2	230°	209°	187°

Table 4.9: Model results for two ships and two helicopters.

Helicopter	Route	Nodes sequence	FT_{rhsd} (h)	Interception course	Ship intercepted	Ship route	Expected survivors	Probability
h_1	r_{12}	3	1.48	240	s_1	d_3	3	0.450
h_2	r_{19}	$1-2$	1.54	029	s_2	d_2	6	0.112

The main differences between presented instances' results are the time to rescue and transport survivors, about 30 minutes shorter in the second instance, and the fact that all nodes may be visited at once, since the helicopters together have enough capacity to transport the maximum expected number of survivors in the rescue zone. Our model shows encouraging results, as demonstrated during the research in solving different instances, where the same logic was applied in calculating routes, probabilities, intercepting times and courses for rescue planning as well as for updating the plan during its application.

4.4 Conclusion

When accidents occur all possible means are used to ensure assistance to those persons without regard to their locations, nationality, or circumstances. The rescue method and facilities to be used are chosen once people or objects have been located, although, occasionally, the type and number of targets detected by searching missions may not be precisely described. In high seas, the combination of air and maritime vehicles produces important operational advantages while, on the other hand, poses challenges for planning their use. In this chapter, a vehicle routing problem was proposed considering heterogeneous fleet of helicopters and ships, displacements during the rescue operation and probabilities to find survivors at each location visited. A mathematical programming model was proposed aiming optimal routing decisions for SAR rescue planning. Numerical examples illustrated the considered problem and results of the developed model show (i) the validity of the model and parameters calculations, (ii) the best choice of routes for rescue planning considering urgency of actions, vehicles of different performances, respective displacements, as well as uncertainty of number of survivors, and (iii) the prompt support of our model in determining alternative routes, times and courses for updating the rescue plan according to its execution. In this research, we analyze the dynamics of rescue operations due to air or maritime emergencies since research in modeling SAR planning problems considering multiple practical aspects is limited in the literature. The contributions of our study can be seen in various aspects. First, we developed a new model that considers important issues for rescue planning as they can occur in real rescue operations in high seas, such as lack of support points, differences in vehicles performances and uncertain information from searching flights. Second, previous traveling salesman problems developed in the literature considering drones and trucks assumed that drones can only merge with a truck at a customer node. In our study, we have cooperation between helicopters and ships and a helicopter can depart, intercept and land on a ship in movement at any point of its route, even on a different ship from previous departure. Third, since we consider the transport capacity of all vehicles, our model can be viewed as a VRP variant aiming at prompt solutions in response to off-shore emergencies. Fourth, in addition to providing scientific support for rescue planning, our model also gives assistance for implementing respective actions. We discuss the dynamics of executing a planned rescue when the number of survivors is uncertain and the support of our model in promptly verifying possibilities of extending rescue activities. In future research, we plan to integrate our model with a geographic information system to develop an efficient and effective solution method for solving larger size SAR problems with short computing time.

4.5 Notes About Cosine Rule and Interception Point Calculations

Considering the triangle of Figure 4.8 where we know the B and C sides and the angle α between them, we can determine the side A by using the cosine rule as in Eq(41).

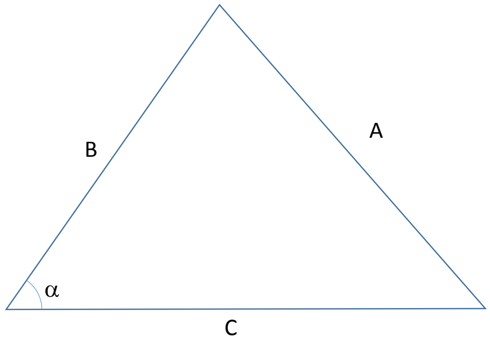


Figure 4.8: Basic triangle for illustrating the cosine rule.

$$A^2 = B^2 + C^2 – 2 \times B \times C \times cos(\alpha) \tag{41}$$

The interception point of two moving vehicles may be calculated using the same principle. Instead to use triangle sides' sizes directly, we consider the speed, time and distance between the two objects, as depicted in Figure 4.9. We assume that in a given time $t = 0$ the distance separating the helicopter and the ship is d and the helicopter speed (v_h) is superior to the ship (v_s). Thus, considering the cosine rule, we can rewrite Eq(41) in Eq(42):

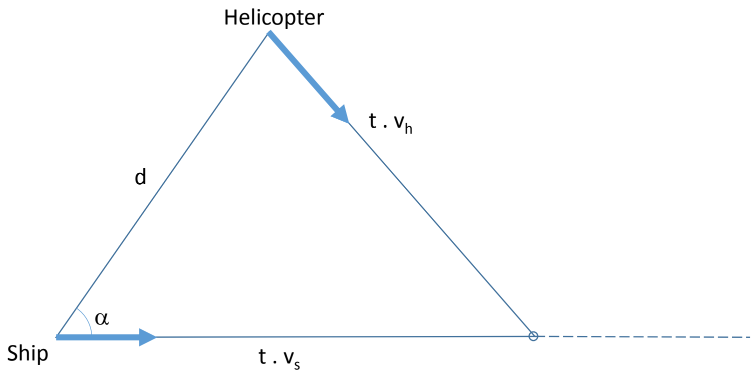


Figure 4.9: Basic triangle for illustrating the intercepting point calculation.

$$(t \times v_h)^2 = (t \times v_s)^2 + d^2 – 2 \times (t \times v_s) \times d \times cos(\alpha) \tag{42}$$

The Eq(42) can be transformed in a quadratic equation and solved by time t, as in Eq(43).

$$(v_h^2 – v_s^2) \times t^2 + (2 \times d \times v_s \times cos(\alpha)) \times t – d^2 = 0 \tag{43}$$

That can be solved by the quadratic formula, as in Eq(44).

$$t = (-b \pm \sqrt{(b^2 – 4 \times a \times c}) / (2 \times a) \tag{44}$$

Where

$$a = v_h^2 {-} v_s^2 \tag{45}$$

$$b = 2 \times d \times v_t \times cos(\alpha) \tag{46}$$

$$c = -d^2 \tag{47}$$

The interception time (the first and only time) is obtained by a non-negative discriminant and considering the addition in the quadratic formula. If the helicopter speed were smaller than the ship, the helicopter should be in the frontal area of the ship (otherwise the interception should not be possible) and we may find two interception moments, as in Figure 4.10. Diverse sites describing how to calculate interception or intersection points between two moving vehicles or objects can be found on Internet. One simple and instructive source, used for writing this Note, is in *Intersection of two Moving Objects* (2016).

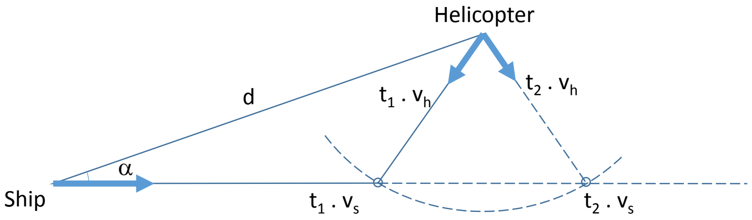


Figure 4.10: Two moments for interception.

Chapter 5

An Aircraft Routing Problem for Long-Range Mass Rescue Operations Planning

Successful search and rescue (SAR) operations provide positive image in emergency situations which normally should be viewed negatively. However, some tragedies occur in remote regions, requesting rescue of a large number of people, creating additional difficulties to the success of SAR missions. In this chapter, the problem for planning aerial long-range mass rescue operations (MROs) inland are modelled as an aircraft routing problem considering pick-up and delivering, weight and endurance limits. Given the characteristics of the available heterogeneous fleet of long-range aircraft, we determine respective routes to minimize the flying time by considering aircraft weight dynamics that condition the choice of routes for a rescue operation. Feasible routes depend on factors such as aircraft endurance, fuel consumption rate, maximum payload, take-off and landing weights considering the support to be delivered and the people to be rescued at specific locations. In addition, some airfields may restrict the operation of determined type of aircraft. A BIP model is proposed and its solution includes the use of spreadsheets to calculate and reduce some parameters to 0/1 indicator tables. Results of two numerical examples show the validity of the model in choosing the best routes for long-range aircraft in performing inland rescuing when urgency of actions and vehicles of different performances are involved to rescue a large number of people in remote regions.

5.1 Introduction

The availability of search and rescue (SAR) resources are important to provide the initial response and relief capabilities vital for saving lives in the first moments of natural and man-made calamities. Successful SAR operations provide positive image in emergency situations which normally are viewed negatively. When a large number of persons in distress need assistance, SAR systems capacities are usually inadequate and a different approach is adopted. Thus, a mass rescue operation (MRO) must be specific planned, since hundreds or thousands of persons may be rescued from remote and hostile regions. Causes are varied, such as large aircraft or ship disasters, flooding, release of hazardous material in the environment, earthquakes as well as armed conflicts. MROs usually require extensive preparation once they may need extra actions related to pollution control, large-scale logistics and medical assistance, hazards mitigation, as well as intense public and political attention. Situations requiring MROs generate high visibility, thus, providing information to the media is very important for shaping of public opinion. MRO efforts must often start immediately at an intense level and be sustainable for days or weeks.

Available rescue time is severely limit by environment-related factors. The use of life jackets, immersion suits, clothing conditions, the clothing's wetness, person activity, physical and psychological condition, hunger and will to live affects survivors' life expectancy. Rescue at sea request immediate actions since, allied to natural danger of drowning, persons are strongly affected by water temperature. Inland, the effects of various wind speed and air temperature combinations may lead people to hypothermia. It shows that MROs need to rescue and shelter survivors in a shorter possible time. Hypothermia causing death is over four times more often in water than on land.

Other important question is about where the situation takes place, requesting additional care to conduct the rescue. At sea, the distance associated is very important since that operation of helicopters may be restricted by endurance, as support points in the route may not be available (i.e. a helideck in an oil rig or a ship), and they are important vehicles in these situations. The weather associated is also critical since waves too high may prevent the deployment of rescue boats, as happened during the Viking Sky rescue in 2019. Also, rescue equipment such as cables, pulleys, nets, may be frozen by cold weather, as occurred during the oil rig Ocean Ranger rescue in 1982. Inland, in short distances, helicopters are preferred vehicles since they may operate in small spaces while maintaining a constant position over the ground, allowing to hoist people from varied places (i.e. people trapped on rooftops during an inundation) and taking them to a safe place. Depending on the type of tragedy, if the operation takes place in a region nearby to big cities, it may be even worse to MROs. The local infrastructure may be seriously affected by the disaster and, more important, the number of casualties tend to be very high. For example, the earthquake that affected Haiti in 2010 affected about 3 million of people. In remote and distant places, given the urgency of actions and distances involved, fixed-wing aircraft are the vehicles most efficient but planning their optimal use presents challenges to the SAR officer once critical decisions must be made on aircraft performances, equipment and routes to be used. Such planning and decision-making processes may be supported by mathematical and numerical tools, as presented in the following referred bibliography. The use of mathematical models in emergency planning considering facility locations, evacuation planning and humanitarian logistics were explored in Dhamala et al. (2018). Alsagoff (2011) proposed a methodology to generate optimal grid pattern model for search and rescue operations forest. Anaya-Arenas et al. (2014) presented a review of studies on relief distribution networks in response to disasters. Bezgodov and Esin (2014) studied problems of efficiency of maritime search and rescue operations at sea. Rahman et al. (2015) and Siljander et al. (2015) discussed the support of geographic information system (GIS) in SAR operations. The optimal location of a SAR base for launching vehicles such as ambulances, boats, helicopters and drones have been studied in considering location models as in Brachner et al. (2019) that developed a multi-objective mathematical programming model to optimize both average and maximum response time in offshore emergencies. Pelot et al. (2015) developed a location model for vessels in maritime SAR. Acar (n.d.) considered set covering, maximal covering and P-median models to define optimum locations for SAR units. The possibility of using autonomous or semi-autonomous vehicles in emergency situations was discussed in Calisi et al. (2007) that developed a strategy for a rescue robot considering autonomous exploration, mapping, victim detection and localization and Karma et al. (2015) considered search and rescue in forest fires. Forsmo et al. (2013) developed a mixed integer linear programming model for planning search missions using cameras or other sensors in drones. Claesson et al. (2017) and Amukele et al. (2017) discussed the use of drones in delivering medical supplies or other articles in disaster areas. Chowdhury et al. (2017) and Chauhan et al. (2019) developed locations models considering drones for delivering supplies in emergencies.

Well-researched vehicles routing problems (VRP) and traveling salesman problems (TSP) are closely related to the SAR problems studied in our work. Deus (2018) considered as a VRP the problem of planning mass rescue operations in maritime areas using helicopters and vessels and Vitetta et al. (2009) the path design for emergency vehicles rescuing handicap persons during calamities. Rabta et al. (2018) consider as a VRP the use of drones in short-range distribution in disaster relief operations. Other work in this area includes Musolino, Polimeni, and Vitetta (2014) that proposed a VRP formulation based on the network fundamental diagram, (Ghiani et al., 2004) that presented the node routing problem set partitioning in which costs are minimized considering a set of feasible routes and a certain number of vehicles, and Joubert (2004) that used the concept of time window compatibility to improve the initial solution algorithm when considering heterogeneous fleet, double scheduling and multiple time windows. In this Chapter, we analyze the dynamics of rescue operations due to land emergencies since research in modelling SAR planning problems considering multiple practical aspects is limited in the literature. Our work considers a heterogeneous fleet where the number and type of aircraft is treated as a decision variable together with the routes and the need of pick-up and delivering in a long-range mass rescue operations requests multiple operational constraints related to weight, endurance, and locations. In this sense, practical contributions of our study can be seen in various points, such as considering a real problem where aircraft need to initiate their flights with a certain amount of fuel to be consumed during the mission without refueling. In consequence, aircraft are limited by endurance and weight to take-off and land in certain locations since the weight varies with distances, fuel consumption rate and the people to be rescued and eventually delivered, also having limits of payload. We enumerate vehicle routes instead of the node-edge network for simpler computation and fast solution implementation, also avoiding the generation of subcircuits in the solution. Finally, we perform precalculations to reduce several constraints to few indicators 0/1 that also simplify computation and contribute to obtain results quickly.

In brief, Section 2 presents our research problem and the developed BIP model, including some particular parameters calculations. Numerical examples and computational results, as well as further discussions, are presented in Section 3. Concluding remarks and future developments are given in Section 4.

5.2 Problem Description and Modelling

In this section, we present specific characteristics of a SAR planning problem and propose a mathematical model for solving it, described as follows. In some situations, people must be rescued from areas affected by some tragedy generated by natural causes or not. When these areas are in remote regions inland and time is a critical factor to be considered, rescue by aircraft may be considered to transport these persons to a safe place. To plan their use we need to verify, for example, which locations offer minimum conditions to aircraft operations, if refueling is available and reliable in the region considered, the demand at each location visited, what are the performance characteristics of available aircraft, and if there are restrictions for operating determined type of aircraft in a given location. If refueling is not available (i.e. when operating in improvised airstrips such as highways) or reliable (i.e. fuel contamination is possible), long-range aircraft are requested due to their large internal fuel capacities. Thus, depending on the distances involved, aircraft may be requested to start their missions using the maximum fuel capacity. However, a large amount of fuel also represents weight, a critical factor for operating aircraft. For safety reasons, the maximum take-off weight and the maximum landing weight are basic limitations that must be respected in normal operation since they are associated with the aircraft design. Sometimes, in addition to pick-up people, some locations to be visited request the delivering of personnel such as medics, military as well as some equipment and food to support the evacuation in that place, as depicted in Figure 5.1. Thus, the weight variation must be carefully accounted to guarantee that aircraft weight limits are respected. Also, given different runways operation characteristics, some locations may be restricted, for example, for jets operation. In summary, if long-range aircraft are used to perform rescue in far regions because of their fuel capacity, on the other hand, the operation may be very limited by weight issues. Our problem is then related to how to route aircraft in a problematic zone to rescue

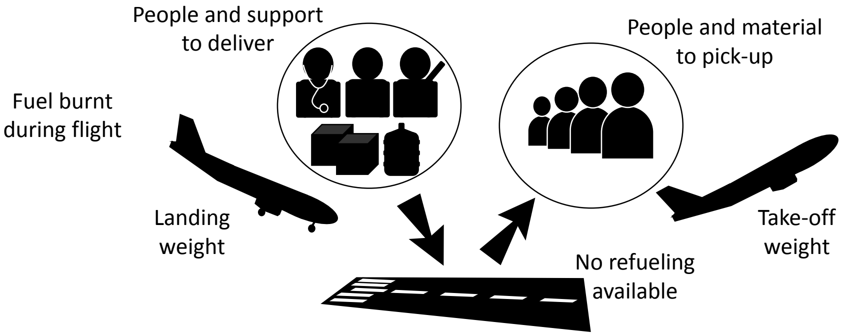


Figure 5.1: Aircraft weight variation without refueling.

people and eventually delivering aids in the shorter possible time, but respecting aircraft weight limitations and local operations restrictions. For simplicity, the use of an aircraft coordinator (ACO) will not be considered in our model, although being desirable in real operations for improving safety, coordination and communications between units. More details about ACO can be found in (IAMSAR, 2016).

5.2.1 Sets, Indices and Variable for Modelling

In this research, we propose a binary integer programming (BIP) model to solve the considered SAR planning problem. In this part, we present the notation used in the mathematical model, as follows.

Sets and Indices

R	Set of routes for aircraft, indexed by $r \in R$.
K	Set of aircraft, indexed by $k \in K$.
K'	Subset of aircraft, indexed by $k' \in K'$.
L	Set of locations to be visited, indexed by $l \in L$.
L'	Subset of locations to be visited, indexed by $l' \in L'$.

Parameters

TT_{kr}	Total flight time of aircraft *k* in route r *r*.
λ_{rl}	0/1 indicator; 1 if node *l* exists in route *r*; 0 otherwise.
ϕ_{kr}	0/1 indicator; 1 if route *r* is feasible to aircraft *k*; 0 otherwise.

Decision Variable

$$x_{kr} = \begin{cases} 1 & \text{if aircraft } k \text{ follows route } r\text{;} \\ 0 & \text{otherwise.} \end{cases}$$

With the above notations, the following mathematical model is formulated for solving the rescuing planning problem, considered as a VRP.

5.2.2 Objective Function

Given the nature of the problem analyzed it is important to reduce the rescue time, translated here by the minimization of the flight time. Thus, the objective function of our model will select the group of feasible routes r that, using a combination of available aircraft k, need the minimum total time flown TT_{kr} to complete the rescue, expressed as follows.

$$\text{Minimize} \qquad \sum_{k \in K} \sum_{r \in R} TT_{kr} \times x_{kr} \tag{48}$$

5.2.3 Parameters Calculations and Constraint Functions

Our model assumes that each aircraft k follows the maximum of one route r, if selected to compose the fleet. It is expressed by the binary decision variable x_{kr}, as in Eq(49).

$$\sum_{r \in R} x_{kr} \leq 1 \qquad \forall\, k \in K \tag{49}$$

Total time flown TT_{kr}

To be in conditions to be selected, each aircraft must be meet some requirements related to endurance, nodes to visit, and especially, weight. To verify these requirements, we star generating a list of possible routes R using the standard permutation formula, as in Eq(50), considering a minimum and a maximum number of nodes i to visit and the total number of locations n.

$$_{n}P_{i} = n!/(n-i)! \tag{50}$$

Considering the origin always as 0 (i.e. the SAR base), we start with $i = 1$ and we generate routes with only one location to visit such as 0 – 1 – 0; 0 – 2 – 0; 0 – 3 – 0… 0 – n – 0. Next, using $i = 2$ (two locations) we generate routes with nodes 0 – 1 – 2 – 0; 0 – 1 – 3 – 0; 0 – 1 – 4 – 0 … 0 – (n-1) – n – 0. We continue with three locations ($i = 3$), four and so on, up to a certain maximum number of locations or nodes. This number is based on the maximum distance that the last available aircraft can cover. In other words, once we know which locations are in these routes and the distance between them (including the origin), we calculate total distances TDR_r. Next we divide TDR_r by each aircraft cruise speed CS_k to obtain the total flying time TT_{kr} as in Eq(51). Thus, we compare TT_{kr} with aircraft endurance E_k, as in Eq(52) and when there is no aircraft that can cover routes with a certain number of locations (i.e. six) because there is no unit with such endurance, we stop and consider the last number of locations that gave us at least one aircraft flying in at least one route (i.e. with five nodes). For simplicity, we are not considering the reserve fuel needed for safety rules.

CS_k	aircraft cruise speed
TDR_r	Total route distance
E_k	Aircraft endurance

$$TDR_r/CS_k = TT_{kr} \qquad \forall\, k \in K, r \in R \tag{51}$$

$$TT_{kr} \leq E_k \qquad \forall\, k \in K, r \in R \tag{52}$$

Based on these considerations, we organize a routes' list in spreadsheets considering minimum to maximum number of nodes, total distances and total flying times. TT_{kr} is used by our model to calculate the minimum flying time, as expressed in the objective function in Eq(48), but also to indicate that a route is infeasible to some aircraft. Thus, TT_{kr} must be below or equal to the endurance of each aircraft E_k, as in Eq(52), and, if TT_{kr} exceeds E_k, the route is infeasible to respective aircraft and the TT_{kr} value goes to a large number N, avoiding to be chosen by the model.

Location indicator λ_{rl}

Our model also considers that all locations are visited once during the rescue, as expressed by Eq(53). The indicator 0/1 λ_{rl} is generated using the list of routes and respective locations. Thus, using spreadsheets, we use all enumerated routes and indicate 1 when location l is in respective route and 0 otherwise.

$$\sum_{k \in K} \sum_{r \in R} \lambda_{rl} \times x_{kr} = 1 \qquad \forall\, l \in L, l \neq 0 \tag{53}$$

Route feasibility indicator ϕ_{kr}

The parameter ϕ_{kr} represents the feasibility of an aircraft to transport a requested demand in a given route. For calculating ϕ_{kr} we need to know:

$ITOW_{kij}$	Initial take-off weigth of aircarft k in a first trip i to j
MPL_k	Maximum payload of each aircraft k
$MTOW_k$	Maximum take-off weigth of aircraft k
MLW_k	Maximum landing weigth of aircraft k
LW_{kj}	Landing weight at destination j
TD_{ij}	Trip distance between i and j
FC_k	Fuel consumption of aircraft k
FB_{kij}	Fuel consumed in a trip i to j
TDD_r	Total demand to deliver in route r
DW_j	Demand weigth to be delivered at location j
PW_j	Demand weigth to pick-up in j
δ_j	Demand weight variation in j

When an aircraft departs or arrives to and from any place, it must respect many conditions, especially about weight. The Figure 5.2 summarizes different factors associated with aircraft weight that must be considered in a trip. For a complete list, aircraft manuals must be consulted. In our study, however, for simplicity we consider only three of them as the maximum payload of each

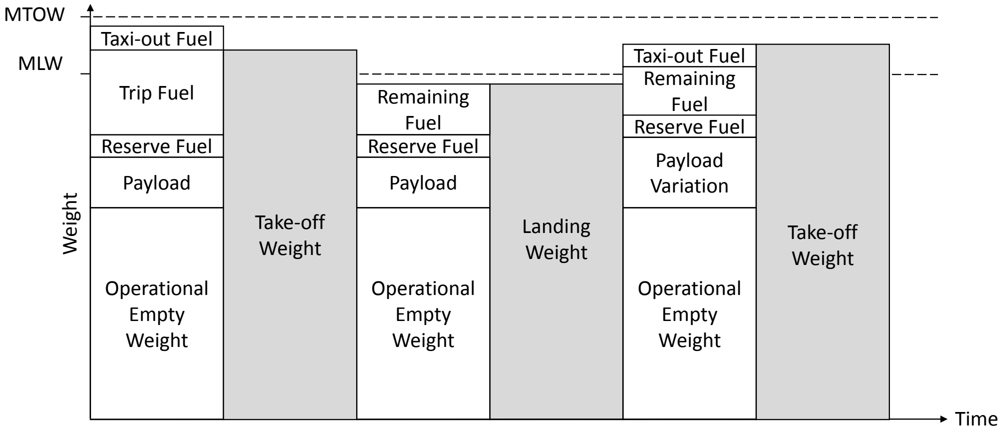


Figure 5.2: A summary of aircraft weight variation during a flight.

aircraft MPL_k, maximum take-off weight $MTOW_k$ and the maximum landing weight MLW_k. If an aircraft does not exceed any of them when landing and departing to rescue people, ϕ_{kr} assumes 1, indicating a route that is feasible to respective aircraft, otherwise, 0. Thus, when an aircraft starts a mission and departs from the SAR base, it will have an initial take-off weight $ITOW_{kij}$, as shown by Figure 5.3. I represents a set of origins ($i \in I$) and J a set of destinations ($j \in J$). First we need to verify that $ITOW_{kij}$, that includes the weight to be delivered in a location j, respects the $MTOW_k$, as in Eq(54). Also, if the total weight to be delivered in the route r, TDD_r, does not exceed the maximum payload MPL_k of aircraft k, as in Eq(55). Given the list of possible routes with respective nodes, we calculate each trip distance (node to node) TD_{ij} in a same route. When we multiply TD_{ij} by the fuel consumption of each aircraft FC_k, that is known, we find the fuel consumed (burnt) in each trip FB_{kij}, as in Eq(56), expressed in terms of weight. Subtracting FB_{kij} from TOW_{kij} we find the landing weight at a destination LW_{kj}, as in Eq(57). If LW_{kj} is below or equal to respective aircraft maximum landing weight MLW_k, the aircraft can arrive at j, as in

Eq(58).

$$ITOW_{kij} \leq MTOW_k \qquad \forall\, k \in K, i \in I, i = 0, j \in J \tag{54}$$

$$TDD_r \leq MPL_k \qquad \forall\, k \in K, r \in R \tag{55}$$

$$TD_{ij} \times FC_k = FB_{kij} \qquad \forall\, k \in K, i \in I, j \in J \tag{56}$$

$$TOW_{kij} - FB_{kij} = LW_{kj} \qquad \forall\, k \in K, i \in I, j \in J \tag{57}$$

$$LW_{kj} \leq MLW_k \qquad \forall\, k \in K, j \in J \tag{58}$$

To know the TOW_{kij} of the next trip, as represented by Figure 5.4, we consider the weight of the demand to be delivered DW_j and the weight demand to be picked-up PW_j at each location j. Both give us the demand weight variation at location δ_j expressed also in terms of weight, as in Eq(59). The variation of payload δ_j must respect the maximum payload of each aircraft MPL_k, as in Eq(60). δ_j added to LW_{kj} must be below or equal to respective aircraft maximum take-off

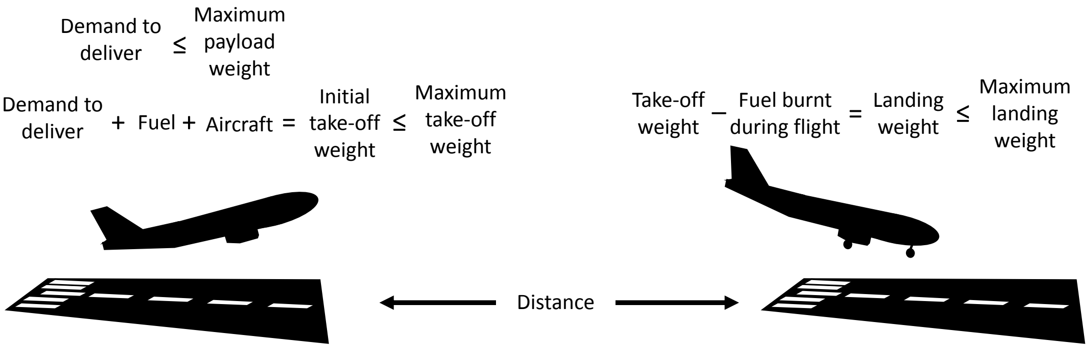


Figure 5.3: Aircraft weight variation after initial take-off.

weight $MTOW_k$, as in Eq(62), to the route be feasible.

$$PW_j - DW_j = \delta_j \qquad \forall\, j \in J \tag{59}$$

$$\delta_j \leq MPL_k \qquad \forall\, k \in K, j \in J \tag{60}$$

$$LW_{kj} + \delta_j = TOW_{kij} \qquad \forall\, k \in K, i \in I, i \neq 0, j \in J \tag{61}$$

$$TOW_{kij} \leq MTOW_k \qquad \forall\, k \in K, i \in I, j \in J \tag{62}$$

We calculate and verify in all trips if any $MTOW_k$, MLW_k or MPL_k are exceeded. If not, the ϕ_{kr} assumes 1, indicating a route that is feasible to that specific aircraft, otherwise, if one of the weight limits is surpassed, ϕ_{kr} assumes 0, indicating an infeasible route for that airplane. The fuel that is burnt during a flight has an important role in the routes calculation. For example, in Figure 5.5 (a) the route 0-1-2-3-0 could be the shortest path for aircraft k. However, supposing that the aircraft had excessive weight to land in nearest location, it should be obliged to augment the distance flown to burn more fuel and reach the maximum landing weight as in letter (b). Such situations may happen, for example, by the impossibility to transport less cargo or fuel weight, allied to the aircraft fuel consumption rate that can be relatively low. Especially in emergency areas, landing and departing may be associated with some complications caused by affected infrastructure or weather conditions, and the use the maximum aircraft fuel capacity may be the solution to guarantee the flight back to a safe place.

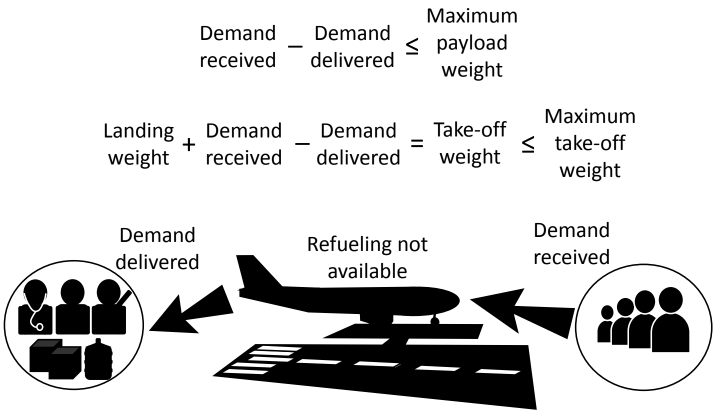


Figure 5.4: Aircraft weight variation during delivering and receiving demand.

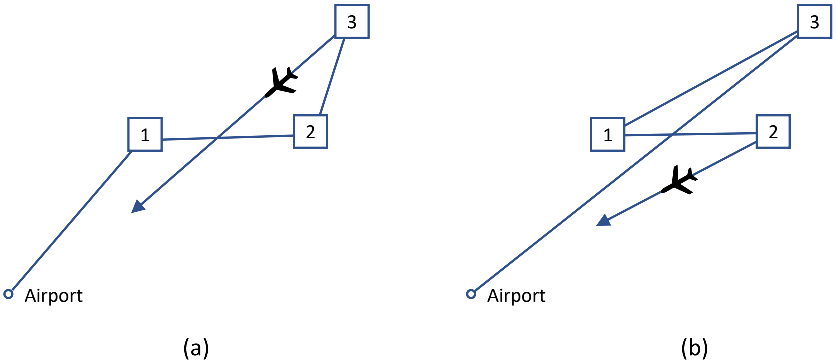


Figure 5.5: Route dependent on weight limits.

Feasibility considering operational characteristics

In addition to weight limits, ϕ_{kr} can indicates the feasibility according to operational characteristics between aircraft and runway types. For example, some locations may not allow the operation of some type of aircraft, caused by factors such as airstrip dimensions, type, resistance or even local temperature or airfield height. Thus, in our model, if some location cannot support the operation of determined type of aircraft, ϕ_{kr} assumes 0. In the Eq(63), l' is in L', a subgroup of locations L that not allow the operation of some aircraft k' in K', respectively a subgroup of K.

$$\sum_{r \in R} \lambda_{rl'} \times \phi_{k'r} \times x_{k'r} = 0 \qquad \forall\, k' \in K', l' \in L' \tag{63}$$

5.2.4 Summarizing the BIP Model

After previous considerations, we may rewrite our BIP model, summarized in Eq(64)-(66), as follows.

$$\text{Minimize} \qquad \sum_{k \in K} \sum_{r \in R} TT_{kr} \times x_{kr} \tag{64}$$

Subject to:

$$\sum_{r \in R} x_{kr} \leq 1 \qquad \forall\, k \in K \tag{65}$$

$$\sum_{r \in R} \lambda_{rl} \times \phi_{kr} \times x_{kr} = 1 \qquad \forall\, k \in K, l \in L \tag{66}$$

Where Eq(64) represents the objective function for minimizing the total time flown by the fleet in doing the rescue. Parameter TT_{kr} goes to a large number N for aircraft k that have their endurance surpassed in a route r, as indicated in Eq(52). Eq(65) limit each aircraft to one route. Eq(66) defines that each location l will be visited once, as expressed in Eq(53); theat the selected aircraft is not exceeding the initial take-off weight, as in Eq(54); also not exceeding the maximum landing weight, as in Eq(58), the maximum payload weight, as in Eq(55) and Eq(60), the maximum taking-off weight, as expressed by Eq(62), and that the aircraft can operate in all locations in the route selected, as in Eq(63). The following sequence of items summarizes the steps used to calculate the model's parameters and constraints.

(1) Define locations to visit, origin of flights and final destination.

(2) Determine distances between nodes, origin and final destination.

(3) Use permutation ($_nPi$) to determine a sequence of nodes to be visited; start with a minimum number of locations ($i_{min} = 1$) in a total number of nodes n.

(4) Define routes using the sequences found adding the origin and final destination.

(5) Organize routes and respective sequence of nodes in a spreadsheet.

(6) Use the distance between nodes (trip distance TD_{ij}) to find the total distance of each route TDR_r.

(7) Divide the total distance of each route by each aircraft cruise speed to find the total flight time TT_{kr}.

(8) Verify if at least one aircraft can fly at least one route by $TT_{kr} \div CS_k \leq E_k$; if yes add one location ($i = i + 1$) to visit and go to step 3, otherwise consider $i = i - 1$ as the maximum ($i_{max} = i - 1$).

(9) Organize TT_{kr} values by route in a separated spreadsheet from i_{min} to i_{max}.

(10) If total flying time exceeds aircraft endurance ($TT_{kr} \geq E_k$), respective TT_{kr} value goes to a large number.

(11) Organize routes with respective sequence of nodes from i_{min} to i_{max} in a separated spreadsheet.

(12) Build a matrix for λ_{rl} considering 1 if the location is in the route, 0 otherwise.

(13) Organize routes with respective sequence of nodes from i_{min} to i_{max} in a separated spreadsheet.

(14) Add respective trip distances between nodes TD_{ij}.

(15) Set $\phi_{kr} = 1$ for aircraft k.

(16) Verify if aircraft k can operate in location l, if NO then $\phi_{kr} = 0$.

(17) Verify the take-off weight for aircraft k; if $ITOW_{kij} \geq MTOW_k$ then $\phi_{kr} = 0$.

(18) In the first departure, verify the total demand weight do be delivered in route r for aircraft k; if $TDD_r \geq MPL_k$ then $\phi_{kr} = 0$.

(19) Multiply the distance between origin and next node TD_{ij} by the fuel consumption rate FC_k to determine the fuel weight burnt FB_{kij} by aircraft k in that trip.

(20) Subtract FB_{kij} from $ITOW_{kij}$ to find the land weight of aircraft k at location j; if $LW_{kj} \geq MLW_k$ then $\phi_{kr} = 0$.

(21) If aircraft is landing the final destination, STOP.

(22) Consider the difference between the weight to be delivered and received; if $\delta_j \geq MPL_k$ then $\phi_{kr} = 0$.

(23) Add δ_j to LW_{kj} to determine the take-off weight; If $TOW_{kij} \geq MTOW_k$ Then $\phi_{kr} = 0$; go to step 19.

These precalculations allow us to have, at the end, three spreadsheets (i.e. three Excel sheets) with TT_{kr} values, 0/1 values for λ_{rl} and 0/1 values for ϕ_{kr}. These tables are then introduced in a commercial solver to calculate the exact solution.

5.3 Numerical Examples and Results

In this section, we use two numerical examples to illustrate the use of the proposed BIP model. In a first instance, we illustrate the question about aircraft weight variations and the time flown comparing two aircraft and two routes only. The second instance uses eigth available aircraft and 35,715 possible routes with a maximum of four locations to be visited.

Comparing the weight variation of two aircraft in a same route

In some cases, the use of faster and more fuel economic aircraft are possible since a longer route is chosen. We consider the rescue of people in four locations in a remote region. The distances involved are in Table 1, where the SAR base is the location 0. The demand of each location, represented by the weight to be delivered and received, is in Table 5.2. We have two available aircraft and their characteristics are in Table 5.3. Aircraft 1 represents a jet and aircraft 2, a four-engines turboprop. The objective is to rescue all persons in the shorter possible time. We will compare only two routes to illustrate the logic of our model. We start considering the route with sequence (a) in Figure 5.6, represented by the sequence 0-1-4-2-3-0. This route gives us 3,958 NM of total distance that both aircraft could cover. There are no restrictions about the type of aircraft to land in considered locations.

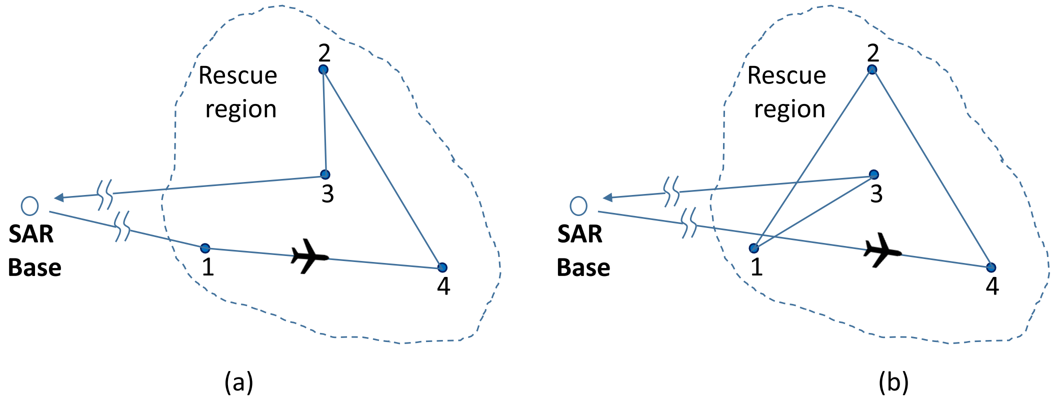


Figure 5.6: Comparing routes with locations' sequence (a) 0-1-4-2-3-0 and (b) 0-4-2-1-3-0.

Aircraft weight variations can be seen in Table 5.4. For example, aircraft 1 departs from the SAR base (location 0) with 70,000 kg of weight (its $MTOW_k$). During the 03:30 h flying in the

Table 5.1: Distances between SAR base and four locations.

Distance (NM)	0	1	2	3	4
0	0	1564	1663	1704	1858
1	1564	0	206	153	294
2	1663	206	0	132	264
3	1704	153	132	0	161
4	1858	294	264	161	0

Table 5.2: Transport demand at each location.

Location	1	2	3	4
PW_j (kg)	1060	1250	4,000	2,200
DW_j (kg)	260	300	0	600
δ_j (kg)	860	950	4,000	1,600

Table 5.3: Aircraft characteristics.

Aircraft	1	2
Speed (kt)	445	335
E_k (h)	09:30	12:00
FB_k (kg/NM)	4.0	7.4
MTOW (kg)	70,000	75,000
MLW (kg)	63,500	64,500
Fuel capacity (kg)	16,800	29,800
Range (NM)	4,200	4,020

trip between locations 0 and 1 it consumes 6,250 kg of fuel, giving a landing weight LW_{kj} of 63,750 kg. This aircraft could deliver 260 kg at location 1 and also receive 1060 kg of people, given an aircraft weight variation of 860 kg (δ_j). This variation would not surpass the especific aircraft maximum payload weight ($MPLk$). Adding (δ_j) to the previous LW_{kj} we would have 64,610 kg of take-off weight (TOW_{kj}) in that location, that would not exceed aircraft $MTOW_k$. However, as we also can see in Figure 5.7 (a) by the red line, the considered sequence of nodes is infeasible to aircraft 1 since in locations 1, 2 and 3 the MLW_k (of 63,500 kg) is surpassed. Once there are no weight issues for aircraft 2, the red line in (b) is not exceeded, it could do the rescue in 11:49 h of flight time, 11 minutes before its maximum endurance.

However, the speed of aircraft 1 is about 33% superior than aircraft 2. Thus, if we consider a different sequence of locations, we can verify that a shorter flight time is obtained even with larger total distance. In the sequence 0-4-2-1-3-0, as shown in Figure 5.8 (b), we reach 4,185 NM of total distance, superior to the previous sequence. This distance is excessive (infeasible) for aircraft

Table 5.4: Comparing the weight variation of aircaft 1 and 2 in the route 0-1-4-2-3-0.

	Aircraft 1				Aircraft 2			
Trip	Take-off weight (kg)	Accumulated time flown (h)	Fuel burnt (kg)	Landing weight (kg)	Take-off weight (kg)	Accumulated time flown (h)	Fuel burnt (kg)	Landing weight (kg)
0-1	70,000	3:30	6,250	63,750	75,000	4:40	11,590	63,409
1-4	64,610	4:10	1,176	63,434	64,269	5:32	2,180	62,089
4-2	65,035	4:46	1,055	63,979	63,689	6:20	1,955	61,733
2-3	64,925	5:03	525	64,399	62,678	6:43	974	61,704
3-0	68,399	8:53	6,809	61,590	65,704	11:48	12,626	53,077

Table 5.5: Comparing the weight variation of aircaft 1 and 2 in the route 0-4-2-1-3-0.

	Aircraft 1				Aircraft 2			
Trip	Take-off weight (kg)	Accumulated time flown (h)	Fuel burnt (kg)	Landing weight (kg)	Take-off weight (kg)	Accumulated time flown (h)	Fuel burnt (kg)	Landing weight (kg)
0-4	70,000	4:10	7,423	62,576	75,000	5:32	13,766	61,233
4-2	64,177	4:46	1,055	63,122	62,834	6:20	1,956	60,877
2-1	64,067	5:13	824	63,243	61,823	6:57	1,527	60,295
1-3	64,104	5:34	611	63,492	61,156	7:24	1,133	60,022
3-0	67,492	9:24	6,809	60,683	64,022	12:29	12,626	51,395

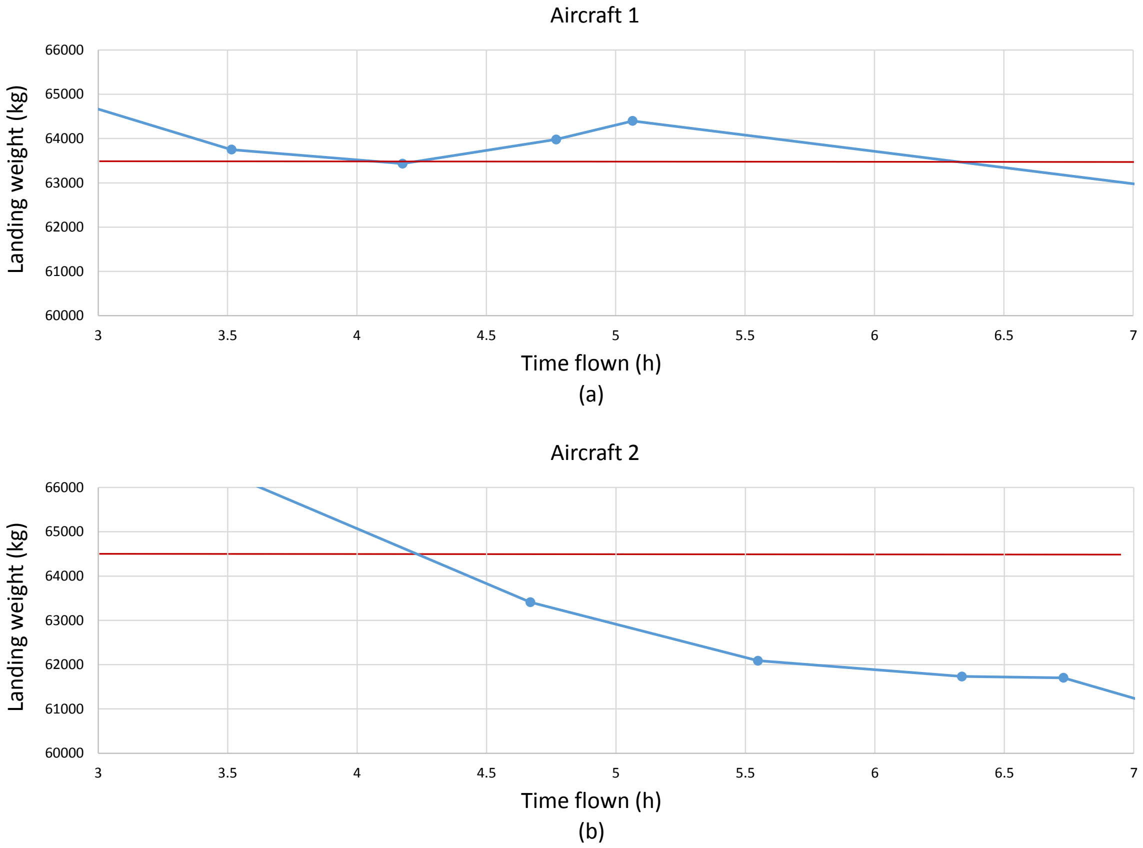


Figure 5.7: Weight variation of (a) aircaft 1 and (b) aircraft 2 in the route 0-1-4-2-3-0.

2 because it would request a TT_{kj} of 12:30 h and its endurance is only 12:00 h. For aircraft 1 there is no endurance problems since this route would require 09:24 h and its endurance is 09:30h. Verifying the weight variation during the mission, as in Table 5.5, there is also no weight issues for aircraft 1 that can do the rescue faster than previously calculated, delivering 1,160 kg of support and receiving 8,510 kg of people to be rescued. In summary, aircraft 1 should be preferred to do the rescue because it could do it in a shorter time than aircraft 2 in the first sequence.

This initial instance considered only two sequences of locations but we know that varied sequences give us different results, eventually better. Thus, we should consider all feasible routes to verify which one minimizes the total flight time, as our objective. The next instance explores such details to illustrate the use of the developed model.

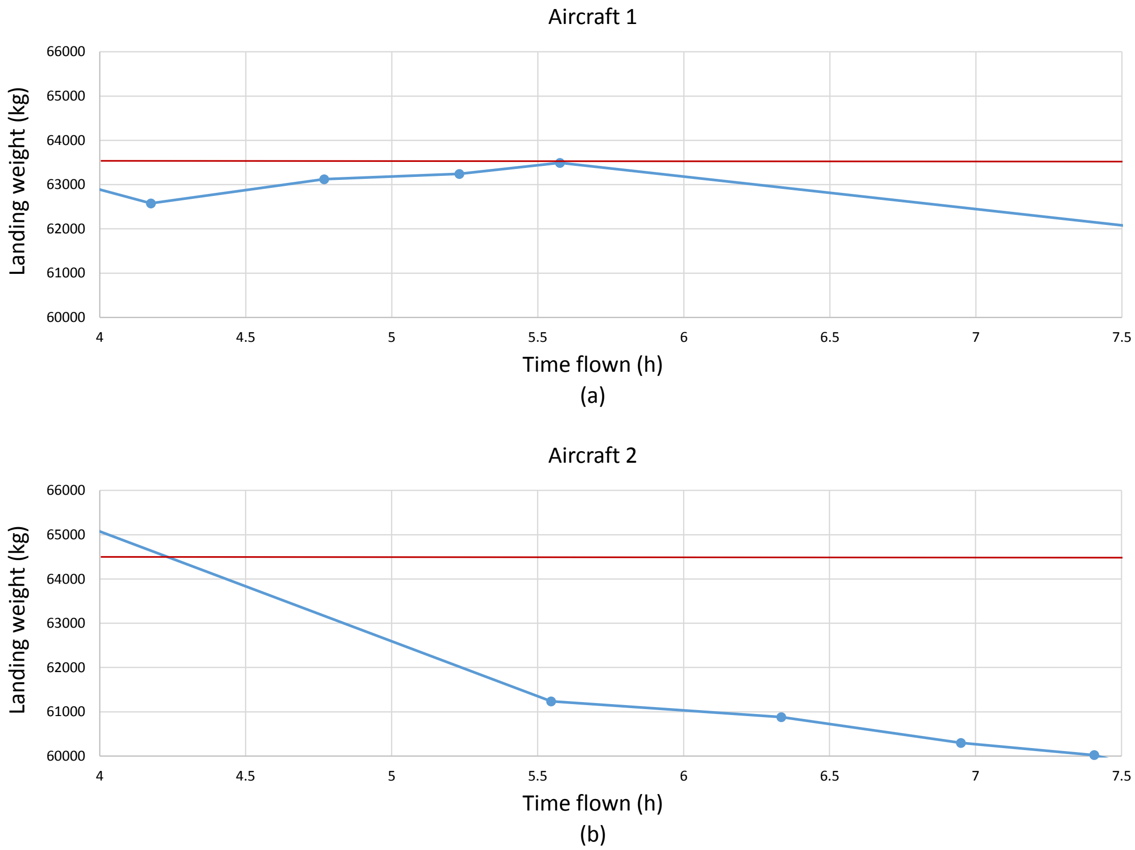


Figure 5.8: Aircraft weight variation in route 0-4-2-1-3-0.

Mass rescue operation planning

In a second instance, we consider a similar situation and use our model to solve a problem with a larger demand, considering eight available aircraft and 15 locations to visit. The distances involved are in Table 5.6. All routes are enumerated considering the node 0 as the SAR base, being the origin and final destination of all flights. All routes are enumerated using the procedure described in the previous section. It avoids that sub routes or closed circuits without the SAR base are generated by the solution. In this instance, the SAR officer needs to plan a mass rescue for transporting people and equipment to and from a zone affected by a calamity back to the SAR base. As shown by Figure 5.9, this region is about 1,600 NM far from the origin and composed by 15 different locations with conditions to operate fixed-wing aircraft, however, jets cannot land or depart in locations 11 and 14. The demand to be delivered and received at each location is represented by weight, as in Table 5.7.

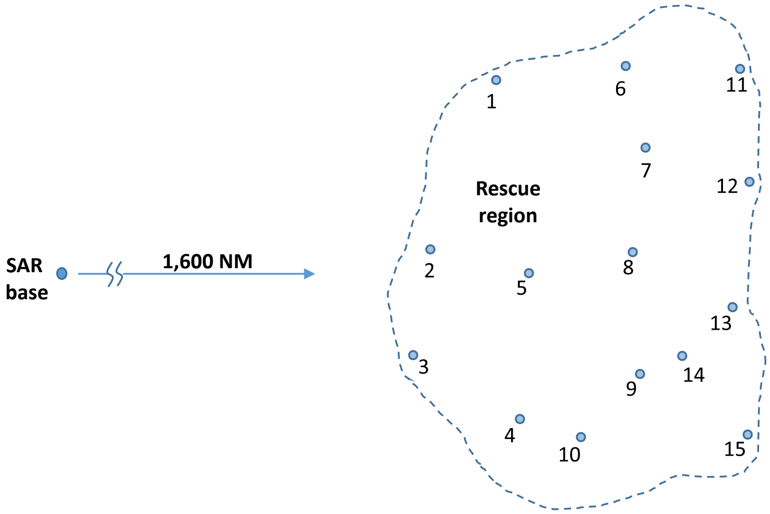


Figure 5.9: Locations to be visited in the second instance.

Refueling facilities in that zone are not available and arriving aircraft must have enough remaining fuel to fly back to the SAR base. Thus, the endurance is an important issue to aircraft as well as speed, since the operation must be done in the shortest time. In addition to speed and endurance, we need to consider aircraft transport capacities to attend the demand at each location. These demand and transport capacity are translated by weight, since in our case it is a main factor to consider for routing planning. To be able to do the rescue without refuelling, aircraft must depart with big amounts of internal fuel, that also represents weight. The take-off weight TOW_{kij} must respect the $MTOW_k$ of aircraft design. During the flight, this fuel weight decreases according to the fuel consumption rate of each aircraft and the distance travelled between the SAR base and the rescue locations, that give us the landing weight LW_{kj} at the destination j, that must be below its maximum landing weight MLW_k. At each destination is verified the weight variation between the weight delivered and received (δ_j), since it cannot exceed the maximum payload weight (MPL_k) nor the $MTOW_k$. To the LW_{kj} will be added the weight variation δ_j verifying if the result will respect again the $MTOW_k$. If any $MTOW_k$, MLW_k or MPL_k cannot be met, other route must be selected. In summary, our problem is about how to choose the best routes to visit all nodes in the shortest time, considering the transport demand to receive and deliver at each location, aircraft weight limits, type of aircraft and endurance, since there is no refuelling.

Table 5.6: Distances (NM) between 15 locations and SAR base.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	0	1500	1433	1437	1564	1547	1630	1613	1663	1704	1625	1760	1805	1771	1740	1858
1	1500	0	188	296	351	212	130	136	242	362	406	260	320	354	366	506
2	1433	188	0	111	206	117	277	210	231	292	275	376	385	340	318	453
3	1437	296	111	0	135	143	367	286	261	268	204	446	430	346	306	422
4	1564	351	206	135	0	140	376	285	206	153	71	416	369	251	196	294
5	1547	212	117	143	140	0	242	153	122	178	194	305	288	224	201	338
6	1547	130	277	367	376	242	0	92	201	332	414	132	208	286	320	448
7	1613	136	210	286	285	153	92	0	117	247	322	166	192	220	242	377
8	1663	242	231	261	206	122	201	117	0	132	225	211	170	117	125	264
9	1704	362	292	268	153	178	332	247	132	0	128	323	247	106	45	161
10	1625	406	275	204	71	194	414	322	225	128	0	434	370	234	172	240
11	1760	260	376	446	416	305	132	166	211	323	434	0	108	240	294	393
12	1805	320	385	430	369	288	208	192	170	247	370	108	0	149	210	290
13	1771	354	340	346	251	224	286	220	117	106	234	240	240	0	64	162
14	1740	366	318	306	196	201	320	242	125	45	172	294	294	64	0	141
15	1858	506	453	422	294	338	448	377	264	161	240	393	393	162	141	0

Table 5.7: Transport demand (tons) at 15 locations.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PW_j	3.40	6.00	5.00	0.96	1.65	0.73	0.67	0.95	4.50	2.40	1.80	1.20	4.50	2.40	1.60
DW_j	0.20	0.50	0.50	0.10	0.20	0.00	0.00	0.00	0.50	0.20	0.20	0.00	0.50	0.20	0.00
δ_j	3.20	5.50	4.50	0.86	1.45	0.73	0.67	0.95	4.00	2.20	1.60	1.20	4.00	2.20	1.60

We consider the nodes and distances in Table 5.6 and use permutation to build a list of possible routes. The order of nodes to be visited is important, especially because the weight computation, thus, reverse routes are not discarded, and we consider 37,715 routes. We organize all data in Excel sheets and do all precalculations using Visual Basic (VBA) for Excel. Starting with routes with only one location to rescue people, we calculate total distances and consider one additional location. We stop when there is no available aircraft that can fly routes with a certain number of nodes. In this instance, four is the maximum number of locations to be visited considered in a route and the SAR base is also the initial and final destination of rescue flights. Total distances are used to generate a Excel sheet with the total flight time TT_{kr} by considering aircraft speeds. TT_{kr} also identifies routes that exceed an aircraft endurance by assuming a large number (considered 10,000 in our study), avoiding the solution to choose that routes for respective aircraft. Knowing the nodes that are in each route, we generate a table for λ_{rl}, an indicator 0/1 that assumes 1 when the location l is used in that route r and 0 otherwise. For generating a table for ϕ_{kr} we consider the list of all possible routes, nodes and respective sequence to be visited, the distances in Table 5.6 and aircraft characteristics in Table 5.8. Aircraft 1 to 4 represent jets while 5 to 8, four-engine turboprop aircraft. Thus, in our instance, the subgroup of aircraft 1 to 4 ($k' \in K'$) cannot operate in locations 11 and 14, a subgroup l' of locations ($l' \in L'$). ϕ_{kr} will assume 1 and only if $MTOW_k$, MLW_k and $MPLW_k$ are exceed in any part of the route, ϕ_{kr} will be 0. ϕ_{kr} also assumes 0 for jets when routes use locations 11 and 14.

Table 5.8: Aircraft characteristics.

Aircraft	Type	1	2	3	4	5	6	7	8
Speed (kt)	Jet	440	440	445	445	330	330	335	335
E_k (h)	Jet	8.5	8.5	11.5	11.5	12	12	12	12
FB_k (kg/NM)	Jet	5.2	5.2	4.0	4.0	6.9	6.9	7.4	7.4
MPL_k (t)	Jet	10	10	12	12	14	14	15	15
$MTOW_k$ (t)	Turboprop	63	63	70	70	52.5	52.5	73	73
MLW_k (t)	Turboprop	57	57	63.5	63.5	47	47	65	65
Fuel Cap. (t)	Turboprop	19.43	19.43	20.71	20.71	27.22	27.22	29.78	29.78
Range (NM)	Turboprop	3,740	3,740	5,117	5,117	3,960	3,960	4,020	4,020

We assume that all aircraft depart from the SAR base in the $MTOW_k$, because refueling is not allowed and some support is may be delivered in specific locations. We subtract the fuel weight consumed during the flight to the first node and verify if the MLW_kconstraint is met. Later, if the addition of the demand variation δ_j does not exceed MPL_k and $MTOW_k$, we repeat these calculations up to reach the SAR base. We generate three Excel sheets with TT_{kr}, λ_{rl} and ϕ_{kr} values that are introduced in a commercial solver to solve the model, requesting insignificant processing time. Results about aircraft, routes and times are summarized in Table 5.9 and represented in Figure 5.10. For minimizing TT_{kr} the model chooses aircraft 2, 4, 7, and 8. Aircraft 2 and 4 are jets and they are going to locations 11 and 14, as expected. In terms of people to be transported, assuming 100 kg for each person, we could rescue a total of 378 persons in this operation.

Table 5.9: Time flown, routes, nodes visited, and total demand transported by aircraft.

Aircraft	Type	TT_{kr}	Route	Sequence of nodes	Demand received (t)	Demand delivered (t)
2	Jet	08:30	27966	0-12-7-5-3-0	8.52	0.70
4	Jet	09:24	34666	0-15-8-4-9-0	8.01	0.60
7	Turboprop	11:52	26800	0-11-14-13-1-0	12.10	1.10
8	Turboprop	11:12	1930	0-10-6-2-0	9.13	0.70

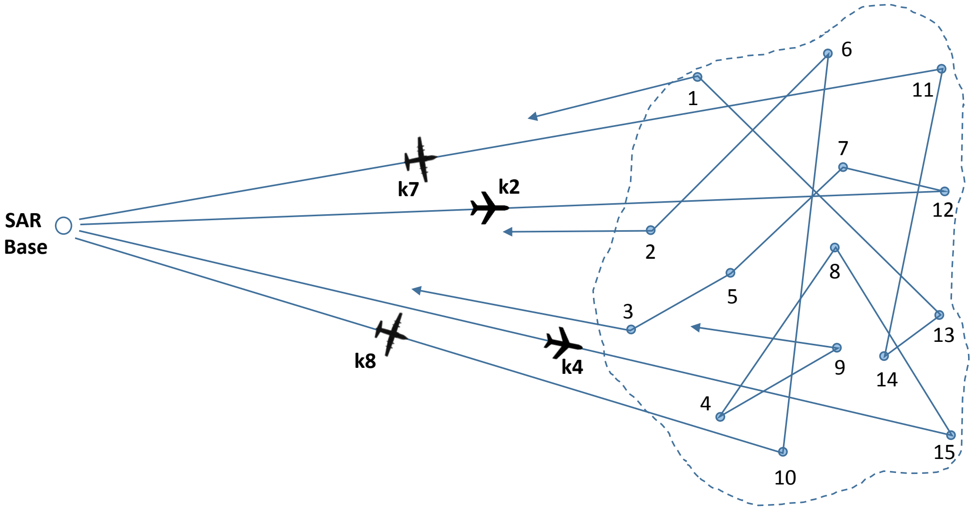


Figure 5.10: Routes and locations visited by the rescuing fleet.

5.3.1 Discussion

Permutation was used to generate all possible routes considering the SAR base as origin and final destination of flights. This procedure prevents the possible formation of sub routes (closed circuits without the SAR base) when solving the model. Knowing the nodes that are in each route and the distances associated we first calculate total distances and flight times TT_{kr}, verifying routes that are infeasible by exceeding aircraft endurance. We then calculate the aircraft weight variation according to the order of locations visited. The use of spreadsheets to calculate the parameters TT_{kr}, λ_{ri} and ϕ_{kr} seems to simplify the computational effort when using commercial solvers since most of their calculations are done before and λ_{ri} and ϕ_{kr} sheets are basically composed by values 0/1. Details about calculations, including VBA codes for Excel may be found in the Appendix B.

Both instances showed the importance to consider the aircraft weight dynamics during a flight, especially when refueling is not possible. The first instance illustrated that, depending on distances involved and aircraft characteristics such as weight limits, speed and fuel consumption, in some cases, longer routes may be flown faster than shorter routes. The second instance was more complex by using a bigger amount of locations to be visited and available aircraft and all features of the developed model, including payload weight limits and restricted locations for some types of aircraft. In both cases, results showed the validity of the model.

Considering same conditions as in the second instance, we could compare two different options of existing aircraft. Suppose (1) that only turboprop aircraft were available. Respective results show that all nodes could be visited and all demand could be delivered and received, as in the previous situation. However, the total flying time would be 43:22 h, or 02:24 h longer than the previous example that considered a mix of jets and turboprops. However, when considering only jets (2), that would request an even shorter total time, the instance is infeasible, even considering locations 11 and 14 without restrictions. It shows that in similar cases, as considered in our instance, a combination of different types of aircraft may produce better results, given different demands, distances and aircraft characteristics.

Some problems considering air cargo transportation may be seen in a similar way as we discussed. The most efficient way to supply or resupply some isolated locations in forest or arid zones is by air and refueling may be difficult or impossible in that locations. In the rescue case, the objective is to minimize the flight time; in a cargo transportation case, however, it could be the maximization of transported weight or the profit generated. Also, in the cargo case, some possibilities to refuel during the flights are expected. For the rescue, the assumption of no refueling is more realistic since in such occasions, highways may be used as improvised airstrips where aircraft fuel is not expected; the ground operation is faster (no waiting time for refueling); as well as the refueling infrastructure in the problematic area that may be compromised (i.e. contaminated or sabotaged). Also, there is no monetary profit to be considered in the rescue case.

For simplicity, we did not consider the use of aircraft coordinator (ACO) in supporting the fleet in the BIP model, but some multi aircraft operations could request it. In this case, considering the results of our second instance, we see that we did not used all available aircraft, thus, the one remaining could be the ACO for the rescue fleet. For example, while the fleet is doing the rescue, this aircraft could receive and retransmit position, landing and departing messages, as well as weather conditions in the visited locations, contributing to improve the safety. As well as refueling, the local communication network may also be compromised or inexistent. In order to do so, the ACO should remain orbiting in the area from the first land to last rescue departure, in an altitude that could allow radio horizon in all locations simultaneously. In our instance, the greater distance considered between two locations (excluding the SAR base) was 506 NM. Using the radio horizon formula as expressed in 2.4.2, $d_{NM} = 1.23 \times \sqrt{h_{ft}}$ where d is given in nautical miles and the antenna height h is in feet (Skolnik et al., 2001), and considering the aircraft orbiting in the middle of the rescue area, an altitude about 41,000 ft (some commercial jets can fly at such altitudes) should be necessary to cover the most distant locations simultaneously (the rest of the area could be covered in this way), as depicted in Figure 5.11. To incorporate an ACO in our model, additional parameters and constraints related to ceiling, navigation, coordination and communications capacities should be necessary. In summary, supposing that an ACO should be required anyway, one solution could be to first evaluate and choose the best ACO in the available aircraft and introduce later the remaining existing units in the actual developed model to choose the best fleet composition.

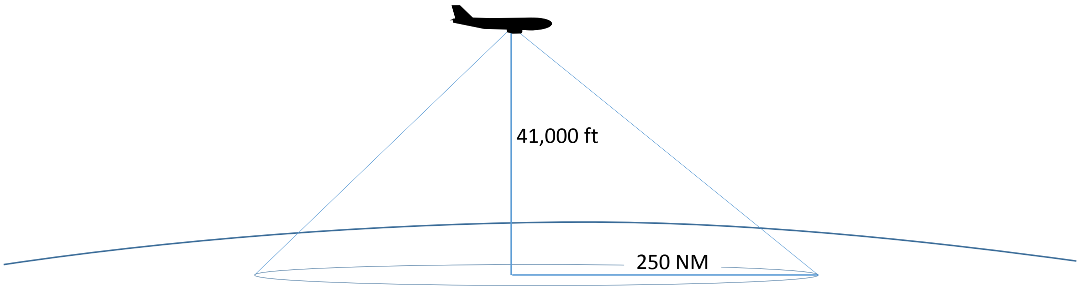


Figure 5.11: Approximated radio horizon for an ACO in the second instance.

5.4 Conclusions

Mass rescue operations are used when a large number of persons in distress need assistance and SAR capacities are usually inadequate. When tragedies occur in remote regions, additional difficulties arise to the success of missions in saving people in distress. In this chapter, planning aerial long-range mass rescue missions inland was considered as an aircraft routing problem with pick-up and delivering, weight and endurance limits. We described how to generate possible routes and how to verify respective feasibility for a fleet of heterogeneous aircraft. Main issues are related to aircraft endurance and weight limits to load, take-off and land. Thus, we presented and discussed aircraft weight dynamics varying with distances, fuel consumption rate and the weight of the support to be delivered and the weight of the people to be rescued, respecting limits for loading, taking-off and landing. These questions were modelled as a BIP to solve the routing problem. The solution method includes the use of spreadsheets to calculate feasibility parameters and posterior introduction in commercial solvers. Results of two numerical examples showed the validity of the model in choosing the best routes for long-range aircraft in performing inland rescuing when a large number of people, urgency of rescue and vehicles of different performances are involved. In future research, we plan to introduce the ACO in the model and to develop an efficient and effective solution method for solving larger size SAR problems with short computing time.

Chapter 6

Conclusions and Future Research

6.1 Conclusions

Search and rescue (SAR) operations in emergency situations require prompt actions to save lives while such operations require careful planning for effective and efficient execution. In addition, valuable information from various sources such as satellite and surface communications will be utilized which adds to the level of difficulties in determining an optimized SAR plan within narrow time window. Searching and rescuing operations are still needed even in the present days where air and maritime transportation can count with a well-structured system of emergency communications based on terrestrial and space stations, able to receive emergency calls from any part of the globe. Thus, as soon as one vehicle such as an aircraft or a ship reports some distress situation, search and rescue procedures are started to follow and help the vehicle, being important actions for saving time. However, in some situations the communication system may not be accessible or available, and the vehicle cannot report its position and conditions. In these cases, additional means such as distress beacons are very important to transmit electronic signals from the crash site, if it the accident occurs. These emissions may be detected by specialized satellites as well as equipment on board of aerial, maritime or ground units, locating the vehicle and people in question and abbreviating the rescuing time. These beacons, however, they may not be present in the vehicle or, even existing, they may not work properly. In consequence, without a precise location of the vehicle in distress, searching missions are started. Even with the support of remote sensing by aerial and spatial platforms, fixed-wing aircraft are the vehicles most used when large areas must be covered in a short time. As soon as a target is located, rescue missions start. Helicopters are the vehicles more adapted to rescue operations given their flying characteristics, especially in the sea, where the combination of helicopters and ships creates a good synergy for operating in such environment. Some especial rescue situations, however, request the transport of a large quantity of people that can be done also by helicopters, but the distances involved must be relatively short. For long distances, fixed-wing aircraft are used, but questions about available airfields, refueling and coordination must be carefully evaluated. Considering these issues, the main purpose of this thesis was to develop new mathematical models to solve multi-SAR vehicles planning problems based on real situations when searching, rescue and mass rescue operations are needed, contributing to scientific literature as well as supporting the decision-making in SAR operations planning and execution, as presented in chapters 3 to 5.

In chapter 3, different types of long-range aircraft were used together in performing searching missions in high seas. They are very important vehicles for SAR operations, given their capability to cover large areas in short time. The SAR aerial fleet, however, is usually formed by aircraft of different types, characteristics, costs, etc. to participate in a specific operation, returning to respective origin when the activities are finished. While the combination of different aircraft performances creates important operational advantages, on the other hand, it poses challenges in achieving the optimal level of search effort and efficiency. In this part, a mathematical programming model was proposed for SAR operation planning considering a heterogeneous fleet of airplanes to be dispatched from available airports and allocated in specific searching areas. The model and respective four variants were developed according to different priorities related to area, time and costs and solved for practical applications. Numerical examples tested the developments and compared results showed that (i) the first formulation to maximize the area covered by the fleet calculated the maximum value for area covered, that is interesting in circumstances such as having an area relatively extensive to the number of available aircraft; (ii) the second and the third formulations that minimize the flight time calculated lower values for total time flown, important in emergency situations, and, between them, the bi-objective found a lower total cost and a better relation total area covered by aircraft; and

(iii) the fourth and the fifth formulations to minimize the costs calculated lowest total costs of all variations, that is interesting in situations such as planning exercises, and the respective bi-objective utilized less means, as indicated by various indexes. In summary, all formulations behaved as expected and the two bi-objective formulations tended to be more efficient for some practical uses. For example, in our instance, the first formulation tends to use all possible means in maximizing the area covered, thus, when compared with the third that maximizes the difference between the area covered and the searching time, we see that P3 covers the minimum area as requested and saves 135h of flying time. The first formulation covers the minimum area also, but it tends to exceed it by the use of all possible aircraft in the search. The other bi-objective formulation is P5 that considers maximizing the area covered while minimizing costs. Again, if compared to the first one, P5 saves costs of about US$1.2 million, being interesting for planning exercises. The instances in the example problem considered in this chapter cover a large area which was partitioned to 9 subareas. The developed model can be applied to solving problems arising from different SAR situations. If additional information is available or due to other considerations, the SAR areas can be partitioned to different number of subareas of various sizes and locations.

In chapter 4 we discussed that the importance of saving lives is globally recognized, as well the need to render aeronautical and maritime search and rescue (SAR) services to persons in distress. The rescue method and facilities to be used are chosen once people or objects have been located, although, occasionally, the type and number of targets detected by searching missions may not be precisely described. In high seas, different types of air and maritime vehicles perform rescue operations together. This combination produces important operational advantages while, on the other hand, poses challenges for planning their use. In this Chapter, we analyzed the dynamics of rescue operations due to air or maritime emergencies since research in modeling SAR planning problems considering multiple practical aspects is limited in the literature. The model considered important issues for rescue planning as they can occur in real operations in high seas, such as lack of support points, differences in vehicles performances and uncertain information from searching flights. Differently from previous traveling salesman problems developed in the literature considering drones and trucks, we considered the cooperation between helicopters and ships where a helicopter could depart, intercept and land on a ship in movement in any point of its route, even on a different ship from previous depart. In our problem we considered re-planning at each location visited because when the number of survivors is updated, the situation is re-evaluated. When a helicopter did a rescue but still had capacity (i.e. endurance and internal space) to go to an additional location, it could be done. However, we also considered survivors' conditions. If the helicopter had enough capacity and rescued survivors did not need immediate medical assistance, the helicopter could go to an additional location to rescue more persons. Otherwise, the helicopter should go to the planned destination. The goal in our problem was to produce a plan to be on board of all units, containing all possibilities for helicopters' re-routing according to the updated information at each location visited and the conditions to be followed to return to a ship (i.e. time and bearing from a specific place), especially in the event of loss of communications, navigation or radar systems. These factors were considered in developing the mathematical model to determine the optimal rescue plans. Thus, a vehicle routing problem was proposed considering heterogeneous fleet of helicopters and ships, displacements during the rescue operation and probabilities to find survivors at each location visited. A mathematical programming model was proposed aiming optimal routing decisions for SAR rescue planning. Numerical examples illustrated the considered problem and results of the developed model show (i) the validity of the model and parameters calculations, (ii) the best choice of routes for rescue planning considering urgency of actions, vehicles of different performances, respective displacements, as well as uncertainty of number of survivors, and (iii) the prompt support of our model in determining alternative routes, times and courses for updating the rescue plan according to its execution.

In chapter 5, planning aerial long-range rescuing missions inland was considered as an aircraft VRP with pick-up and delivering, weight and endurance limits. We described how to generate possible routes by using permutation and considering the SAR base as origin and final destination of flights. This procedure prevents the possible formation of sub routes (closed circuits without the SAR base) when solving the model. As we know the nodes that are in each route and the distances associated, we first calculate total distances and flight times TT_{kr}, verifying routes that are infeasible by exceeding aircraft endurance. We then calculated the aircraft weight variation according to the order of locations visited. The use of spreadsheets to calculate the parameters TT_{kr}, λ_{ri} and ϕ_{kr} seemed to simplify the computational effort when using commercial solvers. Both presented instances showed the importance to consider the aircraft weight dynamics during a flight, especially when refueling is not possible. The first and smaller instance illustrated that, depending on distances involved and aircraft characteristics such as weight limits, speed and fuel consumption, in some cases, longer routes may be flown faster than shorter routes. The second instance was more complex by using a bigger amount of locations to be visited and available aircraft and all features of the developed model, including payload weight limits, and restricted locations for some type of aircraft. In both cases, results showed the validity of the model. When considering same conditions as in the second instance, we could compare two different options of existing aircraft. Considering that only turboprop aircraft were available, respective results showed that all nodes could be visited and all demand could be delivered and received, as in the previous situation. However, the total flying time would be 43:22 h, or 02:24 h longer than the example that considered a mix of jets and turboprops. When considering only jets, that would request even a shorter total time, however, the instance is infeasible, even considering locations 11 and 14 without restrictions. In our case, a combination of different types of aircraft produced better results, given different demands, distances and aircraft characteristics. The assumption of no refueling in a mass rescue operation is realistic since in such occasions the refueling infrastructure in the problematic area may be compromised as well as the no existence in improvised airstrips in highways. Also, without refueling, the ground operation is faster (shorter ground time). For simplicity, we did not consider the use of aircraft coordinator (ACO) in supporting the multi-aircraft operation in the BIP model but some operations could request it. This point is indicated to be treated in future research.

6.2 Future Research

This thesis contributed to add scientific support for planning efficient search and rescue operations. In future research, we plan to extend some presented models to consider more complex problems especially related to optimal composition, dispatching and routing a heterogeneous fleet of vehicles to perform SAR operations, for example:

- the model developed for tactical aerial search and rescue operations planning can be extended to optimize multi-missions planning, such as SAR, ASW, maritime patrol and electronic surveillance;

- the model developed for the search and rescue planning problem for emergencies in high seas may be integrated with some geographic information system (GIS) to facilitate position calculations needed to determine the time flown and intercepting bearings to the helicopters fleet. In addition, the naval fleet could be considered able to perform rescue, since the presented model considered ships only for transporting helicopters; and
- the aerial mass rescue operations planning model can be extended to consider the aircraft coordinator and multi-period operations.

Respective efficient solution methods need to be developed, however, given the urgent nature of SAR operations, it is important that both modelling and solution methods aim short computing time.

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Appendix A

Calculations Support for Capter 4

Given the data about total flying time according to each helicopter and ships' routes, the following VBA code for Excel build a table for FT_{rhsd}, substituting respective values with a big number when the flight time exceeds helicopter's endurance.

```
Private Sub Command Button1-Click()
' excessive flight time goes to a big number (1000)
' helicopter 1 endurance: 02:15 h
' helicopter 2 endurance: 02:00 h
Dim r As Long
Dim c As Long
For r = 4 To 117
For c = 2 To 7
If Cells(r, c).Value > 2.25 Then
Cells(r, c).Value = 1000
End If
Next c
Next r
c = 0
r = 0
```

```
For r = 4 To 117
For c = 8 To 13
If Cells(r, c).Value > 2 Then
Cells(r, c).Value = 1000
End If
Next c
Next r
End Sub
```

Given a list of routes and nodes visited (i.e. 1, 2, 3, 12, 13, 21, etc.), the following VBA code for Excel generates a table 0/1 for λ_{ri}, meaning if node i is present in respective route r.

```
Private Sub CommandButton1-Click()
’Substitute by 0/1 according if node in is route
Dim r As Long ’ rows
Application.CutCopyMode = False
For r = 2 To 115
If Cells(r, 10).Value = 1 Then
Cells(r, 2).Value = 1
End If
If Cells(r, 10).Value = 2 Then
Cells(r, 3).Value = 1
End If
If Cells(r, 10).Value = 3 Then
Cells(r, 4).Value = 1
End If
If Cells(r, 10).Value = 12 Then
Cells(r, 2).Value = 1
End If
```

```
If Cells(r, 10).Value = 12 Then

Cells(r, 3).Value = 1

End If

If Cells(r, 10).Value = 13 Then

Cells(r, 2).Value = 1

End If

If Cells(r, 10).Value = 13 Then

Cells(r, 4).Value = 1

End If

If Cells(r, 10).Value = 21 Then

Cells(r, 2).Value = 1

End If

If Cells(r, 10).Value = 21 Then

Cells(r, 3).Value = 1

End If

If Cells(r, 10).Value = 23 Then

Cells(r, 3).Value = 1

End If

If Cells(r, 10).Value = 23 Then

Cells(r, 4).Value = 1

End If

If Cells(r, 10).Value = 31 Then

Cells(r, 2).Value = 1

End If

If Cells(r, 10).Value = 31 Then

Cells(r, 4).Value = 1

End If

If Cells(r, 10).Value = 123 Then

Cells(r, 3).Value = 1
```

```
End If
If Cells(r, 10).Value ≥ 123 Then
Cells(r, 2).Value = 1
End If
If Cells(r, 10).Value ≥ 123 Then
Cells(r, 3).Value = 1
End If
If Cells(r, 10).Value ≥ 123 Then
Cells(r, 4).Value = 1
End If
Next r
End Sub
```

Figure A.1 shows the data organization for calculating interception time for helicopters 1 and 2, from the last node i_1 only, considering routes and capacities for ships 1 and 2. Similar calculations must be done for different last nodes. Figure A.2 shows the data organization in a Excel sheet for calculating distances, angles and time.

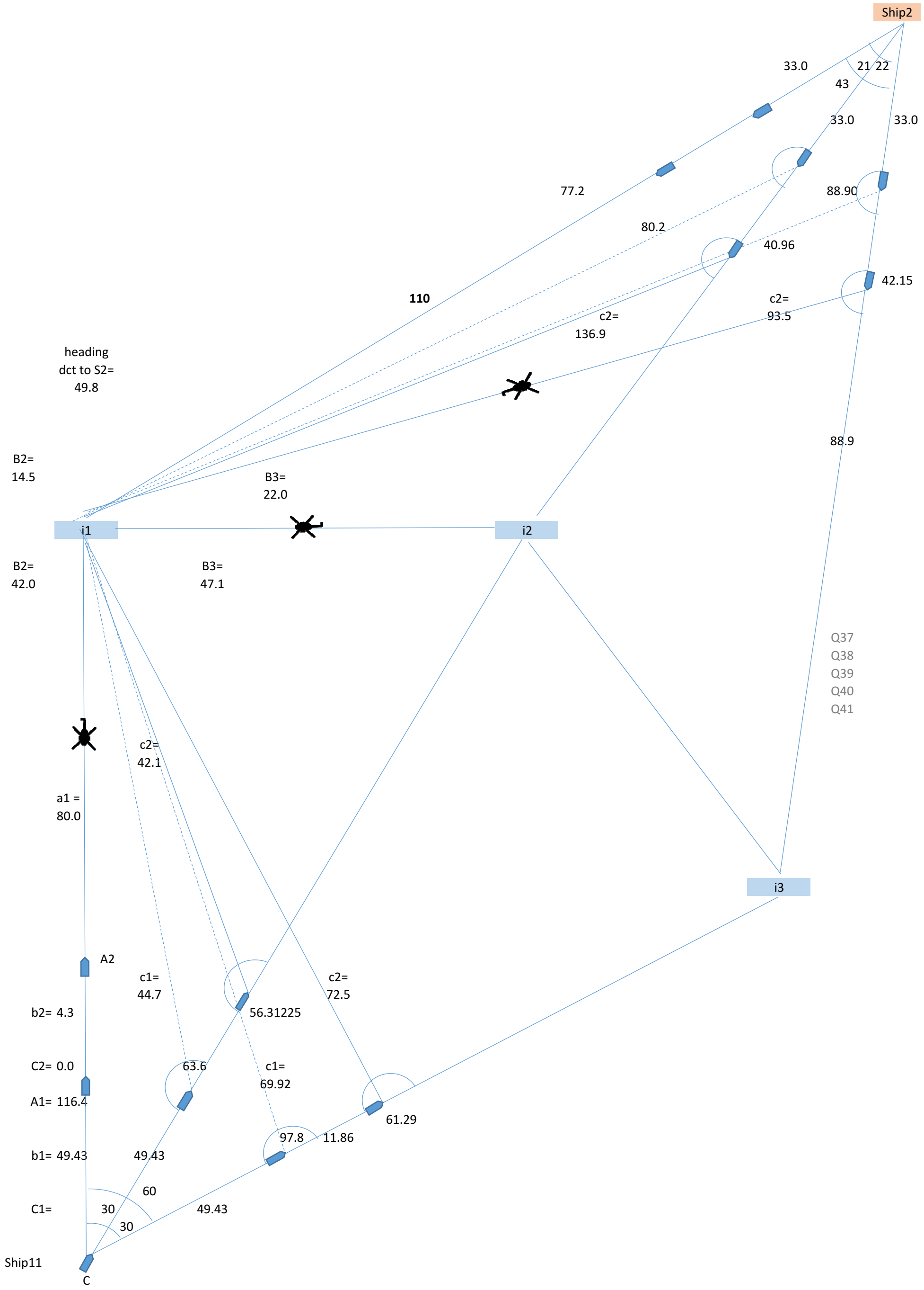
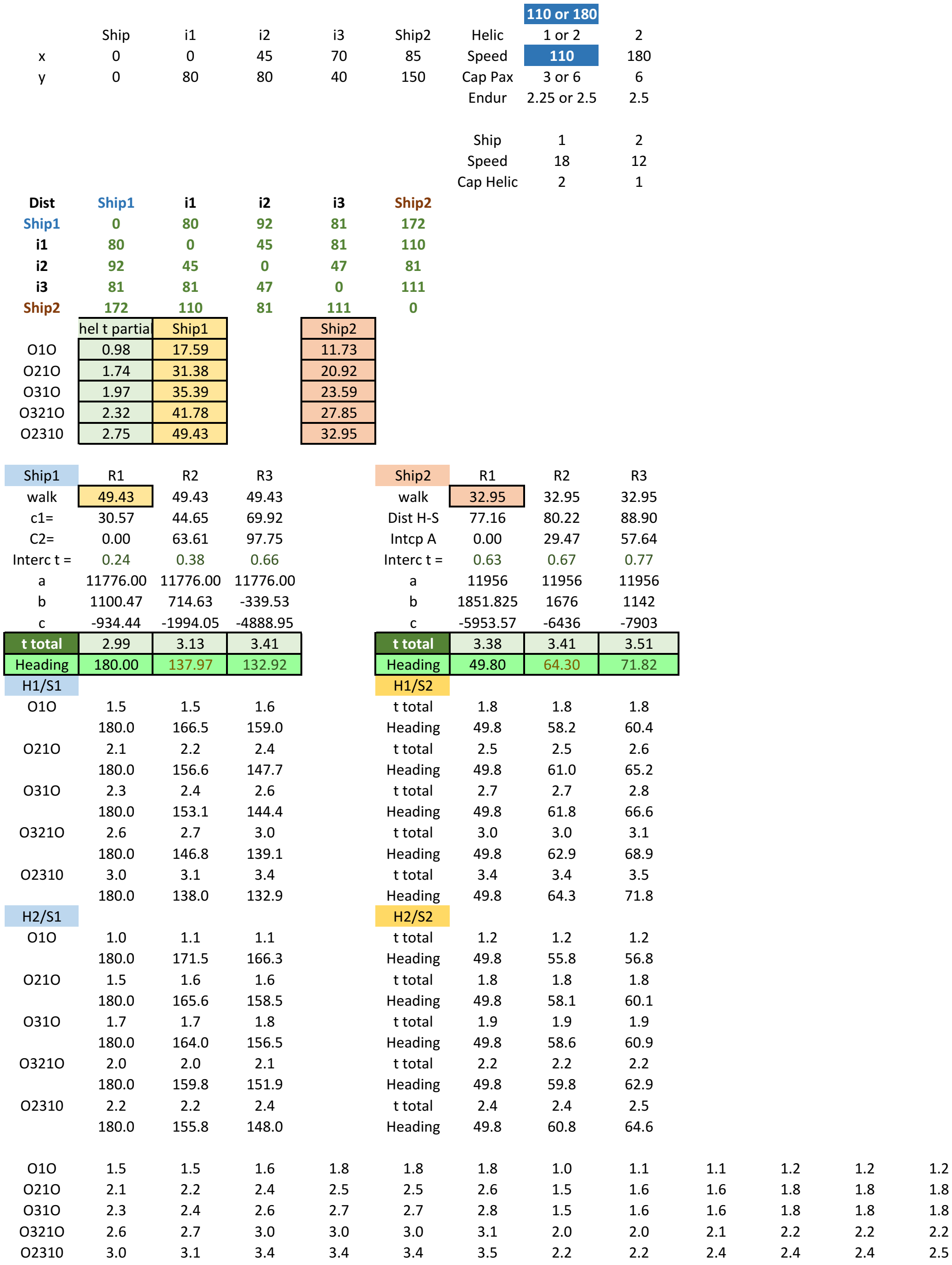


Figure A.1: Interception point calculations considering distances, angles and time.



							110 or 180	
	Ship	i1	i2	i3	Ship2	Helic	1 or 2	2
x	0	0	45	70	85	Speed	110	180
y	0	80	80	40	150	Cap Pax	3 or 6	6
						Endur	2.25 or 2.5	2.5
						Ship	1	2
						Speed	18	12
						Cap Helic	2	1

Dist	Ship1	i1	i2	i3	Ship2
Ship1	0	80	92	81	172
i1	80	0	45	81	110
i2	92	45	0	47	81
i3	81	81	47	0	111
Ship2	172	110	81	111	0

	hel t partia	Ship1		Ship2
O1O	0.98	17.59		11.73
O21O	1.74	31.38		20.92
O31O	1.97	35.39		23.59
O321O	2.32	41.78		27.85
O231O	2.75	49.43		32.95

Ship1	R1	R2	R3
walk	49.43	49.43	49.43
c1=	30.57	44.65	69.92
C2=	0.00	63.61	97.75
Interc t =	0.24	0.38	0.66
a	11776.00	11776.00	11776.00
b	1100.47	714.63	-339.53
c	-934.44	-1994.05	-4888.95
t total	2.99	3.13	3.41
Heading	180.00	137.97	132.92
H1/S1			
O1O	1.5	1.5	1.6
	180.0	166.5	159.0
O21O	2.1	2.2	2.4
	180.0	156.6	147.7
O31O	2.3	2.4	2.6
	180.0	153.1	144.4
O321O	2.6	2.7	3.0
	180.0	146.8	139.1
O231O	3.0	3.1	3.4
	180.0	138.0	132.9
H2/S1			
O1O	1.0	1.1	1.1
	180.0	171.5	166.3
O21O	1.5	1.6	1.6
	180.0	165.6	158.5
O31O	1.7	1.7	1.8
	180.0	164.0	156.5
O321O	2.0	2.0	2.1
	180.0	159.8	151.9
O231O	2.2	2.2	2.4
	180.0	155.8	148.0

Ship2	R1	R2	R3
walk	32.95	32.95	32.95
Dist H-S	77.16	80.22	88.90
Intcp A	0.00	29.47	57.64
Interc t =	0.63	0.67	0.77
a	11956	11956	11956
b	1851.825	1676	1142
c	-5953.57	-6436	-7903
t total	3.38	3.41	3.51
Heading	49.80	64.30	71.82
H1/S2			
t total	1.8	1.8	1.8
Heading	49.8	58.2	60.4
t total	2.5	2.5	2.6
Heading	49.8	61.0	65.2
t total	2.7	2.7	2.8
Heading	49.8	61.8	66.6
t total	3.0	3.0	3.1
Heading	49.8	62.9	68.9
t total	3.4	3.4	3.5
Heading	49.8	64.3	71.8
H2/S2			
t total	1.2	1.2	1.2
Heading	49.8	55.8	56.8
t total	1.8	1.8	1.8
Heading	49.8	58.1	60.1
t total	1.9	1.9	1.9
Heading	49.8	58.6	60.9
t total	2.2	2.2	2.2
Heading	49.8	59.8	62.9
t total	2.4	2.4	2.5
Heading	49.8	60.8	64.6

O1O	1.5	1.5	1.6	1.8	1.8	1.8	1.0	1.1	1.1	1.2	1.2	1.2
O21O	2.1	2.2	2.4	2.5	2.5	2.6	1.5	1.6	1.6	1.8	1.8	1.8
O31O	2.3	2.4	2.6	2.7	2.7	2.8	1.5	1.6	1.6	1.8	1.8	1.8
O321O	2.6	2.7	3.0	3.0	3.0	3.1	2.0	2.0	2.1	2.2	2.2	2.2
O231O	3.0	3.1	3.4	3.4	3.4	3.5	2.2	2.2	2.4	2.4	2.4	2.5

Figure A.2: Data organization in a Excel sheet for calculating intercept point.

Appendix B

Calculations Support for Capter 5

In a first step, given a list of routes, sequence of nodes and respective distance between them, the following VBA code for Excel shows how to read and put the weight variation beside respective trip. In this code is considered only three nodes (01230, 01240, 01250, etc.). The initial weight is known.

```
Private Sub CommandButton2-Click()
’put delta beside each trip
Dim i As Long
For i = 3 To 13651 ’step 4
If Cells(i + 1, 3).Value = 1 Then
Cells(i, 8).Value = Cells(2, 16).Value
End If
If Cells(i + 1, 3).Value = 2 Then
Cells(i, 8).Value = Cells(3, 16).Value
End If
If Cells(i + 1, 3).Value = 3 Then
Cells(i, 8).Value = Cells(4, 16).Value
End If
If Cells(i + 1, 3).Value = 4 Then
Cells(i, 8).Value = Cells(5, 16).Value
```

```
End If
If Cells(i + 1, 3).Value = 5 Then Cells(i, 8).Value = Cells(6, 16).Value End If
If Cells(i + 1, 3).Value = 6 Then
Cells(i, 8).Value = Cells(7, 16).Value
End If
If Cells(i + 1, 3).Value = 7 Then
Cells(i, 8).Value = Cells(8, 16).Value
End If
If Cells(i + 1, 3).Value = 8 Then
Cells(i, 8).Value = Cells(9, 16).Value
End If
If Cells(i + 1, 3).Value = 9 Then
Cells(i, 8).Value = Cells(10, 16).Value
End If
If Cells(i + 1, 3).Value = 10 Then
Cells(i, 8).Value = Cells(11, 16).Value
End If
If Cells(i + 1, 3).Value = 11 Then
Cells(i, 8).Value = Cells(12, 16).Value
End If
If Cells(i + 1, 3).Value = 12 Then
Cells(i, 8).Value = Cells(13, 16).Value
End If
If Cells(i + 1, 3).Value = 13 Then
Cells(i, 8).Value = Cells(14, 16).Value
End If
If Cells(i + 1, 3).Value = 14 Then
Cells(i, 8).Value = Cells(15, 16).Value
End If
```

```
If Cells(i + 1, 3).Value = 15 Then
Cells(i, 8).Value = Cells(16, 16).Value
End If
Next i
End Sub
```

In a second step, given the list of routes with the nodes, distances, and respective weight variation, the following VBA code for Excel shows how to calculate the fuel burnt in each trip i to j.

```
’calc fuel consumption
Private Sub CommandButton3-Click()
Dim i As Long
Dim cons As Double
cons = Cells(22, 16).Value
For i = 3 To 13651
Cells(i, 6).Value = Cells(i, 4).Value * cons
Next i
End Sub
```

In a third step, given the list of routes with the nodes, distances, weight variation, and respective fuel consumed in the trip i to j, the following VBA code for Excel verifies if some weight limit is exceed.

```
Private Sub CommandButton1-Click()
’Weight limits exceed? (0/1)
Dim i As Long
Dim MTOW, TOW, MLW, LW, PAY As Double
MTOW = Cells(24, 16).Value
MLW = Cells(25, 16).Value
’PAY = Cells(26, 16).Value
```

```
TOW = 0
LW = 0
For i = 3 To 13651 Step 5
Cells(i, 5).Select
Cells(i, 5).Value = MTOW
Cells(i, 7).Select
Cells(i, 7).Value = MTOW - Cells(i, 6).Value
LW = Cells(i, 7).Value
If Cells(i, 7).Value > MLW Then
Cells(i, 10).Value = 0
Else: Cells(i, 10) = 1
End If
’1111111111111111111111111111111111111111
TOW = LW + Cells(i, 8).Value
Cells(i + 1, 5).Value = TOW
If Cells(i + 1, 5).Value > MTOW Then
Cells(i, 10).Value = 0
End If
Cells(i + 1, 7).Select
Cells(i + 1, 7).Value = Cells(i + 1, 5).Value - Cells(i + 1, 6).Value
LW = Cells(i + 1, 7).Value
If Cells(i + 1, 7).Value > MLW Then
Cells(i, 10).Value = 0
End If
’222222222222222222222222222222222222222
TOW = LW + Cells(i + 1, 8).Value
Cells(i + 2, 5).Value = TOW
If Cells(i + 2, 5).Value > MTOW Then
Cells(i, 10).Value = 0
```

```
End If

Cells(i + 2, 7).Select

Cells(i + 2, 7).Value = TOW - Cells(i + 2, 6).Value

LW = Cells(i + 2, 7).Value

If Cells(i + 2, 7).Value > MLW Then

Cells(i, 10).Value = 0

End If

'3333333333333333333333333333333333333333

TOW = LW + Cells(i + 2, 8).Value

Cells(i + 3, 5).Value = TOW

If Cells(i + 3, 5).Value > MTOW Then

Cells(i, 10).Value = 0

End If

Cells(i + 3, 7).Select

Cells(i + 3, 7).Value = TOW - Cells(i + 3, 6).Value

LW = Cells(i + 3, 7).Value

If Cells(i + 3, 7).Value > MLW Then

Cells(i, 10).Value = 0

End If

Next i

End Sub
```