Maritime Search and Rescue (MSAR) Operations: An Analysis of Optimal Asset Allocation

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Abstract Managing sea rescue assets and their distribution in the various search and rescue (SAR) locations should be carried out according to some well-defined criteria in order to cover SAR areas of the world properly. In this chapter, we intend to give a comparative literature review of maritime search and rescue (MSAR) operations with more emphasis on asset allocation. A framework of a new approach that aims to locate SAR stations and allocate SAR assets to the stations is introduced to the MSAR literature that takes into account the traffic density of sea and air roads over an SAR responsibility area. The model itself is not covered within this book chapter, but instead its main features are discussed and the differences and novelties with respect to the modeling approaches generally used in the literature are presented.

Keywords Search and rescue · SAR · Maritime search and rescue · Maritime rescue · Global maritime distress and safety · Sea rescue

1 Introduction

According to World Health Organization (WHO) media center fact sheet [36], drowning is the 3rd leading (7% of all injury related deaths) cause of unintentional injury death worldwide. It is estimated that approximately 372,000 drowning deaths occur annually. A similar statistic is given by Golden and Tipton [12] which reveals that each year approximately 140,000 water-related deaths happen worldwide. Even though the estimated casualties show the importance of the maritime search and rescue (MSAR) operations, regardless of the numbers given above, a single life is impor-

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tant when planning an MSAR operation. The first thing we will examine about the MSAR is the conventions that regulate rescue at sea.

The international convention regulating the search and rescue (SAR) operations worldwide is “The International Convention on Maritime Search and Rescue (Hamburg, 1979)” [17]. According to the 1979 Convention which entered in force in 1985, it is intended to develop an international SAR plan, so that, no matter where a sea accident happens, the rescue of persons in distress at sea will be coordinated by an SAR organization and, when necessary, by co-operation between neighboring SAR organizations. After the adoption of the 1979 SAR Convention, International Maritime Organization (IMO)’s Maritime Safety Committee segmented the world’s seas/oceans into 13 SAR areas, in each of which the concerned countries have their own SAR responsibility areas. Within these SAR areas, upon a rescue operation is initiated, how well it is managed by the rescue centers depends mainly on the allocation of the rescue assets.

Most of the MSAR operations are initiated by a distress signal received by any means of communication. Sometimes, without having a distress signal, the information of a ship or an aircraft not reaching its final destination within a certain time period can initiate the MSAR operations. High sea conditions, illegal immigration, ship collisions, man overboard etc. are among the major causes of the sea-accidents.

When a man or any floatable object goes overboard at sea, without propulsion, it is subject to drift due to waves, sea currents and wind conditions.[1] Accurately locating the position of such a drifting target without RFID, Global Maritime Distress and Safety System (GMDSS),[2] etc. needs a reliable estimation of the environmental conditions and the target’s last known position. If no reliable last know position is provided when rescue center (RC) is informed about the accident, then, all SAR responsibility areas should be searched. The key questions arising from the uncertainty are “How should the area be searched?”, “Where should the SAR stations be located?” and “How should the SAR assets (helicopters, ships, fixed wing aircrafts, etc.) be allocated to shorten the rescue time?” With this inspiration, we intend to give a literature review of maritime search and rescue (MSAR) operations with more emphasis on asset allocation.

In Sect. 2 of this chapter, we review the literature on the MSAR and discuss their shortfalls. In Sect. 3, we describe the basics of a model for the location of SAR stations and the allocation of SAR assets, without going into the mathematical and modeling details. In Sect. 4, possible extensions to the chapter are discussed, and in Sect. 5, we give some concluding remarks.

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[1] The wind speed by itself is a key factor to generate surface waves and currents. Surface currents can be estimated to be approximately 2% of the wind speed when navigating close to the shore. The single affect of the wind over sea currents is itself a research area in the SAR literature [8] and will not be addressed here.

[2] The Global Maritime Distress and Safety System (GMDSS) [11] is the international radio safety system mandated by the International Maritime Organization (IMO) for vessels at sea. The GMDSS was implemented on February 1, 1999 through amendments to the Safety of Life At Sea (SOLAS) Convention. The main aim of GMDSS is to organize and improve emergency communications for the world’s shipping industry.

2 Literature Review

Search and rescue operations can be conducted during either wartime or peacetime. The literature is divided into two by this separation. Although there is a significant amount of research about combat search and rescue [25] in the literature, this is outside the scope of this chapter.

One can categorize the SAR literature into three parts by considering peacetime MSAR operations. In general, these research areas are about,

- Locating SAR stations,
- Leeway (the motion of a drifting object) formulations and search plans[3] to locate the objects under consideration,
- Allocating SAR assets.

Almost all of the studies in the literature on the research areas above deal with a time called "rescue time" and/or with a plan called "search plan". However, no integrated model encountered in the MSAR literature combining all the three research areas listed above. In fact, minimizing rescue time, locating SAR stations, allocating SAR assets with respect to available/required SAR stations, search plans, budget, areal density of sea and air accidents, etc. are the cornerstone of solving such a complex real-life support problem.

In addition, no MSAR modelling approach in the literature covers both sea accidents and air accidents occurred over seas in the same model. There are separate modeling examples, but not addressing both dimensions. Our proposed modelling approach projects air roads into the sea area and deals with both sea and air accidents over seas simultaneously.

In the MSAR literature, one is more likely to find papers/theses written about locating SAR stations than allocating the SAR assets. One of them is written by Basdemir in 2000 [3] that aims to find the optimal location of new SAR stations. The optimum SAR locations are found by solving a maximal covering location problem. Main emphasis is given to find the minimum number of SAR locations that achieves maximum coverage in the operation area. The SAR locations considered by Basdemir are just for locating SAR helicopters. No other assets other than helicopters are considered in the paper. A similar research is conducted by Haagensen et al. [14] who examined Long-range Rescue Helicopter Missions in the Arctic. A comprehensive model should cover not only SAR helicopters but also other essential rescue assets used in an integrated MSAR operation like fixed wing planes, rescue ships and even unmanned aerial vehicles.

Some part of the literature about MSAR is engaged with the leeway formulations. One of them is written by Oyvind and Allen in 2008 [27] in order to provide a new

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[3] A search plan is the method that SAR assets will use in the SAR area. Various types of search plans are introduced to the literature so far, but the one that attracts most of the attention is the CASP (The United States Coast Guard Computer Assisted Search Planning System) [30]. The CASP methodology is mainly based upon Monte Carlo simulation to obtain an initial probability distribution for target location and to update this distribution to account for drift due to currents and winds.

operational, ensemble-based search and rescue model for the Norwegian Sea and the North Sea. A new, robust formulation for the relation between the wind and the motion of a drifting object (leeway) is provided by this paper. Another research about leeway computations is "Optimal Search for a Moving Target: A Geometric Approach" by Snorrason and Ablavsky [31]. Coming up with a path-planner that simultaneously optimizes path efficiency and search-effort allocation is the main contribution of this research. One of the significant properties of the research results is that the paths calculated are also suitable for unmanned aerial vehicles (UAV). The use of UAVs in SAR operations is getting more frequent nowadays, and in our point of view, this fact keeps this particular research up-to-date.

One part of the leeway formulations is to determine an optimal search pattern for a lost target. Optimal search algorithms commonly use Bayesian approach. One of them is "Optimal Search for a Lost Target in a Bayesian World" written by Bourgaut et al. in 2006 [5]. This paper mainly presents a Bayesian approach to the problem of searching for a single lost target by a single autonomous sensor platform. The target may be static or mobile but not evading. The mean time to detection and the cumulative probability of detection are the two significant factors they try to determine by using the Bayesian approach.

It may not be an exaggeration when one claims that one of the greatest contributions to the literature of allocating SAR assets is given by Abi-Zeid and Frost [1]. They present SARPlan, a geographic decision support system designed to assist the Canadian Forces in the optimal planning of search missions for missing aircraft. Its primary purpose is to ensure that the available search resources are deployed in a way that will maximize the mission's probability of success. The optimization modules are based on search theory, gradient search methods, and constraint satisfaction programming. Results demonstrate that SARPlan improves the performance when compared to the manual method. In 2001, SARPlan was the winner of three prestigious excellence awards in the information technology domain. Even though, SARPlan is mainly developed to search missing aircrafts (which is a kind of weakness of the model), it can be applied to find other missing objects of similar size. There are more than a dozen MSAR search methods like expanding square, parallel search, etc. Deciding on the search plan to be used in an MSAR operation is an essential part in the optimization of the rescue time.

Another research about planning sea rescue resources and their distribution in various locations is conducted by Azofra et al. [2]. In the research, they emphasize the difficulties that can be faced when allocating SAR assets in countries with autonomous regional governments. Their main contribution to the literature is realized by formalizing a general methodology based on gravitational models which can be used to define individual and zonal distribution models. They define the following five factors in the process of assigning sea rescue resources:

- Characteristics of the accident, the vessel and the damage produced,
- Types of the accidents and establishment of a scale of severity,
- Distribution of resources such as helicopters, tug-boats and rescue boats with a definition of their radius of action,

- Placement of resources assigning indicators of suitability to locations,
- Cost-effectiveness.

They also introduce the Zonal Distribution Model which considers the zones of the sea whose size means that the conditions of access to any of its geographical position must be quite similar. They name accidents occurring in each of these zones as “superaccident”. With this approach, they categorize the sea area into zonal parts just considering the occurance rate of sea accidents. They also further categorize the accidents with respect to their severity into five category (superaccident, very serious, serious, moderate, and slight). They state that all these five types of accidents happen close to each other within a zone. The likelihood of accidents within the SAR area are based on the historical accident data of the region. Point-wise zonal accident density is the key part within their study.

When we examine the Zonal Distribution Modelling introduced by Azofra et al., we realize that “choke points” of sea accidents do not explain the gravitational modelling needs entirely. The historical data of accident locations does not entirely explain the point estimation of future sea accidents. In our model, we also plan to benefit from the traffic density of sea and air roads over an SAR responsibility area. It can be clearly seen from an instant map presented by www.marinetraffic.com [23] that the traffic density of sea roads does not follow a point-wise zonal pattern, instead, a rectangular pattern compatible with shortest paths is followed by the ships.

Most of the location models on the MSAR are summarized in the thesis by Li [21]. A maximal covering location problem model with weights on incident classes, workload capacities and stochastic considerations are discussed within the thesis. Response times, workload, vessel utilization, and locating rescue vessels are studied with a range of 5–50 rescue vessels.

Another useful reference about the MSAR operations is the Coast Guard Addendum (2013) to the United States National Search and Rescue Supplement [34], which is a supplement to the International Aeronautical and Maritime Search and Rescue Manual. This Addendum establishes policy, guidelines, procedures and general information for Coast Guard use in search and rescue operations. The manual covers the following topics in general:

- Search and Rescue (SAR) organization,
- SAR agreements,
- International SAR,
- General SAR policies,
- SAR communications,
- Rescue planning and operations,
- Coast guard SAR units,
- Procedures for underwater incidents,
- Search planning guide.

It is one of the few references on the procedures for underwater incidents. In addition to that, various types of theoretic SAR data can be found within the manual (i.e., visual search altitudes, height of eye versus horizon range).

There are three famous national search models (U.S., Canadian, and Norwegian) and all the three search models are summarized by Hillier [15]. Inputs for SAR planning and environmental data sets (i.e., types of currents, wind forecasts) are two important topics covered in separate chapters in this work.

Malik et al. in [22] present a joint work with the U.S. Coast Guard's Ninth Disctrict and Atlantic Area Commands where they developed a visual analytics system to analyze historic response operations and assess the potential risks in the maritime environment associated with the hypothetical allocation of coast guard resources.

According to our assessment, evaluation of the risk should be supported by the real time areal usage of the region. Our proposed model will use in addition to the historic data, the traffic density of the sea and air roads for a given region.

A multi-objective model, Incident Based-Boat Allocation Model (IB-BAM), for allocating search and rescue boats is proposed by Razi et al. in [29]. The model consists of three parts. First, by using the Analytic Hierarchy Process (AHP), it determines the weight of each incident type considering its severity. Second, considering historical incident data, a Zonal Distribution Model generates aggregated weighted demand locations. Third, a multi-objective mixed integer program determines locations and responsibility zones of search and rescue boats. Azofra et al. [2] and this particular article both use Zonal Distribution Model and categorize the accidents with respect to their severity. However, neither of them considers the real-time areal density of sea and air roads. They just rely on the historical data of the incidents. In fact, historical data of incidents itself can not explain all the risk associated with future accidents.

3 Model Structure

Our MSAR literature review shows that the following MSAR modelling approaches have been mainly used/developed so far.

- Location modelling of SAR stations [3],
- Allocation modelling of SAR assets [2, 14, 15, 21, 24, 27, 29, 30],
- Risk assessment modelling of SAR areas [4, 13, 22, 35],
- Search theory and SAR planning modelling [1, 5–10, 12, 15, 16, 18–20, 25, 27, 28, 30–33].

We realized the gap in the MSAR literature that there is no integrated or comprehensive modelling approach dealing with locating SAR stations, allocating SAR assets to these SAR stations, making risk assessment of the SAR area, and finally SAR planning to rescue the casualties within an acceptable time frame at the same time. Also, narrowing the scope of our review, to the best of our knowledge, MSAR modelling approaches do not consider airspace over seas as a source of incident. Obviously, air accidents over seas should be taken into account by using historical data of air incidents and the real-time areal density of air roads over seas.

Risk assessment models mainly benefit from past data of sea accidents of a certain SAR region [22]. After mapping the events occurred before, these models forecast a future risk of the SAR area without considering real-time air and sea road traffic densities of the area under consideration.

It is a well known fact that by allocating any kind of asset to any proper station, we intend to maximize the utility of the assets to be assigned. Before stating the intended framework of our model structure, we need to say a few words about "how can SAR assets' utility be assessed?" A short answer would be "The closer to the SAR area (the theatre, i.e., the accident location), the greater the utility of an SAR asset will be." One aim of our model is to distribute SAR assets (ships, helicopters, fixed wing aircrafts, etc.) to SAR stations in such a way that the distance between the SAR stations and the possible accident locations would be the minimum. Since the location of any possible accident is unknown and to be predicted, we intend to focus on traffic density of sea[4] and air[5] roads together with the past data of the accidents occurred before. We will map the real-time traffic density area of sea and air roads [23] and the historical data of accidents occurred on the same chart in order to assess the risk of a particular SAR region. This is a new risk assessment approach to the literature of the MSAR. Most of the models in the literature are generated under the assumption that sea accidents occur in a uniformly manner, or based on the limited historical data. The main concern of most of the models provided so far is to cover all SAR responsibility area within a reasonable time frame. We will not cover explicitly our model structure here, since it is a part of an ongoing research.

In our model, we would like to decide on the number of SAR stations and where to locate them, the allocation of the SAR assets to the SAR stations, the risk assessment of the SAR area and possible search plans to be conducted. We consider the traffic density[6] of each air and sea roads within the SAR area. There can be two kinds of accident possibility related with the sea. First, a vessel could sink due to an accident or rough sea conditions (ship-based accidents). Second, an aircraft flying over the sea could crash or land over sea (aircraft-based accidents). We do not consider swimming-activity-based accidents close to the shores in the model, since these individual accidents do not require time consuming rescue efforts frequently.

The objective of the model is to minimize the average rescue time while having the constraints:

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[4] The Sea Roads: These roads are invisible to notice at sea, but followed by most of the sailors, since they provide the shortest distance between departing and last port of calls. Most of the navigation charts does not include them unless you are sailing under a regulated straight or a narrow channel.

[5] The Air Roads: These roads are invisible to notice in the air, but followed by all of the civilian pilots, since there is a multinational convention (Convention on International Civil Aviation by International Commission for Air Navigation (ICAN), 1944, Paris) regulating the air safety. All of the aviation charts include them and, it is mandatory for civilian aircrafts to follow these air roads.

[6] i.e., the traffic density rate of sea and air roads in the ith station SAR responsibility area. (It is the rate of ships and aircraft in the area per hour). Arrival of the ships and aircraft is assumed to be a Poisson process. It is assumed that an aircraft/ship can use either side of their route within a 5 NM buffer zone. These 10 NM-width areas along the routes are assumed to be subject to the highest risk of an air/sea accident. In short, not every part of the SAR area has the same probability of accident occurance.

- Cover all MSAR responsibility area with the search capacity of all assets,[7]
- Decide on the number of SAR stations and allocate each SAR asset to the proper station,[8]
- Consider national regulations on the assets and the stations,
- Consider available budget.
- Consider the risk assessment by using historical data of accidents and the real-time air and sea road traffic densities.

The following assumptions are taken into account:

Assumption 1 In order to determine the percentage of ith station SAR responsibility area subject to the sea and air roads, it is assumed that a ship or an aircraft can use either side of this route within a 5 NM buffer zone. These 10 NM-width buffer areas along the routes are assumed to be subject to the highest risk of sea and air accidents.

This assumption is based on the observation of routes used by the commercial ships and aircrafts. It is observed that a great majority of the ships tend to use shortest path between their departure port and last port of calls. The spread from the center of the route course is assumed 5 NM to the right (starboard) and 5 NM to the left (port) side.

A similar assumption is made for the airlines. But, this time, the center route courses (head of the plane) are regulated by ICAO, i.e., by air maps. These roads may not be the shortest path between departing airport and the destination due to the air safety. The spread from the center of the route course is also assumed 5 NM to the right and 5 NM to the left.

Assumption 2 In order to determine area coverage factor of a single SAR asset, it is assumed that the rescue operation is being conducted under day time and good visibility conditions.

Day time or night rescue operations under good or poor visibility have different probabilities to detect an object at sea. We can further categorize the visibility and sea state on a numeric scale as in the U.S. Coast Guard addendum [34].

Next, we intend to generate a simulation method to test average rescue times with respect to positions of the accidents within the MSAR area. Since the SAR assets are dependent to each other, especially the ship-airborne helos, the area to be reached by

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[7] Area coverage factor of a single rescue ship, a helicopter and a fixed wing aircraft: A rescue ship is assumed to have $25kts.$ (nautical miles per hour) permanent cruise speed and a 2 NM-radius detection range. In an hour, a ship will sail 25 NM and will cover a 4 NM-width rectangle area, which equals 100 NM^2.

A rescue helicopter is assumed to have $90kts.$ permanent speed and a 5 NM-radius detection range. In an hour, a helicopter will fly 90 NM and will cover a 10 NM-width rectangle area, which equals 900 NM^2.

A rescue fixed wing aircraft is assumed to have $200kts.$ permanent speed and a 5 NM-radius detection range. In an hour, a fixed wing aircraft will fly 200 NM and will cover a 10 NM-width rectangle area, which equals 2,000 NM^2.

[8] Proportion of SAR responsibility area subject to the air/sea roads are used to differentiate the importance of the SAR areas under concern.

each asset should be simulated in terms of their operation radius considering their fuel replenishment at sea or ashore.

4 Further Discussions

In the preceding section, we stated the framework of a model that takes into account sea and air roads. What if a rescue center in a SAR station does not have suitable geographical formation to accommodate an SAR asset (e.g., high mountains along the shore may be an obstacle for rescue aircrafts to operate.). Then, such assets will not be assigned to this SAR station and they have to operate from a neighboring SAR station. As an extension, one may also consider the negative affects of environmental difficulties. In such cases, the rescue times will increase. In addition to that, it is a common practice for neighboring SAR stations to cooperate in case of a sea accident which is not taken into account in the current version of our model.

On the other hand, if an SAR region has islands or man-made platforms at sea, this will shorten the rescue times for two reasons. First, SAR assets can be located at these places and reaction time will decrease eventually. Second, a platform or a geographical formation (an island, etc.) may act as an SAR asset by itself, since they have an observation range over the sea.

5 Summary and Concluding Remarks

Managing sea rescue resources and their distribution in the various locations should be conducted according to well-defined criteria in order to cover the 13 SAR areas of the world. Decision makers should be urged to optimize their MSAR efforts by benefitting from various allocation algorithms.

The reason for us to write this chapter is to provide a brief literature review and give a new approach of allocating SAR assets. As of our knowledge, especially the air road density over seas is not considered by any other paper or book written before. According to The National Air Traffic Controllers Association (NATCA) of USA [26], at any given moment, roughly 5,000 planes are in the skies above the United States (approximately 70,000 flights daily). Looking at these numbers, we can evaluate the importance of the air roads when considering air-based accidents over seas.

A possible extension of the model stated can be to predict the traffic intensity rates of sea and air roads. Here, we use marinetraffic.com real time merchant ship data which excludes navy ships [23]. Because of this missing data, the actual traffic densities of sea roads may be higher than the ones we used in the model.

The results found are expected to change according to the visibility and day & night conditions of the SAR areas. Poor visibility or a night SAR operation will result in an increased rescue time and more rescue assets.

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