Optimal combination choice of submersible search and rescue equipment based on AHP-multi-objective planning

Xinyang Zhang *

College of Economics and Management, China Agricultural University, Beijing, China, 100083

* Corresponding Author Email: 13661233162@139.com

Abstract. There are a variety of accidents that can occur when a submersible is traveling in the ocean. The main solution to improve the survival rate of the passengers in the submersible is to optimize the combination of search equipment on the main ship. In this paper, the preparation cost, maintenance cost and usage efficiency of different types of equipment are firstly identified as decision variables, safety, availability and inter-equipment compatibility as constraints, and minimization of total cost under the premise of maximizing usage efficiency as the objective function. By establishing a multi-objective planning model, the optimal equipment brand is found. Finally, the optimal equipment combination is solved by the combination of a robotic arm, Forum Sub-Atlantic Mohican ROV, and an underwater light, Underwater Kinetics Aqualite Pro, and the minimized overall cost is $90, 619. 05. This result not only reduces the cost of submersible search and rescue, but also improves the search efficiency, which is a strong guidance for the future underwater search and rescue field.

Keywords: Submersible, AHP, Multi-objective planning, Navigational safety.

1. Introduction

Nowadays, with the development of technology, it is no longer a fantasy for people to explore the sea by submarine, but the safety issue still cannot be ignored. According to the two marine acoustic imaging techniques, side-scan sonar and seabed profiling, the sea bed is characterized by the presence of a large number of boulders and seagrasses [1]. At the same time, the global seabed has upwelling and baroclinic changes in the summer, leading to changes in seawater flow [2], and along with the effects of global warming, the ocean heat wave effect is intensifying, leading to an increase in ocean temperature and changes in salinity [3]. These changes will affect the safety of submarines traveling in the ocean; therefore, it is extremely important to ensure the safety of submarines and tourists. At present, the emergence of many new scientific and technological products has contributed to the safe driving of submarines, such as passive omnidirectional sonar buoys [4] and autonomous underwater robots can effectively provide driving direction and route [5], corrugated sharkskin vortex generator can be controlled by the flow rate of the surrounding seawater, to achieve the reduction of resistance, improve the stability of driving role [6]. The invention of the underwater robotic arm has also made underwater extraction activities and personnel rescue a reality [7]. However, when the submarine loses contact with the ground or mechanical failure occurs, how to make timely position prediction and rescue still need to be solved. Obviously, this aspect still needs further research. From the perspective of this paper, selecting proper rescue equipment combination in main rescue ship is of great importance to enhance the survival rate in wrecked submersible.

2. The types and characteristics of search equipment

2.1. Search for different features and functions of the device

This paper argues that search equipment can be divided into five parts, namely, positioning equipment, communication equipment, extraction equipment, search equipment and lighting equipment. Positioning equipment is mainly used for the main ship to determine the position of itself and the missing submersible, which is convenient for the rescue operation, including sonar [8], radar and other equipment; the role of the communication equipment is to mark its own position [9] and communicate its own positional information, so that the main ship can find the missing submersible in time and rescue the people in distress; the main role of the extraction equipment is to get the valuable material or other information in the ocean, which can help the main ship to find the missing submersible faster; the search equipment is an extension of the extraction equipment, which can reach the distance from the main ship to find the missing submersible. The search equipment is an extension of the extraction equipment and can reach locations farther away from the main ship and conduct relatively independent operations; the lighting equipment helps the main ship to search for deeper locations in the sea and provides possible guidance for the missing diver at night. Each type of search equipment has a unique function and produces different results.

2.2. Selection of main ship related search equipment

The five search devices have different characteristics in different dimensions which will have an impact on the choice of device. In this paper, we categorize the dimensions to be considered for a search device into six main parts, namely readiness cost, maintenance cost, usability, security, usage efficiency and compatibility. Among them, readiness cost includes the purchase cost of the equipment and the costs necessary to put the equipment into use, including installation, transportation, etc. Availability refers to the magnitude of the probability that such equipment will perform its function and successfully fulfill its intended use. Safety refers to the stability of the equipment during operation and the probability of downtime. Efficiency of use refers to the length of time it takes for such equipment to start operating; the shorter the time, the more efficient it is and vice versa. Compatibility is the main consideration is whether the various types of search equipment can be realized between each other, the use of the same time, to achieve better search results. Through these six dimensions of each of the five categories of devices to screen the brand model, select a representative device, and ultimately choose which category is the best search device selection. The paper selects some pragmatical equipment brand to be chosen in the following AHP model. These brands and usage introduction are as followed in Table 1.

Table 1. Brands and usage introduction of five classifications

Classification	Brand	Usage Introduction
Positioning equipment	Kongsberg MS1000; Blue View M900 Series; Teledyne RESON Sea bat T50-R; Furuno NavNet TZT Radar	underwater target detection and formation
Communication equipment	Pains Wessex Marine Signals; Orion Maritime Signal Flares; NOAA Buoy; Spotter Buoy	Facilitates marking of survivors and submersible positions by the primary vessel to facilitate communication of positional information and rapid rescues
Extraction equipment	Saab Seaeye Falcon DR ROV; Deep Trekker DTG3; Forum Sub-Atlantic Mohican ROV; DOER H2000D Hardsuit SCUBA	Equipped with a robotic arm for search and rescue and inspection missions. It is suitable for undersea search, localization and rescue missions
Search equipment	Bluefin Robotics Bluefin-9 AUV; VideoRay Pro 4 ROV;	For searching and surveying the underwater environment. It can perform underwater terrain survey, search and image acquisition tasks

	Ocean Infinity Armada Fleet; Saab Sabertooth AUV	
Lighting equipment	SeaVision SV Series; Underwater Kinetics Aqualite Pro; SubConn Underwater Connectors; Keldan Luna 8 CRI	A lighting device designed for underwater applications to provide high brightness underwater illumination

3. Integrated analysis model based on AHP-multi-objective planning

3.1. Premise assumptions

Due to the complexity of equipment maintenance costs and the large depreciation losses in deep-sea operations, the amount of depreciation, i.e., maintenance costs, for all equipment over the service life is set to 30% of the equipment cost to simplify the calculation. Meanwhile, when calculating the minimum critical value of availability and safety in the multi-objective planning model, the valid data under this dimension have the same calculation weight.

3.2. Analysis of the representative brands

Hierarchical analysis is widely used in the fields of product design, safety management evaluation, resource development, socio-economic analysis, and decision-making evaluation. In the field of decision-making, hierarchical analysis is mainly used for organizational evaluation and prioritization. For example, in organizational evaluation, Hierarchical Analysis can be used to assess the performance of an organization and predict its future development trends. In prioritization, hierarchical analysis can be used to rank raw materials, equipment, products and services. This approach is applicable to the selection and screening of representative brands of various types of search equipment. The advantages of hierarchical analysis include:

(1) Simple: only need to carry out hierarchical decomposition, judgment and solution, simple and easy to learn;

(2) Flexible: it can deal with uncertainty, ambiguity and randomness;

(3) Hierarchical: the problem is decomposed into a hierarchical structure, which reduces the complexity of the problem;

(4) Objectivity: it can quantify subjective comparisons and eliminate subjective components.

Within the five broad categories of search equipment mentioned in 2.1, there will be obvious differences in price, efficacy, and efficiency that will affect the judgment of equipment selection. Therefore, a hierarchical analysis is first applied to the analysis. Hierarchical analysis refers to the decomposition of elements related to decision-making into levels such as objectives, guidelines, and options, on the basis of which qualitative and quantitative analyses are conducted and decisions are made [10]. The objective in this model is to select the most cost-effective equipment brand or version for each type of equipment, there are four guidelines, and the program is the pre-selected equipment brand or version.

In detail, the four pre-selected devices in each category of search devices are analyzed hierarchically in terms of total cost advantage, usability, safety ratings, and usage efficiency, and a judgment matrix is created. The paper also input the judgment matrix and use the eigenvalue method to find out the size of the dominance of the 4 branded versions in the 4 criteria. Then conduct a consistency test on the relative advantage results between each version or model in each type of equipment. If the consistency ratio $CR<0.1$, the results are valid, and based on the results, the brand or version with the greatest advantage in each type of equipment is selected.

3.3. Optimal equipment mix

Considering that using only one class or one type of search equipment in the search and rescue process does not match the reality, and that there is a functional intersection between the five types of search equipment, considering different combinations of the five types of search equipment in the context of minimizing the cost and maximizing the efficiency of their use is the way that best meets the requirements of the realistic rescue scenarios. The paper chooses a multi-objective planning model based on the AHP results in 2.1 to derive the target equipment combinations. Multi-objective planning refers to a method of maximizing or minimizing multiple objectives. The goal of multi-objective planning is to optimize multiple objectives of a system to find an optimal solution under constraints, where each objective function represents its own objective. This approach shows unique advantages in decision problems that require simultaneous consideration of multiple factors such as time, cost, reliability, quality, environment, energy and safety [11]. The advantages of multi-objective planning include:

(1) Multiple objectives can be considered, avoiding the limitations of single-objective decision making;

(2) It can ensure the balance between different objectives and will not help one objective to be too high;

(3) It can help decision makers to make choices between different objectives and make the results more scientific and reasonable.

Among the six dimensions, availability, security, and compatibility are calculated as constraints, and two costs and utilization efficiency are calculated as objectives. Specific data and indicators are shown in the Table 2. and Fig.1.below:

Table 2. The optimal product and its costs of five types of search equipment

Classification	Optimal Product	Preparation Costs	Maintenance Costs
Positioning equipment: sonar, radar	Kongsberg MS1000	\$ 27806.8	\$ 8342
Communication equipment: buoys, flares	SOFAR Spotter Float	\$ 97324	\$ 2919.7
Extraction equipment: robotic arms	Forum Sub-Atlantic Mohican ROV	\$ 69517	\$ 20855.1
Search equipment: underwater robots	Saab Sabertooth AUV	\$ 83420.4	\$ 25026.1
Lighting equipment: underwater lights	Underwater Kinetics Aqualite Pro	\$ 190	\$ 57

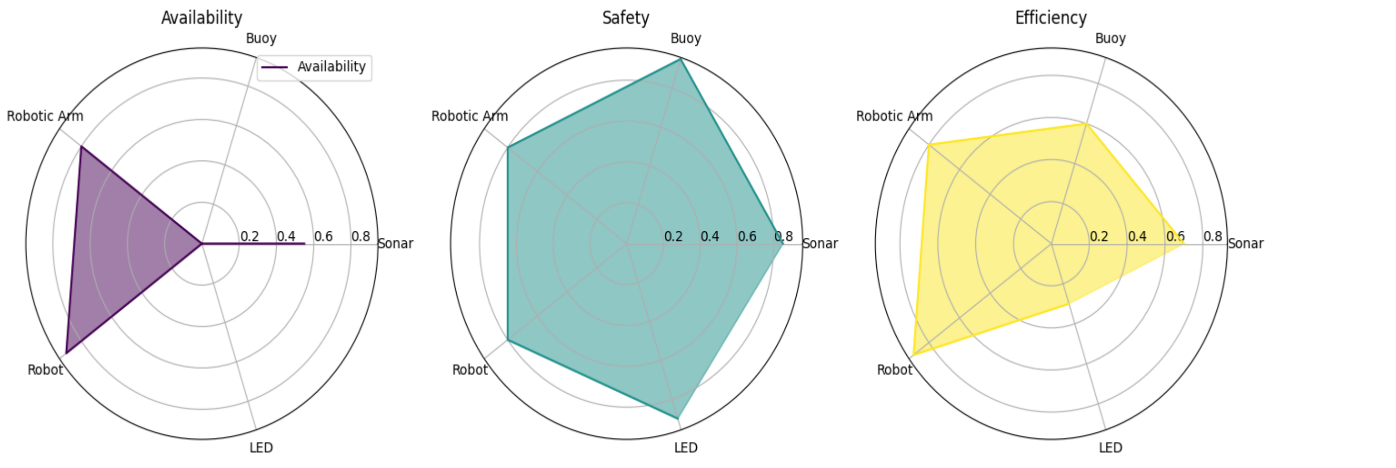

Figure 1. The availability, safety and efficiency of five types of search equipment

For the constraints, this paper uses the constraint threshold approach. In several simulations, it is found that the efficiency of the selected efficiency combination fluctuates up and down from 2 when the success rate of the search can reach a relatively high level. To ensure that the maximum threshold is not overly optimistic, we choose to use 2 as the maximum threshold for using the efficiency combination to reflect various factors that may occur in practice, such as maintenance and environmental conditions. When calculating the constraint thresholds for the availability and safety metrics, the effective products are calculated with equal weights.

$$\begin{cases} \sum_{i=1}^{5} A_i X_i \geq 0.75 \\ \sum_{\mathrm{i}=1}^{5} \mathrm{S_i} \mathrm{X_i} \geq 0.86 \\ \sum_{i=1}^{5} E_i X_i \leq 2 \\ X_2, X_3, X_5 \geq 0, X_1 \geq 0, X_4 \leq 1 \end{cases} \tag{1}$$

For cost and utilization efficiency, this paper believes that the importance of efficiency is stronger than cost, and utilization efficiency should be given priority before cost, so the hierarchical sequence method is used to solve $MaxE(x)$ under the premise of constraints remaining unchanged in the original model, and then solve $MinE(x)$ after obtaining the optimal solution and the optimal value, which, through the planning, can not only satisfy the high requirements of the SAR operation itself for efficiency and ensure the quality of the operation, but also maximize the savings of the SAR.

$$\mathrm{Maxf_1(x)} \;\; \mathrm{s.t.} \, \mathrm{X} \in \mathrm{D} \tag{2}$$

$$\mathrm{Minf_2(x)} \;\; \mathrm{s.t.} \begin{cases} \mathrm{f_1(x)} \leq \mathrm{f_1^*} \\ \mathrm{x} \in \mathrm{D} \end{cases} \tag{3}$$

4. Conclusion

Based on the calculation of the optimal search and rescue equipment combination, the cost of overall equipment on the foundation of former model is as followed and the basic consequence is listed below:

Minimized overall cost calculated by the program: 90619.05 (USD), Optimal number of devices: x_1: 0.0; x_2: 0.0; x_3: 1.0; x_4: 0.0; x_5: 1.0

It can be seen that the combination of a robotic arm, Forum Sub-Atlantic Mohican ROV, and an underwater light, Underwater Kinetics Aqualite Pro, is optimal and should be used as additional search equipment carried on the main vessel. Of these, the Forum Sub-Atlantic Mohican ROV is a small ROV equipped with a robotic arm for search and rescue and inspection missions. It is suitable for both deep and shallow sea environments. The Underwater Kinetics Aqualite Pro 100 is a small, portable underwater light for underwater photography and survey missions.

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