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Multi-Objective Optimization for Submarine Cable Route Planning Based on the Ant Colony Optimization Algorithm

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Abstract: It is essential to design an appropriate submarine cable route to reduce costs and improve reliability. A methodology that can be used for multi-objective optimization in submarine cable route planning is proposed and numerically studied in this paper. The costs and risks are numerically assessed and mapped to the geographical map. The pheromone and heuristic functions of the ant colony optimization (ACO) algorithm are associated with the geographical map of costs and risks, which enables it to search for a submarine cable route with multi-objective optimization. The results show that the submarine cable route designed by the methodology can effectively avoid high-cost and high-risk regions, which means that the designed submarine cable route is cost-effective and highly reliability.

Keywords: submarine cable route planning; multi-objective optimization; ant colony optimization



Citation: Zhao, Z.; Wang, J.; Gao, G.; Wang, H.; Wang, D. Multi-Objective Optimization for Submarine Cable Route Planning Based on the Ant Colony Optimization Algorithm.

Photonics **2023**, *10*, 896.

<https://doi.org/10.3390/photonics10080896>

photonics10080896

Received: 14 June 2023

Revised: 21 July 2023

Accepted: 28 July 2023

Published: 2 August 2023



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1. Introduction

Submarine cabling is a critical infrastructure for international communications, carrying 99% of communication services [1] and playing an important role in promoting the development of global economy and culture. With rapid global development, the demand for submarine cable will further increase thanks to its advantages of large capacity, low latency, low attenuation, and so on.

However, the deployment and maintenance of submarine cables are costly [2]. These cables face potential damage from various risks including natural and anthropological activities [3–5]. Submarine cable route planning, the process of determining the laying path of the submarine cable, has a profound impact on the construction cost of the submarine cable and the hazards that it will face in the future. Therefore, the costs and reliability of the submarine cables must be taken into account in the process of submarine cable route planning. However, the optimization of the cost and reliability of the submarine cable cannot be achieved at the same time. For example, increasing the protection level of submarine cables can reduce its potential breakage, improving its reliability, but will increase its costs. The multi-objective optimization problem of cable cost and cable breakage probability causing by earthquake was formulated and studied in references [6,7]. Wang et al. converted the multi-objective optimization of the construction costs and potential repair number of important infrastructures to a single one through a weighted sum method [8]. The problem of optimizing both the cable planning path as well as the choice of protection levels for submarine cables, with the two conflicting objectives of minimizing cable failures and minimizing laying cost, was formulated and studied as a multi-objective optimization problem [9,10]. In addition, other risk factor considerations, such as volcano, terrain slope, and marine protected areas, were taken into account in the optimization [11]. The method used

for solving the multi-objective optimization in the previous works, converting the multi-objective optimization into a single one through the weighted sum method, means that appropriate empirical weight values were required for different optimization objectives.

In this paper, we propose a methodology that can be used for solving the multi-objective optimization in submarine cable route planning based on the ant colony optimization (ACO) algorithm. We improve the pheromone and heuristic functions of the ACO algorithm, so that the weighted sum method is not required in our scheme. In addition to the threat of human and natural disasters to submarine cables, the threat of marine organisms to submarine cables is also taken into account in this paper. The costs and risks are numerically assessed and then are mapped to the geographical map through a digital raster (DS) map. The pheromone and heuristic functions of ACO are modified so it can be used for searching the Pareto sets of submarine cable route with multi-objective optimization on the geographical map. The results show that the submarine cable path designed by the methodology proposed in this paper can clearly avoid high-cost and high-risk regions.

The remainder of this paper is organized as follows. The numerical models of DS map, total costs, and risks assessment are described in Section 2. The multi-objective optimization for the submarine cable route planning and its solution are presented in Section 3. The validity of methodology is investigated in Section 4. Section 5 concludes the paper.

2. Models

2.1. Model of Earth's Surface

A digital elevation model (DEM) is used to depict the key factors that are closely related to submarine cable path planning. Any point in the target region can be described by a 3-dimensional coordinate (x, y, z) , $z = \xi(x, y)$. z is the elevation corresponding to the geographic location $\xi(x, y)$. The costs and risk assessment are simultaneously considered as key factors in cable path planning, and constructed into two elevation maps.

The DS map is used to depict the location of the X–Y plane, which is then used by the ant colony to search for the submarine cable path with multi-objective optimization. As shown in Figure 1, the target region is divided into a two-dimensional map of $M \times N$ grid cells, which are identified through a two-dimensional label of $L_{2d}(I, J)$. For an ant that is located at grid cell (i, j) , there are eight candidate points as the next point of the target submarine cable route. To improve the efficiency of search, the one-dimensional label L_{1d} is used to replace L_{2d} to identify the grid cell in this paper. Assuming that a grid cell locates at $l_{2d}(i, j)$ in the two-dimensional map, and its one-dimensional label is l_{1d} . Their relationship can be described as

$$l_{1d} = N \cdot (i - 1) + j \quad i \in [1, M], j \in [1, N] \quad (1)$$

$$\begin{cases} i = \lfloor l_{1d}/N \rfloor \\ j = l_{1d} - N \cdot i \end{cases} \quad (2)$$

where $\lfloor \cdot \rfloor$ represents the operation of rounding down.

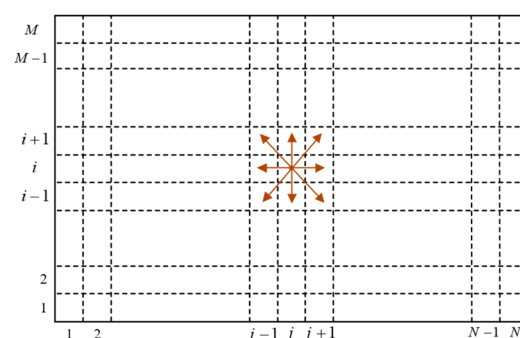


Figure 1. The schematic diagram of digital raster.

2.2. Model of Costs

The costs including construction costs and material costs are considered in this paper.

(1) Material costs

Material costs represent the costs of purchasing submarine cable, which is mainly related to the protection level of the submarine cable. Assuming that C_{LW} (CNY 1000/km) is the material costs of light protection optical cable (LW). The material costs of the single-armor (SA) cable and double-armor (DA) cable are 1.3 times and 1.6 times that of the LW, respectively. The material costs of cable at location ξ can be described as

$$C_1(\xi) = \begin{cases} C_{LW} & H > 1000 \text{ m} \\ 1.3C_{LW} & 200 \text{ m} < H < 1000 \text{ m} \\ 1.6C_{LW} & 0 < H < 200 \text{ m} || R_i = 1 \end{cases} \quad (3)$$

where H represents the depth of water, and R_i is the decision factor of submarine cable type, which is set to 1 if more reliable protection measures need to be taken; otherwise, it is set to 0.

(2) Construction costs

The construction costs of the submarine cables are mainly related to its deployment way. Assuming that C_{Lay} (CNY 1000/km) denotes the construction costs of laying the submarine cables on the seabed directly, and the construction costs of burying submarine cables increases exponentially with the burial depth. In addition, for some forbidden areas, e.g., military areas, the construction costs are set to a maximum value of C_{max} . Therefore, the construction costs at ξ can be described as

$$C_2(\xi) = \begin{cases} C_{max} & H < 0 \text{ m} || T_i = 1 \\ C_{Lay} & H > 1000 \text{ m} \\ C_{Lay} \cdot e^{h/2} & \text{other} \end{cases} \quad (4)$$

where H and h represent the depth of water and that of burial, and T_i denotes the decision factor of deployment, which is set to 1 if the location is a forbidden zone; otherwise, it is set to 0.

Assume a submarine cable path denoted with γ is made up of n nodes, which is described as $\gamma = (v_0, v_1, \dots, v_{n-1})$. $e_i = (v_i, v_{i+1}) (v_i \neq v_{i+1})$ represents the segment between nodes v_i and v_{i+1} , whose length is denoted with $l_{v_i v_{i+1}}$. The total costs per kilometer at position ξ can be described as $C(\xi) = C_1(\xi) + C_2(\xi)$. The $l_{v_i v_{i+1}}$ is divided into two parts with identical length, and $C(v_i)$ and $C(v_{i+1})$ is uses to calculate their total costs, respectively. Therefore, the total costs of $e_i = (v_i, v_{i+1})$ and that of γ can be respectively described as

$$f_c(e, v_i, v_{i+1}) = \frac{l_{v_i v_{i+1}}}{2} C(v_i) + \frac{l_{v_i v_{i+1}}}{2} C(v_{i+1}) \quad (5)$$

$$F_c(\gamma, v_0, v_{n-1}) = \sum_{i=0}^{n-2} f_c(e_i, v_i, v_{i+1}) \quad (6)$$

2.3. Model of Risk Assessments

Although the damage of some risks is not serious, they cannot be ignored because of their high probability of occurrence. Therefore, the damage level of risks and its occurrence probability should be taken into account simultaneously in the assessment. We define five classification levels for risk occurrence possibility and damage, respectively, as ranked in Table 1. The risk occurrence possibility covers the range from very low probability to very high probability, and the risk occurrence possibility covers the range from no cable damage to major cable damage. The classification levels of damage are defined based on

the occurrence probability of risks and the protection measures experience in engineering. Therefore, the scheme proposed in this paper can comprehensively evaluate both risk occurrence possibility and different protection measures simultaneously. In this paper, six kinds of risks proven to have a significant impact on the reliability of submarine cables will be evaluated.

Table 1. The rank of risk occurrence possibility and damage levels.

Rank Level	Occurrence Possibility	Damage Levels
V	very high probability	major cable damage
IV	high probability	severe cable damage
III	medium probability	moderate cable damage
II	low probability	slight cable damage
I	very low probability	no cable damage

(1) Fishery activities

The hazard arising from fishery activities on the submarine cables is trawling. The occurrence possibility of the submarine cable breakage caused by fishery activities can be assessed by the number of hits of submarine cable per kilometer in a year [12]. The number of hits of submarine cable per kilometer in a year denoted with $P_{hit, trawl}$ are related to the number of trawls per ship, the density of fishing vessels, the speed of the trawler, the submarine cable length exposed to trawl path, and the angle of prevailing trawl direction relative to pipe vertical. The damage to submarine cables caused by fishing trawls is related to the trawls' hitting depth and the burial depth of submarine cables [13]. The occurrence possibility and damage levels of the fishery activities are ranked in Table 2.

Table 2. The occurrence possibility and damage levels of fishery activities.

Rank Level	Occurrence Possibility (Number of Hits/km/Year)	Burial Depth h (m), Cable Type
V	$P_{hit, trawl} > 100$	$0 \leq h \leq 0.5$, SA
IV	$80 < P_{hit, trawl} \leq 100$	$0.5 \leq h \leq 1.5$, SA
III	$40 < P_{hit, trawl} \leq 80$	$1.5 \leq h \leq 2.5$, SA
II	$20 < P_{hit, trawl} \leq 40$	$2.5 \leq h \leq 3$, SA
I	$0 \leq P_{hit, trawl} \leq 20$	$h > 3$, DA

(2) Shipping activities

The hazard arising from shipping activities on the submarine cables is anchoring. The occurrence possibility of submarine breakage resulting from shipping activities has been studied in [14], and can be evaluated as the probability that shipping anchors hit submarine cables. The probability that shipping anchors hit submarine cables denoted with $P_{hit, anchor}$ is related to the number of anchors, the probability of the ship dropping anchor in the submarine cable routing area, and the probability that the submarine cable could be hit in one time of anchoring. Damage to submarine cables resulting from anchoring is related to the depth of anchor penetration and the burial depth of submarine cables [15]. The occurrence possibility and damage levels of the shipping activities are ranked in Table 3.

Table 3. The occurrence possibility and damage levels from shipping activities.

Rank Level	Occurrence Possibility (100%)	Burial Depth h (M), Cable Type
V	$5 \times 10^{-1} < P_{hit, anchor} \leq 10^0$	$0 < h \leq 0.5$, SA
IV	$10^{-1} < P_{hit, anchor} \leq 5 \times 10^{-1}$	$0.5 < h \leq 1.5$, SA
III	$10^{-2} < P_{hit, anchor} \leq 10^{-1}$	$1.5 < h \leq 2$, SA
II	$10^{-3} < P_{hit, anchor} \leq 10^{-2}$	$2 < h \leq 3$, SA
I	$0 \leq P_{hit, anchor} \leq 10^{-3}$	$h > 3$, DA

(3) Earthquakes

The seismic force caused by earthquake may lead to the sliding of the fault zone, which could further result in submarine cable interruption. Referring to [16], the occurrence possibility of submarine breakage caused by earthquakes can be assessed through peak ground velocity (PGV), and then using the PGV to calculate the repair rate of the submarine cable. The repair rate is denoted by P_{rr} . P_{rr} is further used to evaluate the probability of damage to submarine cables caused by earthquakes. The damage level of submarine cables caused by earthquakes is related to its margin length as the margin length of submarine cables can release the tension resulting from earthquakes [17]. The occurrence possibility and damage levels of the earthquakes are ranked in Table 4.

Table 4. The occurrence possibility and damage levels of earthquakes.

Rank Level	Occurrence Possibility	Margin Length L (m), Cable Type
V	$10^{-1} < P_{rr} \leq 10^0$	$0 < L \leq 0.5$, SA
IV	$10^{-2} < P_{rr} \leq 10^{-1}$	$0.5 < L \leq 1$, SA
III	$10^{-3} < P_{rr} \leq 10^{-2}$	$1 < L \leq 3$, SA
II	$10^{-4} < P_{rr} \leq 10^{-3}$	$3 < L \leq 12$, SA
I	$0 \leq P_{rr} \leq 10^{-4}$	$L > 12$, DA

(4) Volcanos

Volcanos could cause other disasters, such as earthquakes, tsunamis, and landslides and so on, which would further increase the tension of submarine cables resulting in breakage. The occurrence possibility of submarine breakage caused by volcanos can be assessed through volcanic explosivity index (VEI) [18]. The eruption probability of the volcano in the next year can be calculated based on the VEI, which is related to the number of volcanic eruptions with VEI level, and the time interval between the earliest eruption in history and the most recent one. The eruption probability denoted with P_{vol} is used to evaluate the probability of damage to submarine cables caused by volcanos. Since the volcanos cause damage to submarine cables by increasing the tension of submarine cables, which is similar to that of the earthquakes. Therefore, the damage levels of volcanoes are the same as that of earthquakes. The occurrence possibility and damage levels of the volcanos are ranked in Table 5.

Table 5. The occurrence possibility and damage levels of volcanos.

Rank Level	Occurrence Possibility	Margin Length L (m), Cable Type
V	$10^{-1} \leq P_{vol} < 10^0$	$0 < L \leq 0.5$, SA
IV	$10^{-2} \leq P_{vol} < 10^{-1}$	$0.5 < L \leq 1$, SA
III	$10^{-3} \leq P_{vol} < 10^{-2}$	$1 < L \leq 3$, SA
II	$10^{-4} \leq P_{vol} < 10^{-3}$	$3 < L \leq 12$, SA
I	$0 < P_{vol} \leq 10^{-4}$	$L > 12$, DA

(5) Submarine slope

Seabed areas of higher slope are more prone to generate hazards, which would increase the tension of submarine cables, and could further lead to damage. Therefore, the possibility of damage to submarine cables caused by the slope can be assessed with its angle denoted with β . To improve the resistance of submarine cables to damage caused by the slope, some margin of submarine cable should be reserved [19]. The occurrence possibility and damage levels of the submarine slope are ranked in Table 6.

Table 6. The occurrence possibility and damage levels of submarine slope.

Rank Level	Occurrence Possibility (°)	Margin Length L (m), Cable Type
V	$\beta > 40$	$0 < L \leq 0.5$
IV	$30 < \beta \leq 40$	$0.5 < L \leq 1$
III	$20 < \beta \leq 30$	$1 < L \leq 3$
II	$10 < \beta \leq 20$	$3 < L \leq 10$
I	$0 < \beta \leq 10$	$L > 10$

(6) Marine organisms

The potential hazard to the submarine cable caused by marine organisms is that the submarine cable could be bitten by marine organisms, such as sharks in the deep sea. We use the proportion of submarine cables bitten by marine organisms denoted with P_{fish} to evaluate the possibility of marine organism damage to the submarine cables. Previous research has revealed that P_{fish} is correlated with latitude [20] and the depth of the water [21]. An effective way to prevent the submarine cables from being bitten by marine organisms is using submarine cables with proper protection measures. The occurrence possibility and damage levels of marine organism are summarized in Table 7.

Table 7. The occurrence possibility and damage levels of marine organisms.

Rank Level	Occurrence Possibility (%)	Cable Type
V	$P_{fish} > 60$	Light cable
IV	$30 < P_{fish} \leq 60$	SA
III	$20 < P_{fish} \leq 30$	Light protective cable
II	$10 < P_{fish} \leq 20$	DA
I	$0 < P_{fish} \leq 10$	Rock armored cable

The risk matrix is used to generate a hybrid assessment considering both the occurrence probability and damage levels of risks. To assess the relative importance of the six risks mentioned above, the ranking method and analytical hierarchical process (AHP) introduced in [22] are used to determine the weight values w_i for the i th risk consideration. Assuming that $A_{s_i}(\xi)$ denotes the hybrid assessment score of i risk at ξ and its weight is w_i , the final evaluation score of i risk can be described as

$$A(\xi) = \frac{\sum w_i \times A_{s_i}(\xi)}{\sum E_i \times w_i} \quad (7)$$

where i represents six types of the risk and E_i is a symbol factor. E_i is set to 1 when the i risk consideration exists; otherwise, it is set to 0. Therefore, the risk assessment score of $e_i = (v_i, v_{i+1})$ and that of γ can be respectively described as

$$f_s(e, v_i, v_{i+1}) = \frac{l_{v_i v_{i+1}}}{2} A(v_i) + \frac{l_{v_i v_{i+1}}}{2} A(v_{i+1}) \quad (8)$$

$$F_s(\gamma, v_0, v_{n-1}) = \sum_{i=0}^{n-2} f_s(e_i, v_i, v_{i+1}) \quad (9)$$

3. Problem Formulation and Solution**3.1. Multi-Objective Optimization**

Based on the models of the costs and the risk assessments, the multi-objective optimization model of submarine cable path γ can be described as

$$\min Z(\gamma) = [F_c(\gamma, s, d), F_s(\gamma, s, d)] \quad (10)$$

where $F_c(\gamma, s, d)$ and $F_s(\gamma, s, d)$ refer to the costs and the risk assessment score of the submarine cable path γ . The starting point and the ending point of γ are marked as s and d . Then, $F_c(\gamma, s, d)$ and $F_s(\gamma, s, d)$ can be described as

$$F_c(\gamma, v_0, v_{n-1}) = \sum_{i=0}^{n-2} f_c(e_i, v_i, v_{i+1}) \quad (11)$$

$$F_s(\gamma, v_0, v_{n-1}) = \sum_{i=0}^{n-2} f_s(e_i, v_i, v_{i+1}) \quad (12)$$

subject to: $e_i = (v_i, v_{i+1}), e_i \in \gamma$

$v_0 = s, v_{n-1} = d$

$\forall v_i \in \gamma$, the number of segments containing v_i does not exceed 2.

3.2. Solution

To solve the multi-objective optimization problem described in Formulas (10)–(12), the ACO is adopted in this paper. The ACO is generally used to solve distance-related or single-goal optimization problems. However, the costs and risks of the submarine cable path should be optimized simultaneously in submarine cable route planning. Therefore, some improvements to the ACO should be made for achieving multi-objective optimization of submarine cable route planning.

Assuming the total number of ants is N_{ant} , each ant is tagged with $k (k = 1 \dots N_{ant})$. The ant k located at v_i position at the t moment, will go to v_j with the probability of p_{ij}^k . p_{ij}^k can be described as

$$p_{ij}^k = \begin{cases} \frac{[\tau_{ij}(t)]^\alpha [\eta_{ij}(t)]^\beta}{\sum_{j \in allowed_{ik}} [\tau_{ij}(t)]^\alpha [\eta_{ij}(t)]^\beta} & j \in allowed_{ik} \\ 0 & \text{other} \end{cases} \quad (13)$$

where τ, η refer to pheromone and heuristic function, respectively; α, β are the pheromone factor and heuristic function factor, which indicate the importance of pheromone and heuristic function, respectively; $allowed_{ik}$ represents the node sets that can be selected by the ant k , which is composed of the neighbor points of v_i excepting the nodes that have already been chosen by ant k . As mentioned above, τ and η need to be modified to make the ACO suitable for use in submarine cable route planning in the case of multi-objective optimization. The η_{ij} considering both the costs and risks can be described as

$$\eta_{ij} = 2 - \frac{f_c(i, j) - Minf_c(i)}{Maxf_c(i) - Minf_c(i)} - \frac{f_s(i, j) - Minf_s(i)}{Maxf_s(i) - Minf_s(i)} \quad (14)$$

$$Minf_a(i) = \min\{f_a(i, j)\}, j \in allowed_{ik}, a = c, s \quad (15)$$

$$Maxf_a(i) = \max\{f_a(i, j)\}, j \in allowed_{ik}, a = c, s \quad (16)$$

To accelerate the convergence process and to avoid falling into suboptimal solution, two strategies—global pheromone update and local pheromone update—are proposed in this paper. The global pheromone update uses the global information to calculate τ_{ij} in the next moment after all the ants have already finished searching, which can be described as

$$\tau_{ij}(t+1) = (1 - \rho) \times \tau_{ij}(t) + c \sum_{k=1}^{N_{ant}} \Delta \tau_{ij}^k(t, t+1) \quad (17)$$

where ρ is the pheromone volatilization factor and $\Delta\tau_{ij}^k(t, t+1)$ is the pheromone released by ant k on the segment $e_i = (v_i, v_j)$. Considering both the costs and risks, $\Delta\tau_{ij}^k(t, t+1)$ can be described as

$$\Delta\tau_{ij}^k(t, t+1) = 1 - \left[\left(\frac{f_{tot_c}^k - \text{Min}f_{tot_c}}{\text{Max}f_{tot_c} - \text{Min}f_{tot_c}} \right) + \left(\frac{f_{tot_s}^k - \text{Min}f_{tot_s}}{\text{Max}f_{tot_s} - \text{Min}f_{tot_s}} \right) \right] \quad (18)$$

where $f_{tot_c}^k$ and $f_{tot_s}^k$ represent the total costs and the total risk assessment score of a feasible submarine cable route searched by the ant k . The minimum costs and minimum risk assessment score of all the feasible submarine cable paths are denoted by $\text{Min}f_{tot_c}$ and $\text{Min}f_{tot_s}$, respectively, and the corresponding the maximum ones are represented using $\text{Max}f_{tot_c}$ and $\text{Max}f_{tot_s}$. In addition to the global pheromone update, the pheromone of the feasible submarine cable path should be updated when an ant has already arrived at the ending point, i.e., the local pheromone update. The local pheromone update can expand the search space, allowing the ACO to avoid falling into local optimum, and it can be described as

$$\tau_{ij}(t+1) = (1 - \gamma) \times \tau_{ij}(t) + \gamma\tau_0 \quad (19)$$

where γ is the pheromone volatilization factor, which is set to be the same as ρ in the simulation, and τ_0 represents the initial pheromone. The combination rules of randomness and directionality is adopted for next node selecting to accelerate convergence and achieve global searching, which chooses the next node selecting rule through a random variable. Assuming that $q_0 (0 < q_0 < 1)$ is a decision threshold constant, q is a random number in the range (0–1). The node of $\max_{j \in \text{allowed}_{ik}} \{ [\tau_{ij}(t)]^\alpha [\eta_{ij}(t)]^\beta \}$ will be chosen as the next node if $q \leq q_0$, i.e., the directionality rule. Otherwise, the next node will be chosen from Equation (13) by means of a turntable, i.e., the randomness rule.

The flow chart of the ACO is shown in Figure 2. First, the method depicted in Section 2 is used to create the DS maps of costs and risks. Second, each ant will be placed at the starting point, and they will search for the feasible submarine cable paths point by point according to the methods described in Section 3.1. Finally, the Pareto sets could be obtained by analyzing all feasible submarine cable paths. It is worth emphasizing that the search ability of the ACO algorithm is closely related to N_{ant} , and the optimal N_{ant} will be studied later. Meanwhile, it is reasonable to divide N_{ant} into several ant subgroups, and these ant subgroups search in parallel to accelerate the convergence process in practice.

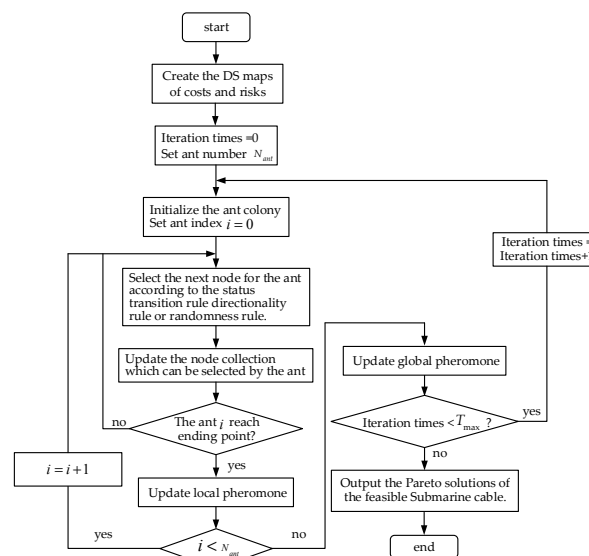


Figure 2. Flow chart of multi-objective ant colony optimization algorithm.

4. Results and Discussion

To verify the search ability of the ACO algorithm, we design an area with a high density of risks as the target region. A bay-like region $\mathbb{R}$ from the southwest point (18.52°N, −72.83°W) to the northeast point (18.76°N, −72.4339°W) is chosen to illustrate the methodology mentioned above. The DEM of $\mathbb{R}$ can be obtained from the website <https://download.gebco.net>, as shown in Figure 3a. The DS map is adopted to build the situation field of various factors, with a resolution of about 500 m × 500 m. Several risk factors, e.g., volcanos, are designed in region $\mathbb{R}$ to illustrate the effectiveness of the methodology, as shown in Figure 3b. It can be seen from Figure 3b that the risks are dense in region $\mathbb{R}$, which is harsh enough to test the search ability of the ACO algorithm. The locations of the starting point and the ending point refer respectively to (18.7326°N, −72.8082°W) and (18.5436°N, −72.4813°W), which are marked with green pentagrams in Figure 3b.

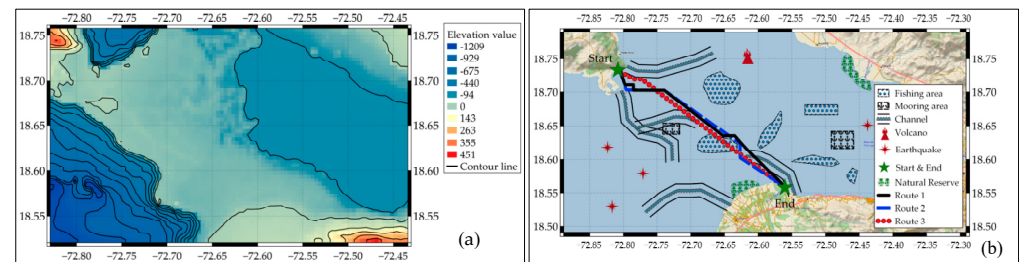


Figure 3. The (a) DEM and (b) risk distribution map in region $\mathbb{R}$.

4.1. Quantification of Costs and Risks

The risk matrix is used to generate a hybrid assessment for the six risks given in the Tables 2–7, in which both the risk occurrence probability and its damage levels are taken into account. The risk occurrence probability and its damage levels are distributed in two dimensions of risk matrix, respectively. The intersection of the two dimensions is evaluated and ranked according to practical experience, which is then used as the hybrid assessment. The hybrid assessments are categorized into four levels, high risk, medium-high risk, medium risk and low risk, with corresponding scoring bands of [0, 1], (1, 2], (2, 3], and (3, 4], respectively, as shown in Figure 4.

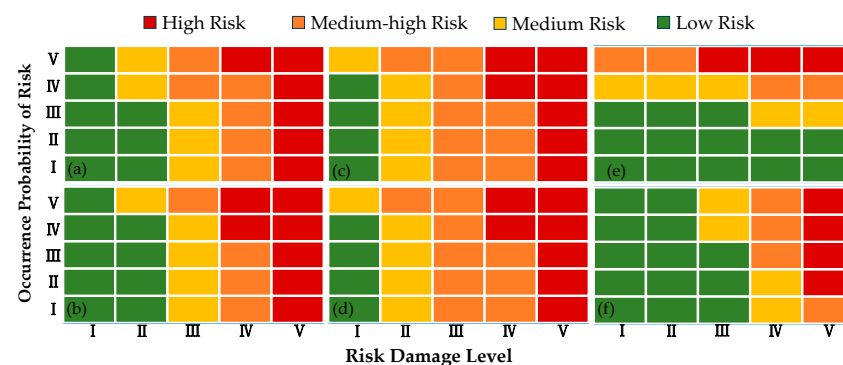


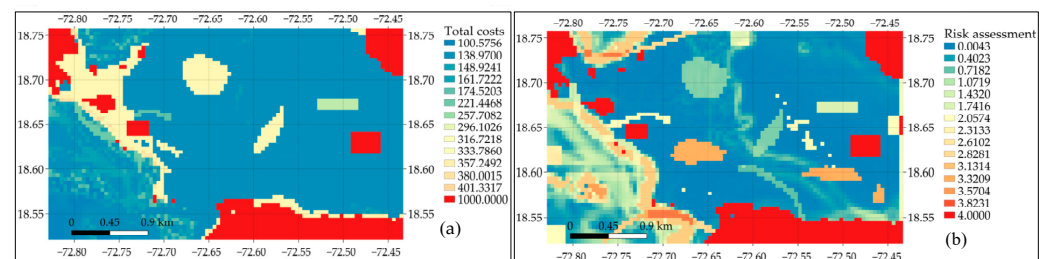
Figure 4. The hybrid assessments of (a) fishery activities, (b) shipping activities, (c) earthquakes, (d) volcanos, (e) submarine slope, and (f) marine organism, respectively.

Saaty’s ranking method is used to calculate the w_i of the i th risk considerations, for which the comparison matrix is summarized in Table 8. Assuming that n_{ij} represents an element of the assessment matrix, then the i th risk is more important than the j th one if $n_{ij} > 1$. Then, the AHP introduced in [22] is utilized to translate the qualitative prioritization into weight values for the corresponding design considerations. The weight values for earthquake, volcano, marine organism, submarine slope, fishery activities, and shipping activities are 7.138%, 8.968%, 2.976%, 7.138%, 52.134%, and 21.645%, respectively.

Table 8. The comparison matrix for risks.

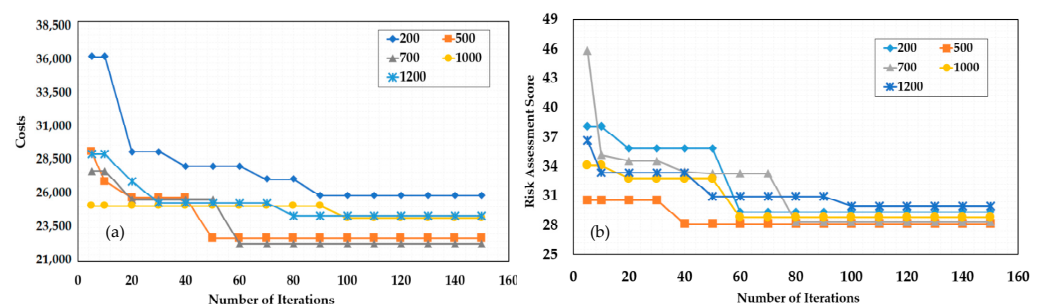
Risk Types	Earthquake	Volcano	Marine Organism	Submarine Slope	Fishery Activities	Shipping Activities
Earthquake	1	0.5	4	1	0.143	0.25
Volcano	2	1	3	2	0.125	0.2
Marine organism	0.25	0.333	1	0.25	0.111	0.167
Submarine slope	1	0.5	4	1	0.143	0.25
Fishery activities	7	8	9	7	1	6
Shipping activities	4	5	6	4	0.167	1

Based on the quantification of costs and risks, we can calculate the distribution of various risk factors. According to engineering experience, the C_{LW} is set to 70. The C_{max} should be set to a high value so that the ACO algorithm can effectively avoid some forbidden areas, and the C_{max} is set to 1000 in the simulation. The depth of water can be obtained by DEM. The total costs per kilometer of a node in region $\mathbb{R}$ can be calculated through Formulas (3) and (4), for which the distribution is shown in Figure 5a. To maximize the reliability of submarine cables, the occurrence probability of all risks is assumed to be the highest level. The distribution of risk assessment can be obtained through risk matrices and the AHP, as shown in the Figure 5b.

**Figure 5.** The distribution of (a) total cost and (b) risk assessment in region $\mathbb{R}$.

4.2. Optimal Setting Parameters of the Ant Colony Algorithm

As mentioned above, the search ability of the ACO algorithm is closely related to N_{ant} . To find the optimal number of ants, we set α , β , τ_0 , p_0 , and T_{max} to 1, 1, 1, 0.9, and 150, respectively, and we set N_{ant} to 200, 500, 700, 1000, and 1200, respectively. The convergence process of the total costs and risk assessment score in the case of different ant numbers is shown in Figure 6a,b. It can be seen that the convergence process of the total cost and risk assessment scores first accelerates and then slows down as the number of ants increases. The fastest convergence of both total costs and risks assessment score can be achieved when N_{ant} is 500. However, the minimum of both total costs and risk assessment score can be obtained in the case of $N_{ant} = 700$. As the target of this paper is to achieve multi-objective optimization of total cost and risk assessment, N_{ant} is set to 700 in the simulation. In addition, the number of iterations at which both total cost and risk assessment score reach convergence in the case of $N_{ant} = 700$ is less than 100. Therefore, T_{max} is set to 100, which has reserved sufficient margin.

**Figure 6.** The convergence of (a) total costs and (b) risks in cases of different N_{ant} .

4.3. Multi-Objective Optimized Submarine Cable Path Planning

Based on the models described above, we plan to design a submarine cable path conforming to the multi-objective optimization described in Formulas (10)–(12). The feasible solution sets and Pareto frontier is shown in Figure 7a. Each point of feasible solution sets represents a feasible submarine cable route, which are dominated by the Pareto frontier. The Pareto frontier is the non-dominated feasible solutions, which provide us with the results of the optimization problems of minimizing total costs subject to a risk assessment score and minimizing risk assessment score subject to certain total costs. As can be seen from Figure 7a, there are three feasible solutions located at the Pareto frontier. When the costs of a Pareto submarine cable path are low, its risks are higher, such as route 3. When the costs of a Pareto submarine cable path are high, its risks are low, such as route 2. Therefore, the costs and risks of submarine cables are two conflicting optimization objectives.

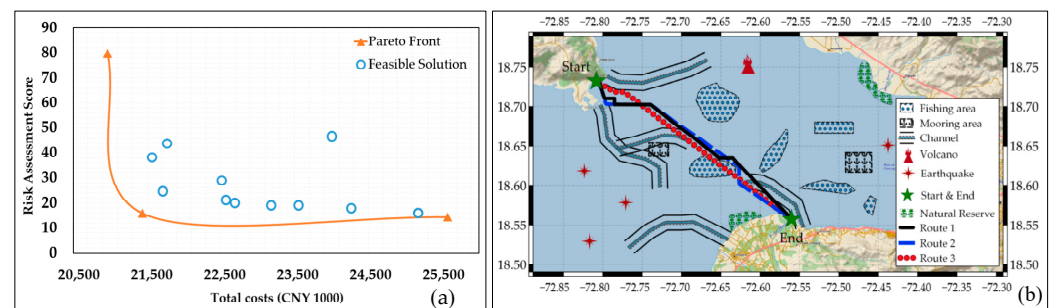


Figure 7. The (a) Pareto optimal frontier and (b) corresponding submarine cable route.

The paths of three feasible solutions locate at the Pareto frontier are drawn in Figure 7b. Since the Pareto frontier may have more than one solution, we define a composite score based on total costs and risk assessment score to further judge which solution is the optimum. Assuming the number of Pareto sets is N_p and the index of the Pareto solution is p ($p = 1 \cdots N_p$), F_c^p and F_s^p are the total cost and risk assessment of the Pareto solution denoted with p . The average total cost and average risk assessment of the Pareto sets are F_c^{avg} and F_s^{avg} , respectively; then, the composite score of the solution p can be described as $U_p = F_c^{avg} / F_c^p + F_s^{avg} / F_s^p$. The optimal solution of the Pareto sets is the one with the maximum composite score. The total costs of routes 1–3 are 21,437.9, 25,574.8, and 20,967, and their corresponding risk assessment scores are 15.9852, 14.4235, and 79.8103, respectively. Then, the composite score of submarine cable routes 1–3 are 3.3554, 3.4332, and 1.5411, respectively. The maximum composite score of the Pareto sets is 3.4332, corresponding to submarine cable route 2. It can be seen from Figure 7b, compared with route 1 and route 3, route 2 obviously avoids both high-cost and high-risk areas more effectively, which further confirms that the scheme proposed in this paper has a guiding function on submarine cable route planning in practice. Relying on the robust search ability of ACO, we can obtain the Pareto solutions for total cost and risk assessment score optimization for submarine cable route planning, which does not require converting the multiple objective optimization to the single one.

5. Conclusions

A methodology that can be used for submarine cable route planning under the conditions of multi-objective optimization was proposed and numerically studied in this paper, in which the total cost and six classical risks were taken into account simultaneously. The total cost and risks were numerically evaluated and mapped to the geographical location. An improved ACO algorithm was designed, making it suitable for searching the Pareto sets of submarine cable route under the condition of optimizing both the total cost and risks through associating its pheromone and heuristic functions with the total cost and risks. A composite score was defined to determine which solution of Pareto sets could be

used as the optimum submarine cable path. Finally, the methodology was verified through a scenario of submarine cable route planning. The results show that the submarine cable route planned by the methodology clearly avoids both high-cost and high-risk areas, which confirms that the methodology has a guiding function on submarine cable route planning in practice.

Author Contributions: Conceptualization, G.G. and J.W.; methodology, J.W. and Z.Z.; software, J.W. and Z.Z.; validation, J.W., H.W. and Z.Z.; formal analysis, J.W. and Z.Z.; investigation, H.W.; resources, H.W.; data curation, H.W.; writing—original draft preparation, J.W. and Z.Z.; writing—review and editing, J.W., Z.Z., D.W. and G.G.; visualization, Z.Z. and D.W.; supervision, G.G.; project administration, G.G.; funding acquisition, G.G. and D.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by National Key Research and Development Program of China (2022YFB2903300), State Key Laboratory of Information Photonics and Optical Communication Grant (IPOC2020ZZ02), and the National Natural Science Foundation of China (No. 62141505).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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