Vessel-UAV Collaborative Routing Problem for Offshore Oil and Gas Fields Inspection*

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***Abstract*—This paper proposes a new mode of vessel-UAV collaborative inspection to address the challenges of high cost, low frequency, and high risk in the traditional offshore oilfield inspection. In the studied problem, a patrol vessel with a UAV departs from the port, sails to a specific location, releases the UAV for oilfield inspection, and retrieves the UAV at another location after the inspection. Considering the spatio-temporal cooperation between ships and UAVs and the variation of endurance capability of UAVs, the collaborative inspection routing problem of "single vessel and UAV take off to visit multiple target points" is studied, with a target of minimizing the total variable cost of the vessel and UAV and the sailing time of the vessel. A mixed integer second-order cone programming model based on the time period and the moment of time was established, respectively, to calculate the objective function value of the inspection routing cost. The commercial solver CPLEX is used to solve the proposed models. Numerical experiments based on actual and randomly generated cases are conducted to verify the efficiency of the model. In addition, sensitivity analysis is performed in our paper, including UAV endurance and speed, which can inspire managers for scheduling optimization in practice.**

***Index Terms*—offshore oilfield inspection, vessel-UAV collaborative, integrated routing optimization, mixed integer second-order cone programming**

I. INTRODUCTION

Regular inspections of oil and gas fields are crucial for preventing leaks and ensuring safe oilfield production. Traditionally, people utilize the patrol vessel to perform inspection tasks, which have proven inefficient, risky, and costly. With the advancement of intelligent technology, unmanned aerial vehicles (UAVs) have emerged as promising solutions in various fields, including logistics [1] and inspection [2−3], to improve efficiency and reduce costs. By replacing traditional joint inspections, UAVs can be equipped with lasers, cameras, and other essential tools to conduct oilfield inspections. However, given their limitations in cruise ability and the challenging environmental conditions, such as harsh weather, wind, and fog, it can be challenging for UAVs to conduct inspections independently, particularly considering the vast span and wide range of oilfield distribution sea areas. Therefore, it is recommended to utilize the vessel-UAV collaborative inspection mode for inspections, which combines the long endurance and stability of patrol vessels with the flexibility and mobility of UAVs.

The vessel-UAV collaborative inspection mode involves a vessel departing from the port with a UAV onboard to perform inspection tasks. Upon arrival at the designated location, the UAV is released from the vessel to conduct the necessary oilfield inspections. Once the tasks are complete, the UAV returns to the vessel, which then proceeds to other tasks. During the UAV's operation, the vessel moves slowly instead of staying in a fixed location. This mode has gained significant attention from various enterprises and led to a new vessel-UAV routing problem(VURP). This problem requires consideration of the coordination between the UAV and the vessel in both time and space dimensions, resulting in a combined decision for both vessel and UAV routing. This is in contrast to single UAV scheduling [4−5] and routing problems [6−7].

The vessel-UAV routing problem(VURP) is a kind of vehicle-UAV problem where the vehicle can be a truck, vessel, or any other tool capable of carrying UAVs. In the context of road transportation, UAVs are usually transported on trucks. For example, Murray et al. [8] investigated the single-vehicle UAV problem and introduced the concept of "accompanying flying travel." This involves the truck delivering goods while the UAV is in flight, aiming to minimize the maximum completion time of all distribution tasks. Cavani et al. [9] focused on the single-drone scenario, allowing one vehicle to carry multiple drones. They formulated a mixed-integer programming model and proposed an accurate algorithm combining MILP and branch cutting. Wang et al. [10] extended the problem to consider multi-vehicle-multi-UAV cases with an objective function of minimizing travel time. Schermer et al. [11] developed the first MILP model for the multi-vehicle-multi-UAV problem and proposed inequalities to strengthen the model. A mathematical heuristic algorithm based on the problem's structure and characteristics was designed for this problem. In road transportation, most of the studies above assume that vehicles travel along a fixed path in a given road network, with UAVs taking off and landing at designated mission nodes.

When UAVs are transported by vessels, the navigation of the carrier and UAV is not restricted by road networks, allowing them to sail in any direction within a designated area. UAVs can take off and land at any position within the plane, known as the mothership-UAV routing problem (MURP). Currently, the MURP has captured the attention of some researchers. For example, Poikonen et al. [12] investigated a type of MURP facing multiple monitoring and rescue tasks, aiming to minimize the time required to visit all nodes under a given stage access order. Amorosi[13] focus on the mothership-multi-UAVs problem to minimize the weighted traveling distance between the mothership and UAVs. Subsequently, the author extended the above problem to the case of access to multiple target points, considering access to a single point or polygon chain[14]. Gambella et al. [15] modeled the MURP problem as a mixed integer second-order cone programming model and proposed an accurate algorithm. Erdogan et al. [16] analyzed the structure of MURP and proposed a mixed integer second-order cone programming model. In the oilfield inspection task scenario, only Xue et al. [17] have studied the VURP problem. However, this problem is formulated as a two-stage optimization model. The first stage optimized the UAV inspection route, and the second stage optimized the vessel inspection route without considering the collaborative optimization of the patrol vessel and UAV routing.

To this end, we study a novel vessel-UAV routing problem, which aims to optimize both vessel and UAV routing while allowing for the visitation of multiple target points in each flight. For this problem, we propose two types of formulations. Numerical experiments are then conducted on these formulations, and sensitivity analysis is designed to gain valuable insights and managerial implications.

II. Problem description and model formulation

A. problem description

Given a port denoted as P_0 and n oil field points located in a designated sea area, represented by P_i where $i = 1, 2, \ldots, n$, the coordinates of each location are known. A patrol vessel, equipped with UAVs, departs from the port to inspect the oil fields. Both the vessel and UAVs are unrestricted in their movement within the Euclidean plane $\mathbb{R}^2$. Once the vessel reaches a nearby location $P_{t_0,k}$, the UAV is released to perform one or more inspection tasks on the oil field points within its endurance range R. During UAV inspection, the vessel continues to sail at a constant speed until the UAV returns to the vessel at location $P_{l,k}$. The cost of vessel travel per unit distance is denoted by C_v, while the UAV cost per unit distance is represented by C_d. The speed of the vessel and UAV is defined as v_v and v_d, respectively.

In order to develop an effective inspection plan, several critical decisions need to be made, including: a) the route of the patrol vessel, b) the route of UAVs in each flight, including tasks assignment and sequence. The objective of the optimization problem is to minimize the total routing cost of both vessels and UAVs.

The question assumes:

• The system consists of one patrol vessel and one UAV;

• Both the patrol vessel and the UAV can move freely in the Euclidean plane;

• The departure port is also the final destination;

• The UAV has a limited endurance of R and can visit one or more oil field points within the endurance range per takeoff;

• The patrol vessel can depart only once from the departure port within the scheduling period;

• The charging time of the UAV is ignored, assuming battery replacement is used.

B. Mixed integer second-order cone model based on time period

The set, parameters, and decision variables are shown in Table I, Table II, and Table III, respectively.

TABLE I
SET

Parameter	Definition
N	Set of oil fields, $N = \{1, 2, \cdots, n\}$
K	Set of UAV takeoff times, $K = \{1, 2, \ldots, h\}$
Z	Set of integer

TABLE II
PARAMETER

Parameter	Definition
n	Number of target points
k	Number of UAV takeoffs
R	UAV endurance(distance)
p_0	Starting (initial port) coordinates of vessel
p_{n+1}	Destination (destination port) coordinates of vessel
p_i	The coordinates of the oil field i
C_v	Unit distance cost of the patrol vessel
C_d	Unit distance cost of UAV
v_v	The speed of the patrol vessel
v_d	The speed of UAV
c_{ij}	The distance between the i oil field and the j oil field is $\parallel p_i - p_j \parallel$
M	A huge constant

TABLE III
VARIABLE

Variable	Definition
$p_{to,k}$	The taking off coordinates for the k_{th} of the UAV
$p_{l,k}$	The landing coordinates for the k_{th} of the UAV
t_{vk}	The navigation time of the patrol vessel at the k_{th} UAV takeoff
t_{dk}	The service time of the UAV at the k_{th} takeoff
$t_{k,k+1}$	The navigation time of the patrol vessel from the k_{th} landing of the UAV to the $k+1_{th}$ takeoff point
T_s	The navigation time of the patrol vessel from the initial point to the first take-off of the UAV
T_f	The navigation time of the patrol vessel from the last landing of the UAV to the end point
v_{ik}	Equal to 1 if UAV takes off for the k_{th} time and inspects oil field i, 0 otherwise
x_{ij}^k	Equal to 1 if UAV flies from field i to field j on the k_{th} take-off, 0 otherwise

Using the symbols defined above, we formulate a mixed integer second-order cone programming as follows:

obj:

$$Z=\min\left\{C_v v_v(T_s+T_f)+\sum_{k\in K}C_v v_v(t_{vk}+t_{k,k+1})+\sum_{k\in K}C_d v_d t_{dk}\right. \tag{1}$$

s.t.

$$\| p_0-p_{to,1}\| \leq v_v T_s \tag{2}$$

$$\| p_{n+1}-p_{l,h}\| \leq v_v T_f \tag{3}$$

$$\| p_{to,k}-p_{l,k}\| \leq v_v t_{vk} \qquad \forall k\in K \tag{4}$$

$$\| p_{to,k+1}-p_{l,k}\| \leq v_v t_{k,k+1} \qquad \forall k\in K \tag{5}$$

$$\| p_{to,k}-p_i\| + \| p_{l,k}-p_j\| + \sum_{i=1}^{N}\sum_{j=1}^{N}x_{ij}^k c_{ij} \leq v_d t_{dk}+M(2-x_{0i}^k-x_{j0}^k) \qquad \forall i,j\in N,k\in K \tag{6}$$

$$\sum_{k=1}^{K}v_{ik}=1 \qquad \forall i\in N \tag{7}$$

$$\sum_{i\in N}x_{0i}^k\leq 1 \qquad \forall i\in N \tag{8}$$

$$\sum_{i\in N}x_{i,n+1}^k\leq 1 \qquad \forall i\in N \tag{9}$$

$$\sum_{i\in N_0\backslash\{n+1\}}x_{ih}^k=v_{hk} \qquad \forall k\in K,h\in N \tag{10}$$

$$\sum_{i\in N_0\backslash\{0\}}x_{hj}^k=v_{hk} \qquad \forall k\in K,h\in N \tag{11}$$

$$u_i-u_j+nx_{ij}^k\leq n-1 \qquad \forall i,j\in\{N\mid i\neq j\},k\in K \tag{12}$$

$$1\leq u_i,u_j\leq n \qquad \forall i,j\in N,i\neq j,u_i,u_j\in Z \tag{13}$$

$$v_d t_{dk}\leq R \qquad \forall k\in K \tag{14}$$

$$t_{vk},t_{dk},t_{k,k+1},T_s,T_f\geq 0 \qquad \forall k\in K \tag{15}$$

$$v_{ik},x_{ij}^k\in\{0,1\} \qquad \forall i,j\in N,k\in K \tag{16}$$

The objective function (1) represents minimizing the total inspection distance cost. Constraint (2) is the distance constraint of the first travel of the patrol vessel. Constraint (3) refers to the constraints on the distance of the patrol vessel in the last leg of its journey. Constraint (4) is the patrol vessel's sailing distance during the takeoff of the UAV. Constraint (5) is the sailing distance constraint of the ship between the first k landing and the first $k+1$ takeoff of the UAV. Constraint (6) is the distance constraint of the UAV. Constraint (7) means that each oilfield must be visited by a UAV. Constraints (8) and (9) indicate that the UAV can only go out once from the starting point. Constraints (10) and (11) represent the flow balance constraint. Constraint (12) and (13) is the subtour-elimination constraint. Constraint (14) is the constraint on the endurance capability of the UAV. Constraints (15) and (16) give the non-negative constraints of each decision variable and the 0,1 constraint.

C. Mixed integer second-order cone model based on time moment

Using time moment variables, such as UAV departure time $t_{t_0,k}$ and UAV landing time $t_{l,k}$, we proposed another formulation method for this problem. The decision variables are shown as follows:

TABLE IV
VARIABLE

Variable	Definition
$t_{to,k}$	The k_{th} departure time of the UAV (the moment when the ship sails to the departure point)
$t_{l,k}$	The landing time of the k_{th} UAV takeoff
$t_{k,k+1}$	The navigation time of the patrol vessel from the k_{th} landing of the UAV to the $k+1_{th}$ takeoff point
t_f	The moment the vessel returned to port
t_i	The moment when the UAV visits i

Based on time moment variables, this model can be reformulated as follows:

$$Z=\min\left\{C_v v_v t_f+\sum_{k\in K}C_d v_d(t_{l,k}-t_{to,k})\right\} \tag{17}$$

s.t. (8)–(12)

$$\| p_0-p_{to,1}\| \leq v_v t_{to,1} \tag{18}$$

$$\| p_{n+1}-p_{l,h}\| \leq v_v(t_f-t_{l,K}) \tag{19}$$

$$\| p_{to,k+1}-p_{l,k}\| \leq v_v(t_{to,k+1}-t_{l,k}) \qquad \forall k,k+1\in K \tag{20}$$

$$\| p_{to,k}-p_{l,k}\| \leq v_v(t_{l,k}-t_{to,k}) \qquad \forall k\in K \tag{21}$$

$$\| p_i - p_{to,k} \| \leq v_d(t_i - t_{to,k}) + M(1 - x_{0i}^k) \quad \forall i \in N, k \in K \tag{22}$$

$$\| p_{l,k} - p_i \| \leq v_d(t_{l,k} - t_i) + M(1 - x_{i0}^k) \quad i \in N, k \in K \tag{23}$$

$$v_d(t_j - t_i) \geq c_{ij} - M(1 - x_{ij}^k) \quad \forall i, j \in N, k \in K \tag{24}$$

$$v_d(t_{l,k} - t_{t_0,k}) \leq R \quad \forall k \in K \tag{25}$$

$$t_{to,k}, t_{l,k}, t_f, t_i \geq 0 \quad \forall k \in K, i \in N \tag{26}$$

$$v_{ik}, x_{ij}^k \in \{0, 1\} \quad \forall i, j \in N, k \in K \tag{27}$$

The objective function (17) is to minimize the total inspection cost. Constraint (18) represents the constraint of the first journey of the patrol vessel from the port. Constraint (19) represents the distance constraint of the patrol vessel in the last leg of its journey. Constraint (20) is the sailing distance constraint of the ship between the first k landing and the first $k+1$ takeoff of the UAV. Constraint (21) is the patrol vessel's sailing distance during the takeoff of the UAV. Constraint (22) represents the distance constraint from the takeoff point of the UAV to the first point. Constraint (23) is the distance constraint between the landing point of the UAV and the last access point. Constraint (24) represents the distance constraint between any two points. Constraint (25) is UAV endurance constraint. Constraint (26)–(27) denotes the domain of variables.

D. Valid inequalities

When M is set to a large value, the constraints become highly restrictive, resulting in a more challenging linear programming problem. We can define a suitable value of M to improve the solving efficiency. The definition of this value is presented below:

$$M = 2R + \sum_{i=1}^{N-1} \sum_{j=1}^{N} c_{ij} \tag{28}$$

In formula (28), the constant M is a maximum value used to assist in determining the flight distance of unmanned aerial vehicles, which is constrained by calculating the double UAV endurance R and the total distance between any two points in the whole inspection area to ensure that the inequality remains true.

III. Experimental analysis

We conduct numerical computational experiments to evaluate the performance of our model. First, we present a real-world case of a company's offshore oilfield inspection task. Then, we generate 11 random instances to compare the above models and conduct a sensitivity analysis. The models are solved by CPLEX and coded in C++. The running environment is Intel(R)Core(TM)i5-7200UCPU,2.50GHz,8.0G machine with RAM.

A. Case studies based on actual data

In a real-world case, the oilfield inspection area contains one port and eight oilfields. The port coordinate is (0,0), and each oil field point is distributed within the horizontal coordinates of (0,150km) and the vertical coordinates of (-200km,200km). The specific coordinates are shown in Table V:

TABLE V
Port and oilfield data

Node	Type	Abscissa(km)	Ordinate(km)
0	Port	0.0	0.0
1	Oilfield	23.8941	-112.425
2	Oilfield	62.2837	-48.84
3	Oilfield	69.4232	-60.1657
4	Oilfield	108.632	31.0981
5	Oilfield	135.21	80.666
6	Oilfield	138.972	88.1536
7	Oilfield	92.176	162.927
8	Oilfield	19.421	42.1231

The oilfield inspection requires both patrol vessels and UAVs. Each patrol vessel has a sailing speed of 20km/h and a unit distance cost of 85 yuan/km. In contrast, UAVs offer faster speed and lower cost, with a flying speed of 90km/h and a unit distance cost of 5 yuan/km. It is worth noting that the drone has a maximum sailing distance of 90km.

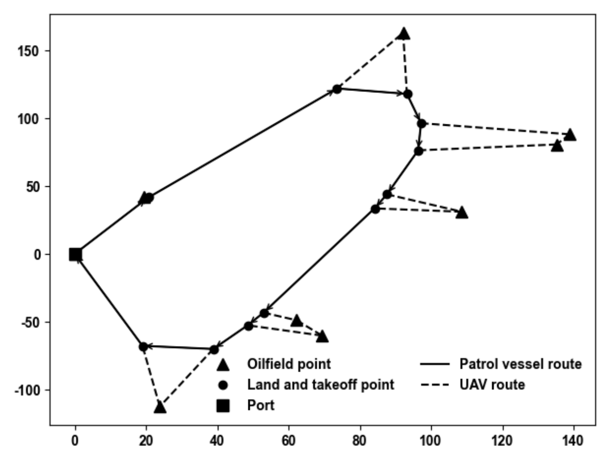

Fig. 1. Inspection roadmap

For this example, we provide an optimal inspection scheme with the lowest travel cost of 4,0313.7 yuan. The route of the vessel and UAV are shown in Figure 1. The detailed UAV take-off position and landing position are given in Table VI. Evidently, by leveraging the proposed model and solving for the optimal route, managers can effectively optimize vessel-UAV routing, leading to significant cost-saving benefits.

TABLE VI
RELEVANT COORDINATES OF UAVS

Node	Take-off coordinate	landing coordinate
Port	0.0	0.0
8	[20.4557,41.1668]	[20.7679,41.7096]
7	[73.6366,121.924]	[93.2357,117.939]
6→5	[97.2064,96.3189]	[96.3866,76.3357]
4	[87.6379,43.9276]	[84.1519,33.5631]
2→3	[53.0019,-43.2541]	[48.5557,-52.5647]
1	[38.8976,-70.0027]	[19.0323,-67.6857]

B. Model comparison based on random instances

This section compares two models introduced in Sections 2.B and 2.C. The model based on the time period allows the patrol vessel to wait at the same location for the UAV inspection. In contrast, the model based on the time moment requires the vessel to continue moving at a constant speed of v_v during the UAV inspection. The two models result in different cost patterns, and managers can choose a cost-saving route by comparing the objective function values of the two models. The number of oilfields to be inspected ranges from 5 to 15, and we use CPLEX to solve the solution for 3 hours (10800 seconds). "K" represents the takeoff times of the UAV, "Time" indicates the calculation time of each example, "LB" is the lower bound value, "Obj" is the target value obtained by solving the solution, and "Gap" is the percentage difference between the upper and lower bounds of CPLEX. The results are presented in Table VII and Table VIII.

TABLE VII
TIME PERIOD MODEL

Node	k	LB	Obj	Time	Gap
Example5	5	43519.5	43519.5	8.2	0.00%
Example6	4	44575.9	44575.9	137.2	0.00%
Example7	5	51204.2	51209.2	1366.9	0.01%
Example8	8	47517.4	47522.0	6997.4	0.01%
Example9	8	260.3	38285.7	10800.0	99.32%
Example10	5	280.3	49302.7	10800.0	99.43%
Example11	9	15446.2	39465.3	10800.0	60.86%
Example12	9	6.2	38697.5	10800.0	99.98%
Example13	12	0.0	62217.7	10800.0	100.00%
Example14	11	0.0	54232.1	10800.0	100.00%
Example15	11	0.0	43028.5	10800.0	100.00%
Average		18437.3	46550.6	**7646.3**	**59.97%**

The results presented in Tables VII and VIII show that waiting for the UAV inspection by the patrol vessel has a lower upper bound value than an unequal UAV inspection by the patrol vessel. This suggests that there will be higher costs when there are more time coordination constraints between the patrol vessel and UAV. Thus, when inspecting 15 or fewer oilfields, it would be more cost-effective for the patrol vessel to promptly wait for the UAV inspection.

TABLE VIII
MOMENT OF TIME MODEL

Node	k	LB	Obj	Time	Gap
Example5	5	46155.7	46155.7	22.0	0.00%
Example6	4	47121.6	47121.6	566.3	0.00%
Example7	5	26829.3	53686.6	6856.5	50.03%
Example8	7	2134.4	50594.0	10800.0	96.78%
Example9	8	0.0	41029.5	10800.0	100.00%
Example10	7	0.0	51350.7	10800.0	100.00%
Example11	9	0.0	43407.8	10800.0	100.00%
Example12	8	0.0	41460.9	10800.0	100.00%
Example13	11	0.0	61985.1	10800.0	100.00%
Example14	10	0.0	58492.3	10800.0	100.00%
Example15	12	0.0	68875	10800.0	100.00%
Average		11112.8	51287.2	**8889.8**	**76.89%**

IV. SENSITIVITY ANALYSIS

A. UAV endurance

Table IX shows the computation results where UAV endurance R=180. Compared with Table VII of the results with R=90, the objective value decreases significantly. The decrease in total cost can be attributed to two factors: firstly, the increase in endurance leads to an increased number of visited fields, thereby reducing the distance traveled by the UAV; secondly, the UAV can take off from a position further away from the field, thus reducing the travel distance of the vessel.

TABLE IX
ENDURANCE:R=180

Node	k	LB	Obj	Time	Gap
Example5	3	29544.5	29544.5	19.5	0.00%
Example6	4	30643.7	30641.0	308.2	0.00%
Example7	4	36691.9	36695.4	6856.5	0.01%
Example8	6	10358.5	34588.5	10800.0	70.05%
Example9	6	0.0	24075.2	10800.0	100.00%
Example10	6	0.0	36475.4	10800.0	100.00%
Example11	7	0.0	26281.4	10800.0	100.00%
Example12	7	0.0	25037.1	10800.0	100.00%
Example13	9	0.0	42926.5	10800.0	100.00%
Example14	10	0.0	39483.8	10800.0	100.00%
Example15	10	0.0	43619.3	10800.0	100.00%
Average		9748.7	33579.2	**8507.7**	**70.01%**

B. Vessel and UAV velocity

In this section, we investigate the effects of changing the speed of the vessel and UAV. Table VII presents the results for the initial parameters, where the UAV speed $v_d = 90$ and the vessel speed $v_v = 20$. We then analyze the impact of changing the UAV speed v_d to 180 and present the results in Table X. Similarly, we explore the effect of changing the vessel speed v_v to 40 and show the results in Table XI.

The experimental results indicate that the objective value increases as the speed of the UAV or vessel increases. When the speed of the UAV increases, it can complete the oilfield inspection task in less time, resulting in more cases of the UAV visiting an oilfield once taking off. As a result, the ship must travel a greater distance, increasing the total inspection cost.

TABLE X
VELOCITY:v_d=180

Node	k	LB	Obj	Time	Gap
Example5	5	44710.4	44710.4	6.1	0.00%
Example6	4	45694.3	45694.3	54.0	0.00%
Example7	6	52330.6	52335.6	1551.78	0.01%
Example8	8	48474.2	48479.0	9910.45	0.01%
Example9	7	17802.3	39575.4	10800.0	55.02%
Example10	6	751.9	50174.1	10800.0	98.50%
Example11	9	9111.2	40606.8	10800.0	77.56%
Example12	9	0.0	40559.5	10800.0	100.00%
Example13	11	0.0	69774.5	10800.0	100.00%
Example14	14	0.0	58467.3	10800.0	100.00%
Example15	12	0.0	49649.3	10800.0	100.00%
Average		19897.7	49093.3	**7920.2**	**57.37%**

TABLE XI
VELOCITY:v_v=40

Node	k	LB	Obj	Time	Gap
Example5	4	49679.0	49679.0	8.1	0.00%
Example6	5	50802.7	50802.7	89.2	0.00%
Example7	4	57212.7	57217.0	1509.0	0.01%
Example8	8	52885.7	52891.0	8675.8	0.01%
Example9	7	2688.6	45184.4	10800.0	94.05%
Example10	7	3373.8	54502.4	10800.0	93.81%
Example11	8	6595.6	47058.9	10800.0	85.98%
Example12	10	0.0	45681.7	10800.0	100.00%
Example13	12	0.0	84242.1	10800.0	100.00%
Example14	11	0.0	64855.3	10800.0	100.00%
Example15	11	0.0	59604.2	10800.0	100.00%
Average		20294.4	55610.8	**7807.5**	**61.26%**

Moreover, the consumption cost of the inspection vessel is directly proportional to its speed. The following formula can describe this relationship:

$$P = kv_v^3 \tag{29}$$

P denotes the fuel consumption cost of the inspection vessel, which is associated with speed v_v by a constant k. Obviously, as the vessel speed increases from v_v=20 to v_v=40, the cost also increases.

V. CONCLUSION

Implementing a novel collaborative vessel-UAV inspection mode can greatly improve efficiency and reduce operational costs. This study investigates a new vessel-UAV routing problem involving a single vessel and UAV that takes off to visit multiple target points to minimize total distance cost. Two models are proposed and solved using CPLEX, providing optimal solutions and significantly reducing total costs. Numerical experiments, including real-world examples and randomly generated instances, are conducted in this paper to demonstrate the effectiveness of our model. In addition, we perform sensitivity analysis for UAV endurance and speed changes, which is helpful for managers in selecting suitable parameters. Future research may expand this problem to multi-vessel and multi-UAV access scenarios and develop heuristics or exact algorithms for this problem.

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REFERENCES

[1] Daosen Zhai, Chen Wang, Haotong Cao, Sahil Garg, Mohammad Mehedi Hassan, Salman A. AlQahtani, "Deep neural network based UAV deployment and dynamic power control for 6G-Envisioned intelligent warehouse logistics system[J]," Future Generation Computer Systems,Volume 137, December 2022, Pages 164-172.

[2] Bartolini N, Coletta A, Maselli G, "A multi-trip task assignment for early target inspection in squads of aerial drones[J],"IEEE Transactions on Mobile Computing, 2020, 20(11): 3099-3116.

[3] Xia J, Wang K, Wang S, "Drone scheduling to monitor vessels in emission control areas[J]," Transportation Research Part B: Methodological, 2019, 119: 174-196..

[4] Peters J R, Bertuccelli L F, "Robust task scheduling for multi-operator supervisory control missions[J]," Journal of Aerospace Information Systems, 2016, 13(10): 393-406.

[5] Glock K, Meyer A, "Mission planning for emergency rapid mapping with drones[J]," Transportation Science, 2020, 54(2): 534-560.

[6] Otto A, Agatz N, Campbell J, et al, "Optimization approaches for civil applications of unmanned aerial vehicles (UAVs) or aerial drones: A survey[J]," Networks, 2018, 72(4): 411-458.

[7] Cheng C, Adulyasak Y, Rousseau L M, "Drone routing with energy function: Formulation and exact algorithm[J]," Transportation Research Part B: Methodological, 2020, 139: 364-387.

[8] Murray, C. C, Chu, A. G, "The flying sidekick traveling salesman problem: Optimization of drone assisted parcel delivery," Transportation Research Part C: Emerging Technologies, 2015, 54, 86-109.

[9] Cavani, S., Iori, M.,Roberti, R, "Exact methods for the traveling salesman problem with multiple drones," Transportation Research Part C: Emerging Technologies, 2021, 130, 103280.

[10] Wang, X., Poikonen, S.,Golden, B (2017), "The vehicle routing problem with drones: several worst-case results," Optimization Letters, 2017, 11(4), 679-697.

[11] Schermer, D., Moeini, M., Wendt, O, "A branch-and-cut approach and alternative formulations for the traveling salesman problem with drone," Networks, 2020, 76(2), 164-186.

[12] Poikonen, S.,Golden, B, "The mothership and drone routing problem," INFORMS Journal on Computing, 2020, 32(2), 249-262.

[13] Amorosi L, Puerto J, Valverde C, "Coordinating drones with mothership vehicles: The mothership and drone routing problem with graphs[J]," Computers & Operations Research, 2021, 136, 105445.

[14] Amorosi L, Puerto J, Valverde C, "An extended model of coordination of an all–terrain vehicle and a multivisit drone[J]," International Transactions in Operational Research, 2022.

[15] Gambella, C., Lodi, A., Vigo, D, "Exact solutions for the carrier–vehicle traveling salesman problem," Transportation Science, 2018, 52(2), 320-330.

[16] Erdoğan, G.,Yildirim, E. A. (2021), "Exact and heuristic algorithms for the carrier–vehicle traveling salesman problem," Transportation Science, 55(1), 101-121.

[17] Xue G, Li Y, Wang Z, "Vessel-UAV Collaborative Optimization for the Offshore Oil and Gas Pipelines Inspection[J]," International Journal of Fuzzy Systems, 2023, 1-13.