



## Modeling the optimal flight route of an unmanned aerial vehicle for conducting forest fire exploration

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**Abstract.** Between 2018 and 2023, more than 3,600 forest fires were recorded in Kazakhstan, burning 561,000 hectares and causing losses exceeding 192.8 billion tenge. Fire-prone areas such as the Borovoe forest illustrate a key operational challenge: when multiple ignition sites are detected simultaneously, no formal procedure exists for sequencing fixed-wing UAV reconnaissance to ensure minimal coverage time. In practice, route selection relies on operator judgment, increasing the risk of redundant paths and delayed assessment. This study evaluates the applicability of the Travelling Salesman Problem (TSP) as a computational basis for UAV mission planning within forest fire management. The reconnaissance task is formulated as an asymmetric integer programming model with subtour-elimination constraints. For a four-node test case based on representative distances, the optimal Hamiltonian circuit (1→4→2→3→1) achieves a total route length of 860 m, up to 47.7% shorter than non-optimal alternatives. The proposed approach is platform-agnostic and can support integration into decision-support systems for forest fire monitoring.

**Keywords:** unmanned aerial vehicle, forest fires, monitoring, travelling salesman problem, route optimization, discrete mathematics, decision support.

## Introduction

Kazakhstan's forests cover roughly 4.7% of the country's territory, yet they are disproportionately vulnerable to fire. The pine and birch stand of the Borovoe forest area in Akmola region – one of the ecologically and recreationally most important forest zones of northern Kazakhstan – regularly appears among the areas most seriously affected by summer fires. Statistical data for 2018-2023 paint a troubling picture nationwide: over 3,600 fire incidents, a total burnt area of 561,000 hectares, and verified material damage exceeding 192.8 billion tenge [1-2]. These numbers are not abstract: they represent destroyed ecosystems, displaced wildlife, degraded soils, and in the worst cases, human casualties among firefighting personnel.

Reducing this toll requires faster, more accurate initial reconnaissance and that is precisely where current practice falls short. When a fire is reported, the Commander of Forest Fire Extinguishing (CFE) needs a complete picture of the fire's perimeter, intensity, and spread direction before issuing a resource allocation order. Under current procedures, that picture is assembled piecemeal, and the time lost in the process can mean the difference between containment and catastrophe.

Forest fires carry human costs alongside material ones. Firefighting personnel operate under severe time pressure, and the CFE's decision-making capacity is directly constrained by information quality. Research on fire management practice in Kazakhstan confirms that commanders at the initial stage of a fire typically work with incomplete data on fire location, insufficient time to coordinate forces, and no standardized tool for rapid reconnaissance planning [3-7]. These are not isolated failures of individual commanders; they reflect a systemic gap in the operational toolkit.

Analysis of after-action reports from major fires that occurred in Kazakhstan between 2021 and 2023 identified four recurrent organizational failures that allowed fires to escalate beyond initial containment efforts [8]:

- absence of a unified system for determining the coordinates of the fire source between emergency response firefighting services and forestry workers;
- incorrect determination of fire scales;
- incorrect alignment of forces and means;
- untimely concentration of the needed number of forces and means.

Nowadays, innovative technologies are being integrated into all spheres of society, contributing to the development of various sectors of the economy and security assurance. Unmanned aerial vehicles (UAVs) are used to ensure fire safety in forests. Enabling forest monitoring and efficient detection of fires.

It should be noted that one of the ways to solve the problem of using UAVs for forest fire extinguishing is to use end-to-end digital technologies. In addition, there is currently no effective method of using UAVs for localization and elimination of forest fires, allowing for support of the implementation of appropriate measures aimed at ensuring protection of the population and territories.

Unmanned aerial vehicles offer a direct answer to several of these failures. A fixed-wing UAV, with its extended endurance and wide area coverage relative to multirotor platforms, is particularly well suited to reconnaissance over the large, sparsely accessible forest blocks typical of the Akmola region. Deployed early in an incident, it can supply the CFE with a georeferenced picture of multiple fire sites within minutes, closing the information gap that has historically driven poor initial resource allocation. Regulatory support for this approach already exists: current fire safety rules in Kazakhstani forests explicitly require the CFE to use UAVs for aerial visual

reconnaissance to assess fire scale and prepare a tactical extinguishing plan [8].

Yet the regulatory mandate to use UAVs has run ahead of the planning tools available to operators. The literature on UAV applications in forest fire contexts has developed rapidly over the past decade, addressing platform selection [9], sensor configuration [12], multi-UAV cooperative coverage [10], and base station placement [14]. What remains conspicuously underdeveloped is the route-planning layer: given a set of known or suspected fire sites that a single UAV must inspect, in what sequence should it visit them? This question is operationally critical because fixed-wing UAVs operate under tight energy budgets: a longer-than-necessary route can exhaust battery reserves before all sites have been covered. The thermal imaging payload carried by reconnaissance UAVs – whether scanning or matrix, short-wave or long-wave, observational or measuring – delivers value only if the aircraft reaches every target site. Route optimization is therefore a prerequisite for effective sensor use, not an optional refinement.

- based on the principle of obtaining aerial photographs (categorized into scanning and matrix thermal imagers);
- based on the spectral range (categorized into short-wave and long-wave thermal imagers);
- based on the possibility of temperature measurement (categorized into observational and measuring thermal imagers).

### **The methodology**

The study draws on published scientific literature, monographs, and regulatory materials related to UAV applications in emergency management, combinatorial optimisation, and forest fire response in Kazakhstan and internationally. Works were selected based on relevance to the research problem rather than journal prestige alone, with priority given to sources that either describe operational UAV deployments or present formal mathematical models applicable to route planning. Kazakhstani regulatory documents, particularly MES guidelines on fire safety in forests, were consulted to ensure that the proposed model aligns with existing procedural requirements rather than proposing solutions detached from operational context.

Three methodological threads run through the research. The first is systems analysis, which we use to map the UAV-based reconnaissance process as a whole – from the moment a fire alarm is received to the moment the CFE issues a tactical response order. Viewed as a system, the process involves the fixed-wing UAV platform and its endurance constraints, the thermal imaging sensor and its coverage requirements, the spatial distribution of fire sites across a forested landscape, wind and visibility conditions that affect flight paths, and the command structure of the responding fire service. Decomposing the process in this way reveals where the critical bottleneck lies: not in sensors or platforms, which are commercially available and operationally proven, but in the absence of a computationally grounded procedure for deciding the visit sequence across multiple sites. The central research question is therefore: can the Travelling Salesman Problem provide an exact, operationally viable solution to this sequencing task under the time constraints of a live firefighting operation? Our working hypothesis is that a TSP-based integer programme will produce a route measurably shorter than operator-intuitive planning, while satisfying the hard operational constraints of complete site coverage and a single visit per node.

The second methodological thread is integer linear programming, used to formalise the routing problem and derive an exact optimal solution. The UAV reconnaissance task is cast as an asymmetric TSP: asymmetric because flight time between two sites may differ depending on direction of travel (due to wind, terrain, or approach angle for a fixed-wing aircraft that cannot hover). The model introduces a virtual depot coinciding with the UAV launch point, and applies

subtour-elimination constraints to guarantee that the solution is a single connected circuit rather than disconnected sub-loops. The third thread is numerical scenario analysis: a concrete four-node distance matrix, constructed from plausible inter-site distances in a forested terrain context, is used to test the model and compare the optimal solution against all feasible alternative routes. The research proceeded through four sequential stages: (1) problem identification through literature analysis; (2) formal mathematical model construction; (3) numerical solution using the branch-and-bound method, appropriate for a small exact problem of this size; and (4) comparative analysis of the optimal route against alternatives to quantify the practical efficiency gain. Model assumptions and scalability limits are assessed in the final stage.

### Findings/Discussion

The core operational task addressed in this section is the following: a fixed-wing UAV is deployed from a base point to conduct reconnaissance over several fire sites detected within a forest zone. The operator must determine the visit sequence that minimizes total flight distance (or, equivalently, flight time at constant airspeed), subject to the requirement that every site is visited exactly once and the aircraft returns to its departure point. This is precisely the Travelling Salesman Problem, and we apply it here to produce a provably optimal route rather than rely on operator judgement.

Three hard constraints structure the problem. First, every designated fire site must be included in the route – partial coverage is operationally unacceptable because an unvisited site may represent a flank fire that could cut off extinguishing teams. Second, each site may be visited only once, since re-visits waste flight time and battery reserve. Third, the route must form a closed circuit, returning the fixed-wing UAV to its launch point for data download, refueling, or handover to a second mission. The objective is to minimize the total cost of the circuit, expressed here in terms of inter-site distance but directly convertible to flight time by dividing by cruise speed.

To apply the TSP model, we first compile the inter-site distance matrix. Distances are asymmetric, reflecting the fact that a fixed-wing UAV travelling between two sites may cover different ground distances depending on flight direction – a real operational consideration when wind or terrain affects the approach bearing.  $C^{ij}$ .

Let us determine that the formulated problem is integer. While  $x^{ij} = 1$ , if the UAV route runs from the  $i$ -th site to  $j$ -th site, and  $x^{ij} = 0$ , if it is not the case [15].

Formally, we introduce  $(n + 1)$  fire site, located where the first site is; then the distances from  $(n + 1)$  fire site to any other site, different from the first one, are equal to the distances from the first fire site. At the same time, if you can only fly out of the first fire site, then you can only fly into the  $(n + 1)$  site [16-18].

Additionally, we introduce integer variables equal to the number of the fire site on the UAV flight path:  $u_1=0$ ,  $u_{n+1}=n$ . In order to avoid closed flight routes, departure from the starting point and return to  $(n+1)$ , we introduce additional limitations linking variables  $x_{ij}$  and variables  $u_i$  ( $u_i$  – non-negative integers) [19].

Let us construct a mathematical model of the problem [16]:

$$\min \left( \sum_{i=1}^n \sum_{j=1}^n C^{ij} x^{ij} \right), i, j = 1, \dots, n, i \neq j, \quad (1)$$

$$\sum_{i=1}^n x^{ij} = 1, i \neq j, \sum_{j=1}^n x^{ij} = 1, j \neq i, \quad (2)$$

$$u^j + nx^{ij} \# n - 1, j = \frac{2}{n} + 1, i = \frac{1}{n}, i \neq j, \\ i=1, i \neq n+1, 0 \# u \# nx^{n+1} = x^1, i=2, \dots, n \quad (3)$$

To model the UAV flight route, a matrix of distances  $c_{ij}$  between fire sites is set (Table 1).

**Table 1. Matrix of distances between fire sites**

| Site № | 1        | 2        | 3        | 4        |
|--------|----------|----------|----------|----------|
| 1      | $\infty$ | 190      | 250      | 110      |
| 2      | 370      | $\infty$ | 260      | 580      |
| 3      | 100      | 500      | $\infty$ | 390      |
| 4      | 380      | 390      | 240      | $\infty$ |

To determine the optimal UAV flight route, let us create a mathematical model [15]:

$$Z_{\min} = 190x^{12} + 250x^{13} + 110x^{14} + 370x^{21} + 260x^{23} + 580x^{24} + 100x^{31} + \\ + 500x^{32} + 390x^{34} + 380x^{41} + 390x^{42} + 240x^{43} \quad (4)$$

$$\begin{aligned} x^{12} + x^{13} + x^{14} &= 1 & x^{21} + x^{31} + x^{41} &= 1 \\ x^{21} + x^{23} + x^{24} &= 1 & x^{12} + x^{32} + x^{42} &= 1 \\ x^{41} + x^{43} + x^{34} &= 1 & x^{13} + x^{23} + x^{43} &= 1 \\ x^{21} + x^{23} + x^{24} &= 1 & x^{14} + x^{42} + x^{34} &= 1 \end{aligned}$$

$$U^1 - U^2 + 4x^{12} \# 3$$

$$U^1 - U^3 + 4x^{13} \# 3$$

$$U^2 - U^3 + 4x^{23} \# 3$$

$$U^2 - U^4 + 4x^{24} \# 3$$

$$U^2 - U^1 + 4x^{21} \# 3$$

$$U^3 - U^1 + 4x^{31} \# 3$$

$$U^3 - U^2 + 4x^{32} \# 3$$

$$U^3 - U^4 + 4x^{34} \# 3$$

$$U^4 - U^2 + 4x^{42} \# 3$$

$$U^4 - U^3 + 4x^{43} \# 3$$

$$U^4 - U^1 + 4x^{41} \# 3$$

$$x^{ij} = \begin{matrix} 0 \\ 1 \end{matrix} - \text{non-negative integers}$$

where  $Z_{\min}$  – minimum UAV flight route;  $c_{ij}$  – distance between fire sites;  $U_i$  – number of visits to the  $i$ -th fire site.

Let us construct a graph of possible UAV flight routes between the fire sites (Figure 1).

The result of the numerical experiment is unambiguous: of all possible closed circuits connecting four fire sites and returning to the departure point, the sequence 1→4→2→3→1 at 860 m is the shortest. But the more telling finding is how much longer the alternatives are. Routing through sites in the order 1→2→3→4→1 adds 270 m to the journey, a 31.4% overhead and

1→3→2→4→1 adds 410 m, a 47.7% overhead. For a fixed-wing UAV operating on a finite battery, those overheads are not trivial.

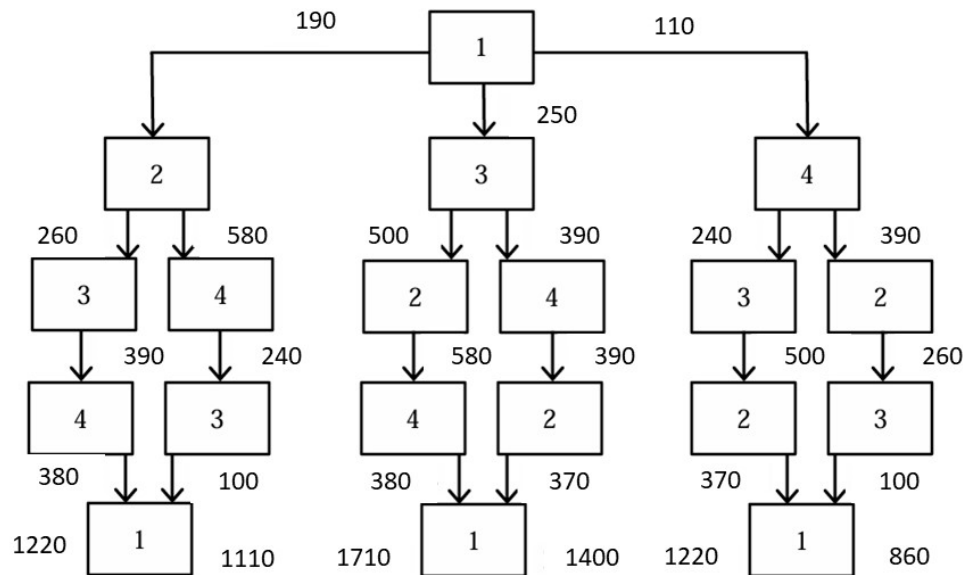


**Figure 1. Graph of possible UAV flight routes between the fire sites**

It can be seen from the figure 1 that the most optimal UAV flight route between the fire sites is  $1 \rightarrow 4 \rightarrow 2 \rightarrow 3 \rightarrow 1$ , while the distance amounts to 860 meters [20].

At a typical cruise speed of 60-80 km/h, a 400 m excess translates to roughly 20-25 additional seconds per reconnaissance cycle: a modest figure in isolation, but operationally significant when a fast-developing crown fire can double its perimeter in the same interval. The point is not the absolute numbers, which depend on specific site coordinates; it is that the TSP model consistently finds the optimum that an unassisted operator may miss, particularly under the cognitive load of a live emergency. How does this work relate to what has been done before? Studies of UAV deployment in forest fire contexts have tended to focus on two distinct problems: where to position UAV ground stations to maximize coverage [14], and how to coordinate multiple UAVs when several targets must be monitored simultaneously [10]. Both lines of research treat route assignment as important but stop short of providing an exact computational procedure for single-UAV multi-site sequencing in the specific operational scenario that a CFE faces when receiving an initial fire report covering several ignition points. Research on UAV sensor selection and platform specification for agricultural and environmental monitoring [9, 12] similarly leaves the routing layer unaddressed. The contribution here is narrow but necessary: it fills the gap between «we have a UAV with a thermal camera» and «here is the exact flight sequence that wastes least time and energy visiting every site». Within the Kazakhstan MES context specifically, to our knowledge, no prior published work has formalized this task as an integer program with subtour-elimination constraints. The formal model connects cleanly to the regulatory requirement in [8] for the CFE to conduct aerial reconnaissance, giving that requirement a computational backbone it currently lacks. Three practical implications follow from the model. First, it is directly implementable: a CFE

or UAV operator enters the coordinates of known fire sites, the system computes the inter-site distance matrix and solves the TSP, and outputs the optimal visit sequence within seconds a computation that requires no specialist mathematical knowledge from the user. Second, the objective function is interchangeable: substituting flight time (distance divided by cruise speed) or expected battery consumption (a function of distance and payload weight) does not change the model structure, only the coefficient matrix. This means the same framework works for different fixed-wing UAV models with different endurance profiles. Third, the model scales gracefully: for small numbers of sites ( $n \leq 10$ ), the branch-and-bound approach used here finds the exact optimum efficiently; for larger deployments involving 15-30 sites, well-tested heuristics such as nearest-neighbor initialization followed by 2-opt improvement can produce near-optimal solutions in real time. Several limitations require honest acknowledgement. The test case assumes that fire site positions are known before the mission begins in practice; a first-pass reconnaissance may reveal additional sites, requiring route revision mid-flight. The model also treats inter-site distances as deterministic, ignoring wind drift and restricted airspace that would affect a real fixed-wing UAV. Finally, four nodes constitute a minimal proof of concept; validation against scenarios with eight to twelve sites, using coordinates drawn from actual Borovoe or Kostanay region fire reports, is needed before operational deployment can be recommended.

## Conclusion

The question this paper set out to answer was whether the Travelling Salesman Problem can serve as a practical planning tool for fixed-wing UAV reconnaissance over multiple forest fire sites. The answer, supported by formal model development and numerical testing, is yes and the efficiency gain over intuitive routing is substantial enough to matter operationally. In the four-site test case, the TSP-optimal route was up to 47.7% shorter than the worst feasible alternative, a margin that translates directly into faster situation reporting and reduced risk of battery exhaustion before all sites have been covered.

For emergency management practice in Kazakhstan, where fire-prone regions such as the Borovoe forest zone of Akmola region place recurring demands on MES resources, the model offers a concrete and immediately codable upgrade to existing UAV operating procedures. It replaces the operator's subjective judgement on visit sequence, a weak link under the time pressure and informational stress of a live fire response, with a computation that takes seconds and produces a verifiably optimal result. The model requires no change to existing UAV hardware or sensor loadouts; it acts as a planning layer above the current workflow. Three directions for future work stand out: extending the model to handle eight to twelve sites typical of larger fire events, using fire report coordinates from Akmola or Kostanay region records as input data; incorporating wind-adjusted flight time into the cost matrix to make the model more accurate for fixed-wing operations; and developing a prototype decision-support interface that allows the CFE to generate and approve the optimal route before takeoff, within the existing MES software environment.

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### The contribution of the authors

A.I. Zaharov – conceived the research idea and defined the conceptual framework of the study; provided scientific supervision and critically revised the article for intellectual content.

A.B. Kussainov – contributed to the development of the mathematical model and the integer programming formulation; co-authored the Methods and Results sections.

M.M. Almenbayev – conducted the systematic literature review and synthesized source materials for the Introduction; participated in writing the article.

Zh.K. Makishev – performed the numerical implementation of the TSP model and verified the optimality of the computed route; contributed to drafting the Discussion section.

B.G. Salauat – participated in the interpretation of results in the context of Kazakhstan emergency management practice; finalized the article and verified compliance with journal formatting requirements.

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