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A Real-Time Decision Support Framework for Helicopter Dispatch During Multiple Simultaneous Forest Fires in the Republic of Korea

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Abstract

The Republic of Korea experiences over 500 forest fires annually, consuming more than 4000 ha. Helicopters are the primary resource for initial attack, but effectively dispatching these limited resources during multiple simultaneous fires poses a significant challenge, as these incidents compete for the same pool of helicopter resources. To support real-time, operational-level helicopter dispatch decisions, an interactive decision support framework was developed that integrates information gathering, fire prioritization, and dispatch optimization. This framework employs an integer linear programming (ILP) approach to minimize the weighted sum of suppression costs and resulting burn perimeters, while allowing for uncontained fires when fire spread rates exceed the cumulative suppression capacity of available helicopters. The framework was applied to two test cases: (1) five hypothetical simultaneous fire incidents, and (2) four actual simultaneous fire incidents recorded on 22 March 2025, with the resulting solutions compared against manual dispatch decisions made by the Korea Forest Service (KFS). The results demonstrate the framework's capability to analyze diverse fire suppression scenarios and generate a range of effective dispatch options. By integrating real-time fire behavior simulation and optimization, incorporating fire damage potential, and replicating the Republic of Korea's unique suppression practices, this framework aims to enhance real-time helicopter dispatch decision-making, contributing to the KFS's ongoing efforts to integrate scientific knowledge into forest fire suppression and management.

Keywords: fire suppression; integer linear programming; fire simulation; resource allocation; initial attack; wildland fire

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1. Introduction

The Republic of Korea, despite its relatively small land area of 100,363 km^2, faces significant challenges from forest fires due to its extensive mountainous terrain and the

close proximity of highly populated communities. Annually, the country experiences 567 forest fires, consuming more than 4000 ha per year on average between 2014 and 2023 [1]. The fire season is concentrated between February and May, frequently resulting in multiple simultaneous fire incidents across the country. Between 2014 and 2018, 62 percent of forest fires occurred simultaneously at different locations [2].

Helicopters are the primary resource for initial fire attack in the Republic of Korea, with 46 aircraft strategically positioned across 12 aviation stations [2]. Korea Forest Service (KFS) firefighting guidelines mandate that helicopter dispatch decisions, including type, number and origin, must be made within 15 min of the initial fire report [2]. While rapid and effective dispatch is crucial for successful fire containment, these decisions have been made manually by the Forest Fire Control Center (FFCC) of the KFS, relying heavily on the expert judgment and past experiences of a small group of experts. Helicopters are typically dispatched within their jurisdictional boundaries (e.g., province, district), but may be deployed to other areas for large-scale fires. A persistent challenge for the FFCC and local governments is making objective and justifiable dispatch decisions when multiple simultaneous fires compete for limited helicopter resources, particularly when incidents occur near jurisdictional boundaries or necessitate borrowing resources from other districts due to the large scale of fires.

Numerous studies have addressed the optimal allocation of initial attack resources at strategic, tactical, and operational decision levels [3]. Strategic decision-making involves pre-fire season allocation of key resources for long-term goals. For example, the LEOPARDS system developed in Ontario, Canada [4], provides a planning tool to evaluate fire management policies, budgets, and suppression resources for cost-efficient outcomes. Similarly, the SINAMI model in Spain [5] integrates fire suppression costs and net value changes due to fire damage in the development of suppression policy and budget. More recently, Gustafsson et al. [6] utilized optimization modeling and available fire risk data to support pre-wildfire location planning of aerial firefighting resources, aiming to increase the effectiveness of initial attacks.

Tactical decision-making, in contrast, focuses on resource allocation and relocation within a smaller area over shorter periods [3], including daily or weekly deployment and sharing of fire attack resources. Islam et al. [7] developed a daily air tanker simulation model to optimize dispatch for minimum initial attack response time, analyzing the impact of initial attack range, fire arrival rate, and operational timing for resource planning. Chow and Regan [8] proposed a location and relocation model for air tankers in California, using a statistical model of daily fire weather changes to inform effective resource reallocation during the fire season. Mathematical optimization approaches have been employed for daily dispatch decisions. Haight and Fried [9] developed a Stochastic Integer Programming (SIP) model to maximize the number of fires receiving a 'standard response' under initial attack. Lee et al. [10] expanded this model, combining scenario-based optimization with stochastic simulation to improve fire attack resource dispatch under budget and location constraints. However, these models mainly focused on pre-fire season tactical deployment of fire attack resources based on the probability of fire occurrence and spread. More recently, Mendes and Alvelos [11] developed a metaheuristic approach to identify effective locations for available fire suppression resources, aiming to minimize both the burned area and the number of deployed resources while considering fire spread across the landscape.

While strategic and tactical decision tools offer valuable insights for future resource allocation, the unpredictable nature of fire occurrence and spread highlights the importance of effective operational decisions at the time of fires. Yet, until recently, few studies had focused on real-time operational decision support for immediate resource dispatch, despite computer-aided operational decision-making having long been developed in other fields

such as urban fires and emergency vehicles [12,13]. Operational decision-making, which must consider fire behavior, risks, and resource availability [3], is complicated by short decision-making windows, the uncertainty of fire behavior, and limited resources [14]. Donovan and Rideout [15] developed a deterministic Integer Linear Programming (ILP) model to minimize costs of initial attack and damage for a single fire. Hu and Ntaimo [14] extended this with a two-stage Stochastic Integer Programming (SIP) approach that integrated fire spread simulation, resource optimization, and suppression simulation under uncertainty. The first stage determines initial resource dispatch, while the second compares different firefighting tactics. However, these models were limited to single fires and did not account for escaped fires. Rideout et al. [16] adapted the single-fire ILP model to address multiple fires, developing another ILP model to minimize expected loss due to fires for a given budget. More recently, Wei et al. [17] proposed a two-step approach using mixed integer programming for daily large fire containment strategies, incorporating fire risk assessment for ground resource assignment.

Matos et al. [18] proposed a constructive heuristic for jointly dispatching and routing ground firefighting resources across multiple simultaneous fires, incorporating water-tank refilling constraints to more realistically represent resource cycling during active suppression. Granda et al. [19] developed a mixed integer linear programming model to dispatch ground brigade resources for fire-line construction during the suppression stage of a single wildfire. Most recently, Zhou et al. [20] proposed an integrated mixed-integer nonlinear programming model that jointly optimizes forest fire task scheduling and emergency resource delivery under uncertain fire recovery and delivery times, solved via a hybrid tabu search–simulated annealing heuristic. While these studies represent important advances toward coupling real-time fire behavior prediction with operational resource optimization, they focus on ground suppression resources and do not address the expert decision-making processes specific to helicopter resources, nor do they validate optimized solutions directly against expert manual decisions.

For a broader overview, Granda et al. [21] reviewed more recent studies employing operations research (OR) techniques for fire suppression. These authors classified OR applications as focusing on firefighting preparedness, response, or combined strategies. Furthermore, they categorized OR applications for resource dispatch based on fire-line, fire points, grid, or Potential Operational Delineations (POD)-based approaches. Their review highlighted that many previous studies [14,15,22] are limited to single-fire suppression, multiple fire suppression without allowing for escaped fires, or lack of real-time operability.

In the Republic of Korea, a small expert group within the FFCC manually develops helicopter dispatch decisions. When fires occur, the local government confirms the incident and reports it to the local Forest Service District Office, collectively establishing an incident command system at the scene. The incident commander then assesses weather and fire spread conditions, deciding on and requesting helicopter dispatch from the FFCC. FFCC staff receive essential data, including weather, current and predicted fire spread rates, helicopter availability and locations, water supply locations, and protection needs for people, assets, and infrastructure, from multiple sources (i.e., local governments, local Forest Service districts, and the National Institute of Forest Science), via maps and reports. This information facilitates helicopter dispatch planning by the FFCC, detailing the number, type, and locations of helicopters, as well as water supply points. Following a helicopter request, dispatch decisions must be made within 15 min, and helicopters must begin suppression within 50 min, as mandated by KFS firefighting guidelines [2]. Helicopters are also restricted to daytime operations, and although a helicopter's daily dispatch location generally remains fixed throughout the day, it may occasionally be relocated to respond to a fire in a different area.

This study presents a decision support framework to enhance real-time operational-level decision-making for helicopter dispatch during multiple simultaneous fires in the Republic of Korea. This framework integrates: (1) real-time weather and fire data, (2) real-time fire spread modeling, (3) helicopter suppression productivity, (4) resource availability, (5) fire-specific priorities, (6) resource dispatch rules and constraints, and (7) discrete optimization. An ILP approach was used to solve helicopter dispatch problems, allowing for uncontained fires within a given planning horizon. The objective function minimizes the weighted sum of helicopter operating costs and resulting burn perimeters, incorporating helicopter suppression effects on fire perimeter growth.

The discrete optimization model adopts the fire-line based approach identified by Granda et al. [21]. It dispatches helicopters for fire line construction and evaluates the fire spread rate against the line construction rate. In parallel, the model solves a helicopter dispatch problem, linking available resources to multiple demand points of simultaneous fires. Unlike other studies that favored heuristic optimization techniques for reduced computation times [11,18,20,23], often at the expense of solution optimality, an ILP approach with an open-source solver was chosen based on its demonstrated ability to achieve optimal solutions relatively quickly (i.e., within a minute).

The decision framework replicates the Republic of Korea's unique fire suppression decision-making process by incorporating helicopter dispatch rules, constraints, and prioritization strategies based on both fire spread and damage potential. As a product of collaboration among FFCC experts, fire specialists, and operations researchers, this framework supports daily, real-time helicopter dispatch decisions for new and ongoing fires, and for re-evaluation as fire situations change. This functionality is contingent on simulating the spread of each fire across the user-defined planning horizon (6 h in this study) and knowing current helicopter availability (i.e., number, type, and location).

This framework aims to provide a rapid and interactive approach for real-time helicopter dispatch by improving upon key areas identified in previous studies:

- Integrating real-time fire behavior simulation, monitoring, and analysis into fire suppression decisions for multiple simultaneous fires [15,21,24–27].
- Replicating the Republic of Korea's unique fire suppression decision-making process through collaboration between operations researchers and fire specialists, and validating the model by comparing its solutions against expert manual decisions [6,21].
- Incorporating partial suppression effects and allowing for uncontained fires within a given planning horizon [14,15].
- Combining fire damage potential (e.g., vulnerability) with real-time fire spread modeling to support suppression prioritization and decision-making.

The following sections detail the decision-making framework and the ILP model. To demonstrate the model's effectiveness, optimized dispatch outcomes are compared against expert manual decisions for five hypothetical and four actual simultaneous fire incidents.

2. Materials and Methods

2.1. Decision Support Framework

The framework developed in this study outlines a structured helicopter dispatch decision-support process comprising four key stages: (1) information gathering and data preparation, (2) objective and fire prioritization, (3) problem formulation and solution, and (4) outcome assessment and reporting (Figure 1). The framework also includes an iterative process that generates solutions across various prioritization scenarios, allowing for exploration of the decision space and assessment of model outcome sensitivity.

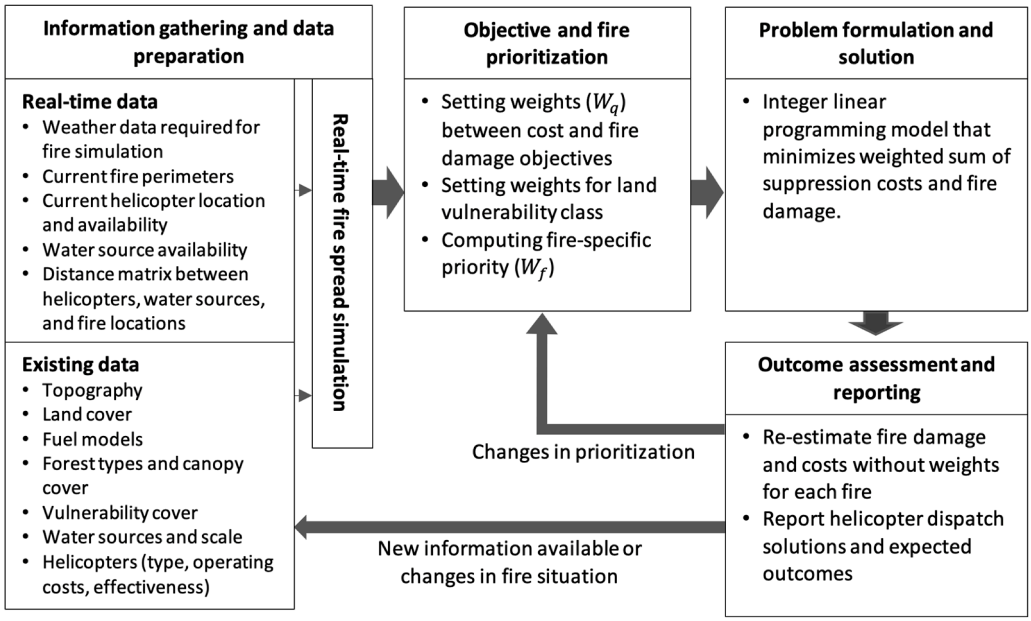


Figure 1. A graphic representation of the conceptual decision support framework developed in this study.

2.2. Information Gathering and Data Preparation

2.2.1. Weather, Geospatial Data, and Fire Simulation

Since 2000, the KFS has utilized the Forest Fire Spread Prediction System (FFSPS) to predict fire spread rates and burn perimeters based on fire occurrence and fire duration [28]. The weather data required for this simulation include wind direction, wind speed, precipitation, relative humidity, and temperature. Real-time weather information is collected by 464 automatic weather systems across the Republic of Korea and is accessible via a web interface [29]. The fire simulation also requires geospatial datasets available in the Republic of Korea, including terrain, forest types, surface fuels, roads, infrastructure, and administrative boundaries. For fire suppression purposes, spatial data on water sources, aviation stations, and the locations of suppression resources are also available [28]. In this study, fire perimeter growth rates predicted by the FFSPS serve as input data to estimate potential damage areas over time. Fire spread is simulated over a 6 h planning horizon at 10 min intervals.

2.2.2. Helicopter Fleet Data

The FFCC gathers and updates the current locations of helicopters. Helicopters typically return to their designated aviation stations nightly following daytime operations, but may also remain at alternative stations when required. The operability status of each helicopter is updated and communicated in real time. Pre-determined helicopter performance and cost data are used to estimate flight times, operational costs, and suppression efficacy. The following categories of helicopter performance data were used in this study:

- Speed empty: Average travel speed without water load (km/h).
- Speed loaded: Average travel speed with a full water load (km/h).
- Water capacity: Amount of water carried at full capacity (L).
- Water supply time: Time taken to fill the water tank (s).
- Suppression range: Effective water drop distance in length (m) and width (m) under the following conditions: flight speed of 100 km/h, wind speed of 3–5 knots, and mountainous terrain [30].

- Operating costs: Costs associated with operating each helicopter, including pilot, fuel, maintenance and repair, and other operational expenses (USD per 10 min). Fixed costs (e.g., ownership and administration costs) were not considered in this study because the helicopters are government-owned, and these costs are incurred regardless of operation.

2.2.3. Water Source Data

In 2018, the KFS designated 3663 water sources nationwide for aerial firefighting. The KFS annually maintains and updates this database, which includes the location, size, water storage capacity, and minimum, maximum and average water depth, as well as safety considerations for each water source. This database is used to construct distance matrices between available water sources, helicopter locations (i.e., aviation stations), and fire locations.

2.3. Objective and Fire Prioritization

To account for both cost-efficiency and suppression effectiveness, the objective is to simultaneously minimize the total operating costs of helicopters and the total resulting burn perimeters from multiple fires. Since these two objectives are measured in different units (i.e., currency for cost and length for perimeter), a weighted sum approach is employed to combine them into a single objective function for minimization. Various relative weights can be used to develop and analyze diverse dispatch scenarios.

Furthermore, fire suppression priorities may differ among fires due to the varying significance of potential damage based on location. For example, fires occurring near residential areas may be prioritized for suppression efforts. In the Republic of Korea, a forest fire vulnerability land classification system was developed based on factors such as past fire occurrence data, forest type, population density, land use, and protected areas [31]. This system was applied nationwide, resulting in a forest fire vulnerability map in 2018. The map classifies each land parcel into four vulnerability classes: A (highest), B, C and D. In this study, this classification system is used to prioritize individual fires when multiple incidents occur simultaneously. Relative importance weights are assigned to each vulnerability class (i.e., A = 4, B = 3, C = 2, D = 1) and a fire priority score is calculated by summing the vulnerability weights within the predicted burn area of each fire (Figure 2).

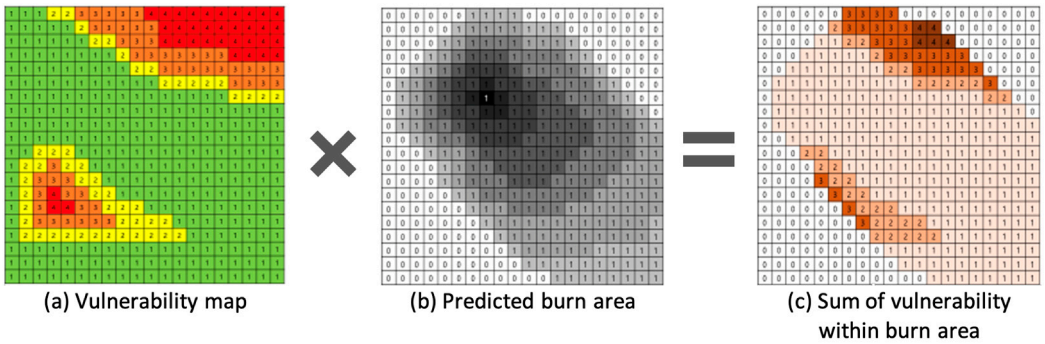


Figure 2. Map overlaying of the KFS fire vulnerability map and fire spread simulation results to prioritize fires. The more areas in high vulnerability class are included, the higher priority the fire takes.

2.4. Problem Formulation and Solution

An Integer Linear Programming (ILP) model was developed to minimize the weighted sum of helicopter operating costs and the total resulting burn perimeters from multiple fires, while incorporating the priority of individual fires into the objective function. Consistent

with typical operational practices in the Republic of Korea, the model assigns helicopters for exclusive use on individual fires, while allowing the possibility of fire escape beyond a given suppression time horizon. The optimization model is described in detail below.

Sets

$f \in F$	Set of fires ($f = 1, 2, \ldots, F$)
$h \in H$	Set of helicopters ($h = 1, 2, \ldots, H$)
$t \in T$	Set of 10 min time periods ($t = 1, 2, \ldots, T$)

Parameters

C_h	Operating costs of helicopter h for a 10 min time period (USD/10 min).
$C_{hf}^{roundtrip}$	Round-trip costs for the initial deployment of helicopter h from its aviation station to the nearest water source for fire f, and the return trip from the fire to the aviation station at the end of the operation (USD).
PER_{ft}	Fire perimeter growth rate of fire f during time period t (m/10 min).
PR_{hf}	Line production rate of helicopter h for fire f during a 10 min time period (m/10 min).
$t_{hf}^{initial}$	Number of 10 min time periods required for helicopter h from initial take-off to first water drop at fire f.
W_q	Relative weight assigned to total operating costs and total resulting burn perimeter objectives.
W_f	Priority weight for fire f.

Decision variables

D_{hft}	Binary variable: 1 if helicopter h is assigned to fire f during time period t, 0 otherwise.
$Heli_{hf}$	Binary variable: 1 if helicopter h is dispatched to fire f, 0 otherwise.
Y_{ft}	Continuous variable representing the resulting burn perimeter contribution to the objective function for fire f at time period t. Only positive resulting burn perimeters (i.e., uncontained fires) are counted, while contained fires contribute zero.
N_{ft}	Binary variable: 1 if fire f is not contained during time period t, 0 otherwise. N_{f0} is initialized to 1 for all fires, indicating that each fire is initially uncontained.

Intermediate variables

RBP_{ft}	Resulting burn perimeter of fire f at time period t, calculated as the cumulative fire perimeter growth rates minus the cumulative helicopter line production rates up to time period t.

Integer linear programming model

$$\text{Minimize } Z = (1 - W_q) * \left[\sum_{h \in H} \sum_{f \in F} \sum_{t \in T} (C_h * D_{hft}) + \sum_{h \in H} \sum_{f \in F} \left(C_{hf}^{roundtrip} * Heli_{hf} \right) \right] + W_q * \left[\sum_{f \in F} \sum_{t \in T} (W_f * Y_{ft} + N_{ft}) \right] \quad (1)$$

Subject to the following constraints:

$$\sum_{t \in T} D_{hft} \leq M * Heli_{hf} \quad \text{for all } h \in H, f \in F \quad (2)$$

$$\sum_{f \in F} Heli_{hf} \leq 1 \quad \text{for all } h \in H \quad (3)$$

$$\sum_{t_1=1}^{t} PER_{ft_1} * N_{f(t-1)} - \sum_{t_1=1}^{t} \sum_{h \in H} \left(PR_{hf} * D_{hft_1}\right) = RBP_{ft} \quad \text{for all } f \in F, t \in T \tag{4}$$

$$RBP_{ft} \leq M * N_{ft} \quad \text{for all } f \in F, t \in T \tag{5}$$

$$\sum_{t=1}^{t_{hf}^{initial}} D_{hft} = 0 \quad \text{for all } h \in H, f \in F \tag{6}$$

$$Y_{ft} \geq RBP_{ft} \quad \text{for all } f \in F, t \in T \tag{7}$$

$$Y_{ft} \geq 0 \quad \text{for all } f \in F, t \in T \tag{8}$$

The parameter value $C_{hf}^{roundtrip}$ is calculated by multiplying the helicopter cost per unit time (C_h) by the round-trip flight time from the helicopter's aviation station to the nearest water source for fire f at the beginning of suppression, and the return flight time from the fire scene back to the aviation station at the end of the operation. PR_{hf} for each helicopter is calculated by the helicopter's suppression range and the number of turns it makes between the fire scene and the water source in a 10 min time period. The number of turns is calculated using (1) the distance between the fire scene and the water source, (2) loaded and empty flight speeds, and (3) water supply time. The value of $t_{hf}^{initial}$ represents the number of 10 min time periods, rounded up, encompassing the 15 min dispatch preparation time, flight time to the water source, water supply time, and flight time to the fire scene.

The objective function (Equation (1)) minimizes the weighted sum of total helicopter operating costs and the total resulting burn perimeters. The weight, W_q, controls the relative contribution of these two objectives to the overall objective function. Total operating costs are estimated by multiplying each helicopter's total operation time by its operating cost per unit time. Total operation time includes the initial flight from the aviation station to the water source, time spent on suppression, and the return flight from the fire scene to the aviation station. Total resulting burn perimeters are computed by multiplying the priority weights of individual fires, W_f, by the resulting burn perimeter contributions (Y_{ft}). The resulting burn perimeter (RBP_{ft}) for each fire is calculated as the cumulative predicted fire perimeter growth minus the cumulative helicopter line production up to time period t, and the contribution (Y_{ft}) then captures only positive resulting burn perimeters through Equations (7) and (8). Although N_{ft}, contributes minimally to the objective function value, with a maximum cumulative value of 36 for a fire that remains uncontained throughout the entire planning horizon, it is included to ensure that the containment status is correctly set to zero once a fire is contained. This objective function accommodates both contained and uncontained fires, as it accounts for partial suppression effects through the resulting burn perimeter calculation.

Equation (2) ensures that if helicopter h is assigned to fire f, the binary variable of $Heli_{hf}$ is set to 1. M is an arbitrarily large number. Equation (3) ensures that each helicopter can be dispatched to only one fire during planning horizon. Equation (4) calculates the resulting burn perimeter, RBP_{ft}, for fire f up to time period t. The cumulative predicted burn perimeter is computed as the sum of fire perimeter growth rates, and the cumulative helicopter line production is computed as the sum of line production rates. The resulting difference (RBP_{ft}) therefore reflects the net burn perimeter after accounting for partial suppression effects up to time period *t*.

Equation (5) links the resulting burn perimeter (RBP_{ft}) to the containment status variable (N_{ft}). If RBP_{ft} is positive, indicating that cumulative fire perimeter growth exceeds cumulative helicopter line production and the fire remains uncontained, N_{ft} is forced to 1. Equations (4) and (5) work together with the objective function to ensure that once the fire is contained, the value of N_{ft} for future time periods will be 0 based on the previous period's containment status ($N_{f(t-1)}$), and that no further helicopter deployment is necessary

(D_{hft} = 0) after the fire is contained. Conversely, if the fire remains uncontained throughout the entire planning horizon, all N_{ft} will remain 1.

Equation (6) ensures that the binary variable D_{hft} has a value of 0 during the initial preparation time periods, $t_{hf}^{initial}$, to prevent the double-counting of operational costs and the inclusion of suppression effects during the preparation period. The number of time periods, $t_{hf}^{initial}$, includes the time consumed by helicopter *h* from dispatch preparation to the first arrival at the fire scene.

Equations (7) and (8) ensure that Y_{ft} captures only positive resulting burn perimeters in the objective function, as RBP_{ft} may become negative at the time period when the fire is contained. These constraints establish a lower bound, ensuring that Y_{ft} takes the value of RBP_{ft} when positive, and 0 when RBP_{ft} is zero or negative.

The ILP model was encoded and solved using R (version 4.4.0; R Foundation for Statistical Computing, Vienna, Austria) and the Gurobi optimizer (version 12; Gurobi Optimization, LLC, Beaverton, OR, USA) (https://www.gurobi.com/ (accessed on 1 June 2026)).

2.5. Model Application—Hypothetical Simultaneous Fire Incidents

The decision support framework was applied to five hypothetical simultaneous forest fires in the Republic of Korea. The optimization model was used to generate helicopter dispatch decisions across a range of objective weights and fire priorities. For model evaluation, manual dispatch solutions for the same hypothetical fires were obtained from the FFCC. The FFCC was provided with identical information, including fire locations, fire spread simulation results, nearby water sources, and helicopter availability (e.g., aviation stations, number, and types of helicopters at each station). This information was presented through GIS-based maps and tabular formats, designed to mirror the operational materials FFCC personnel typically use. The resulting model solutions were then compared against these manual solutions.

2.5.1. Hypothetical Fires

Table 1 summarizes the five hypothetical fire incidents located across the Republic of Korea. Five incidents were selected, as the majority (83%) of simultaneous fires in the country involve fewer than five incidents [2]. The hypothetical fire scenarios were developed and validated through close collaboration with KFS fire specialists, who confirmed that the selected fire locations, weather conditions, and forest characteristics were reasonable and representative of typical fire season conditions in the Republic of Korea. The five hypothetical fires were deliberately distributed across different geographic regions and forest types to capture the diversity of fire environments encountered in practice.

Table 1. Five hypothetical simultaneous forest fires developed for the optimization model application.

Fire	Location	Latitude and Longitude	Altitude (m)	Ground Slope (°)	Stand Type and Age
H1	Pyeongchang-gun, Gangwon-do	37.6718530° N 128.3248897° E	937	39	Hardwood, 50 yr
H2	Cheongsong-gun, Gyeongsangbuk-do	36.2536111° N 128.9117153° E	394	18	Hardwood, 30 yr
H3	Gokseong-gun, Jeollanam-do	35.2328422° N 127.3760394° E	176	27	Softwood, 30 yr
H4	Jeonui-myeon, Sejong-si	36.6624322° N 127.1493644° E	116	24	Hardwood, 30 yr
H5	Namyangju-si, Gyeonggi-do	38.4998975° N 127.2829408° E	251	35	Mixed, 40 yr

The fires were simulated for a planning horizon of 360 min using the Forest Fire Spread Prediction System (FFSPS), incorporating weather data specific to each fire location (Table 2). The weather data used in the simulations represent typical fire season conditions in the Republic of Korea. Figure 3 illustrates the fire simulation results for each hypothetical fire.

Table 2. Weather data used for fire spread simulation of each hypothetical fire.

Fire	Wind Direction	Precipitation (mm)	Wind Speed (m/s)	Humidity (%)	Temperature (°C)
H1	SW	0	4.9	39	12.9
H2	N	0	2.4	25	15.1
H3	N	0	2.4	16	17.2
H4	NNW	0	3.1	34	16.3
H5	N	0	4.6	26	15.2

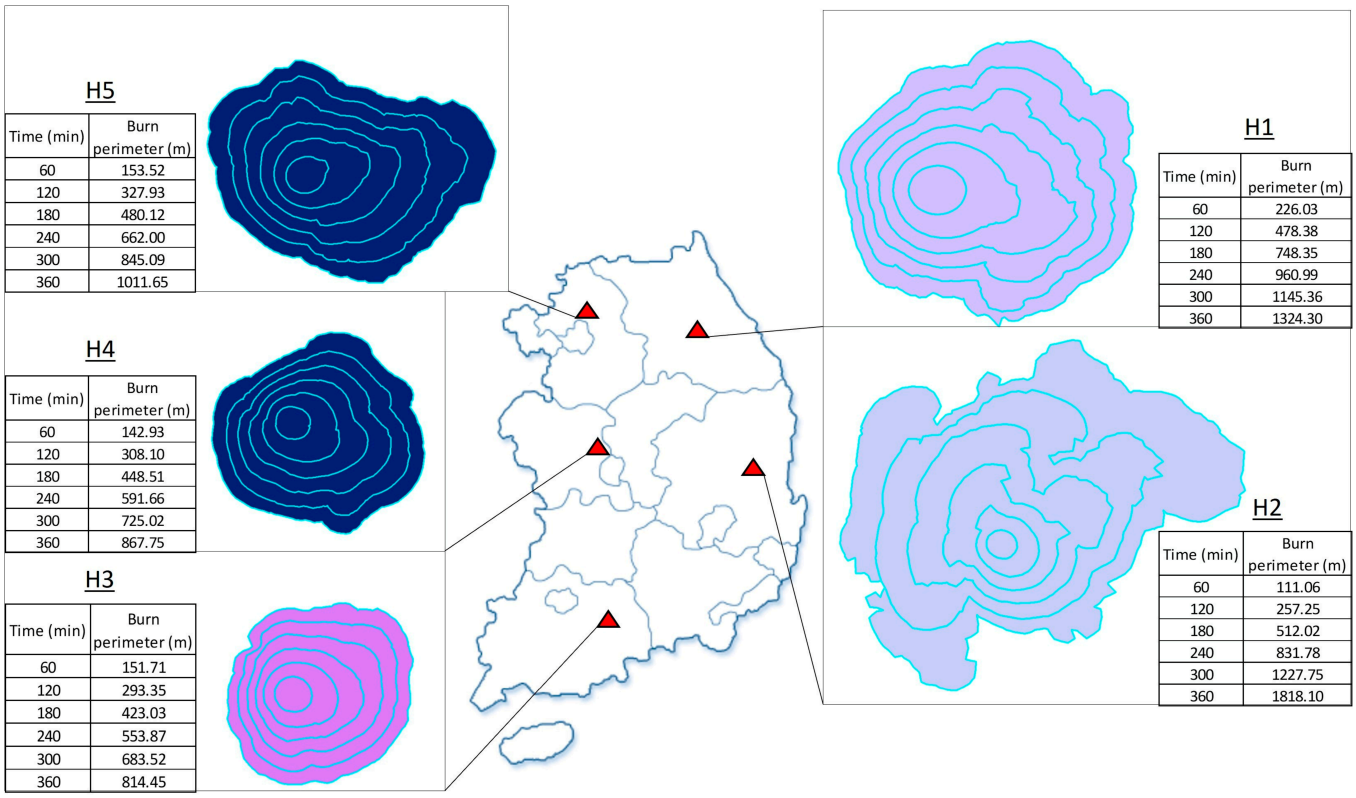
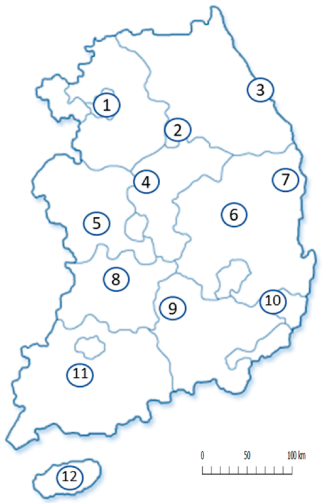


Figure 3. Locations of hypothetical fire incidents across the Republic of Korea and fire spread simulation results illustrating changes in burn perimeter over a 360 min planning horizon.

2.5.2. Helicopter Data

Figure 4 shows the locations of the 12 aviation stations and the helicopters assigned to each aviation station in the Republic of Korea. Of the 46 helicopters, 45 helicopters were included in the analysis, as one Bell 412 helicopter stationed in Wonju was out of operation at the time of simulation. For water sources, the 3867 water source locations nationwide designated by the KFS were used [2].

Table 3 summarizes the helicopter models operated by the KFS, categorized as extra-large (S-64), large (KA-32), and medium-sized (Bell-206 and AS-350). A flight distance matrix (Table 4) was developed to calculate the following three optimization model parameters for all possible helicopter-fire pairs: $C_{hf}^{roundtrip}$, PR_{hf}, and $t_{hf}^{initial}$.



No.	Aviation station	Helicopter type					
		S-64	KA-32	Bell-206	Bell-412	As-350	Total
1	Seoul	-	3	-	-	2	5
2	Wonju	1	4	-	1	-	6
3	Gangneung	-	3	-	-	1	4
4	Jincheon	1	3	-	-	-	4
5	Cheongyang	-	2	2	-	-	4
6	Andong	1	3	-	-	-	4
7	Uljin	-	2	-	-	1	3
8	Iksan	1	2	-	-	-	3
9	Hamyang	-	3	2	-	-	5
10	Yangsan	-	2	3	-	-	5
11	Yeongam	-	2	-	-	-	2
12	Jeju	-	1	-	-	-	1
	Total	4	30	7	1	4	46

Figure 4. Locations of aviation stations across the Republic of Korea and helicopters assigned to each station.

Table 3. Helicopter attributes, suppression efficacy, and operating costs used in this study.

Attribute	**Helicopter Model**			
	S-64	**KA-32**	**Bell-206**	**AS-350**
				
Size category	Extra-large	Large	Medium	Medium
Number of helicopters	4	30	7	4
Speed unloaded (km/h)	204	230	241	287
Speed loaded (km/h)	178	148	161	148
Water load (L/turn)	8000	3000	600	800
Water supply time (s/turn)	45	60	120	60
Fire suppression range per trip (length × width in meters)	150 × 9	45 × 18	20 × 9	27 × 9
Operating costs (USD/10 min)	1746	1034	249	249

Table 4. Flight distances between aviation stations and hypothetical fire incidents in km. The last row shows the flight distance (km) between each fire and the nearest available water source.

Aviation Station	**Fire H1**	**Fire H2**	**Fire H3**	**Fire H4**	**Fire H5**
Seoul	134.38	235.34	260.96	103.03	112.73
Wonju	45.70	155.36	245.30	106.86	131.61
Gangneung	55.59	166.20	311.75	199.30	166.13
Jincheon	123.44	142.28	172.19	30.47	188.73
Cheongyang	196.20	189.25	137.33	44.44	237.35
Andong	129.88	35.39	187.92	140.42	250.46
Uljin	139.14	75.73	252.19	204.01	267.61
Iksan	217.92	164.49	83.25	78.17	281.09
Hamyang	245.78	130.86	46.88	142.26	335.67
Yangsan	249.23	84.96	157.15	215.67	367.42
Yeongam	345.09	252.92	75.41	206.13	408.04
Jeju	492.60	375.16	210.98	359.77	562.22
Nearest water source	8.36	5.13	5.11	7.42	3.95

2.5.3. Prioritization Scenarios

Initial scenario: A weight of 0.99 (W_q) was assigned to the objective function with a uniform priority weight ($W_f = 1$) applied to all fires. This scenario prioritizes maximum helicopter deployment to minimize fire damage while maintaining a marginal cost penalty to prevent the inefficient allocation of aerial resources.

Objective weight scenarios: To examine the influence of objective weights on helicopter dispatch decisions, W_q was varied from 0.1 to 0.9 in increments of 0.1, along with extreme values of 0.01 and 0.99. A uniform fire priority ($W_f = 1$) was maintained for all fires.

Fire priority scenarios: To evaluate the impact of fire priorities (W_f) on helicopter dispatch, we developed two scenarios with varying vulnerability importance levels (Table 5). In the first scenario, the importance level increased linearly with vulnerability class: A = 4, B = 3, C = 2, and D = 1. In the second scenario, this importance level was amplified by a factor of 5. These vulnerability class weights were then multiplied by the proportion of the predicted burn area belonging to each vulnerability class and summed across the four vulnerability classes to calculate the priority (W_f) for each fire (Table 5). Consequently, fires burning in areas with higher vulnerability received greater priority due to the increased contribution of their burn perimeters to the objective function. The objective weight (W_q) was held constant at 0.7.

Table 5. Fire priority scenarios with priorities computed for each hypothetical fire based on the area of vulnerability classes and their relative importance.

Vulnerability Class		**Predicted Burn Area Percentage of Each Vulnerability Class**				
		Fire H1	**Fire H2**	**Fire H3**	**Fire H4**	**Fire H5**
A		-	-	-	-	-
B		-	-	62%	-	-
C		100%	70%	38%	-	64%
D		-	30%	-	100%	36%
Priority Scenario	Relative importance	Computed fire priority (W_f)				
		W_1	W_2	W_3	W_4	W_5
Initial	A: 1, B: 1, C:1, D:1	1.0	1.0	1.0	1.0	1.0
1	A: 4, B: 3, C: 2, D:1	2.0	1.7	2.6	1.0	1.6
2	A: 15, B: 10, C: 5, D:1	5.0	3.8	8.1	1.0	3.6

2.6. Model Application—Actual Simultaneous Fire Incidents

To further validate the decision support framework, the model was applied to a series of simultaneous fire incidents recorded in the southeastern region of the Republic of Korea on 22 March 2025. The optimized dispatch solutions generated by the framework were then compared against the actual helicopter dispatch records documented by the KFS.

2.6.1. Actual Fires

Table 6 summarizes the four actual fire incidents. Fire A1 originated on March 21 and continued burning into March 22, while Fires A2 through A4 ignited sequentially at different times throughout the day. The spread of each fire incident was simulated over either a 360 or 480 min planning horizon using the Forest Fire Spread Prediction System (FFSPS) on March 22, incorporating location-specific weather variables to estimate burn perimeters at different time intervals (Figure 5). Both helicopter dispatch records and fire spread simulation results were obtained from the KFS. Despite suppression efforts, none of the four fire incidents were contained on March 22, and all continued burning for 5–21 days, primarily due to abrupt weather changes with extreme wind speeds.

Table 6. Summary of four actual simultaneous forest fire incidents and fire spread simulations recorded on 22 March 2025, in the Republic of Korea.

Fire	Location	Ignition Date and Time	Containment Date	Total Area Burned (ha)	Time Fire Spread Simulation Conducted
A1	Hadong-gun, Gyeongsangnam-do	21 March 2025, 15:26	12 April 2025	3398	12:00
A2	Uiseong-gun, Gyeongsangbuk-do	22 March 2025, unknown (before 10:00)	28 March 2025	99	10:01
A3	Ulju-gun, Ulsan	22 March 2025, 12:12	27 March 2025	1117	13:11
A4	Gimhae-si, Gyeongsangnam-do	22 March 2025, 14:02	27 March 2025	97	15:22

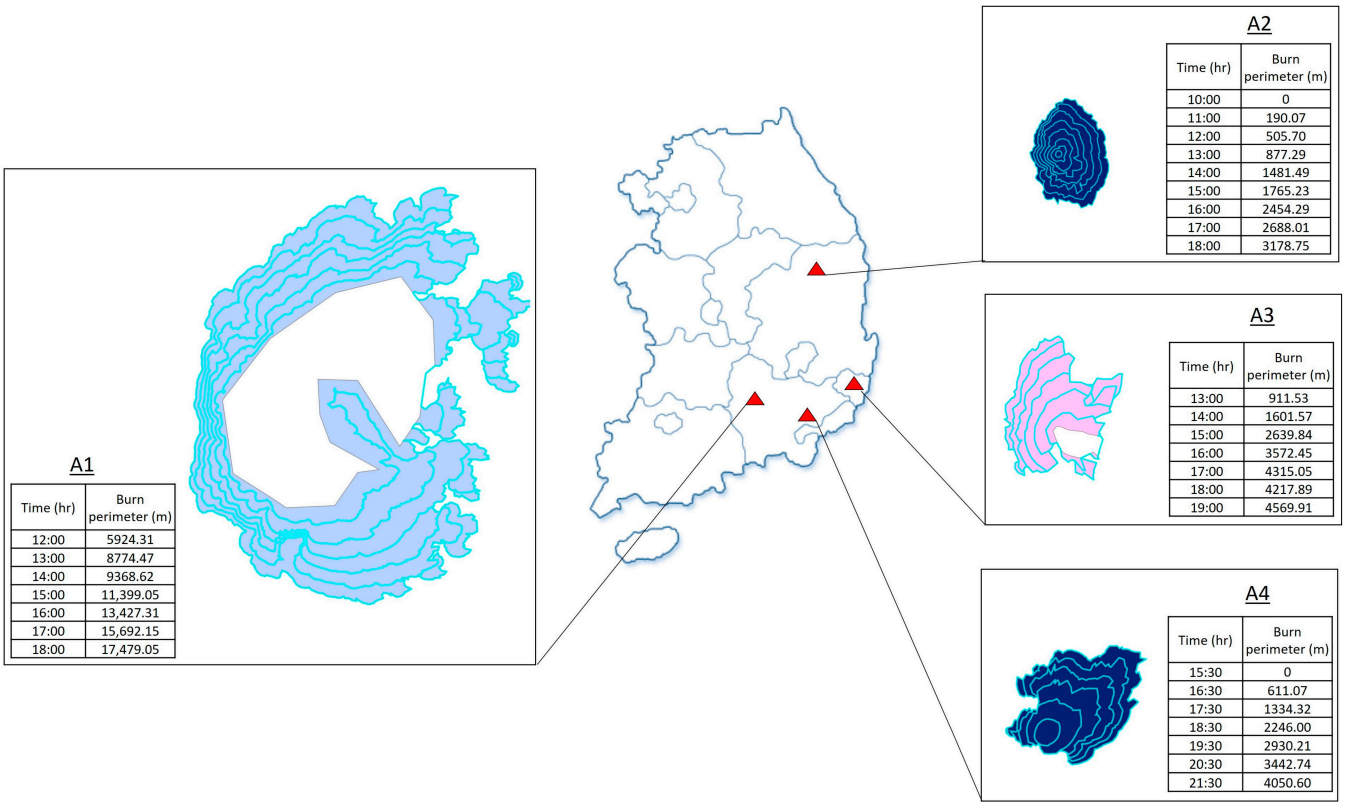


Figure 5. Locations of the four actual simultaneous fire incidents on 22 March 2025, and corresponding fire spread simulation results. As Fire A1 originated on 21 March 2025, its fire spread simulation was initialized from the burn perimeter established at the time of simulation on 22 March 2025.

As Fire A1 was an ongoing fire, KFS dispatch records indicate that helicopters were already deployed to Fire A1 early in the morning of March 22. As subsequent fires ignited in the region, some of these helicopters were relocated to respond to the emerging fires. Since the decision support framework requires fire spread simulation results as input, it was assumed that the optimization model would be applied at the times when fire simulations were conducted and multiple fires were simultaneously active (i.e., 12:00 for Fires A1 and A2, 13:11 for Fires A1 through A3, and 15:22 for all four fires).

Although Fire A2 was simulated at 10:01, the optimization model was first applied to the simulation data at 12:00, when simulation results from both Fires A1 and A2 were available, with fire spread rates projected from 12:00 onward to ensure consistent time periods were used across all simultaneously active fires. The resulting model solutions were then compared against the actual KFS helicopter dispatch records during the time periods

between consecutive simulations (i.e., 12:00–13:11 for Fires A1 and A2, 13:11–15:22 for Fires A1 through A3, and 15:22–19:00 for all four fires).

2.6.2. Helicopter Data and Fire Prioritization

This actual fire analysis included 25 available helicopters across the nation, as the remaining fleet was either undergoing maintenance or already assigned to other regions on March 22 (Table 7). The available fleet included several helicopters that were repositioned from other aviation stations to the Hamyang station near Fire A1 on March 21 to suppress the ongoing Fire A1. To accurately reflect real-world operational conditions, the optimization model was initialized with the recorded helicopter location and inventory data as of the evening of 21 March 2025. The nearest water sources were also identified for each of the actual fire incidents.

Table 7. Helicopters and associated aviation stations available for deployment during the actual simultaneous fire incidents in the southeastern region of the Republic of Korea as of the evening of 21 March 2025.

No.	Aviation Station	Helicopter Type				
		S-64	KA-32	Bell-206	As-350	Total
1	Seoul	-	-	2	-	2
2	Wonju	1	-	-	-	1
3	Gangneung	-	1	-	-	1
4	Jincheon	-	2	-	-	2
5	Cheongyang	-	2	-	-	2
6	Andong	1	2	-	-	3
7	Uljin	-	1	-	-	1
8	Iksan	-	1	-	-	1
9	Hamyang	2	8	-	2	12
10	Yangsan	-	-	-	-	0
11	Yeongam	-	-	-	-	0
12	Jeju	-	-	-	-	0
	Total	4	17	2	2	25

Actual helicopter flight records indicated that some of the 25 helicopters became unavailable after morning flights or experienced a prolonged inactive period between flights (e.g., exceeding 5 h), likely due to mechanical issues or crew unavailability. Helicopters identified as unavailable prior to each fire spread simulation were assumed to be grounded for either the remainder of the day or a prolonged period and were therefore excluded from the optimization model. Accordingly, the assumed number of available helicopters was 24 at 12:00, 23 at 13:11, and 20 at 15:22.

Consistent with the hypothetical fire analysis, a weight of 0.99 (W_q) was assigned to the objective function, with a uniform priority weight ($W_f = 1$) applied to all fires. This configuration reflects the KFS's primary operational objective of maximizing suppression efforts while imposing a marginal cost penalty to prevent unnecessary resource allocation.

3. Results

3.1. Hypothetical Simultaneous Fire Incidents

3.1.1. Initial Scenario

Figure 6 illustrates the optimal helicopter dispatch solutions generated by the ILP model for the five hypothetical fires. Under initial scenario parameters, Fire H1 received two large and one medium helicopter from the Wonju and Gangneung stations, while a single large helicopter from Andong was assigned to Fire H2. For Fires H3 and H4, the

model dispatched one large and one medium helicopter each. Fire H3 utilized the nearest station (Hamyang), whereas Fire H4 drew from the two closest stations (Jincheon and Cheongyang). Finally, Fire H5 received two medium helicopters from the Seoul station. All incidents were contained within 50 min, with the operating costs per fire ranging between USD 884 and USD 3276.

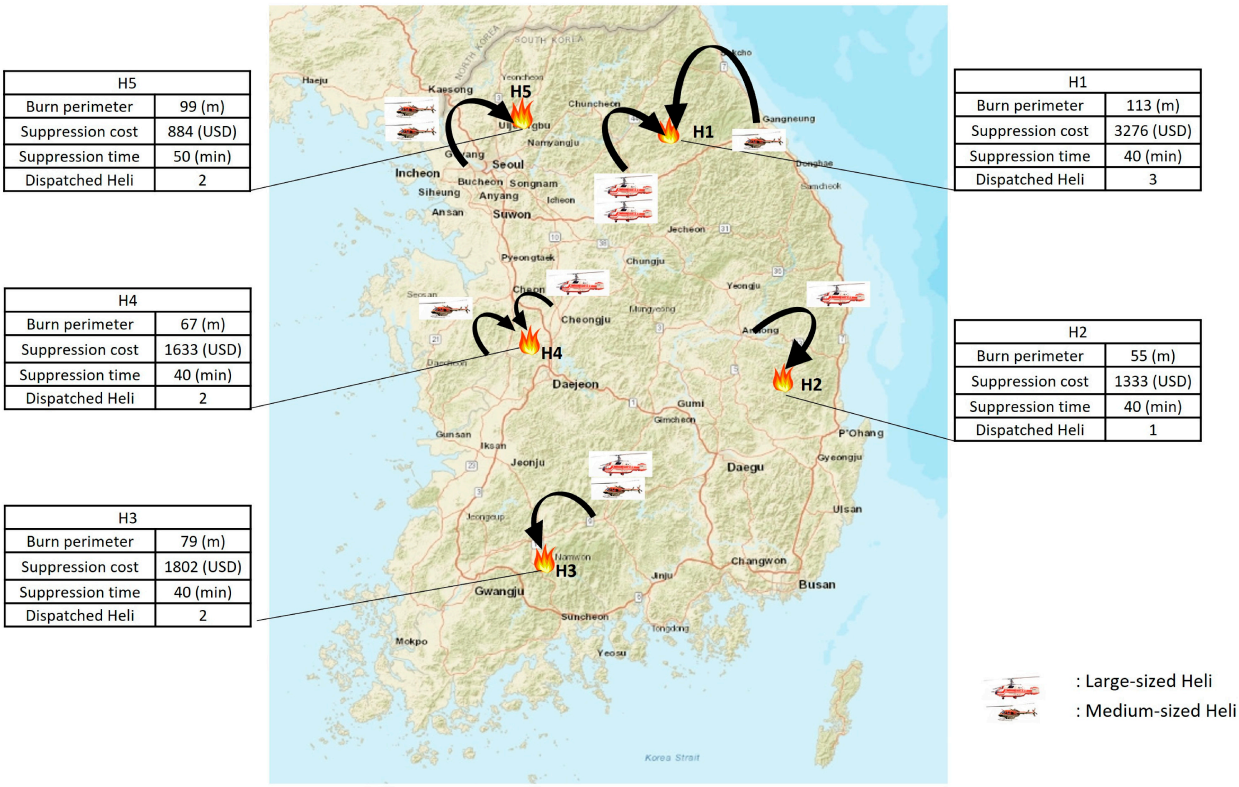


Figure 6. The helicopter dispatch solutions developed by the ILP optimization model for the five hypothetical fires, showing the suppression results in terms of burn perimeters, helicopter operating costs, and suppression time.

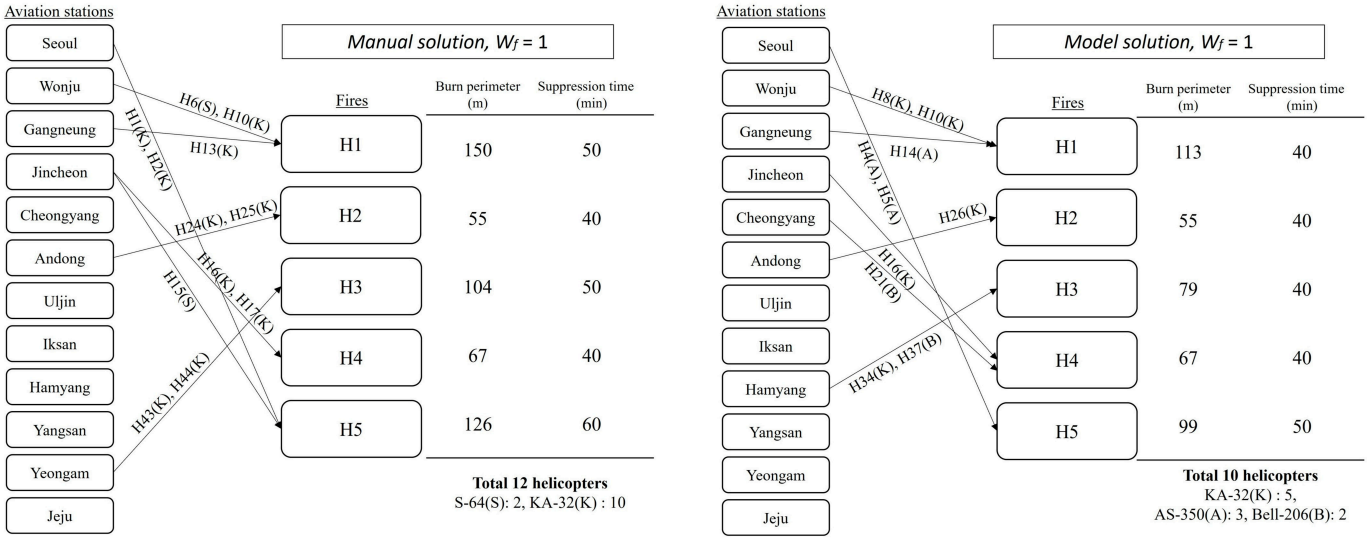
The optimal solutions demonstrate considerable variation in helicopter dispatch strategies across the five fires. For example, Fire H1 received a total of three helicopters, while Fire H2 received only one helicopter. This higher allocation for Fire H1 is attributed to its rapid initial spread during the first 60 min, as depicted in Figure 3, necessitating a larger response for effective containment. Interestingly, despite the availability of an extra-large helicopter at Wonju station near Fire H1, it was not dispatched to the fire. Our verifications indicated that the extra-large helicopter's slower flight speed (204 km/h) compared to the large helicopter (230 km/h) resulted in a two-minute longer travel time from Wonju to the fire. In the model, this slight delay meant that an extra-large helicopter alone could not contain the fire within the 40 min timeframe achieved by the two large helicopters and one medium helicopter.

The results also highlight that Fire H5 required the longest suppression time (50 min) among the fires. This is primarily due to the greater flight distance between Fire H5 and its nearest aviation station, resulting in longer initial travel times of 40 min for medium helicopters.

All optimal solutions were found within one minute, using a desktop computer with an Intel 3.40 GHz processor and 16 GB of memory.

3.1.2. Comparisons Between Model and Manual Solutions

We compared the optimization model solution of the initial scenario with the expertise-driven manual dispatch decisions developed by the FFCC (Figure 7). To facilitate the comparison, the manual decisions were integrated into the optimization model by fixing the helicopter assignments, allowing us to estimate the resulting operating costs, burn perimeters, and suppression duration for each fire.



(a) Manual solution **(b) Optimization model solution**

Figure 7. Comparisons between the manual solution developed by the Korea Forest Service Fire Control Center (**a**) and the optimization model solution (**b**) for five hypothetical fires.

The model solution dispatched a total of 10 helicopters (5 large, 5 medium), whereas the FFCC manual plan assigned 12 helicopters (2 extra-large, 10 large). The total operating cost for the model solution was USD 8928, significantly lower than the USD 23,548 estimated for the manual solution. While both the model and manual solutions resulted in full containment of the five fires, the model solution reduced containment time for Fires H1, H3 and H5 by 10 min.

Figure 7 and Table 8 provide a detailed breakdown of the dispatch decisions for both the manual and model solutions for each hypothetical fire. For Fire H1, both solutions selected a total of three helicopters from the Wonju and Gangneung aviation stations, yet the spatial allocation of the fleet differed. The model solution dispatched two large helicopters from Wonju and one medium helicopter from Gangneung, whereas the manual solution dispatched one extra-large and one large helicopter from Wonju, and one large helicopter from Gangneung. Although the primary distinction between the two solutions was the type of helicopters dispatched, the model solution proved superior in operational efficiency. The optimized solution resulted in a 25% reduction in final burn perimeter and a 20% reduction in suppression time compared to the manual decisions, according to the simulation results.

For Fire H2, the model solution dispatched a single large helicopter from Andong, the nearest aviation station from the fire. While the manual solution also utilized the Andong station, it assigned two large helicopters to the fire. Notably, both solutions yielded the same results: 55 m burn perimeter and a 40 min suppression time. This indicates that one helicopter was sufficient for containment, and the additional helicopter provided no marginal benefit to suppression speed, due to the fixed constraints of preparation and initial travel times.

Table 8. Comparison between manual and model solutions in terms of the number of helicopters and operating costs for five hypothetical fires.

Fire	Manual Solution				Optimization Model Solution			
	Number of Helicopters Dispatched			Total Operating Costs	Number of Helicopters Dispatched			Total Operating Costs
	Extra-Large	Large	Medium	(USD)	Extra-Large	Large	Medium	(USD)
H1	1	2	-	7611	-	2	1	3276
H2	-	2	-	2666	-	1	-	1333
H3	-	2	-	3428	-	1	1	1802
H4	-	2	-	2575	-	1	1	1633
H5	1	2	-	7268	-	-	2	884

The dispatch decisions for Fire H3 showed a notable divergence between the manual and model solutions. The manual solution assigned two large helicopters from the Yeongam station, despite the availability of two other geographically closer stations. According to the FFCC, the rationale for this decision was their practice of reserving resources for districts with historically higher fire occurrences, even at the cost of increased travel times for active incidents. In contrast, the optimization model that prioritizes immediate suppression response dispatched two helicopters from the Hamyang station. Because Hamyang is significantly closer to Fire H3, the solution achieved full containment within 40 min.

For Fire H4, the manual solution selected only the closest aviation station (Jincheon), dispatching two large helicopters. However, the model solution dispatched one large helicopter from Jincheon and one medium helicopter from the second closest station (Cheongyang). Although both solutions achieved the same suppression outcomes in terms of burn perimeter and suppression time, the model lowered total operating costs by USD 942. This reduction was achieved by optimizing the fleet through utilizing more cost-effective medium helicopter while maintaining the same suppression outcome.

For Fire H5, the model solution dispatched two medium helicopters from the Seoul station, while the manual solution assigned two large helicopters from Seoul and one extra-large helicopter from Jincheon. Our analysis indicated that the large helicopters utilized in the manual solution have a slower flight speed (230 km/h) compared to the medium helicopter (287 km/h), resulting in a ten-minute delay in arrival at the incident site. Consequently, the model solution achieved a 21% reduction in the final burn perimeter and a 17% reduction in suppression time compared to the manual solution.

3.1.3. Effects of Weights (W_q) Between Operating Costs and Burn Perimeters

The weight (W_q) assigned to the operating cost and burn perimeter objectives significantly influenced the optimal dispatch solutions, with this influence becoming more pronounced at the extremes of its range (Table 9). When W_q was 0.01, the model prioritized operating cost minimization, resulting in no helicopter dispatch and all five fires remaining uncontained throughout the entire planning horizon. Conversely, when W_q was 0.99, the objective shifted almost exclusively to minimizing burn perimeters, leading to the dispatch of sufficient helicopters to achieve the minimum possible burn perimeters across all fires.

Generally, as W_q increased, the model dispatched more helicopters, resulting in shorter suppression times and smaller final burn perimeters, albeit at the cost of higher total operating costs. Due to the discrete nature of helicopter dispatch decisions, the optimal solution remained unchanged across specific weight intervals (e.g., 0.1–0.7). The most significant improvement in burn perimeter reduction occurred between $W_q = 0.01$ and $W_q = 0.1$, suggesting that even a modest weight assigned to burn perimeter minimization yields substantial suppression benefits. The results indicate that full containment of all five fires was achieved when $W_q \geq 0.1$. Further changes in the number of dispatched helicopters and suppression times were observed when $W_q \geq 0.8$.

Table 9. The optimal solutions were generated across a range of the weight between cost and burn perimeter objectives.

W_q	Total OP [1]	Total BP [2]	H1		H2		H3		H4		H5		N [4]
			BP	ST [3]	BP	ST	BP	ST	BP	ST	BP	ST	
0.01	0	5877	1324	>360	1860	>360	815	>360	866	>360	1012	>360	0
0.1	5768	677	264	80	91	60	104	50	92	50	126	60	8
0.2	5768	677	264	80	91	60	104	50	92	50	126	60	8
0.3	5768	677	264	80	91	60	104	50	92	50	126	60	8
0.4	5768	677	264	80	91	60	104	50	92	50	126	60	8
0.5	5768	677	264	80	91	60	104	50	92	50	126	60	8
0.6	5768	677	264	80	91	60	104	50	92	50	126	60	8
0.7	5768	677	264	80	91	60	104	50	92	50	126	60	8
0.8	6489	601	188	60	91	60	104	50	92	50	126	60	9
0.9	7872	463	113	40	55	40	104	50	92	50	99	50	10
0.99	8928	413	113	40	55	40	79	40	67	40	99	50	10

[1] OP: Operating cost (USD); [2] BP: Burn perimeter (m); [3] ST: Suppression time (min); [4] N: Total number of helicopters dispatched.

3.1.4. Effects of Fire Priorities (W_f)

The optimal dispatch solutions demonstrated a trend of allocating more helicopters to fires with higher priority (W_f) (Table 10). For Fire H1, which held the second highest priority, one additional large helicopter was dispatched in Priority Scenario 1 along with the two medium helicopters used in the initial scenario, resulting in a 29% reduction in burn perimeter and a 25% reduction in suppression time. In Priority Scenario 2, two large helicopters and one medium helicopter were dispatched to Fire H1, achieving further reductions in both burn perimeters and suppression time. Despite having the highest priority, Fire H3 did not experience any changes in helicopter dispatch across all priority scenarios, as the optimal suppression outcome at $W_q = 0.7$ was already achieved by two medium helicopters from the nearest aviation station. This suggests that the fire priority weight (W_f) alone was insufficient to overcome the operating cost contribution to the objective function defined by $W_q = 0.7$, as dispatching additional helicopters would increase costs more than the gains achieved through reductions in burn perimeters. The lowest priority fire, Fire H4, did not experience any changes in helicopter dispatch decisions across all priority scenarios.

Table 10. Optimal solutions of each priority scenario showing the number and type of helicopters dispatched to each hypothetical fire, operating costs, burn perimeters and suppression times.

Priority Scenario	Solution Outcomes		H1	H2	H3	H4	H5	Total
Initial	# of Helicopters	Extra-large	-	-	-	-	-	0
		Large	-	-	-	-	-	0
		Medium	2	1	2	2	1	8
		Sub total	2	1	2	2	1	8
	Burn perimeters (m)		264	91	104	92	126	677
	Suppression time (min)		80	60	50	50	60	-
	Total operating costs (USD)				5786			
1	# of Helicopters	Extra-large	-	-	-	-	-	0
		Large	1	-	-	-	-	1
		Medium	2	1	2	2	1	8
		Sub total	3	1	2	2	1	9
	Burn perimeters (m)		188	91	104	92	126	601
	Suppression time (min)		60	60	**50**	50	60	-
	Total operating costs (USD)				6489			

Table 10. *Cont.*

Priority Scenario	Solution Outcomes		H1	H2	H3	H4	H5	Total
2	# of Helicopters	Extra-large	-	-	-	-	-	0
		Large	2	1	-	-	-	3
		Medium	1	-	2	2	2	7
		Sub total	3	1	2	2	2	10
	Burn perimeters (m)		113	55	104	92	99	463
	Suppression time (min)		40	40	50	50	50	-
	Total operating costs (USD)		7872					

3.2. Actual Simultaneous Fire Incidents

The actual helicopter dispatch records indicate that 16 helicopters were already deployed to Fire A1 by 07:00 on 22 March 2025, with three additional helicopters deployed later in the morning while Fire A1 remained the only active fire in the region (Figure 8). These helicopters were mobilized from six aviation stations across the nation, including Seoul, Wonju, Cheongyang, Andong, Iksan, and Hamyang. Following the outbreak of Fire A2, six helicopters were dispatched from the Gangneung, Jincheon, Andong, and Uljin stations to Fire A2 between 10:30 and 12:30. Following the outbreak of Fire A3, three helicopters originally assigned to Fire A1 from the Hamyang station (IDs 17, 20, and 21) were relocated to respond to Fire A3 between 12:20 and 13:15. At approximately 15:00, following the outbreak of Fire A4, one helicopter originally assigned to Fire A3 (ID 17) was further relocated to Fire A4.

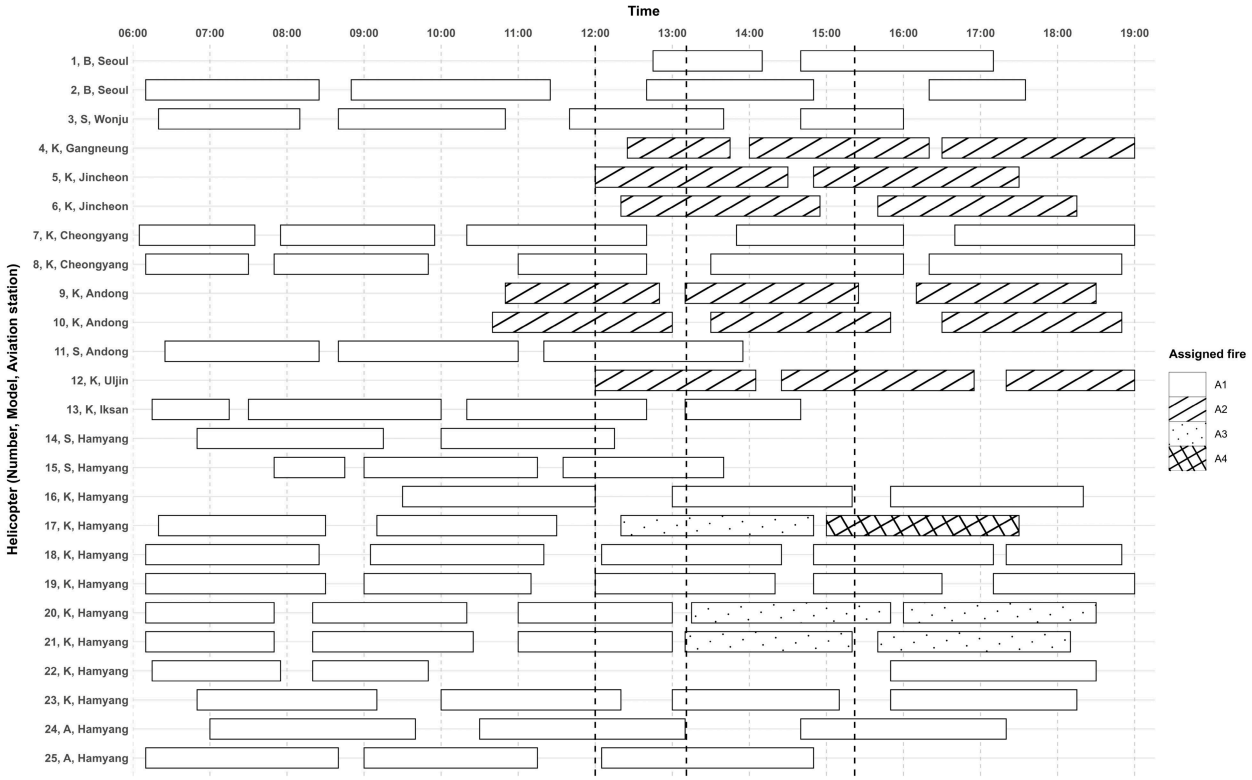


Figure 8. Actual helicopter flight records by helicopter type, aviation station, and assigned fire. Horizontal bars represent the flight periods of each helicopter from 06:00 to 19:00, with fill patterns indicating the assigned fire incident. Each helicopter is labeled with an ID number, model abbreviation, and aviation station. Helicopter model abbreviations are as follows—S: S-64; K: KA-32; B: Bell-206; A: AS-350. Three vertical black dashed lines indicate the times at which the fire spread simulations were conducted by the KFS.

Compared to the actual helicopter dispatch records during the multiple simultaneous fire periods, the model solutions dispatched fewer helicopters when two and three were active, and an equal number when all four fires were considered (Table 11). When Fires A1 and A2 were considered (12:00–13:11), a total of 19 helicopters were dispatched in the model solution compared to 23 in the actual dispatch records. Notable differences include the assignment of more helicopters to Fire A1 from aviation stations near the fire, compared to the actual dispatch records which mobilized helicopters from the more distant Seoul and Wonju stations. Additionally, the model assigned only one extra-large helicopter to Fire A2 from the Andong station, the nearest station to the fire, as opposed to six large helicopters from the Gangneung, Jincheon, Andong, and Uljin stations in the actual dispatch records.

Table 11. Comparison of helicopter dispatch decisions by aviation station between actually dispatched helicopters and optimization model solutions for the actual simultaneous fire incidents.

Aviation Station	A1, A2 (12:00–13:11)						A1, A2, A3 (13:11–15:22)								A1, A2, A3, A4 (15:22–19:00)									
	Actual Dispatch Records			Optimization Model Solution			Actual Dispatch Records				Optimization Model Solution				Actual Dispatch Records					Optimization Model Solution				
	A1	A2	Total	A1	A2	Total	A1	A2	A3	Total	A1	A2	A3	Total	A1	A2	A3	A4	Total	A1	A2	A3	A4	Total
Seoul	2	-	2	-	-	-	2	-	-	2	-	-	-	-	2	-	-	-	2	1	1	-	-	2
Wonju	1	-	1	-	-	-	1	-	-	1	-	-	-	-	1	-	-	-	1	1	-	-	-	1
Gangneung	-	1	1	-	-	-	-	1	-	1	-	-	-	-	-	1	-	-	1	-	-	-	1	1
Jincheon	-	2	2	2	-	2	-	2	-	2	2	-	-	2	-	2	-	-	2	2	-	-	-	2
Chongyang	2	-	2	2	-	2	2	-	-	2	2	-	-	2	2	-	-	-	2	2	-	-	-	2
Andong	1	2	3	2	1	3	1	2	-	3	-	1	2	3	-	2	-	-	2	-	1	1	-	2
Uljin	-	1	1	-	-	-	-	1	-	1	-	-	1	1	-	1	-	-	1	-	-	1	-	1
Iksan	1	-	1	1	-	1	1	-	-	1	1	-	-	1	-	-	-	-	-	-	-	-	-	-
Hamyang	10	-	10	11	-	11	7	-	3	10	9	-	1	10	6	-	2	1	9	8	-	-	1	9
Total	17	6	23	18	1	19	14	6	3	23	14	1	4	19	11	6	2	1	20	14	2	2	2	20

When three fires were considered (Fires A1 through A3, 13:11–15:22), the model continued dispatching fewer total helicopters than the actual dispatch records (19 versus 23). The number of helicopters dispatched to Fire A1 was identical in both solutions (14); however, the model solution utilized more helicopters from the Hamyang station, the nearest station to Fire A1, than the actual record (9 versus 7). The model solution continued assigning one helicopter to Fire A2, substantially fewer than the six in the actual records. For Fire A3, the model assigned one more helicopter than the actual records (4 versus 3). Interestingly, the model relocated two helicopters originally assigned to Fire A1 from the Andong station to Fire A3 following the outbreak of Fire A3, whereas the actual records show three helicopters originally assigned to Fire A1 from the Hamyang station were relocated to Fire A3. Although the distances to Fire A3 from both Andong and Hamyang stations were similar, the Hamyang station was the nearest station to Fire A1. Consequently, the model retained the helicopters from the Hamyang station at Fire A1 and drew resources from the Andong station for Fire A3.

When all four fires were simultaneously considered (Fires A1 through A4, 15:22–19:00), both the model solution and actual dispatch records utilized 20 helicopters in total. However, the distribution of helicopters across fires and aviation stations differed notably. The model assigned 14, 2, 2, and 2 helicopters to Fires A1 through A4, respectively, compared to 11, 6, 2, and 1 in the actual records. For Fire A1, the model assigned more helicopters than the actual records (14 versus 11), again drawing more resources from the Hamyang station (8 versus 6) while also utilizing helicopters from the Seoul and Wonju stations. For Fire A2, the model assigned two helicopters compared to six in the actual records, with resources drawn from the Seoul and Andong stations. For Fire A3, both solutions assigned two helicopters; however, the model drew resources from the Andong and Uljin stations,

whereas the actual records show two helicopters from the Hamyang station were relocated to Fire A3. For Fire A4, the model assigned two helicopters, whereas the actual records show one helicopter was assigned to the fire. Interestingly, both solutions relocated one helicopter previously assigned to Fire A3 from the Hamyang station to Fire A4.

The model results suggest that the optimization successfully emulates the priorities of human decision-making, such as prioritizing fast-spreading fires (i.e., Fire A1). However, the optimization model tends to utilize helicopters located near the fire incidents, whereas the actual dispatch records show helicopters being mobilized from more distant stations. This pattern is consistent with findings from the hypothetical fire analysis, suggesting that human experts tend to reserve nearby resources for unknown future events and mobilize helicopters from more distant stations when they are available. Additionally, the model tends to take advantage of the higher suppression capacity of extra-large helicopters compared to the actual dispatch records. Notably, several extra-large helicopters (ID 11, 14, 15) were not utilized in the afternoon dispatch records, despite their availability earlier in the day.

4. Discussion

Decision-making for resource dispatch during simultaneous forest fires presents an extreme challenge, particularly when limited resources must be rapidly allocated based on incomplete information. In the Republic of Korea, and likely in numerous other countries, these critical decisions currently rely heavily on the experience and subjective judgment of a small group of experts [6]. To address this gap, we developed a decision support framework encompassing information gathering and solution generation for real-time helicopter dispatch support. A discrete optimization model, formulated as an integer linear program, was developed to generate dispatch solutions based on the dual objectives of minimizing operational costs and final burn perimeters.

To evaluate the performance and utility of the optimization model, it was applied to two test cases: (1) five hypothetical simultaneous fire incidents, and (2) four actual simultaneous fire incidents recorded on 22 March 2025. By varying the weights assigned to operating costs and burn perimeter objectives, a range of suppression scenarios was generated for the hypothetical fires, illustrating the decision space and potential trade-offs. While prioritizing fires near residential areas is a common practice, the inter-jurisdictional movement of suppression resources can face significant political and social obstacles. The optimization model offers a tool to analyze different prioritization strategies and demonstrate the potential benefits of resource mobility when strategically implemented. This analytical capability can facilitate communication and consensus-building among local governments for more effective resource allocation.

The comparison between the optimization model solutions and the expertise-driven manual decisions of the FFCC may not constitute a perfect validation method. There are also limitations in the retrospective comparison between the model solutions and the actual helicopter dispatch recorded for the four actual simultaneous fire incidents, as manual dispatch decisions were continuously evolving, while the model was applied at a limited number of discrete points in time. Additionally, the fire spread simulations used in this application were conducted only once per fire rather than being updated at subsequent time points to reflect evolving fire conditions. Consequently, the model assumed that fires ignited earlier continued to spread according to the initial simulation results. In real-world operational settings, fire spread simulations should be conducted at regular intervals for all active fires, both ongoing and newly ignited, especially at each optimization time point, to reflect current fire conditions and generate more realistic projections for the subsequent suppression period.

Nevertheless, these applications demonstrated the model's capability to generate quality alternative solutions that could be considered for greater effectiveness compared to the decisions relying solely on the experience of individual personnel. Specifically, the model was able to identify resource inefficiencies and suggest allocating helicopters to fires where they would yield a higher marginal suppression benefit or operational cost savings across the multiple simultaneous fire incidents. The application to the four actual fire incidents demonstrated the flexibility of the optimization framework, which can be applied at any critical time points when ongoing fires exist, new fires break out, or resource availability changes.

Feedback from the KFS revealed that their manual decision-making process incorporated uncertainties and preferences derived from their past operational experience. These factors include strategically reserving resources for potential fires in historically high-risk areas and a preference for certain types of helicopters due to pilot familiarity and perceived suitability for large fires. Although the model facilitates qualitative inputs through suppression priority weighting, it is fundamentally limited by its deterministic quantitative approach. Consequently, it cannot directly account for uncertainties and other factors that are not explicitly modeled within the framework, such as helicopter type preference and fire containment by ground resources [22]. Future studies should explore diverse operational applications while extending the model to incorporate the suppression contributions of ground and other aerial resources and more realistic resulting burn perimeters.

The quality of the model output is inherently dependent on the accuracy of the input data. The model relies significantly on fire spread simulations and the assumed suppression efficacy of helicopters, operating under the assumption that containment is achieved when suppression rates exceed fire growth rates. A forest fire spread simulation tool developed by the KFS was used, which currently relies on a single-point-in-time weather data. This reliance fundamentally affects simulation accuracy, as weather conditions and fire–atmosphere interactions are highly dynamic [32]. Similarly, the suppression productivity of helicopters is subject to variability based on factors such as weather, terrain, and pilot experience, for which time- and site-specific data are currently lacking [24]. Additionally, the use of 10 min discrete time intervals as the model's temporal unit limits its ability to capture time differences of less than 10 min. A further limitation is the model's singular focus on the defined objective function, without explicitly incorporating social and political conditions or the potential for new fire outbreaks in other districts, all of which could influence dispatch decisions.

Future enhancements to the decision support framework should focus on improvements in modeling accuracy and precision, including the integration of dynamic weather conditions into fire spread simulations, the development of methods to estimate time- and site-specific aerial suppression efficacy, and the incorporation of the suppression effects of ground and other aerial resources. These improvements will be crucial for enhancing the reliability and operational applicability of solutions generated by this framework.

5. Conclusions

This study developed a decision support framework that standardizes information gathering, prioritization, and optimization to generate real-time helicopter dispatch solutions for suppressing multiple simultaneous forest fires. The framework and optimization models were designed as analytical tools for the rapid evaluation of fire situations and the generation and assessment of various helicopter dispatch options. Importantly, this framework is not intended to autonomously make resource allocation decisions, but it aims to assist decision-makers by enhancing their understanding of fire dynamics and potential trade-offs between dispatch strategies, facilitating the determination of resource allocation

priorities, and ultimately supporting more informed decisions. The framework provides a standardized operating procedure that improves current decision-making practices in the Republic of Korea by offering more objective and diverse alternatives, particularly during multiple simultaneous fire incidents. Further research is essential to enhance the accuracy and capabilities of the framework, particularly with respect to fire spread modeling, suppression resource effectiveness, fire spread and suppression interactions, and the combined effects of aerial and ground resources.

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