

MODELING, SIMULATION AND EVALUATION OF LARGE FOREST FIRE EXTINGUISHING AND RESCUE BASED ON AVIATION MATERIEL

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Abstract

Large scale forest fires are a major challenge for emergency rescue in China, and aviation materiel provides an increasingly practical and efficient solution for fire suppression. Focus on the current demand and typical scenarios for large-scale forest fire extinguishing mission, task process of typical aviation forest fire extinguishing has been analyzed, and a series of models including materiel model, fire spread model, and operation model, etc., has been constructed for simulate the process in fire prevention and rescue of large forest. Then, taking the forest fires in northeast area as the object, some typical aviation materiel was selected for static effectiveness evaluation and task effectiveness evaluation, and the advantages and limitations of using aviation materiel in large-scale forest fire extinguishing tasks were presented, providing support for the subsequent construction of the national fire extinguishing emergency rescue system layout. The results indicate that mixed schemes combining large amphibious aircraft and helicopters can improve task duration and burned-area control, while medium and large helicopters remain cost-effective options when fixed-wing operating conditions are limited.

Keywords: fire extinguishing and rescue, helicopter, modeling simulation and evaluation, aviation materiel, amphibious aircraft

1. Introduction

Forest fire management is a global challenge, with aviation fire extinguishing and rescue playing a important role in international efforts. In recent years, rising global temperatures and frequent forest fires have caused significant economic and ecological losses. Many countries such as the United States, Canada, and Australia possess notable advantages in aviation fire extinguishing technology and materiel. Modern aviation fire extinguishing materiel includes fixed-wing fire extinguishing aircraft, amphibious aircraft, helicopters, and drones, which are widely used for many years and have formed standards and guidance. At the same time, technological innovations such as night fire extinguishing systems, and efficient spray systems have significantly improved fire extinguishing efficiency. China also faces with enormous challenges in forest fire fighting, both in frequency and in scale. With the social and economic development, forest coverage rate has been increased year by year. The forest resources are widely distributed in the northeast, southwest and southeast regions [1-3].

However, with increased climate change and the expansion of human activities, the frequency and scale of forest fires has increased significantly, raising higher requirements for forest fire prevention and emergency rescue. The aviation fire extinguishing equipment system has become indispensable in dealing with large-scale forest fires by rapid response and wide coverage characteristic. It is essential to establish an evaluation model for aviation materiel fire extinguishing mission assessment.

The typical aviation fire extinguishing and rescue mission scenarios were studies and an evaluation index system with algorithm model are established for assessing the effectiveness in this paper. Some case studies with quantitative calculations and analyses are presented, which may provide recommendations for Chinese typical fire scenarios and operation, particularly in northeast and southwest regions.

2. Requirement Analysis and Scenario for Forest Fire Extinguishing

2.1 The Distribution of Forest Fires in Major Regions

The distribution of forest fires in China has significant regional and seasonal characteristics. As for the regional characteristics, the major forest fires comprise three major zones: the Northeast Forest Zone, the Southeast Forest Zone, and the Southwest Forest Zone. Among these, the Northeast and Southwest Forest Zones are natural forest areas, while the Southeast Forest Zone primarily consists of plantations and secondary forests. Generally, forest fires are mainly concentrated in the northeast and southwest regions, where forest resources are abundant and the climate conditions are relatively dry, easily causing fires. As shown in figure 1.

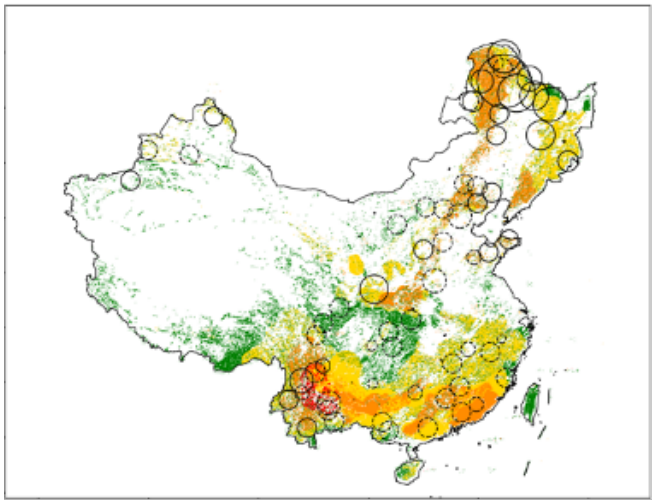


Figure 1 – A schematic diagram of comprehensive fire danger and terminal coverage capacity

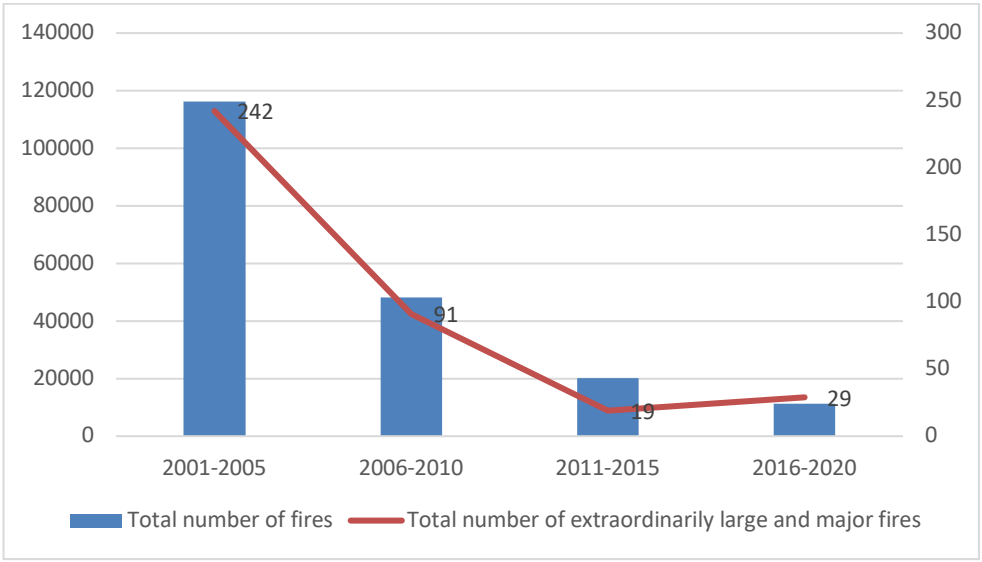


Figure 2 – Statistics of number of fires and major fires during 2001-2020

As for the seasonal characteristics, in northeast area, spring and autumn are the high occurrence

period of forest fires, especially in spring, when the temperature rises and the wind strength increases, and the agricultural activities are frequent, which can easily cause fires. However, in the winter and spring of the southwestern region every year, the precipitation is less, and the moisture content of vegetation decreases, which can easily cause fire.
The total number of fires decreased between 2001 and 2020, and the total number of extraordinarily large and major fires has been below 100 per year since 2006, which may be due to better fire prevention measure and more and more development and deployment of aviation materiel.

2.2 The Scenario for Large Forest Fire Extinguishing

The large forest fire extinguishing is one of the most scenarios, which may divide into three categories:

- High frequency scenarios, i.e. scenarios with high probability of occurrence, such as daytime fire extinguishing scenes in the original forest area of northeast.
- Boundary scenarios, i.e., scenarios where fire extinguishing is carried out under extreme conditions, such as cliff fire extinguishing scenarios.
- Special scenarios, i.e., scenes under special circumstances or special conditions, such as fire extinguishing scenes applied by human drone fusion.

Taking major and extraordinarily fire extinguishing in northeast forests for example, more than 100 hectares area and more than 10 human death or 50 human serious injuries occur in the key areas, which needs capable of controlling the fire conditions or extinguishing fire within specified time using aviation power.

2.3 Requirements Analysis for Major Fire Extinguishing Typical Scenario

The large forest fire extinguishing task requirement is analyzed according the typical scenario, and the task lists is shown in table 1.

Table 1 –Capacity requirements for aviation fire extinguishing task

No.	Task capability	Task capability decomposition
1	Reconnaissance and Early Warning Ability	Patrol Ability
		Reconnaissance capability
		Early warning capability
2	Fire Response Capability	Response preparation capability
		Responsiveness
3	Rescue Capacity	Fire extinguishing capability
		Search and rescue capability of trapped personnel
4	Delivery capacity	Capability of transporting fire extinguishers
		Capacity to transport fire extinguishing materials
		Capacity to transport large equipment
5	Communication command capability	Fire field communication capability
		Information transmission capability of fire field
		Fire field command capability

3. Modeling and Simulation for Aviation Fire extinguishing Process

3.1 Analysis of Aviation Fire Extinguishing Mission Processes

Aircraft emergency rescue equipment includes helicopters, fixed-wing aircraft, amphibious aircraft, drones, and other equipment. From the perspective of typical mission scenarios, aviation fire extinguishing tasks encompass five categories: extinguishing large forest fires in Northeast area,

combating major and above forest fires in Northeast area, suppressing large forest fires in Southwest area, tackling major and above forest fires in Southwest area, and forest/grassland fire patrol.

Table 2 – Analysis for aviation technological innovation activities based on Zachman model

No.	Operation process
1	Before executing water-dumping fire extinguishing missions, fixed-wing aircraft crews, flight observers, and ground personnel receive the mission, assess the operational environment, develop fire extinguishing plans, and complete all pre-flight preparations.
2	After completing the task preparations, the fixed-wing aircraft takes off and climbs to the route flight altitude, then proceeds to the selected water source area according to the flight plan water source area.
3	The fixed-wing aircraft descends to a relative altitude of 100~300 meters for approach, lands at the water source according to established procedures to extract water, and selects the addition of fire retardants based on the fire extinguishing plan.
4	After completing the water intake, the fixed-wing aircraft climbs away from the water source and follows the predetermined route to the target fire scene.
5	After the fixed-wing aircraft enters the target fire area, it opens the water-dropping hatch according to the established fire extinguishing strategy to spray water and extinguish the fire, while monitoring the suppression progress of the current target fire spot.
6	During the mission, if the fixed-wing aircraft requires refueling, it shall select an airport or base for replenishment according to the mission management method, and continue executing the current task after completing the refueling.
7	Repeat the task sequence of "flying to the water source - landing to draw water - flying to the fire scene - spraying water to extinguish the fire" until the fire is completely put out.

3.2 Modeling of Aviation Fire Extinguishing Mission

3.2.1 Fire process simulation model

The coupling Rothermel model is selected to simulate the forest fire spread [4], as shown.

$$Ro = \frac{I_R \zeta (1+\phi_W+\phi_S)}{\rho_b \varepsilon \varphi_{ig}} \quad (1)$$

Ro is the spreading speed of forest fire; I_R is the reaction intensity of flame zone; ζ is the rate of forest fire spread; ϕ_W is the correction coefficient of wind speed; ϕ_S is the slope correction coefficient; ρ_b is the density of combustibles; ε is the effective thermal coefficient; ϕ_{ig} is the heat required to ignite a unit of combustible matter.

The seed point velocity is calculated based on the Rothermel model and then dynamic evolution of particle system is used to realize the coupling of physical model and flame visualization method.

3.2.2 Fuel consumption model

In aviation fire extinguishing missions, the impact of altitude on fuel consumption of fixed wing aircraft is particularly important, directly affecting the planning, execution efficiency, and mission cost of fire extinguishing missions. The fuel consumption curve of fixed-wing aircraft contains the variation of fuel consumption under different load and flight conditions. The following text takes amphibious aircraft as an example to analyze the fuel consumption changes of fixed wing aircraft corresponding to different altitudes [5-7].

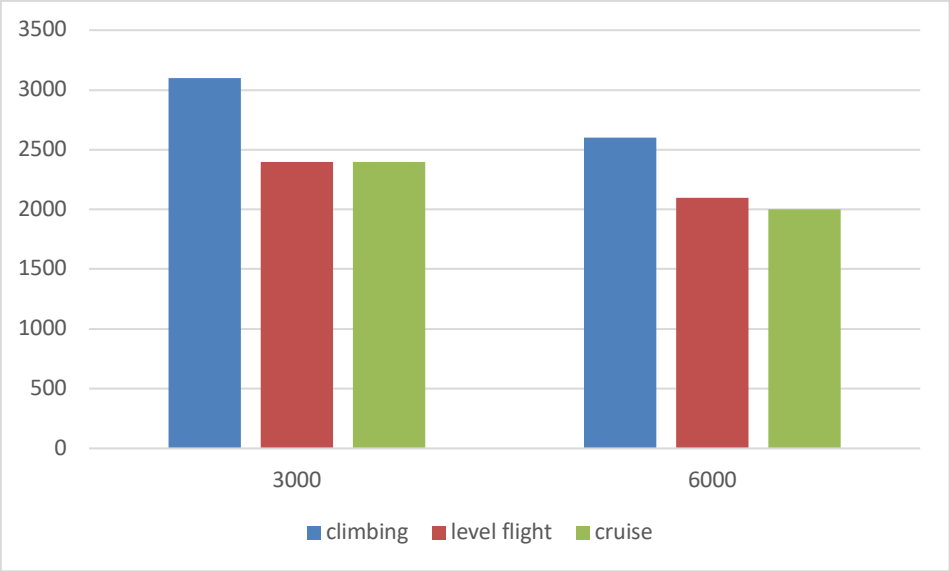


Figure 3 – Comparison of fixed wing fuel consumption rates

The relationship between fuel consumption and flight condition is established through recording discrete fuel consumption data for different flight conditions.

3.2.3 Operation model

Usually, the trajectory of the water drop follows a parabolic trajectory, with the aircraft flying forward, showing multiple parallel waterline integrated trajectory, as shown in figure4.

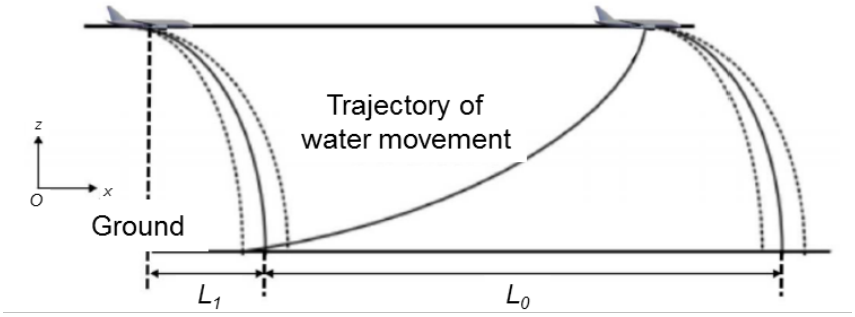


Figure 4 – The trajectory of water movement in operation model

According to the theory of turbulent jet, the width of the water zone after jetting is a linear function of the falling distance. The formula for calculating the width of the water belt is

$$R = f(H) = 0.5 * H \tag{2}$$

The ground distribution length of the water body, i.e. the length of the water belt, is determined by the flight speed and spraying time of the aircraft. The calculation formula is as follows:

$$L = V * Q/q \tag{3}$$

V is the flying speed, Q is the amount of water, q is usually 1000.

For typical vegetation in northeast, the water demand for fire extinguishing is about 1-2.5kg/m^2. The minimum fire extinguishing demand in this model is η_{need}=1.5kg/m^2. The precipitation distribution of the sprinkler belt follows a Gaussian function, and the formula for calculating the water volume at the sprinkler center point is:

$$\eta_{max} = \frac{Q}{L} / \int_{-\lambda}^{\lambda} e^{\frac{-y^2 ln2}{4\lambda^2}} \tag{4}$$

The true effective area of the sprinkler hose is:

$$R_{eff} = \sqrt{\frac{-2R^2 \ln(\eta_{need}/\eta_{max})}{9}} \quad (5)$$

Based on the analysis of watering accuracy (*IP*) and water sprinkling success probability (*POS*) of different types of aircraft, the effective area of sprinkler fire extinguishing is calculated by combining the sprinkling area of the aircraft.

$$R = R_{eff} * IP * POS \quad (6)$$

The accuracy of water spraying (*IP*) quantifies the proportion of air drops that interact with fire, which is affected by wind speed; Water Sprinkler Success Probability (*POS*) refers to the ratio of effective fire extinguishing area to total interaction area, affected by sprinkler height, flight speed and wind speed.

3.3 Evaluation of Aviation Fire Extinguishing Mission

According to the task flow and task characteristics of the direct fire extinguishing task of aviation fire extinguishing equipment, the task effectiveness evaluation index system is constructed from the perspectives of static capability of single machine and overall parameter of task. An efficiency evaluation model has been established in this paper to assess the typical aviation fire extinguishing and recue scenario, as shown in figure 5.

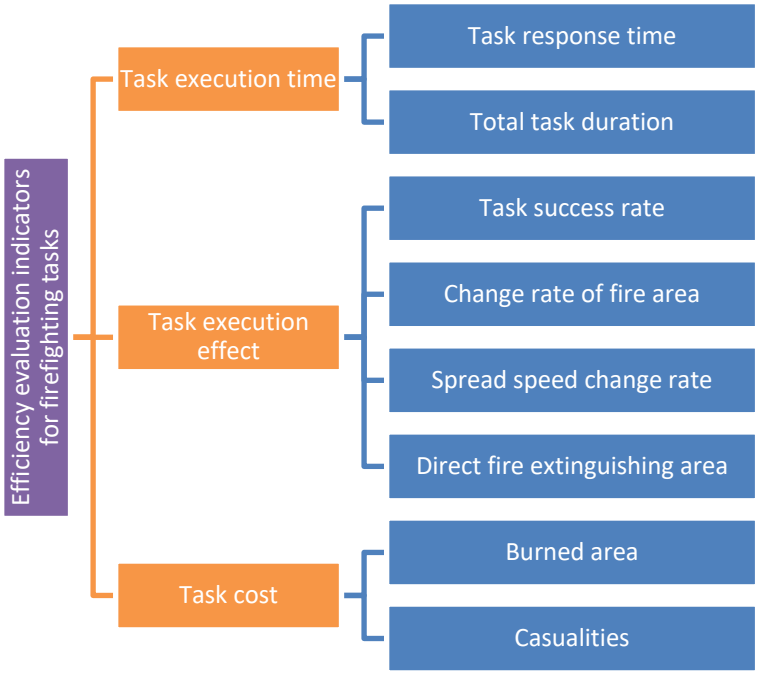


Figure 5 – The assessment index for efficiency evaluation model

4. Case Studies

4.1 Task scenario

Taking fire extinguishing in northeast forest for example, the fire station include Gagedaqi, Genhe station, which are the two minimum operating units in the system that deploy different aviation materiel. In this scenario, we choose different minimum units for the typical fire extinguishing materiel to simulate and assess.

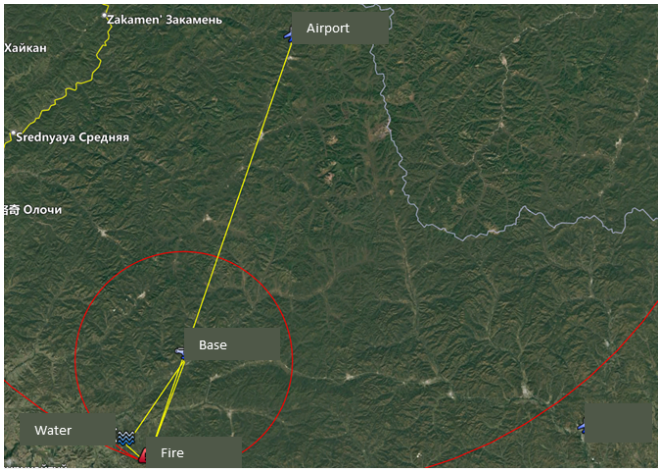


Figure 6 –Schematic diagram of large fire extinguishing in northeast area

4.2 Static capability evaluation

Based on the AHP evaluation method, an evaluation matrix for the static capability of aviation fire extinguishing is constructed. Then selecting four kinds of aircraft such as Mi-26, Ka-32, as typical aviation fire extinguishing equipment for static capability evaluation, the quantitatively calculated static capability evaluation is as follows in table 3.

Table 3 – Static capability evaluation result of typical aviation fire extinguishing materiel

Index		Alternative 1	Alternative 2	Alternative 3	Alternative 4	Overall
Task Response Capability	Orig.	0.53	0.76	0.72	0.51	0.63
	Norm.	0.70	1.00	0.95	0.67	
direct fire extinguishing capacity	Orig.	0.75	0.42	0.43	0.87	0.62
	Norm.	0.86	0.48	0.49	1.00	
Task Adaptability	Orig.	0.48	0.52	0.6	0.47	0.52
	Norm.	0.80	0.87	1.00	0.78	
Maintenance Guarantee	Orig.	0.75	0.87	0.96	0.75	0.83
	Norm.	0.78	0.91	1.00	0.78	

The analysis results indicate that the static capability evaluation of most aviation fire extinguishing equipment is concentrated in the range of 0.5 to 0.7. Among them, the static capability evaluation of medium and large helicopters is generally in the range of 0.5 to 0.6, while heavy helicopters are relatively higher, above 0.6. The comprehensive static capabilities and primary capabilities of each typical equipment are shown in figure 7.

The alternative 4 for fire extinguishing shows a significant lead in static capability which is about 0.7, about 9% higher than typical helicopter (alternative 1, Mi-26) and about 24% higher than medium and large helicopters. The results show that alternative 4 has strong competitiveness in static performance and can play a reinforcing role in airborne fire extinguishing mission system. In addition, the alternative 3 has an advantage over Mi-171 in terms of static capability, with a relative improvement of 4.2%, indicating that it has the potential to effectively replace Mi-171, or can be used as a key supplement for aviation fire extinguishing materiel.

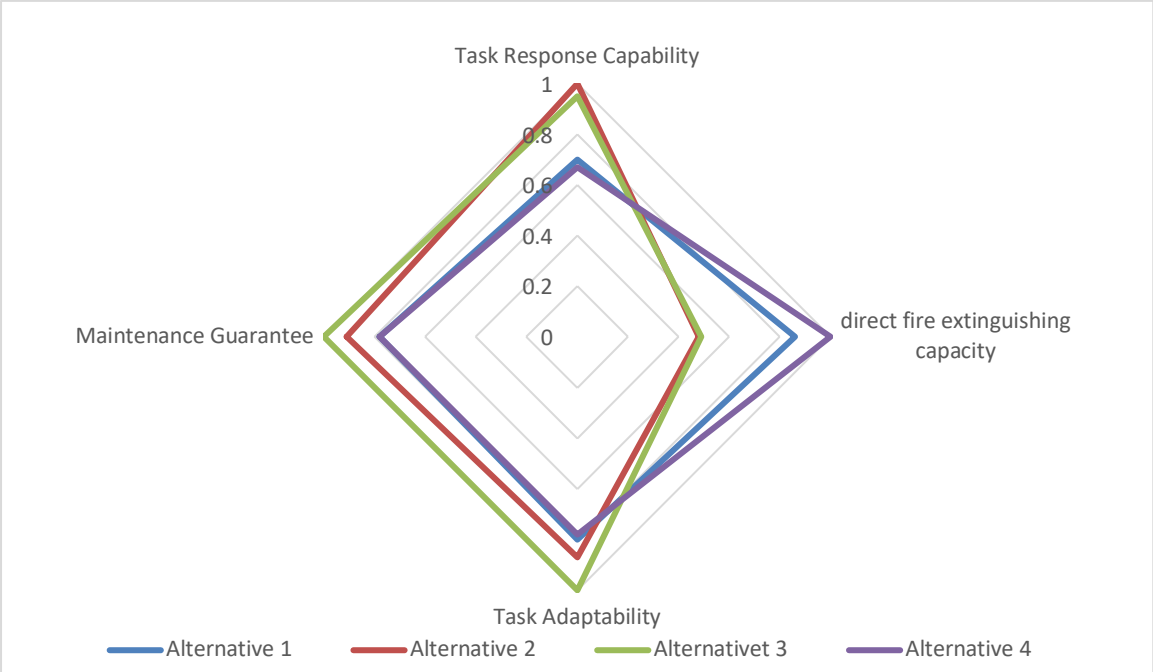


Figure 7 – Comparison chart of typical aviation fire extinguishing equipment capability items

4.3 Task efficiency evaluation

4.3.1 Parameter setting

The initial setting of simulation environment for the large fire extinguishing task scenarios in northeast area is as follows in table 4.

Table 4 –Parameters of large fire field in northeast area

Items	Parameter setting
Location of fire field	121°06'35"E，50°15'00"N (0，0)
Types of combustibles	deciduous/coniferous mixed forest
Average humidity of fire site	10%
Maximum temperature of fire site	800°C
Maximum width of fire line	20m
Fire field capacity	15 persons
local wind	0m/s
Local slope	0°
Spread Speed Multiplier	1.2
GPC Grade	4.5
Whether reconnaissance is required	Yes
Fire site reconnaissance time	15 minutes
Execution or Extinction	No
Discover Time Random Range	60 minutes

4.3.2 Aviation fire extinguishing materiel solutions

The direct fire extinguishing mode is chosen in the simulation, which use helicopters, fixed-wing aircraft, unmanned aircraft and other aircraft to transport water, chemical liquid and fire extinguishing bombs to forest fire area, and directly extinguish fires by spraying liquid and projectile. According to different stage in forest fire extinguishing task, four alternative solutions are designed, as shown in table 5, including large fixed wing aircraft and helicopter.

Table 5 –Comparison of large fire extinguishing task schemes in northeast area

Mission	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Fire field reconnaissance	AS-350	AS-350	AS-350	AS-350
manned fire extinguishing	Mi-171	AC-313A	N/A	AC-313A
Suspended bucket fire extinguishing	2 Mi-171	2 AC-313A	2 Ka-32	N/A
Water tank fire extinguishing	N/A	N/A	N/A	A-X

Here, the helicopter in the direct fire extinguishing task is generally dominated by bucket spraying water, i.e. the helicopter hangs the bucket in the air and sprays water to the fire area after taking water in the appropriate water area to achieve the purpose of extinguishing fire. And the fixed wing aircraft generally use water tank to take water from near lake to the fire zone.

4.3.3 Simulation process and results

The simulation sets 100 times of simulation calculation for each task scheme. The main output parameters include: task consumption time, task entry time, direct fire extinguishing area, fire area change rate, spread velocity change rate, fire area, casualties and direct cost. In addition, the task success rate shall be calculated according to simulation records. The termination conditions of simulation calculation include time termination conditions and task completion conditions. When the fire site is set without open fire, it is considered that the task is completed. If the task is not completed continuously for more than 10 hours, it is considered that the task fails.

Task effectiveness and related parameters for each task scheme are as shown in table 6. According to the overall task effectiveness, the task efficiency of the mixed scheme of A-X and AC-313A is the highest, about 0.82. The three-machine scheme of AC-313A and Mi-171 are the second, 0.778 and 0.716 respectively. The alternative 3 dual-machine scheme has the worst task efficiency, about 0.587.

Table 6 – Comparison of task efficiency of major fire extinguishing task plans in northeast area

Project	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Task time(min)	231.8	197.42	295.2	167.25
Entry time(min)	29.5	27.5	49.5	27.5
Direct fire extinguishing area(ha)	0.79	0.72	0.68	0.69
Fire scene area change rate	100%	100%	100%	100%
Spread speed change rate	100%	100%	100%	100%
Burnt area(ha)	11.22	9.45	13.66	8.59
Casualties	0	0	0	0
Task success rate	100%	100%	100%	100%
Aircraft num (except AS-350)	3	3	2	2
Task efficiency	0.716	0.778	0.587	0.82

Since all schemes achieved fire control within the termination condition, the differences are mainly reflected in task duration, entry time, burned area, and resource consumption.

The relative distribution of each task parameter in each task scheme is as shown in figure 8.

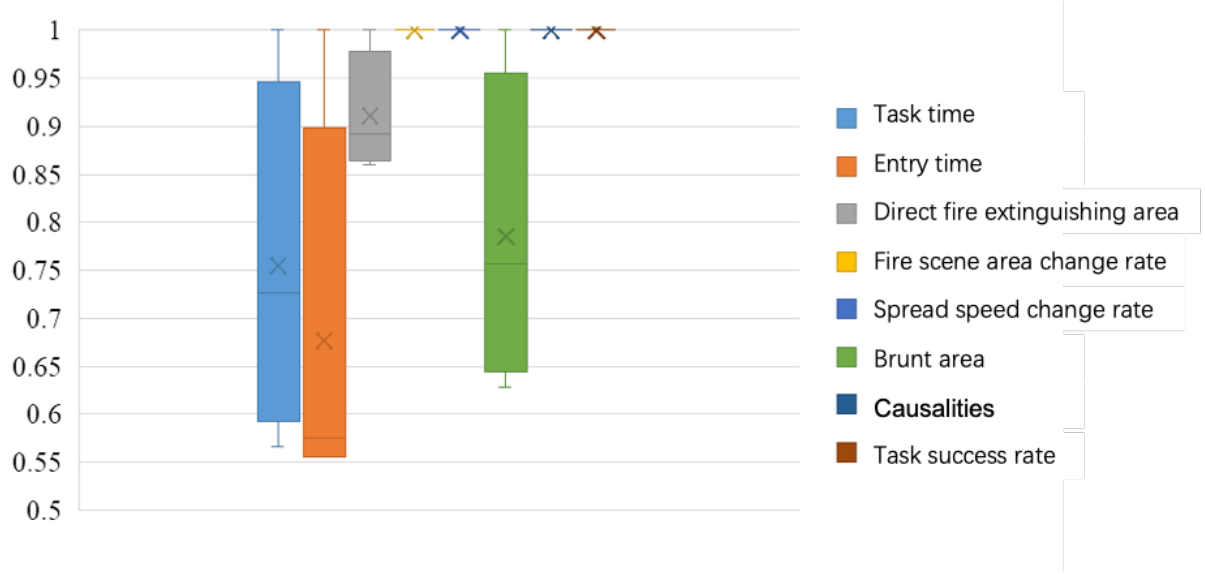


Figure 8 – Comparison of major fire extinguishing tasks in northeast area

Overall, the overall mission performance gap of each mission scheme is relatively small for the larger fire extinguishing tasks in the typical northeastern area, and all can effectively complete the aviation fire extinguishing task. The main disparities mainly focus on three types of time-consuming tasks, entry time and direct fire extinguishing area.

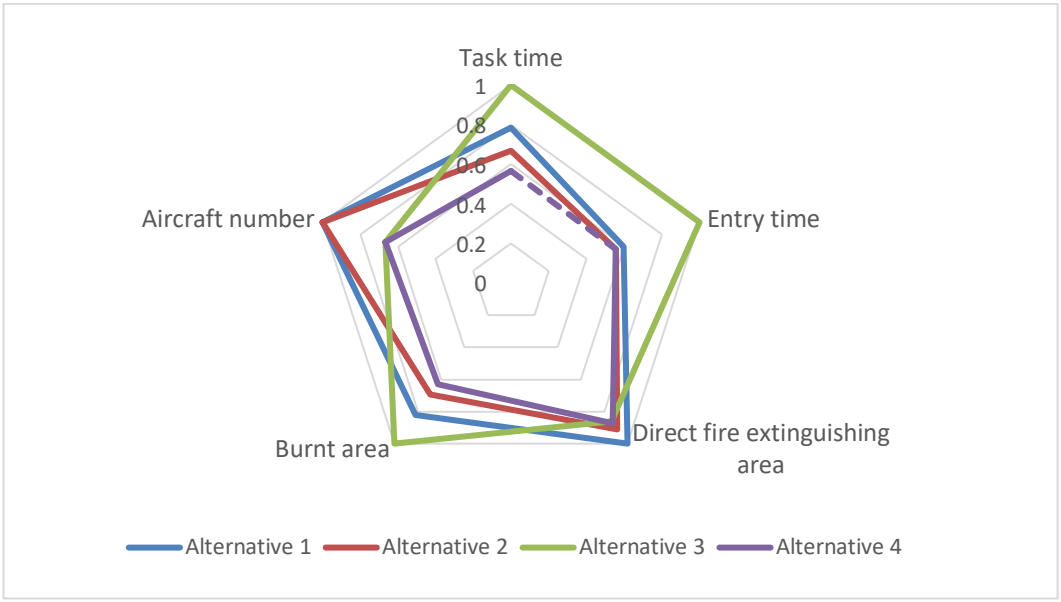


Figure 9 – Normalized parameter distribution comparison chart of each task scheme for large fire extinguishing tasks in northeast area

According to several main task effectiveness sub-items such as mission time consumption, entry time, direct fire extinguishing area, burnt area and aircraft number. The overall mission performance of Mi-171 fleet and AC-313A fleet is basically the same. Mi-171 fleet is less than AC-313A in task consumption and fire area. The AC-313A can effectively replace the currently equipped Mi-171 in future typical northeast forest fire missions.

Overall, four alternatives can successfully complete a typical large fire extinguishing task in northeast forest, except for alternative 3 dual-machine scheme is not ideal. The completion effect of AC-313A and Mi-171 scheme exceeds 0.7, reaching the pass level. The mixed formation of A-X and AC-313A

is good, close to the excellent level (0.85). In addition, the task effectiveness of A-X is slightly higher than that of two large helicopters in large forest fire extinguishing tasks in northeast area, and that large helicopters can effectively replace international aircraft in typical large forest fire extinguishing missions in northeast area. In future development, the hybrid mission scheme of large amphibious aircraft and large helicopters can achieve the best and most comprehensive mission effect.

5. Conclusion

Focusing on the large forest fire suppression in northeast area, a modeling, simulation and evaluation method is established using fixed wing aircraft and helicopter to optimize the fleet solution and improve the effectiveness. The following inspirations and suggestions are provided:

(1) The modeling and simulation for large forest fire extinguishing includes materiel modeling, environmental modeling, and operational modeling, such as fire process simulation model, and fuel consumption model, etc., which reveals the underlying logic of fire and extinguishing process underlying. In addition, evaluation model is needed to assessment the extinguishing task effectiveness, which must include economic analysis.

(2) In modeling and simulation for large forest fire extinguishing, usually, the evaluation results usually indicate a trade-off between task efficiency and operating cost, rather than pointing to a single optimal solution. For example, in northeast major fire extinguishing scenario, a fixed wing aircraft which may complete the mission in 2 hours, or three helicopters may complete mission in 1.5 hour, and using the same cost. The two can be chosen as alternative in normal fire extinguishing activities.

(3) For typical low altitude areas in northeast area, when there are conditions for the use and maintenance of fixed wing aircraft, medium and large helicopters should be used as the backbone of aviation fire extinguishing equipment, gradually equipped with amphibious aircraft, and heavy helicopters should be used as a reinforcement for aviation fire extinguishing plans. When fixed wing aircraft maintenance conditions are not available, medium and large helicopters have the best cost-effectiveness performance. Overall, the most cost-effective mission plan is 3-5 medium to large helicopters equipped with A-X as heavy support for the aviation fire extinguishing fleet.

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