Operations Research Forum (2026) 7:77
https://doi.org/10.1007/s43069-026-00664-9

RESEARCH

# A Constructive Heuristic for Dispatching and Routing Firefighting Resources to Attack Multiple Fires

**Marina A. Matos[1] · Rui Gonçalves[1] · Ana Maria A. C. Rocha[1] · Lino A. Costa[1] · Filipe Alvelos[1]**

Received: 25 March 2025 / Accepted: 7 June 2026
© The Author(s) 2026

**Abstract**
Forest fires are natural phenomena that have become increasingly serious in recent decades. It has therefore become essential to manage firefighting in order to prevent and reduce the damage caused by fires, such as loss of life, the impact on the economy, and damage to ecosystems. In order to reduce the impact of a fire, firefighting resources must be available and deployed to extinguish a given ignition in order to be as effective as possible in fighting fires. In this work, we address the problem of dispatching and routing a set of resources to attack multiple fires. Given the need for quick decisions, we propose a constructive heuristic. The approach is based on a time discretization and on estimates of the growth of the different fires. The heuristic has the advantage of producing results in a short time, indicating where and when each resource should move to extinguish the fire, so that the burned area is as small as possible. A set of 60 instances, comprising 5, 7, and 10 resources to extinguish 20 and 30 ignitions, is generated to test and validate four variants of the constructive heuristic. A case study in northern Portugal is presented to demonstrate the practical feasibility of the proposed approach. The results showed the effectiveness of the constructive heuristic, which may be used to support firefighting services in making decisions.

**Keywords** Forest fires · Fire suppression · Constructive heuristic

✉ Marina A. Matos
mmatos@algoritmi.uminho.pt

Rui Gonçalves
rgoncalves0320@gmail.com

Ana Maria A. C. Rocha
arocha@dps.uminho.pt

Lino A. Costa
lac@dps.uminho.pt

Filipe Alvelos
falvelos@dps.uminho.pt

[1] ALGORITMI Research Centre/LASI, University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal

Published online: 19 June 2026

## 1 Introduction

In recent years, the number of large forest fires has increased alarmingly [1, 2]. This increase represents high-risk situations for the health of living beings and the ecosystems, that is why good forest management is essential. The aim of forest management is to produce forest products, protect fauna and flora, maintain watersheds, conserve soil, reduce losses from forest fires, etc [3]. It is therefore essential to carry out forest fire management, which consists of preventing the occurrence of fires, anticipating when and where fires may occur, and adopting the necessary and effective measures to reduce the damage caused by forest fires [4].

Every year, around 4 million $km^2$ of land (roughly the size of the European Union) is burned around the world [5]. In Europe, more than 1500 $km^2$ of land burned in 2021, of which 1000 $km^2$ belong to protected areas in the European Union [6]. In 2017, Portugal faced several forest fires, making it a record year for the number of deaths that occurred. The main causes were high temperatures and dry thunderstorms [7]. The increase in the number of forest fires around the world has caused several negative impacts, such as deaths, pollution, and damage to infrastructure, making it a very concerning issue for society and planet Earth.

Firefighting is a very important and studied area in the literature. In particular, studies are carried out to support the decisions of professionals in forest firefighting (firefighters, civil protection, etc.) [8–13]. Forest fire suppression encompasses strategies that determine the quantity and type of firefighting resources to be sent to forest fire(s), with the goal of extinguishing it efficiently and quickly while minimizing its negative impacts. Optimization approaches have been used to address problems related to fire suppression, aiming to find the optimal trajectory of firefighting resources (vehicles) and their attack location, obtain the shortest route between the location of the forest firefighting vehicles and the location of the active forest fires, and determine the number and type of resources to dispatch [14, 15]. Rodriguez-Veiga et al. [16] proposed a mathematical model based on integer linear programming to optimize resource allocation in forest firefighting. The main objective was to maximize the effectiveness of firefighting operations, taking into account availability constraints, costs, and time requirements. The model integrated variables related to the selection of resources (such as teams, equipment, and vehicles) and their allocation in specific periods, aligning decisions with the dynamics of the fires and the scarcity of resources. The approach took into account the characteristics of the event, such as the location and intensity of the fire, as well as operational costs, to determine the most efficient and economically viable strategies. The tests in simulated scenarios demonstrated the model's potential to support managers in planning and executing firefighting operations, providing a robust analytical tool to optimize resource allocation in critical situations. The article by Matos et al. [17] presented the use of genetic algorithms (GA) to optimize resource allocation in forest firefighting. The approach considered factors such as the availability of resources, logistical restrictions, and fire progression, aiming to find efficient solutions to minimize the burned area. The tests in simulated scenarios showed that the method is promising in rationalizing the use of resources, highlighting the applicability of optimization techniques in the strategic management of forest fires. Tian et al. in [18] solved the emergency scheduling problem in forest firefighting, minimizing the

number of vehicles while minimizing the extinguishing time, using a multi-objective approach, in order to reduce the operational cost and improve the efficiency of fire extinguishing services. However, all these studies address the problem of firefighting as a resource scheduling problem, without taking into account the characteristics of the fire (such as fuel, slope, or wind intensity) or whether multiple resources are required to extinguish it.

The fire spread is strongly influenced by when firefighting efforts begin. Early attack can slow or contain the fire before it grows large, while delays allow it to spread more rapidly, potentially burning more area and requiring more resources. The minimization of the impacts of forest fires can be achieved if the necessary resources are available and can respond to the fire in a short time. It should be noted that in the forest firefighting, the longer it takes to fight, the bigger they become and the more difficult it is to control them. Only a few works have considered the fire suppression problem as a resource dispatch and routing problem to extinguish forest fires. In [19], a preliminary study aiming to minimize the burned area in solving the firefighting resource problem was developed. However, this strategy had some limitations, as it did not allow for the refilling of the resources. In other words, if a resource ran out of water, it would return to the fire station and become inactive.

This paper addresses the problem of, given a set of resources and a set of fires, deciding, for each resource, the sequence of fires it will attack with the objective of minimizing the total burned area. The firefighting dispatch and routing problem jointly determines the location of available resources and their routing among fires. This kind of problem considers these two decisions jointly: allocation of resources to fires and routing decisions. The latter takes the form of a dispatching list that defines, for each period of time, an ordered list providing a hierarchy of resources available to be chosen whenever a fire is active. Decisions regarding resource location take into account the amount of water needed to extinguish the fire and the capacity of the resource's water tank. Resource dispatch is a decision that must take into account the current state of the problem (checking whether resources are occupied or available) when selecting the resource to respond to a fire that is burning.

In this work, a constructive heuristic was developed to solve the firefighting dispatch and routing problem, considering the refilling of water tanks of firefighting resources. The main benefit of constructive heuristics is their speed, which is crucial in situations where decisions need to be made quickly. The main objective of the constructive heuristic is to assign each resource to a location of ignition, at each period of time, in order to minimize the total burned area. Four variants of the constructive heuristic will be tested on a set of 60 instances randomly generated, comprising 5, 7, and 10 resources to extinguish 20 and 30 ignitions. To evaluate the performance of the heuristic, a statistical analysis is performed.

In addition, a practical application of the constructive heuristic is implemented in a more realistic way through the presentation of a case study conducted in the district of Braga, northern Portugal. In this case study, three fires are considered. The locations of the fires were selected according to their high historical record of fires. The nearest fire station is located in Póvoa de Lanhoso, within the district of Braga, and has five land vehicles available with limited water tanks. Fire spread was simulated using pyO3F - A Python Framework for Wildfire-Related Optimization [20, 21], that takes into

account factors such as fuel, slope, and wind to estimate, for example, the progression of the burned area.

This paper is organized as follows. Section 2 describes the fire suppression, which presents works from the literature on the subject of forest firefighting. Section 3 presents the constructive heuristic developed in this work, and a toy example is described in detail. In Section 4, the instance generation and the experimental results are presented and discussed. Section 5 describes a case study in the district of Braga, northern Portugal. Finally, the main conclusions and future steps are stated in Section 6.

## 2 Fire Suppression

### 2.1 Related Works

Forest management plays a crucial role in mitigating the extent of forest fires. Two key aspects of effective forest management are controlled fuel type management and field surveillance. These practices are vital for minimizing fire risk and promoting overall forest health and safety. This management is influenced by social factors (culture, population density, law enforcement, regional government, influence of private forest owners) and physical factors (land cover, vegetation types, forest production, terrain, weather, climate). Good forest management also contributes to good forest fire management, which involves understanding the various factors during a fire and the decisions that must be made at that time [8].

To address the problem of forest fires, it is essential to conduct research and provide support for the development of solutions focused on fire prevention and improving firefighting capabilities through effective forest management practices. These solutions can include the adoption of modern monitoring, detection, and control techniques. By investing in these advances, it is possible to improve fire prevention capacity and respond more effectively when fires occur, ultimately promoting better forest management and reducing the impact of forest fires [22].

The serious increase in forest fires is a worrying factor for society. Around 400 million hectares burn every year worldwide, of which only 100 million hectares are forest areas [4, 23].

The spread of a fire depends on the type of fuel, the slope of the area, the strength and direction of the wind, weather conditions, ambient humidity, and temperature [9]. The intensity of the wind and the ambient temperature also influence the spread of fire, which makes it more difficult to extinguish. The first step in a fire is to detect the fire in the shortest time possible, because the shorter the time and distance on the way to the ignition point, the easier it is to extinguish. So, the longer the delay in the initial attack, the more difficult it is to suppress the fire [24].

Forest fire suppression is based on the efforts of firefighting resources to extinguish the fire [25]. Good management of forest fire suppression is one way to help increase the efficiency of the forestry organization in fighting fires [26]. The type and quantity of firefighting resources to be used for each wildfire are two of the decisions to be made when preparing for wildfires [10].

The growing threat of wildfires requires effective strategies to protect multiple assets. Merwe et al. [27] proposed a mixed integer programming (MIP) model to optimize the allocation of limited firefighting resources, such as teams, vehicles, and aircraft, considering the dynamics of fire propagation, the importance of assets to be protected, and the effectiveness of different combat tactics. Unlike heuristic approaches, the MIP model seeks to find the optimal solution to minimize losses, providing fire managers with a powerful tool for real-time decision-making. Despite the computational challenges inherent in large-scale problems and the need for accurate data, this approach represented a significant advance in wildfire management, offering greater flexibility, adaptability, and potential to reduce the devastating impacts of wildfires. A framework was developed to optimize the allocation of firefighting resources by integrating national and regional wildfire records into a vulnerability analysis in [28]. The proposed methodology involved the analysis of fire occurrence patterns, meteorological conditions, and landscape characteristics, both at national and regional levels, to identify areas of high vulnerability. This integrated vulnerability assessment then informed the strategic allocation of firefighting resources, enabling a more proactive and effective response to wildfires. The authors demonstrate the potential of this approach to improve resource distribution and minimize the impacts of wildfires, considering both general trends and local factors.

The firefighting problem has been extensively studied due to its relevance in propagation control scenarios, such as forest fires, disease outbreaks, and contamination in networks. Blum et al. [29] proposed hybrid ant colony optimization algorithms, combining the exploratory capabilities of ant colonies with additional optimization techniques to enhance performance. Experimental results demonstrated the effectiveness of this approach across different problem configurations. Expanding on solution strategies, Hu et al. [30] introduced a novel solution representation, designed to improve efficiency and solution quality compared to previous methods, using evolutionary computing techniques. Michalak et al. [31] developed the ED-LS heuristic, a local search approach that balances multiple objectives, such as minimizing affected areas and optimizing resource allocation (e.g., firefighters). This heuristic effectively explored the solution space, achieving near-optimal results. Similarly, Ramos et al. [32] proposed a matheuristic that integrated mathematical optimization models, such as integer programming, with heuristic methods to address the computational challenges of larger problem instances. The approach generated high-quality solutions efficiently, demonstrating strong applicability to real-world propagation containment scenarios. Focusing on wildfire suppression, Granda et al. [33] proposed a mathematical programming model to optimize resource allocation for fire suppression. They addressed the complex problem of efficiently distributing firefighting resources (such as crews, engines, and aircraft) across a fire area to minimize damage. The model considered factors such as fire spread, resource travel times, and the effectiveness of different resources at various fire intensities. By formulating the problem as an integer linear program, the authors provided decision makers with a tool to determine the optimal distribution of resources over time, leading to more effective wildfire containment and reduced losses.

Mendes and Alvelos [34] proposed an iterated local search (ILS) approach to the wildfire suppression resource allocation problem. The technique aimed to determine

the best locations to position resources, such as combat teams and equipment, with the aim of minimizing the impact of fires and improving the efficiency of suppression operations. The method iteratively explored the solution space, combining local search with perturbation strategies to escape local optima and find high-quality solutions. Experiments validated the effectiveness of ILS, demonstrating its applicability in real wildfire management scenarios.

Alvelos et al. [35] proposed a mixed integer programming model and a heuristic based on it and on shortest path tree algorithms for the problem of defining attack positions for firefighting resources along with safe routes to reach them. The heuristic obtained high-quality solutions for reasonable resolutions and, for most instances based on real data, within a reasonable amount of time.

In Fernandes et al. [9], an analysis was carried out on the allocation of fighting resources in the suppression of forest fires in Portugal, treating large fires. The points studied were the effect of variation in fire suppression force, size of the fire front, growth rate, and environmental conditions (fuel and climate). They found that the fire suppression effort did not affect containment time and recommended management and operational improvements rather than having greater firefighting capabilities. Optimization of the location of a given number of firefighting resources was performed using a set of MIP models in [13]. Four models were considered: protection of specific areas, minimization of the total burned area, and two containment problems (depending on the definition of fire containment: no new ignitions in a given time interval or resources located in all the fire perimeter). Additionally, a transformation of the optimization problem to determine fire arrival times into a feasibility problem based on linear programming was proposed.

### 2.2 Firefighting Dispatch and Routing Problem

The firefighting dispatch and routing problem is a highly relevant issue in the field of firefighting. Dispatching and routing strategies significantly affect the system's ability to make decisions when fighting forest fires. The firefighting resource dispatch and routing problem in forest fires refers to the efficient allocation of teams and equipment to fight forest fires, considering the fire's extent and severity (wind intensity), the terrain's characteristics (slope and fuel), and the limitations of time and resources. In other words, efficient resource allocation means that the better the allocation of resources to extinguishing multiple fires, the less damage the fires will cause and, in turn, the smaller the burned area will be. The firefighting dispatch and routing problem involves determining which resources should go to combat each fire and the period of time that each resource should attack each fire, taking into account the wind intensity and direction, terrain slope, and fuel type.

The type and amount of resources needed are critical for firefighting. An integer linear programming model was proposed by Rodriguez-Veiga et al. [16] in which a problem of resource allocation in different periods of time during the management of a given fire was studied. The objective functions were to minimize the damage caused by forest fires and the time needed for resources to fight forest fires. The simulation analyzed by the authors showed that it is possible to obtain an exact solution quickly

without having to use heuristic algorithms, as long as the planning period does not exceed 5 h.

The resource dispatch and routing problems have been widely debated in the optimization field and have been applied in different areas of study. Haight and Fried [36] and Ntaimo et al. [37] addressed the dispatch of wildfire vehicles and tractors. They used stochastic integer programming methods to determine the best way to deploy and assign resources to a given fire. Their goal was to minimize the number of fires that escaped the initial attack. For this, they combined a simulation of fire behavior and a stochastic integer programming model and the initial attack simulation model, respectively. These methods were used to assign resources to the various fires that occurred over the course of 1 day. However, as a result, they found that there were no major improvements. In the work developed by Fang et al. [38], an emergency routing problem for a forest fire was studied. The main objective was to obtain the optimal firefighting routes, according to attack priorities, minimizing the total distance traveled by all firefighting teams. Several random and benchmark instances were solved using an integer programming model, using the solver CPLEX. The ability to predict fire spread and optimize a firefighting resources plan is essential to support decision-making in forest fire containment. In the paper by Hu and Ntaimo [39], simulations of the spread and suppression of forest fires and the optimization of forest firefighting resources were presented. A stochastic mixed integer programming model was used for the initial attack to generate combat resource dispatch decisions according to each fire scenario. A new agent-based discrete event simulation model was used to simulate fire suppression based on the dispatch decisions.

Yang et al. [40] proposed an emergency logistics model to optimize the fight against forest fires, taking into account predictions about the evolution of the disaster. The model aims to improve the allocation of resources, such as teams and equipment, by integrating predictions about the spread and intensity of the fire. The methodology involved formulating a mathematical problem to minimize costs and maximize the effectiveness of logistics operations. The model was validated in simulated scenarios, showing that the forecast-based approach improves fire response and resource utilization compared to traditional methods. This study contributed to the field by emphasizing the importance of forecasting in firefighting logistics, offering an analytical tool to optimize the response to forest disasters. The authors Zhou and Zhang [41] introduced a new approach that used an event response tree model to determine the various types of firefighting resources to dispatch to fires. This model used the fire suppression index, which evaluated the impact of fire suppression, taking into account factors such as the time, cost, and effectiveness of the resources sent. This model was applied to historical fire data from the Nanjing Laoshan National Forest Park in China, and the results provided firefighters with a clear and intuitive framework to guide their decision-making when dispatching firefighting vehicles.

A preliminary study on the firefighting dispatch and routing problem was presented in [19], involving 7 resources (with water tanks) to be assigned to extinguish 20 ignitions in a forest fire. However, the strategy did not allow the refilling of the water tanks, i.e., if a resource ran out of water, it could not be allocated to any more ignitions. This work used a genetic algorithm adapted to the problem, with the aim of minimizing the total burned area.

## 3 Constructive Heuristic

### 3.1 Problem Definition

The firefighting dispatch and routing problem takes into account a set of active fires (fires burning) and a set of resources to combat them. Thus, this work presents a firefighting land resource routing problem to extinguish multiple fires. The resources are land vehicles with limited water tanks, and the ignitions correspond to different forest fires (one fire for each ignition). The goal is to assign resources to the different fires over time, minimizing the total burned area.

In the initial period of time, the resources are located in the same fire station and all resources are available with full tank water capacity. Furthermore, in a real context, the theater of operations may involve several resources from different locations or fire stations. This situation can easily be taken into account in this work, since the locations of the fire stations and ignitions are known, as well as the travel times between them. In the first period of time, we consider that all ignitions are active. In the practical context of a real situation, fires may start at different times, but we considered the worst-case scenario, in which all fires are active at the beginning.

It is important to note that, over time, the spread of fire increases the burned area and, consequently, the amount of water needed to extinguish it. Therefore, the water available in each resource tank in each time period is an essential aspect to consider. Whenever a resource runs out of water, it can be refilled. In real situations, the time required to refill a vehicle takes into account the capacity of the water tank. Larger fires will require more refills and take longer to suppress.

Note that the description of this problem may simplify the practical context of a real situation, as it does not reflect the reality associated with the time required to extinguish a fire. In fact, suppression time can vary, as it depends on the area, available resources, and other factors such as wind, slope, and fuel type.

### 3.2 Constructive Heuristic Description

In the following, the constructive heuristic to solve the firefighting dispatch and routing problem is described. The great advantage of constructive heuristics is that they are fast in a context where decisions can not take long.

The constructive heuristic aims to allocate each resource to a given ignition at each period of time. Therefore, at each period of time, it is decided which ignition each resource goes to, if it is available, since it may be traveling to an ignition, refilling its tank, or extinguishing an ignition. A resource is dispatched if it has enough water capacity to extinguish a given ignition. If no resource has sufficient capacity in a given period of time, the available resources are dispatched to the ignition until their water tanks run out of water.

Once their tanks are empty, resources refill up to their full water capacity, taking a certain amount of time, and return either to the same ignition or to another that is still active.

**Table 1** Sets

| Data | Description |
|---|---|
| $I$ | Set of ignitions |
| $R$ | Set of firefighting resources |
| $T$ | Set of periods of time |
| $I_a$ | Set of active ignitions ($I_a \subseteq I$) |
| $R_a$ | Set of available firefighting resources ($R_a \subseteq R$) |
| $T_a$ | Set of firefighting resources traveling to an ignition ($T_a \subseteq T$) |

Table 1 describes the sets of the firefighting dispatch and routing problem, namely, information related to ignitions and resources. The sets $I$, $R$, and $T$ are sets with fixed values, and the sets $I_a$, $R_a$, and $T_a$ are sets that vary in time throughout the process.

Table 2 shows the parameters used in the constructive heuristic. The parameter $W$ represents the maximum water tank capacity for each resource, and $A$, $D$, $TT$, $C$, and $L$ are matrices with values used by the constructive heuristic.

Table 3 presents the notation used in the constructive heuristic. The $tt_{i,j}$ represents the travel time between ignition/base $i$ and ignition $j$, $l_{r,t}$ is the location of resource $r$ at time $t$, $a_{i,t}$ corresponds to the burned area of ignition $i$ at period of time $t$, $d_{i,t}$ is the amount of required water to extinguish the ignition $i$ at period of time $t$, and $c_{r,t}$ matches to the water capacity of resource $r$ at period of time $t$.

Algorithm 1 shows the main procedure of the heuristic to deal with the firefighting dispatch and routing problem.

At the beginning, all the resources are at the base and with their water tanks at maximum capacity (lines 2 - 5), and all the ignitions are burning. Thus, at period of time $t = 0$, all the ignitions are active and all the resources are available.

Then, there will be a cycle (lines 6–14) to define the assignment of the resources to the ignitions, at each period of time. The condition is based on the active ignitions, the available resources, and resources that are traveling. An active ignition ($i \in I_a$) is an ignition that has not been completely extinguished. An available resource ($r \in R_a$) is one that is not traveling ($r \notin T_a$) and has not been assigned to an ignition, in that period of time. For all available resources that do not have water capacity at an instant of time $t$ ($c_{r,t} = 0$), their water tank should be refilled. Afterwards, the available resources will be selected and assigned to the active ignitions. At the end of the cycle,

**Table 2** Description of the parameters used in the constructive heuristic

| Data | Description |
|---|---|
| $W$ | Maximum water capacity for each resource ($\#R \times 1$) |
| $A$ | Matrix of burned area for each ignition over time ($\#I \times \#T$) |
| $D$ | Matrix of water needed to extinguish fires over time ($\#I \times \#T$) |
| $TT$ | Matrix of travel times between ignition/base and ignitions ($(\#I + 1) \times (\#I + 1)$) |
| $C$ | Water capacity matrix for each resource over time ($\#R \times \#T$) |
| $L$ | Resource location matrix over time ($\#R \times \#T$) |

**Table 3** Notation

| Symbol | Description |
|---|---|
| $i$ | Ignition index ($i \in I$) |
| $r$ | Firefighting resource index ($r \in R$) |
| $t$ | Period of time index ($t \in T$) |
| $tt_{i,j}$ | Travel time between ignition/base $i$ and ignition $j$ |
| $l_{r,t}$ | Location of resource $r$ at time $t$ |
| $a_{i,t}$ | Burned area of ignition $i$ at period of time $t$ |
| $d_{i,t}$ | Amount of required water to extinguish the ignition $i$ at period of time $t$ |
| $c_{r,t}$ | Water capacity of resource $r$ at period of time $t$ |
| $S_t$ | Sequence order of ignitions to be extinguished based on $Ratio$ at period of time $t$ |
| $Sol$ | Sequence of tuples $(t, i, r), t \in T, i \in I, r \in R$ |
| $TBA$ | Total burned area |

Algorithm 1 returns the TBA and Sol (that is, a sequence of tuples showing the period of time $t$ that the resource $r$ was assigned to ignition $i$).

Next, in Algorithm 2, the active ignitions, at a given instant of time, will be sorted according to a priority indicator.

For all the active ignitions $i$ and for all available resources $r$, the location $k$ of the resource $r$ at period of time $t$ ($l_{r,t}$) is identified. Also, the travel time between the location $k$ and the ignition $i$ ($tt_{k,i}$) is taken from matrix $TT$, and the burned area ($a_{i,t+tt}$) of the ignition $i$ at period of time $t + tt$ is extracted from matrix $A$. Then, two strategies to compute the priority indicator ratio were used (line 6). These ratios give priority to ignitions with larger or smaller areas, depending on the strategy used and the travel times between them and between the base and each of them. One is based on a ratio between the burned area of the ignition $i$, $a_{i,t+tt}$, and the travel time $tt_{k,i}$,

**Algorithm 1** Main.

**Input:** $R, I, W, A, D, TT, T$
1: $t \leftarrow 0, R_a \leftarrow R, T_a \leftarrow \emptyset, I_a \leftarrow I, Sol \leftarrow \emptyset, TBA \leftarrow 0$
2: **for all** $r \in R$ **do**
3: $\quad l_{r,0} \leftarrow$ "$Base$"
4: $\quad c_{r,0} \leftarrow W_r$
5: **end for**
6: **while** $I_a \neq \emptyset$ **and** $\{R_a \cup T_a\} \neq \emptyset$ **do**
7: $\quad$ **for all** $r \in R_a$ **and** $c_{r,t} = 0$ **do** ▷ Refill
8: $\quad\quad c_{r,t} \leftarrow W_r$ ▷ Update water capacity
9: $\quad$ **end for**
10: $\quad S_t \leftarrow$ Sort Ignitions$(t, R_a, I_a, A, TT, L)$ ▷ Algorithm 2
11: $\quad Sol, TBA \leftarrow$ Assign Resources$(t, R_a, I_a, T_a, C, A, D, S_t, Sol, L, TBA)$ ▷ Algorithm 3
12: $\quad$ Update $R_a$
13: $\quad t \leftarrow t + 1$
14: **end while**
**Output:** $Sol, TBA$

**Algorithm 2** Sort ignitions.

**Input:** $t$, $R_a$, $I_a$, $A$, $TT$, $L$
1: **for all** $i \in I_a$ **do**
2: **for all** $r \in R_a$ **do**
3: $k \leftarrow l_{r,t}$
4: Get $tt_{k,i}$
5: Get $a_{i,t+tt_{k,i}}$
6: $aux_ratio_{r,i} \leftarrow Ratio$ ▷ $Ratio$ is computed using (1) or (2)
7: **end for**
8: **end for**
9: $S_t \leftarrow \langle \text{sort}(\max_i(aux_ratio_{r,i})) : i \in I_a \rangle$ ▷ ascending/descending order
**Output:** $S_t$

given by

$$Ratio = \frac{a_{i,t+tt_{k,i}}}{(tt_{k,i})^2}. \tag{1}$$

The other strategy takes into account the percentage of burned area at ignition $i$ and the travel time $tt_{k,i}$ to compute the priority indicator ratio.

$$Ratio = \frac{\frac{a_{i,t+tt_{k,i}}}{\max_i(a_{i,\cdot})}}{(tt_{k,i})^2} \tag{2}$$

where $\max_i(a_{i,\cdot})$ is the maximum burned area of ignition $i$.

Finally, for each ignition, the maximum of the ratio values is computed. Then, they are sorted giving the order of priority ($S_t$) in which each ignition should be extinguished (line 9). Two types of sorting are performed on the ratio values: ascending and descending. The ratio in ascending order promotes the largest burned areas with the shortest travel times. On the other hand, the descending order of the ratio favors the ignitions with longer travel times and the shorter burned areas. When the ratio values for some ignitions are equal, the one that has the shorter travel time is chosen.

The assignment of available resources to the active ignitions, at a given period of time, is presented in Algorithm 3.

For all active ignitions in the sequence order $S_t$, the difference between the capacity of the available resources and the water required to extinguish each ignition is computed (line 4).

A set of operations is then carried out as long as there are available resources and active ignitions (lines 6–27). As long as there are resources available ($R_a$) and active ignitions ($I_a$), a set of resources with sufficient capacity ($R_c$) is created ($y \geq 0$). If the capacity of the resource at a given period of time $t$ ($c_{r,t}$) is greater than or equal to the required water to extinguish the ignition $i$ ($d_{i,t}$), then the resource with lowest capacity is assigned to that ignition (line 9), that ignition is removed from the set of active ignitions $I_a$, the capacity of resource $r$ is updated, and the total burned area is updated. If resource $r$ runs out of water capacity in its tank in a given time period $t$, then it is removed from the set $D_c$ (set of tuples $(r, c_{r,t} - d_{i,t})$ to check the water capacity of the resources for ignitions) (line 14–16). On the other hand, if

**Algorithm 3** Assign resources.

**Input:** $t, R_a, I_a, T_a, C, A, D, S_t, Sol, L, TBA$

1: **for all** $i \in S_t$ **do**
2: $D_c \leftarrow \emptyset$
3: **for all** $r \in R_a$ **do**
4: $D_c \leftarrow D_c \cup \{(r, c_{r,t} - d_{i,t})\}$
5: **end for**
6: **while** $r \in R_a$ **and** $i \in I_a$ **do**
7: $R_c \leftarrow \{(\cdot, y) \in D_c : y \geq 0\}$
8: **if** $R_c \neq \emptyset$ **then**
9: $c \leftarrow x \in \{(x, y) \in R_c : \min(y)\}$ ▷ Assign resource
10: $I_a \leftarrow I_a \setminus \{i\}$ ▷ Update active ignitions
11: $c_{r,t} \leftarrow c_{r,t} - d_{i,t}$ ▷ Update capacity of resource
12: $k \leftarrow l_{r,t}$
13: $TBA \leftarrow TBA + a_{i,j+tt_{k,i}}$ ▷ Update total burned area
14: **if** $c_{r,t} = 0$ **then**
15: $D_c \leftarrow D_c \setminus \{(r, \cdot)\}$ ▷ Update resources list with enough capacity
16: **end if**
17: **else**
18: $R_c \leftarrow \{(\cdot, y) \in D_c : y < 0\}$
19: $c \leftarrow x \in \{(x, y) \in R_c : \max(y)\}$
20: $d_{i,t} \leftarrow -(c_{r,t} - d_{i,t})$ ▷ Update water required
21: $c_{r,t} \leftarrow 0$ ▷ Update capacity of resource
22: $D_c \leftarrow D_c \setminus \{(r, \cdot)\}$ ▷ Update resources list with enough capacity
23: **end if**
24: $R_a \leftarrow R_a \setminus \{r\}$ ▷ Update available resource
25: $T_a \leftarrow T_a \cup \{r\}$ ▷ Update traveling resource
26: $Sol \leftarrow Sol \cup (t, i, c)$ ▷ Update solution
27: **end while**
28: **end for**

**Output:** $Sol, TBA$

there is no resource available with sufficient water capacity to extinguish ignition $i$, then the resource with the largest capacity is assigned to that ignition (line 19), the water required to extinguish ignition $i$ is updated (line 20), the capacity of resource $r$ is updated (line 21), and the resources list with enough capacity is updated (line 22). In the end, the set of available resources (removing this resource $r$ from the set $R_a$) is updated (line 24), and the set of resources that are traveling $T_a$ is also updated (line 25). The solution regarding the resource $r$ assigned to ignition $i$ at period of time $t$ is saved in $Sol$ (line 26). Finally, the algorithm outputs $Sol$ and the value of TBA.

When a resource $a$ is traveling from ignition $i$ to ignition $j$, which in the meantime has already been extinguished by another resource $b$ at a previous period of time, then resource $a$ becomes available at that location $i$ and with the water capacity it had at $i$.

### 3.3 Toy Example

In the following, a toy example of a firefighting dispatch and routing problem comprising 2 resources ($R = \{R_1, R_2\}$) to extinguish 4 ignitions ($I = \{I_1, I_2, I_3, I_4\}$) of a forest fire is described. Resources are vehicles made up of water tanks whose

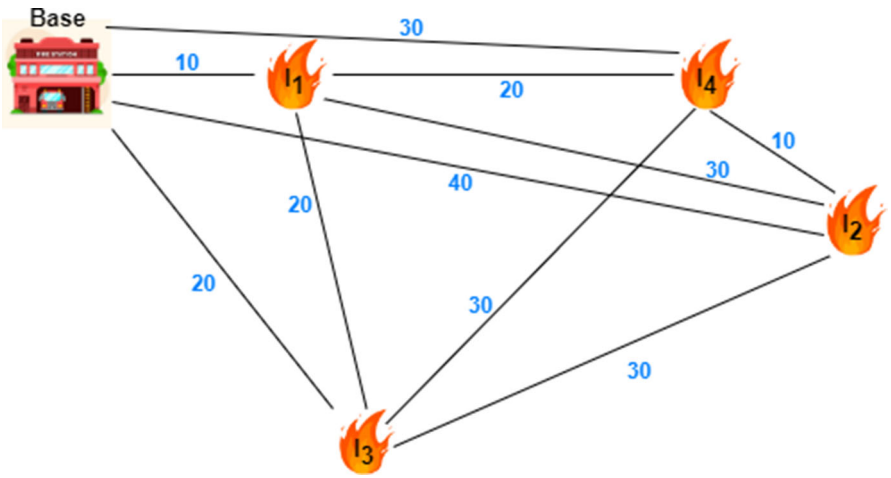



**Fig. 1** Spatial network

capacity of each resource (in liters, l) is 2000l for resource $R_1$ and 1000l for resource $R_2$ ($W = \{2000, 1000\}$). All resources are initially located at the base (fire station).

A randomly generated spatial network representation for the toy example is shown in Fig. 1. i.e., it shows the locations of the base and ignitions in the network.

The numbers 10, 20, 30, and 40 (in blue from Fig. 1) in the spatial network represent the travel times, $TT$ (in minutes), between the base and the location of each ignition, and between the ignition locations, as presented in Table 4.

Since the spread of fire increases at a different rate for the various ignitions, the burned area in each ignition increases over time. Table 5 shows the burned area, $A$ (in $m^2$), of each ignition for each period of time ($T = \{0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100\}$). The rows correspond to each ignition $i \in I$, and the columns correspond to the period of time $t \in T$ (in minutes).

The quantity of water, $D$ (in liters), required to extinguish each ignition at each period of time is provided in Table 6. For each period of time, the larger the burned area, the larger the amount of water required to extinguish a given ignition.

Four variants of the constructive heuristic will be applied to the toy example using (1) or (2) for the ignition priority ratio in ascending or descending order. The ratio (1) is computed between the burned area of an ignition at a given period of time and

**Table 4** Travel times for the toy example

| $I$ \ $I$ | Base | $I_1$ | $I_2$ | $I_3$ | $I_4$ |
|---|---|---|---|---|---|
| Base | 0 | 10 | 40 | 20 | 30 |
| $I_1$ | 10 | 0 | 30 | 20 | 20 |
| $I_2$ | 40 | 30 | 0 | 30 | 10 |
| $I_3$ | 20 | 20 | 30 | 0 | 30 |
| $I_4$ | 30 | 20 | 10 | 30 | 0 |

**Table 5** Burned areas for the toy example

| $I$ \ $T$ | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| $I_1$ | 470.0 | 472.6 | 475.5 | 478.5 | 481.8 | 485.3 | 489.0 | 493.1 | 497.4 | 502.0 |
| $I_2$ | 438.0 | 441.7 | 445.8 | 450.1 | 454.8 | 459.9 | 465.4 | 471.3 | 477.7 | 484.6 |
| $I_3$ | 197.0 | 202.7 | 209.0 | 215.9 | 223.4 | 231.6 | 240.6 | 250.4 | 261.2 | 273.0 |
| $I_4$ | 210.0 | 212.7 | 215.5 | 218.6 | 221.9 | 225.4 | 229.3 | 233.4 | 237.8 | 242.5 |

the travel time to reach it, and the ratio (2) is based on its percentage (considering the maximum area that the ignition can burn):

- $H_{1\downarrow}$ using the ratio (1) in descending order
- $H_{1\uparrow}$ using the ratio (1) in ascending order
- $H_{2\downarrow}$ using the ratio (2) in descending order
- $H_{2\uparrow}$ using the ratio (2) in ascending order

The constructive heuristic solution for the variant $H_{1\downarrow}$ obtained a TBA value of 1345.4 $m^2$. Furthermore, the used water was 2553.4 l to extinguish the 4 ignitions, giving a total of 1446.6 l remaining in the resources, namely, 739.2 l in $R_1$ and 707.4 l in $R_2$.

Initially, both resources ($R_1$ and $R_2$) are at the base (fire station). Firstly, the ratio (1) is calculated for all ignitions, taking into account the burned area values (in Table 5) and the travel times (in Table 4), for the period of time $t = 0$. The ratio values obtained are 4.70, 0.28, 0.51, and 0.24, for ignitions $I_1$, $I_2$, $I_3$, and $I_4$, respectively. Then, for $H_{1\downarrow}$ variant, the ratio values are sorted in descending order, leading to an ignition priority order of $I_1$, $I_3$, $I_2$, and $I_4$. Therefore, the resources combat the ignitions according to this order of ignition priority.

Table 7 shows, for each period of time $t$, the resource that will fight each ignition. The symbol $\rightarrow$ means that the resource is traveling. Note that five periods of time (50 min) are required to extinguish all ignitions.

The selected resource to combat $I_1$ is the one that has the smallest difference ($D_c$) between the capacity of the water tank and the water required; therefore, the resource $R_2$ is selected. Thus, the resource $R_2$ travels to $I_1$, extinguishing it at period of time $t = 10$. Since its water capacity is 10001 and 768.5 l (see Table 6) is needed to extinguish $I_1$, there are only 231.5 l left in its tank. In this ignition, 470.0 $m^2$ of area

**Table 6** Required water for the toy example

| $I$ \ $T$ | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| $I_1$ | 768.5 | 770.7 | 773.0 | 775.5 | 778.1 | 780.9 | 783.9 | 787.1 | 790.6 | 794.2 |
| $I_2$ | 741.9 | 745.0 | 748.4 | 752.1 | 756.0 | 760.2 | 764.7 | 769.6 | 774.8 | 780.4 |
| $I_3$ | 497.6 | 504.8 | 512.5 | 520.9 | 529.8 | 539.5 | 549.9 | 561.0 | 572.9 | 585.7 |
| $I_4$ | 513.7 | 516.9 | 520.4 | 524.1 | 528.0 | 532.3 | 536.7 | 541.5 | 546.6 | 552.0 |

**Table 7** Firefighting resource routing solution for $H_{1\downarrow}$

| $R$ \ $t$ | 0 | 10 | 20 | 30 | 40 | 50 |
|---|---|---|---|---|---|---|
| $R_1$ | Base | → | $I_3$ | → | → | $I_2$ |
| $R_2$ | Base | $I_1$ | → | $I_4$ | Refill, $I_4$ | |

was burned. Following the ignition priority order, the resource $R_1$ goes to combat ignition $I_3$, taking 20 min to travel from the base to $I_3$, requiring 504.8 l to extinguish it (leaving 1495.3 l in the water tank), and burning 202.7 $m^2$ of area.

Subsequently, at period of time $t = 10$, $R_2$ is the only available resource at ignition $I_1$. Therefore, taking into consideration the travel time to active ignitions $I_2$ and $I_4$, the ratio is calculated, obtaining the values 0.51 and 0.54, respectively. Therefore, putting the ratio values in descending order, the resource $R_2$ is selected to extinguish $I_4$, requiring 520.4 l (see Table 6), run out of water, and used all of its capacity (231.5 l). At this period of time, only 95.9 $m^2$ of burned area was considered because the water has a proportional relationship to the required water.

At period of time $t = 20$, resource $R_2$ is traveling and $R_1$ is the available resource. Besides that, ignitions $I_2$ and $I_4$ are active. Taking into account the travel times from $I_3$ to $I_2$ and $I_4$, the ratio values are 0.51 and 0.25, respectively. Thus, resource $R_1$ travels to ignition $I_2$ during 30 min and extinguishes it at period of time $t = 50$, using 756.0 l of water (remaining 739.2 l in $R_1$). In this ignition, 454.8 $m^2$ of burned area.

Next, at period of time $t = 30$, resource $R_1$ is traveling and $R_2$ is at ignition $I_4$. Since this ignition is still active (the only one at this instant), $R_2$ is refilled during 10 min, according to the resource refill assumptions previously described and is again assigned to extinguish $I_4$. Thus, at $t = 40$, 122.0 $m^2$ of burned area in $I_4$ requiring 524.1 l of water, although 231.5 l had already been used in this ignition at the previous period of time ($t = 30$), so $R_2$ uses 292.6 l (remaining 707.4 l). In conclusion, the total burned area in $I_4$ is 217.9 $m^2$.

The solution of the firefighting dispatch and routing problem using $H_{1\uparrow}$ is presented in Table 8. In this solution, the TBA value is 1403.6 $m^2$. Additionally, the water used to extinguish all ignitions is 2612.9 l. Note that nine periods of time ($t = 90$) are required to extinguish all ignitions.

At the first period of time $t = 0$, the ratio values are calculated using (1) as in the variant $H_{1\downarrow}$, but the order of ignition combat priorities is changed to ascending order, resulting in $I_4$, $I_2$, $I_3$, and $I_1$. The first resource to be selected is the $R_2$ to combat ignition $I_4$, following the order of ignition combat priorities, since it is the available resource with the smallest and sufficient capacity. Resource $R_1$ is selected to

**Table 8** Firefighting resource routing solution for $H_{1\uparrow}$

| $R$ \ $t$ | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| $R_1$ | Base | → | → | → | $I_2$ | → | → | $I_3$ | | |
| $R_2$ | Base | → | → | $I_4$ | → | → | $I_3$ | Refill | → | $I_1$ |

**Table 9** Firefighting resource routing solution for $H_{2\downarrow}$

| $R$ \ $t$ | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|---|
| $R_1$ | Base | → | → | $I_4$ | $I_2$ | → | → | $I_3$ |
| $R_2$ | Base | $I_1$ | → | → | $I_2$ | | | |

extinguish ignition $I_2$ (being extinguished at period of time $t = 40$). Then, at period of time $t = 30$, resource $R_2$ is selected to combat $I_3$, but it does not have sufficient water to extinguish it. At $t = 40$ period of time, the available resource $R_1$ is assigned to extinguish $I_3$ (since it was still active) with sufficient capacity to extinguish it (being extinguished at period of time $t = 70$). The resource $R_2$ runs out of water at $t = 60$, and it is refilled, becoming available at $t = 70$. At this instant, ignition $I_1$ is the only active ignition, and both resources are available at the same ignition $I_3$. Since resource $R_2$ is the one with sufficient water, it goes to extinguish $I_1$.

Table 9 presents the solution for the firefighting dispatch and routing problem using the $H_{2\downarrow}$ variant. The TBA value obtained is 1376.2 $m^2$, during 70 min to extinguish all ignitions. Furthermore, the used water was 2590.9 l.

Initially (at $t = 0$), all resources are available at the Base and at full capacity in their tanks. Then, the ratio values are calculated by Eq. 2 for all ignitions, resulting in 3.0e−3, 1.7e−4, 1.2e−4, and 1.0e−4 for $I_1$, $I_4$, $I_2$, and $I_3$ in descending order. Since $R_2$ is the resource with less and sufficient capacity to extinguish ignition $I_1$ at period of time $t = 10$, resource $R_1$ goes to ignition $I_4$ and extinguishes it at period of time $t = 30$. At $t = 10$ instant, there are two active ignitions, $I_2$ and $I_3$. The ratio for these ignitions is then calculated taking into account where they come from, i.e., the travel time between $I_1$ and ignitions $I_2$ and $I_3$, and the travel time between $I_4$ and ignitions $I_2$ and $I_3$. So, in descending order, the priority order for fighting active ignitions is $I_2$ and $I_3$. Then, the only available resource $R_2$ is assigned to ignition $I_2$, but it is unable to extinguish it completely, as it runs out of water in its tank. Ignitions $I_2$ and $I_3$ are active at $t = 30$, and the ignition priority order gives $I_2$ the next ignition to be extinguished by $R_1$ because it is the only available. At $t = 40$ period of time, $I_3$ is the only active ignition and $R_1$ is the only available resource, with sufficient capacity to extinguish it.

The firefighting resource routing solution for the $H_{2\uparrow}$ variant is shown in Table 10. The total burned area is 1367.8 $m^2$, and seven periods of time are required to extinguish all ignitions. It took 2568.8 l of water to completely extinguish the four ignitions.

In the $H_{2\uparrow}$ variant, the ratio values (2) are the same as those calculated in the previous solution, but the order of priority is ascending, which results in $I_3$, $I_2$, $I_4$, and $I_1$, at the first period of time ($t = 0$). So, resource $R_2$ is assigned to extinguish

**Table 10** Firefighting resource routing solution for $H_{2\uparrow}$

| $R$ \ $t$ | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|---|
| $R_1$ | Base | → | → | → | $I_2$ | $I_4$ | → | $I_1$ |
| $R_2$ | Base | → | $I_3$ | → | → | $I_4$ | | |

**Table 11** Comparison of the toy example solutions

| | TBA | UW | Time | Resource utilization time |
|---|---|---|---|---|
| $H_{1\downarrow}$ | 1345.4 | 2553.4 | 50 | 90 |
| $H_{1\uparrow}$ | 1403.6 | 2612.9 | 90 | 160 |
| $H_{2\downarrow}$ | 1376.2 | 2590.9 | 70 | 110 |
| $H_{2\uparrow}$ | 1367.8 | 2568.8 | 70 | 120 |

ignition $I_3$, traveling for 20 min, and $R_1$ for ignition $I_2$, during 40 min. At period of time $t = 20$, the active ignitions are $I_4$ and $I_1$, and resource $R_2$ travels to $I_4$, taking 30 min to get there. However, this resource does not have enough water in its tank to extinguish ignition $I_4$, running out of water in its tank. That is why at period of time $t = 40$, $R_1$ is assigned to $I_4$, since it has not been completely extinguished. Next, at period of time $t = 50$, $R_1$ is assigned to ignition $I_1$, taking 20 min to get there and extinguishing it completely.

Table 11 shows the TBA, UW, time, and resource utilization time values obtained when using each of the four variants. As can be seen, they present distinct solutions, since they have different strategies to select the ignition priority order. The $H_{1\downarrow}$ and the $H_{2\downarrow}$ select first the fires with the largest burned area at the instant of time of the arrival of vehicles. However, $H_{2\downarrow}$ uses the proportion of the burned area considering the maximum area that the fire can burn. $H_{1\uparrow}$ and $H_{2\uparrow}$ proceed in a similar way, but in the reverse order.

The $H_{1\downarrow}$ variant obtained the best solutions in terms of TBA, UW, and time. The solution values obtained in the variants $H_{2\downarrow}$ and $H_{2\uparrow}$ are similar in terms of the TBA and UW, although $H_{2\downarrow}$ involves a less total vehicle utilization time of $70 + 40 = 110$.

In fact, it makes more sense to attack fires with a higher rate of spread first. In the real-world context, this situation can be assessed by taking into account factors such as slope and wind.

## 4 Computational Experiments

### 4.1 Instances Data

Several instances[1] were randomly generated to create data sets with some diversity in terms of the size of the problem. The procedure for generating each instance is described below.

Initially, the number of ignitions that exist in a given forest fire and the number of firefighting resources that are available to extinguish the ignitions are defined. These resources are ground firefighting vehicles with tanks with predefined capacities, based on real firefighting resources (5001, 10001, 15001, 20001, 30001). Once the number of resources is defined, a resource capacity is randomly assigned to each one.

Taking into account the number of ignitions ($NI$), they will be randomly positioned in a spatial network, defined as a square, with coordinates belonging to

[1] Available at https://github.com/MarinaAMatos/Inst_Firefighting

$([0, map_{size}], [0, map_{size}])$, where

$$map_{size} = \left\lfloor \sqrt{(\max(17, 1.5NI)} \right\rfloor .$$

In addition, the fire station (base) location is randomly positioned in the network.

The travel times between each ignition and the base are based on the Euclidean distance, satisfying the triangular inequality. Thus, the travel times are given by rounding the distance times 10, obtaining integer values.

The burned area ($a_{i,t}$) at each period of time $t$ for an ignition $i$ is defined using the expression given by

$$a_{i,t} = \rho \, \exp\left(\frac{t}{\sigma}\right) + a_{i,t-1} \tag{3}$$

where $\rho \sim U(0.1, 5)$ and $\sigma \sim U(100, 200)$, for all $t \in \{1, \ldots, t_{max}\}$. Note that the burned area at the initial instant ($t = 0$) is randomly generated, $a_{i,0} \sim U(1, 500)$. This expression simulates an exponential increase in the spread of fire over time. Note that not all ignitions have the same type of exponential growth, with some ignitions burning faster than others.

Based on the burned area at each period of time $t$, and the perimeter of a circle, the matrix of water required ($d_{i,t}$) to extinguish each ignition $i$ at period of time $t$ is calculated using

$$d_{i,t} = 2\,\pi \sqrt{\frac{a_{i,t}}{\pi}}\,\alpha \tag{4}$$

where $\alpha$ is the amount of water in liters required to extinguish one meter of fire front.

### 4.2 Experimental Details

The numerical experiments were carried out on a PC 11th Gen Intel(R) Core(TM) i7-1165G7 @ 2.80GHz, 2803 Mhz, 4 Nucleus(s), 8 Processor(s) Logic(s), 16 GB RAM. The code was implemented in *python* (version 3.9.35) using *VScode* (Version 1.85).

Firstly, 60 instances of the firefighting dispatch and routing problem were randomly generated. For different sets of ignitions (5, 7, and 10) and resources (20 and 30), 10 instances were randomly generated. Thus, data was generated for the burned area and the water needed to extinguish each ignition for each period of time. In this work, based on Penney et al. [42], we defined $\alpha = 10$ l/m$^2$ for the water flow rate in Eq. 4.

The travel times between the base and the various ignitions and between ignitions were randomly generated and satisfied the triangular inequality. The capacity of each resource's water tanks was also randomly assigned. Note that refilling the water tanks takes a period of time.

The experiments consist of solving each instance of the firefighting dispatch and routing problem, minimizing the burned area, TBA, in order to assess the performance of each variant of the constructive heuristic presented in Section 3. Subsequently, a statistical analysis of the TBA value obtained in each variant of the heuristic is carried out in order to verify which variant is more efficient.

### 4.3 Constructive Heuristic Results

The results obtained for the four variants of the constructive heuristic are presented below. Table 12 shows the average value of the solutions obtained, among the ten instances, for each number of ignitions ($NI$) and resources ($NR$). It can be seen that, among the four variants used in the constructive heuristic, the best solutions found were for the $H_{1\downarrow}$ strategy, where the ratio used is Eq. 1, since the TBA value is the lowest.

In the following, a statistical analysis, using the Student's $t$-test, is performed to assess the performance of each variant for the constructive heuristic. The objective of the statistical analysis was to verify, for each instance, which(s) are the best variant(s) applied in the constructive heuristic. Tables 13, 14, and 15 show the results obtained in the statistical analysis for 20 ignitions, using 5, 7, and 10 resources to extinguish all

**Table 12** Average values of the constructive heuristic solution: the total burned area ($TBA_{avg}$), the total water capacity of all resources (in the base) ($TW_{avg}$), the used water ($UW_{avg}$) using the refill of the water tanks of the combat resources, and the total time ($Time_{avg}$) used to extinguish all ignitions and the processing time ($PT_{avg}$) for the four variants

| $NI$ | $NR$ | $TW_{avg}$ | | $TBA_{avg}$ | $UW_{avg}$ | $Time_{avg}$ | $PT_{avg}$ |
|---|---|---|---|---|---|---|---|
| 20 | 5 | 7300.0 | $H_{1\downarrow}$ | 5402.5 | 11162.7 | 140.0 | 0.0099 |
| | | | $H_{1\uparrow}$ | 6529.9 | 11,929.6 | 230.0 | 0.0055 |
| | | | $H_{2\downarrow}$ | 5836.0 | 11,535.0 | 183.0 | 0.0113 |
| | | | $H_{2\uparrow}$ | 5871.3 | 11,552.5 | 204.0 | 0.0041 |
| | 7 | 9850.0 | $H_{1\downarrow}$ | 5564.0 | 11343.6 | 116.0 | 0.0063 |
| | | | $H_{1\uparrow}$ | 5975.3 | 11,606.9 | 158.0 | 0.0071 |
| | | | $H_{2\downarrow}$ | 5779.8 | 11,514.9 | 143.0 | 0.0068 |
| | | | $H_{2\uparrow}$ | 5702.6 | 11,446.4 | 134.0 | 0.0085 |
| | 10 | 14,700.0 | $H_{1\downarrow}$ | 5530.6 | 11,242.4 | 96.0 | 0.0080 |
| | | | $H_{1\uparrow}$ | 5671.7 | 11,280.2 | 104.0 | 0.0052 |
| | | | $H_{2\downarrow}$ | 5604.4 | 11,264.4 | 97.0 | 0.0093 |
| | | | $H_{2\uparrow}$ | 5587.0 | 11,241.2 | 93.0 | 0.0043 |
| 30 | 5 | 8600.0 | $H_{1\downarrow}$ | 8607.0 | 17,567.2 | 215.0 | 0.0155 |
| | | | $H_{1\uparrow}$ | 18,962.6 | 22,850.6 | 450.0 | 0.0173 |
| | | | $H_{2\downarrow}$ | 11,507.3 | 19,712.5 | 327.0 | 0.0181 |
| | | | $H_{2\uparrow}$ | 10,388.8 | 18,920.2 | 366.0 | 0.0145 |
| | 7 | 11,300.0 | $H_{1\downarrow}$ | 8164.8 | 16,933.5 | 174.0 | 0.0113 |
| | | | $H_{1\uparrow}$ | 10,821.6 | 18,697.6 | 287.0 | 0.0137 |
| | | | $H_{2\downarrow}$ | 9365.5 | 17,899.7 | 230.0 | 0.0152 |
| | | | $H_{2\uparrow}$ | 8893.1 | 17,515.1 | 251.0 | 0.0150 |
| | 10 | 17,000.0 | $H_{1\downarrow}$ | 7782.2 | 16,475.3 | 125.0 | 0.0144 |
| | | | $H_{1\uparrow}$ | 8432.9 | 16,934.6 | 179.0 | 0.0124 |
| | | | $H_{2\downarrow}$ | 8249.5 | 16,932.5 | 156.0 | 0.0147 |
| | | | $H_{2\uparrow}$ | 7959.8 | 16,580.5 | 148.0 | 0.0144 |

**Table 13** Statistical analysis for 20 ignitions and 5 resources problem

| | $H_{1\downarrow}$ | $H_{1\uparrow}$ | $H_{2\downarrow}$ | $H_{2\uparrow}$ |
|---|---|---|---|---|
| $H_{1\downarrow}$ | – | −1127.4 | −433.5 | −468.8 |
| $H_{1\uparrow}$ | $< 0.001$ | – | 693.8 | 658.5 |
| $H_{2\downarrow}$ | $< 0.001$ | 0.008 | – | −35.3 |
| $H_{2\uparrow}$ | $< 0.001$ | 0.002 | 0.369 | – |

**Table 14** Statistical analysis for 20 ignitions and 7 resources problem

| | $H_{1\downarrow}$ | $H_{1\uparrow}$ | $H_{2\downarrow}$ | $H_{2\uparrow}$ |
|---|---|---|---|---|
| $H_{1\downarrow}$ | – | −411.3 | −215.8 | −138.6 |
| $H_{1\uparrow}$ | $< 0.001$ | – | 195.5 | 272.7 |
| $H_{2\downarrow}$ | $< 0.001$ | 0.002 | – | 77.2 |
| $H_{2\uparrow}$ | $< 0.001$ | $< 0.001$ | 0.045 | – |

**Table 15** Statistical analysis for 20 ignitions and 10 resources problem

| | $H_{1\downarrow}$ | $H_{1\uparrow}$ | $H_{2\downarrow}$ | $H_{2\uparrow}$ |
|---|---|---|---|---|
| $H_{1\downarrow}$ | – | −141.1 | −73.8 | −56.4 |
| $H_{1\uparrow}$ | $< 0.001$ | – | 67.3 | 84.7 |
| $H_{2\downarrow}$ | 0.023 | 0.007 | – | 17.4 |
| $H_{2\uparrow}$ | 0.011 | 0.009 | 0.347 | – |

**Table 16** Statistical analysis for 30 ignitions and 5 resources problem

| | $H_{1\downarrow}$ | $H_{1\uparrow}$ | $H_{2\downarrow}$ | $H_{2\uparrow}$ |
|---|---|---|---|---|
| $H_{1\downarrow}$ | – | −10355.6 | −2900.2 | −1781.7 |
| $H_{1\uparrow}$ | 0.003 | – | 7455.4 | 8573.9 |
| $H_{2\downarrow}$ | 0.002 | 0.004 | – | 1118.5 |
| $H_{2\uparrow}$ | $< 0.001$ | 0.005 | 0.047 | – |

**Table 17** Statistical analysis for 30 ignitions and 7 resources problem

| | $H_{1\downarrow}$ | $H_{1\uparrow}$ | $H_{2\downarrow}$ | $H_{2\uparrow}$ |
|---|---|---|---|---|
| $H_{1\downarrow}$ | – | −2656.7 | −1200.6 | −728.3 |
| $H_{1\uparrow}$ | $< 0.001$ | – | 1456.1 | 1928.4 |
| $H_{2\downarrow}$ | $< 0.001$ | $< 0.001$ | – | 472.3 |
| $H_{2\uparrow}$ | $< 0.001$ | $< 0.001$ | 0.036 | – |

**Table 18** Statistical analysis for 30 ignitions and 10 resources problem

| | $H_{1\downarrow}$ | $H_{1\uparrow}$ | $H_{2\downarrow}$ | $H_{2\uparrow}$ |
|---|---|---|---|---|
| $H_{1\downarrow}$ | – | −650.7 | −467.3 | −177.6 |
| $H_{1\uparrow}$ | $< 0.001$ | – | 183.4 | 473.1 |
| $H_{2\downarrow}$ | $< 0.001$ | 0.022 | – | 289.7 |
| $H_{2\uparrow}$ | $< 0.001$ | $< 0.001$ | 0.003 | – |

ignitions. The tables show the $p$-values, in the lower triangular part of the tables, and the average differences between the TBA values and between variants, in the upper triangular part of the tables. Analyzing the results, in all combinations of variants, there are significant differences in the value of TBA, since the $p$-value is less than 5%. However, when combining the variants $H_{2\downarrow}$ and $H_{2\uparrow}$, in the solutions with 5 and 7 resources to extinguish 20 ignitions, it can be seen that there are no significant differences, since the $p$-value is greater than 0.05. In addition, $H_{1\downarrow}$ performed better than the other variants, with the Eq. 1 being the best.

Tables 16, 17, and 18 show the results obtained in the statistical analysis for 30 ignitions, using 5, 7, and 10 resources. It is observed that in all combinations of the variants used in the constructive heuristic, there are significant differences in the value of TBA, since the $p$-value is less than 5%. In addition, $H_{1\downarrow}$ again performed better than the other variants. When comparing the $H_{2\downarrow}$ and $H_{2\uparrow}$, it is possible to observe that $H_{2\uparrow}$ obtained the lowest TBA value.

In conclusion, the most suitable variant of the constructive heuristic for minimizing the burned area of this firefighting dispatch and routing problem is $H_{1\downarrow}$, because it obtained a lower value of the average total burned area in all instances (5, 7, and 10 resources to extinguish 20 and 30 ignitions). Furthermore, in Table 12, it can be seen that in the cases of 5 and 7 resources to combat 20 ignitions and 5, 7, and 10 resources to extinguish 30 ignitions, the $H_{1\downarrow}$ variant also has the lowest value for the average amount of used water. For the problem with 10 resources to extinguish 20 ignitions, the lowest $UW$ value is obtained by the $H_{2\uparrow}$ variant. The $Time$ is lower in the $H_{1\downarrow}$ variant for 5 and 7 resources and 20 ignitions and 5, 7, and 10 resources and 30 ignitions. The average processing time for each variant in all instances is very low, which makes this constructive heuristic faster in obtaining results and an added value for the decision-maker.

## 5 Case study

### 5.1 Description

To illustrate the practical application of the proposed approach, a case study was conducted in the Braga district, located in northern Portugal. This region was chosen due to its historical incidence of forest fires and the availability of detailed geographic and logistics data. The case study demonstrates how the constructive heuristic can be applied in real-world firefighting contexts.

Firstly, three potential initial ignition points were identified. The locations of the three ignitions are depicted in Fig. 2, as well as the initial location of the resources (the Póvoa de Lanhoso Fire station).

These locations were selected because they belong to critical areas where fires frequently occur. This area of interest has 282.26 $km^2$. Fire spread simulations, one for each ignition, were conducted with a spatial resolution (i.e., a distance between adjacent nodes in a grid representing the landscape) of 2000 m. Every 1 min, an estimate of the fire perimeter length was obtained. These simulations were conducted with pyO3F - A Python Framework for Wildfire-Related Optimization [20, 21]. This framework uses the minimum travel time principle to simulate fire spread. In this approach, a network is constructed where each node corresponds to the centroid of a hexagon of a grid, and each arc represents the potential fire transmission between adjacent nodes. Fire transmission times are associated with arcs and are obtained through an estimate of the fire rate of spread with Rothermel's fire behavior model [43]. Rothermel's model uses wind, slope, and fuel characteristics to estimate the fire rate of spread. In this case study, we used the Portuguese fuel models from [44, 45]. For each hexagon, the dominant land use was derived and converted to a fuel model. A wind speed of 60 $km/h$ was set.

The obtained burned area over time (for the first 25 min) is presented in Table 19. The initial burned area, i.e., when $t = 1$ corresponds to the burned area when the fires are detected.




**Fig. 2** Locations of the three ignitions in Braga district

**Table 19** Burned area along the instants of time (in $m^2$)

| | $I_1$ | $I_2$ | $I_3$ |
|---|---|---|---|
| 1 | 48,497.4 | 34,641.0 | 6928.2 |
| 2 | 56,195.4 | 37,720.2 | 11,547.0 |
| 3 | 63,893.4 | 40,799.4 | 16,165.8 |
| 4 | 71,591.4 | 43,878.6 | 20,784.6 |
| 5 | 79,289.4 | 46,957.8 | 25,403.4 |
| 6 | 86,987.4 | 50,037.0 | 30,022.2 |
| 7 | 94,685.4 | 53,116.2 | 34,641.0 |
| 8 | 102,383.4 | 56,195.4 | 39,259.8 |
| 9 | 110,081.5 | 59,274.6 | 43,878.6 |
| 10 | 117,779.5 | 62,353.8 | 48,497.4 |
| 11 | 125,400.5 | 66,510.8 | 54,732.8 |
| 12 | 133,021.5 | 70,667.7 | 60,968.2 |
| 13 | 140,642.5 | 74,824.6 | 67,203.6 |
| 14 | 148,263.5 | 78,981.5 | 73,439.0 |
| 15 | 155,884.6 | 83,138.4 | 79,674.3 |
| 16 | 163,505.6 | 87,295.4 | 85,909.7 |
| 17 | 171,126.6 | 91,452.3 | 92,145.1 |
| 18 | 178,747.6 | 95,609.2 | 98,380.5 |
| 19 | 186,368.7 | 99,766.1 | 104,615.9 |
| 20 | 193,989.7 | 103,923.0 | 110,851.3 |
| 21 | 199,532.3 | 108,772.8 | 119,165.1 |
| 22 | 205,074.8 | 113,622.5 | 127,478.9 |
| 23 | 210,617.4 | 118,472.3 | 135,792.8 |
| 24 | 216,159.9 | 123,322.0 | 144,106.6 |
| 25 | 221,702.5 | 128,171.8 | 152,420.5 |

Ignition $I_1$, at instant $t = 1$, has the largest burned area value, approximately 4.85 ha, while $I_2$ has a moderate burned area. Furthermore, ignition $I_3$ has the smallest initial burned area but exhibits the most marked growth over time, as shown in Table 19. If no resources are considered, all the area of interest burns in 520 min.

To fight these fires, the resources available in the Póvoa de Lanhoso Fire station are used, which consist of five water tank land vehicles, with the following capacities: $R_1 = 3000$l; $R_2 = 3500$l; $R_3 = 4000$l; $R_4 = 9000$l; $R_5 = 600$l. More details can be found on the repository.[2]

### 5.2 Results

The solution obtained using $H_{1\downarrow}$ is presented in Table 20, showing the activity of the five resources to combat the three ignitions. This solution involves a total burned area

[2] https://github.com/MarinaAMatos/Povoa-Lanhoso-Instance

**Table 20** $H_{1\downarrow}$ solution with 3 ignitions and 5 resources

| $t$ \ $R$ | $R_1$ | $R_2$ | $R_3$ | $R_4$ | $R_5$ |
|---|---|---|---|---|---|
| 0 | Base | Base | Base | Base | Base |
| ⋮ | ↓ | ↓ | ↓ | ↓ | ↓ |
| 13 | ↓ | $I_1$ | $I_1$ | $I_1$ | ↓ |
| ⋮ | ↓ | ↓ | * | * | ↓ |
| 15 | $I_3$ | ↓ | * | * | $I_3$ |
| ⋮ | * | ↓ | * | * | * |
| 23 | * | ↓ | Refill | Refill | * |
| ⋮ | * | ↓ | ↓ | ↓ | * |
| 25 | Refill, $I_3$ | ↓ | ↓ | ↓ | Refill, $I_3$ |
| ⋮ | * | ↓ | ↓ | ↓ | * |
| 35 | Refill, $I_3$ | $I_3$ | ↓ | ↓ | Refill, $I_3$ |
| ⋮ | * | * | ↓ | ↓ | * |
| 45 | Refill | Refill | $I_3$ | $I_3$ | Refill, $I_3$ |
| ⋮ | ↓ | ↓ | * | * | ↓ |
| 55 | ↓ | ↓ | Refill | Refill | ↓ |
| ⋮ | ↓ | ↓ | ↓ | ↓ | ↓ |
| 70 | $I_2$ | $I_2$ | ↓ | ↓ | $I_2$ |
| ⋮ | * | | ↓ | ↓ | |
| 80 | Refill, $I_2$ | | $I_2$ | $I_2$ | |

The down arrow (↓) indicates the resource is traveling
The asterisk (*) indicates the resource is refilling

of 1,107,126.88 $m^2$ ($\approx$ 110.71 ha) and the used water was 62,148.40 l. The total time to completely extinguish all the fires was 80 min.

Note that $I_1$ and $I_3$ are the fires with the highest priority order, taking into account the ratio (1); thus, they are the first selected. Ignition $I_3$, despite starting with a smaller area, grows rapidly, becoming an ignition with a larger burned area.

For example, at instant of time 13, resource $R_3$ arrives at ignition $I_1$, and then refills, because it does not have enough water. At instant 23, resource $R_3$ is available with a full tank of water and travels to extinguish the ignition $I_3$, arriving there at instant of time 45. Then, it runs out of water again in its tank and refills it, becoming available at instant of time 55. Next, it travels towards ignition $I_2$, arriving at an instant of time 80, to extinguish it.

As shown before (see Table 12), the constructive heuristic produces results in a short time. Even when including the *a priori* spread simulations, the total execution

time is less than 12 s. The heuristic's speed allows its use in real-time contexts, which are particularly relevant for addressing the well-known uncertainty in fire spread. This case study shows that the resources in Póvoa de Lanhoso are adequate for this situation, which may be described as extreme, since all fires are extinguished in less than 90 min without the need for additional resources, that is, the time limit for the initial attack in Portugal.

## 6 Conclusions

This paper addressed a firefighting dispatch and routing problem in a region where several fires occur simultaneously. A constructive heuristic was proposed. The heuristic provides the sequence of fire attacks of each available resource, taking into account its movements and the need for water refills. Its objective is to minimize the total burned area. Four variants of the constructive heuristic were defined, $H_{1\downarrow}$, $H_{1\uparrow}$, $H_{2\downarrow}$, and $H_{2\uparrow}$, to give the sequential order of the ignitions to be extinguished based on the ratios of the firefighting priority indicator. The ratios were calculated using (1) and (2). Thus, the sequence of ignitions can be positioned in descending or ascending order of the ratio values. An instance generator was built for the firefighting dispatch and routing problem, where 60 instances were generated with different numbers of ignitions (5, 7, and 10) and resources (20 and 30). The constructive heuristic was applied to all instances, and the results were statistically analyzed. Comparing all the solutions, it was concluded that the variant with the best performance was the one that uses the ratio (1) in a decreasing way ($H_{1\downarrow}$).

A case study in the Braga district was presented, demonstrating the effectiveness of the constructive heuristic in solving a problem with five resources to combat three ignitions. The fire rate of spread was simulated with the pyO3F framework, taking into account wind, slope, and fuel characteristics. A reasonable solution was obtained with an extinguishing time of 80 min.

The main goal of the constructive heuristic is to produce the allocation of land vehicles to fires in a reasonable computational time. The land vehicles have water tanks that can be refilled in the local area where they are containing the fire. However, a fixed time to refill the tanks of the vehicles was considered, although it depends on the capacity of their water tanks and the availability of water. Concerning the suppression time, a fixed period of time was considered, not reflecting the reality, since it depends on the burning area, resources, wind, slope, and fuel type, among others.

As future work, taking advantage of its speed, we intend to use the heuristic as a method to solve subproblems arising in approaches to address the dynamic and uncertain behavior of fire.

**Funding** Open access funding provided by FCT|FCCN (b-on). This work has been supported by FCT Fundação para a Ciência e Tecnologia within the R&D Units Project Scope UID/00319/Centro ALGORITMI (ALGORITMI/UM) and PCIF/GRF/0141/2019: "O3F - An Optimization Framework to Reduce Forest Fire" and the PhD grant reference UI/BD/150936/2021.

**Data Availability** Instances available at https://github.com/MarinaAMatos/Inst_Firefighting Case Study: https://github.com/MarinaAMatos/Povoa-Lanhoso-Instance

## Declarations

**Conflict of Interest** The authors declare no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

## References

1. Resco de Dios V, Nolan RH (2021) Some challenges for forest fire risk predictions in the 21st century. Forests 12(4). https://doi.org/10.3390/f12040469
2. Mansoor S, Farooq I, Kachroo MM et al (2022) Elevation in wildfire frequencies with respect to the climate change. J Environ Manage 301:113769. https://doi.org/10.1016/j.jenvman.2021.113769
3. Church RL (2007) Tactical-level forest management models. Springer, US, Boston, MA, pp 343–363
4. Martell DL (2007) Forest fire management, Springer US, Boston, MA, pp 489–509. https://doi.org/10.1007/978-0-387-71815-6_26
5. Naderpour M, Rizeei HM, Khakzad N et al (2019) Forest fire induced Natech risk assessment: a survey of geospatial technologies. Reliabil Eng Syst Safety 191
6. San-Miguel-Ayanz J, Durrant T, Boca R et al (2022) Forest fires in Europe, Middle East and North Africa 2021, Publications Office of the European Union, Luxembourg. EUR 31269 EN. https://doi.org/10.2760/34094
7. Carmo IIV (2021) O papel dos instrumentos de gestão territorial na prevenção e mitigação dos incêndios florestais: o caso do incêndio de pedrogão grande (2017) (in portuguese). PhD thesis, Universidade Nova de Lisboa
8. Martell DL, Gunn EA, Weintraub A (1998) Forest management challenges for operational researchers. Eur J Oper Res 104(1):1–17
9. Fernandes PM, Pacheco AP, Almeida R et al (2016) The role of fire-suppression force in limiting the spread of extremely large forest fires in Portugal. Eur J Forest Res 135(2):253–262
10. Minas J, Hearne J, Martell D (2015) An integrated optimization model for fuel management and fire suppression preparedness planning. Ann Oper Res 232(1):201–215
11. Rönnqvist M, D'Amours S, Weintraub A et al (2015) Operations research challenges in forestry: 33 open problems. Ann Oper Res 232(1):11–40
12. Martell DL (2015) A review of recent forest and wildland fire management decision support systems research. Curr Forestr Rep 1(2):128–137. https://doi.org/10.1007/s40725-015-0011-y
13. Alvelos F (2018) Mixed integer programming models for fire fighting. In: Gervasi O, Murgante B, Misra S et al (eds) Computational Science and Its Applications - ICCSA 2018. Springer International Publishing, Cham, pp 637–652
14. Chan H, Tran-Thanh L, Viswanathan V (2021) Fighting wildfires under uncertainty: a sequential resource allocation approach. In: Proceedings of the twenty-ninth international conference on international joint conferences on artificial intelligence, pp 4322–4329
15. Granberg TA (2022) Optimized dispatch of fire and rescue resources. In: Computational Logistics: 13th International Conference, ICCL 2022, Barcelona, Spain, September 21–23, 2022, Proceedings, Springer, pp 132–146
16. Rodríguez-Veiga J, Ginzo-Villamayor MJ, Casas-Méndez B (2018) An integer linear programming model to select and temporally allocate resources for fighting forest fires. Forests 9(10):583
17. Matos MA, Rocha AMAC, Costa LA et al (2022) A genetic algorithm for forest firefighting optimization. In: Gervasi O, Murgante B, Misra S et al (eds) Computational Science and Its Applications - ICCSA 2022 Workshops. Springer International Publishing, Cham, pp 55–67

18. Tian G, Fathollahi-Fard AM, Ren Y et al (2022) Multi-objective to extinguish forest fires using a multi-objective discrete gravitational search algorithm. Inf Sci 608:578–596
19. Matos MA, Rocha AMAC, Costa LA et al (2023) Resource dispatch optimization for firefighting based on genetic algorithm. In: Gervasi O, Murgante B, Rocha AMAC et al (eds) Computational Science and Its Applications - ICCSA 2023 Workshops. Springer Nature Switzerland, Cham, pp 437–453
20. Alvelos F (2026) Alvelos FPe (2026) pyO3F—a Python framework for wildfire-related optimization, part I: design and fundamentals. In: Alvelos F, Martins I, Rocha AMAC (eds) Advances in optimization and wildfire. O&W 2024. Lecture notes in operations research. Springer, Cham. https://doi.org/10.1007/978-3-032-03108-2_3
21. Alvelos FP (2026) pyO3F—a Python framework for wildfire-related optimization part II: usage. In: Avelos F, Martins I, Rocha AMAC (eds) Advances in optimization and wildfire. O&W 2024. Lecture notes in operations research. Springer, Cham. https://doi.org/10.1007/978-3-032-03108-2_4
22. Attri V, Dhiman R, Sarvade S (2020) A review on status, implications and recent trends of forest fire management. Arch Agricult Environm Sci 5(4):592–602
23. Bento-Gonçalves A, Vieira A (2020) Wildfires in the wildland-urban interface: key concepts and evaluation methodologies. Sci Total Environ 707
24. Gonzalez-Olabarria JR, Reynolds KM, Larrañaga A et al (2019) Strategic and tactical planning to improve suppression efforts against large forest fires in the Catalonia region of Spain. For Ecol Manage 432:612–622
25. Martell DL (1982) A review of operational research studies in forest fire management. Can J For Res 12(2):119–140
26. Castillo E, Rodriguez F et al (2015) Determining response times for the deployment of terrestrial resources for fighting forest fires: a case study: Mediterranean-Chile. Ciencia e investigación agraria revista latinoamericana de ciencias de la agricultura 42(1):97–107
27. Van Der Merwe M, Minas JP, Ozlen M et al (2015) A mixed integer programming approach for asset protection during escaped wildfires. Can J For Res 45(4):444–451
28. Tinaburri A, Ponziani FA (2024) Principles for firefighting assets allocation. integrating national and regional forest fires logs into the vulnerability analysis. In: International scientific conference on woods & fire safety, Springer, pp 397–410
29. Blum C, Blesa MJ, García-Martínez C et al (2014) The firefighter problem: application of hybrid ant colony optimization algorithms. In: Blum C, Ochoa G (eds) Evolutionary Computation in Combinatorial Optimisation. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp 218–229
30. Hu B, Windbichler A, Raidl GR (2015) A new solution representation for the firefighter problem. In: Ochoa G, Chicano F (eds) Evolutionary Computation in Combinatorial Optimization. Springer International Publishing, Cham, pp 25–35
31. Michalak K (2017) Ed-ls - a heuristic local search for the multiobjective firefighter problem. Appl Soft Comput 59:389–404. https://doi.org/10.1016/j.asoc.2017.05.049
32. Ramos N, de Souza CC, de Rezende PJ (2020) A matheuristic for the firefighter problem on graphs. Int Trans Oper Res 27(2):739–766
33. Granda B, Vitoriano B, Figueira JR (2025) A mathematical programming approach for a wildfire suppression problem. Oper Res Int J 25(1):16
34. Mendes AB, Alvelos FP (2023) Iterated local search for the placement of wildland fire suppression resources. Eur J Oper Res 304(3):887–900
35. Alvelos F, Marto M, Mendes A (2025) Dispatching, positioning and routing resources for wildfire initial attack. Networks 86(1):80–102
36. Haight RG, Fried JS (2007) Deploying wildland fire suppression resources with a scenario-based standard response model. INFOR Inf Syst Operat Res 45(1):31–39
37. Ntaimo L, Gallego-Arrubla JA, Gan J et al (2013) A simulation and stochastic integer programming approach to wildfire initial attack planning. Forest Sci 59(1):105–117
38. Fang Y, Deng Y, Zhou Z (2019) Formulation and solution of an emergency routing problem for forest fire with priority areas. In: 2019 International Conference on Industrial Engineering and Systems Management (IESM), pp 1–5
39. Hu X, Ntaimo L (2009) Integrated simulation and optimization for wildfire containment. ACM Trans Model Comput Simul (TOMACS) 19(4):1–29
40. Yang Z, Guo L, Yang Z (2019) Emergency logistics for wildfire suppression based on forecasted disaster evolution. Ann Oper Res 283(1):917–937

41. Zhou K, Zhang F (2023) An event-response tree-based resource scheduling method for wildfire fighting. Forests 14(1). https://doi.org/10.3390/f14010102
42. Penney G, Habibi D, Cattani M, Carter M (2019) Calculation of Critical Water Flow Rates for Wildfire Suppression. Fire 2019, 2, 3. https://doi.org/10.3390/fire2010003
43. Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels (Vol. 115). Intermountain Forest and Range Experiment Station, Forest Service, USA
44. Fernandes P, Gonçalves H, Loureiro C, Fernandes M, Costa T, Cruz MG, Botelho H (2009) Modelos de combustível florestal para Portugal. Actas do 6o Congresso Florestal Nacional (in Portuguese). SPCF, Lisboa, Portugal, 348–354
45. Fernandes P, Loureiro C (2021) Modelos de combustível florestal para Portugal, Documento de referência (in Portuguese)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.