Wildfire Resources Management: a Decision Support Tool Created with `R` to Solve Optimisation Models in Logistics for Fighting Forest Fires

Jorge Rodríguez Veiga, María José Ginzo Villamayor, and Balbina Virginia Casas Méndez

Abstract The first part of this work reviews several mathematical programming models dedicated to resource allocation and planning problems in the context of extinguishing large forest fires. These problems have been studied as part of the research projects *Lumes* and *Enjambre*, which involve both the public and private sectors in Spain. The objective of *Lumes* and *Enjambre* is to develop advanced technologies for fighting forest fires. Moreover, the projects address other tasks such as the design of algorithms to prevent aircraft collisions and estimating the perimeters of forest fires using techniques such as estimating sets from thermal images. The second part of this work is focused on the `R` package and corresponding graphic interface, Wildfire Resources Management (`wrm`), which are designed to offer a user-friendly model interface in terms of the introduction of the necessary data, resolution, and presentation of the results, according to the needs of the interlocutors in the company dedicated to the extinction of forest fires. The auxiliary package uses various solvers, such as `symphony` and `gurobi`. This work presents the various components of `wrm` (which can be viewed in the GitHub repository), a computational study, and a procedure for its use.

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1 Introduction

In recent years, Spain has been one of the European Union countries that is the most affected by forest fires. This problem poses one of the most serious threats to the forest heritage of the country, affecting the integrity of material assets and human lives. Moreover, it is a problem that may intensify owing to the effects of climate change. Various reports by the Ministry of Agriculture, Fisheries and Food (MAPA) of Spain in 2018 ([4]) reflected the severity of the situation.

In the past decade, an average of 12,573 fires occurred per year, of which two thirds were *conatos*[1]. Although *conatos* do not cause significant damage and the affected areas usually recover naturally, they are also relevant. Although the number of fires and *conatos* has been decreasing in the past decade, effective resource management remains essential. The magnitude of the problem results in an expenditure of millions of Euros by state, regional, and local administrations for the prevention and extinction of forest fires. According to the latest numbers from MAPA, 44.4% of the fires in 2019 occurred in the northwest area of the country, which includes the communities of Galicia, Asturias, Cantabria, and the Basque Country, as well as the Castilian provinces of León and Zamora.

Furthermore, although the total number of fires per year is decreasing, there is an increasing threat of large wildfires[2], against which extinction services are ineffective. This significant threat results in the need for large-scale decisions to be made, taking into account numerous variables that affect the decision-making process.

As an example of how dramatic the situation may be, a wave of fires occurred in Galicia between Friday 13 October 2017 and Sunday 15 October 2017, when more than 100 forest fires were active simultaneously. Among the resources involved in the extinction operation, there were 500 soldiers, 35 brigades, 220 motor pumps, 40 blades, and 20 air resources; 45,000 ha of land burned, and there were 3 deaths and 20 injured.

In general, the design of decision support systems for logistics is an extremely active field of research and applications in modern operations. Within the forest fire control framework, it is also essential for efficient decisions to be made. Furthermore, budgets and fire resources are limited in this context ([6]). In this sense, it is worth mentioning that economic theory plays a central role in the management of forest fires. The first works to engage in the economic study of forest fires were [5] and [14], which described the establishment of an optimum fire management programme. A theoretical framework has been used to identify the most efficient means of managing wildfire costs, namely the Cost Plus Net Value Change, (C+NVC, [3]). This framework is intended to minimise the cost of the use of resources in fire fighting plus the cost produced by the hectares of land burned, taking into account the material losses in the fire (such as trees and urban goods) as well as the restocking or reconstruction of these areas. Three types of problems associated with forest fire

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[1] *Conatos* are fires affecting an area of less than 1 ha.

[2] Large wildfires are fires in which more than 500 ha of surface burn.

management have been distinguished in the literature: prevention, detection, and the management of resources for forest fire containment ([8]).

In the case of Spain, different research projects have emerged in light of this growing problem. In 2010, the *Prometeo* project arose, with the goal of improving the efficiency of fire fighting. *Prometeo* was one of the largest applied research projects awarded to a business consortium in Spain to fight forest fires. The project involved more than 16 companies and active government participation, with the aim of achieving the following objectives: mitigating the environmental damage in case of fire in an efficient manner, reducing the number and size of large wildfires, and ensuring the safety of extinguishing devices.

Following the *Prometeo* project, the *Lumes* and *Enjambre* projects were implemented in 2013 and 2015, respectively, which again involved various companies in the public and private sectors, and were funded by the Spanish Centre for the Development of Industrial Technology. Among those involved in these projects was the public consortium the Technological Institute of Industrial Mathematics (ITMATI), which includes three universities of Galicia, Coremain, a computer consulting company located in Santiago de Compostela, and Spain Babcock International, a leading provider of air emergency services and aircraft maintenance. The main objective of these projects is to develop new advanced technologies for comprehensively fighting major forest fires, reducing the number and surface size of these fires, and generating a security enclosure in operations that can significantly reduce the accident rate of the participants (technical, brigade, and pilots).

Various activities have been of substantial interest in projects of this magnitude. These activities include image processing, which provides information regarding the vegetation structure and evolution of the fire (according to which resources are selected), the study of the feasibility of unmanned aircraft in this context, algorithms and strategies to ensure the safety of terrestrial environments, analyses of night extinction operations, and the coordination of air traffic. In particular, the tasks that are of greatest relevance within the *Enjambre* project can be classified as follows:

- An algorithm to estimate the perimeters of forest fires using techniques for estimating sets from thermal images.
- An algorithm to prevent collisions between aircraft that are working on the same forest fire.
- An algorithm to calculate the efficiency of water discharges by air resources in the extinction of forest fires.
- An algorithm to manage resources, taking into account the regulations in force in Spain (such as rest times and the minimum number of resources in the area).

This paper details the final point mentioned above, the efficient management of resources involved in the extinction of a forest fire, and the corresponding computer tools that are designed. Three problems that are of significant relevance can be differentiated:

1. The selection of resources necessary for the containment of a forest fire.
2. The assignment of each air resource to an area of unloading and loading for the retarders used to contain the forest fire.

3. The allocation of air resources to re-fuelling points.

As these problems are strongly interconnected, the following paragraphs explain the integration and use of each of the problems to facilitate the understanding and scope thereof.

To understand the management of a forest fire, it is first necessary to define the roles of certain agents. The extinguishing director is in charge of the entire forest fire management operation. To this end, the director has the support of the air resources air coordinator (who aims to achieve the safety of the operation and optimise the times of the air resources), the air resources land coordinator (who aims to control the fuel available in re-fuelling bases and plans the use of these bases), and the land resources coordinator (who aims to manage the operation of the land resources and ensure their safety).

When a forest fire is detected, the extinguishing director needs to determine a subset of the available resources that will be used to contain the fire (a model has been designed for this purpose, which is referred to as Mathematical Model 1). Once the resources have been selected and their periods of action on the fire have been established, as well as the rest periods, the air resources are allocated to the flight routes (which are defined as the elliptical aerial routes that the aircraft must follow between the points of discharge and retardant loading). In particular, for each set of aircraft working in the same period, the air resources air coordinator carries out the assignment of aircraft to the flight routes (Mathematical Model 2). Moreover, because the air resources land coordinator already knows the time assignments of the air resources for each rest period, Mathematical Model 3 for the assignment of the aircraft to the re-fuelling points must be executed. Thus, with this distribution of tasks, the extinguishing director has assured control over the resources that are working in the fire and those that are re-fuelling. This also allows for the correct management of re-fuelling points, thereby avoiding collapses or shortages. Fig. 1 provides a schematic description of the entire process.

In this paper, the implementation of a mathematical programming model that responds to the interest of the company Spain Babcock International in automating the selection and temporary allocation of resources in the extinction of a forest fire is presented. The collaboration is carried out within the *Lumes* and *Enjambre* projects. The company does not have a similar tool at present and currently uses a human-based method aided by GIS tools. The new tool will serve as a support system for the recommendation of resources to be used by the extinction coordinators, and therefore, according to the computation study carried out, they will be more efficient. The company Coremain, which also participates in the projects, is in charge of integrating this tool with other algorithms created in the project, such as that providing the evolution of the fire perimeter. All of this constitutes an important knowledge transfer for the company. In Section 2, a basic model existing in the literature is presented. Section 3 outlines the model created in the projects for the selection and temporary allocation of resources. Sections 4 and 5 present complementary models created to assign aerial resources to flight routes and re-fuelling bases, respectively. Section 6 explains the implementation programmed with `R`, which solves the main model.

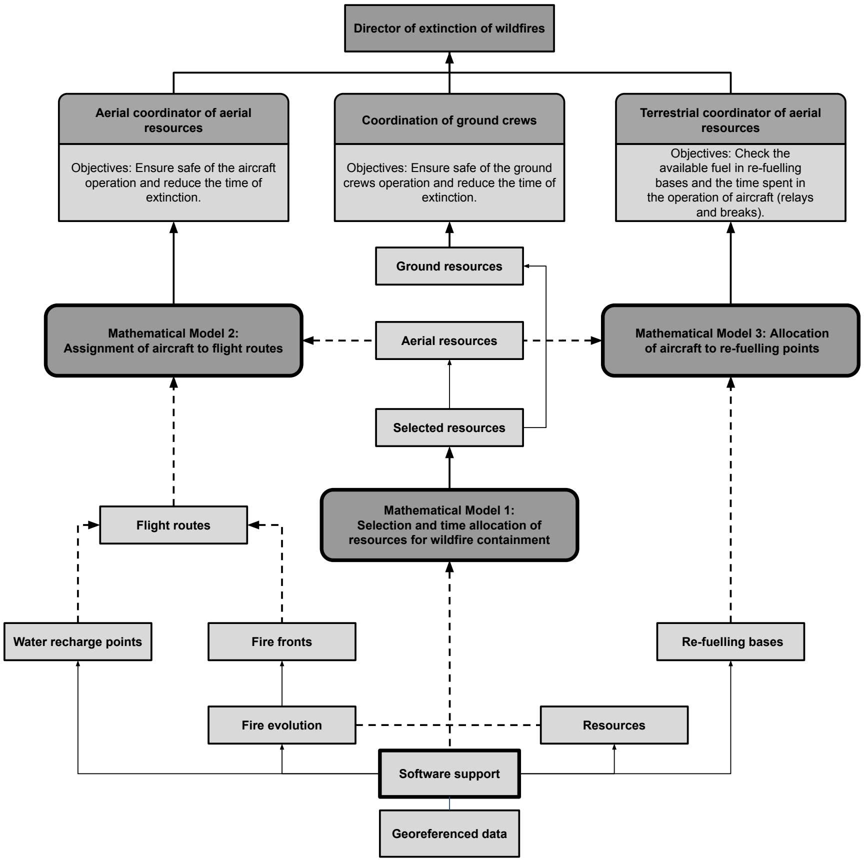

Fig. 1 Workflow of three resource allocation models considered in paper

2 Seminal Model to Select Resources

A seminal study that investigated the optimal initial selection of extinction resources for forest fires using integer linear programming is that of [2]. The approach of this study, with several modifications, was considered to be adequate in responding to any problems arising in the *Lumes* and *Enjambre* projects.

With respect to data, [2] began with information regarding the forest fire, specifically with an estimate of the fire evolution. The authors also used information relating to the resources, regarding both their description and position at the time of the initial planning.

Given the underlying decision problem, the variables used in the developed model are associated with resources and fires.

However, there is an important restriction relating to the fire. It must be able to be contained with the available resources at some point in the considered time horizon. Moreover, restrictions are in place that represent the logical relationships among the model variables.

Several parameters of the model are introduced below.

To include the information of the estimation of the forest fire evolution, for each period of time $t \in T := \{1, \dots, m\}$, where m is the number of time periods constituting the time horizon for which the temporary planning is performed, the following notation is used:

SP_t	**Fire perimeter**, *i.e.* the line surrounding the burning surface (km).
PER_t	**Increment of the perimeter** (km).
NVC_t	**Increment in the cost** of the burned land (monetary units).

For each resource $i \in I := \{1, \dots, n\}$, where n is the number of available resources, the following parameters are considered:

C_i	**Cost per period** of the use of a resource (monetary units).
P_i	**Fixed cost** by resource selection (monetary units).
PR_i	**Resource performance**, *i.e.* extinguished fire perimeter (km/h).

In terms of the information regarding the resources, for each resource $i \in I := \{1, \dots, n\}$, the starting position of the resource is represented as follows:

A_i	**Number of periods** required to reach the fire from the base where the resource is located.

Considering these parameters, the first question to address is: How can these parameters be obtained? To answer this question, it is necessary to take into account the available historical fire data, from which it is possible to obtain estimates of the costs associated with the use of resources and damaged land, as well as the performance of the resources. For example, in Galicia, reports are available on all fires that have occurred since 1 January 1999, in which all of the data relating to each fire are recorded, including the affected area, instants at which the fire started, whether it was controlled and completely extinguished, causes, type of attack, and resources used. Both the public and private entities dedicated to extinction possess historical data on the operations. These data, together with fire simulators and weather forecasts, can be used to obtain estimates of the increase in the fire perimeter and area. The data also provide useful information for computer applications with geographic information related to the location of the resource bases, re-fuelling points, hydrographic network, arrival times between different locations, aerial photos, and loss valuation. In Galicia, the *GIS* application *Xeocode2* is available for the authorities.

Regarding the model decision variables of the model, the first group is associated with the resources. For each resource $i \in I$ and each period $t \in T$:

d_{it}	Binary variable that takes a value of 1 if the resource is used **until this period**.
z_i	Binary variable that takes a value of 1 if the resource is **selected** to work on the forest fire.

The interpretation is that the value of d_{it} is 1 for the resources i that together can extinguish the fire working until a certain period $t' \geq t$.

A second group of variables is associated with the fire. For each period $t \in T$:

y_t Binary variable that takes a value of 1 if the fire is **not contained** in the period (with $y_0 = 1$).

The objective function involves minimising the cost of the use of resources and the cost associated with the burned land, which is formulated as follows:

$$\min \sum_{i\in I, t\in T} C_i \cdot t \cdot d_{it} + \sum_{i\in I} P_i \cdot z_i + \sum_{t\in T} NVC_t \cdot y_{t-1}$$

To complete the model presentation, the restrictions are explained below. These restrictions represent the fact that the fire will be extinguished at some point and also that the logical relationships among the variables must be fulfilled.

Fire containment: At a certain moment of time, the perimeter 'built' by the resources must cover the fire perimeter.

$$\sum_{i\in I} \sum_{t\in T} (t - A_i) \cdot PR_i \cdot d_{it} \geq \sum_{t\in T} PER_t \cdot y_{t-1}$$

Logical relationships among variables: A resource is selected only if it works up to a certain period. Moreover, the fire is considered to be **not extinguished** only if the resources have not covered the entire perimeter.

$$\begin{aligned}
&\forall i \in I,\ \sum_{t\in T} d_{it} \leq z_i \\
&\forall t \in T,\ SP_t \cdot y_{t-1} - \sum_{t'\leq t} \sum_{i\in I} (t' - A_i) \cdot PR_i \cdot d_{it'} \leq M \cdot y_t
\end{aligned}$$

In the above, M denotes a sufficiently large constant.

[2] illustrated their model using an example. The authors employed different tools for the construction and resolution. The inputs related to the fire behaviour were obtained using a fire simulation program known as FARSITE[3], the fire-fighting resource containment rates were based on [9], and the exact solution of the model was obtained using the LINGO solver.

To solve the problems of the *Enjambre* project, another interesting tool is [15], whereby a study is carried out on the estimation of the costs of the forest fire extinction operations.

3 Model to Select and Temporally Allocate Resources

The companies in the *Enjambre* project are not only interested in the selection of resources at the initial moment, but also require a time schedule that takes into account the current regulation on flight and pilot rest times ([13]), known as 16B.

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[3] https://www.fs.usda.gov/treesearch/pubs/4617.

Furthermore, it is desirable to go beyond the initial selection and aspire to employ a methodology involving a *rolling horizon*, which enables the possibility of execution at any instant. According to the interlocutors in the company, it is interesting to have a plan that explicitly includes the rest, flight, and work times for the resources fighting the fire. Moreover, for each resource group (aircraft, machines, and brigades), the extinction coordinators require the minimum and maximum number of resources. Thus, [10] proposed a new model that includes novel variables. For each resource $i \in I$, each period $t \in T$, and each group $g \in G := \{1, \dots, r\}$, where r is the number of different groups of resources:

s_{it}	Binary variable that takes a value of 1 if the resource **starts to work** in the period.
fl_{it}	Binary variable that takes a value of 1 if the resource **flies (travels) without working** in the period.
r_{it}	Binary variable that takes a value of 1 if the resource **rests** in the period.
er_{it}	Binary variable that takes a value of 1 if the resource **ends a break** in the period.
e_{it}	Binary variable that takes a value of 1 if the resource **ends its work** in the period.
w_{it}	Binary variable that takes a value of 1 if the resource **is containing the wildfire** in the period.
u_{it}	Binary variable that takes a value of 1 if the resource **is used** in the period; that is, $u_{it} = fl_{it} + r_{it} + w_{it}$.
z_i	Binary variable that takes a value of 1 if the resource is **selected** in a certain period.
μ_{gt}	Integer variable that counts the number of **missing** group resources to reach the minimum in the period.

In the new model, the objective function minimises the cost of the use of the resources as well as the cost associated with the burned land. Furthermore, the objective function penalises non-compliance with the minimum number of resources of each group that must be present. The objective function is formulated as follows:

$$\min \sum_{i \in I, t \in T} C_i \cdot u_{it} + \sum_{i \in I} P_i \cdot z_i + \sum_{t \in T} NVC_t \cdot y_{t-1} + \sum_{g \in G,\, t \in T} M' \cdot \mu_{gt}$$

Here, M' denotes a large constant. The restrictions of this model are as follows:

Fire containment: At a certain point, the extinction will progress sufficiently to end the tasks of the resources.

Start of the activity: If a resource is used, it is selected in a certain period. The resources acting on the fire at the time of executing the algorithm continue to act or fail to act for the entire period considered.

Start and end of the activity: If a resource is selected, it must fly (in general, travel) from the base to the fire. At the end of the intervention, the resource must have sufficient time to return to the base.

Logical relations among the variables.

Number of resources: The minimum and maximum number of resources cannot be violated as long as the fire is not contained.

Breaks: This is the main difference from the model in [2]. It is useful to create a variable that **acts as a counter** of the number of periods that have been spent without rest for each resource in each period.

The formulation of the restrictions is not included in this setup, but they can be viewed in [10].

4 Model for Allocation of Aerial Resources to Flight Routes

As mentioned in Section 1, once the resources that will participate in the extinction during a set of periods have been selected, one task of the aerial coordinator of aerial resources is the allocation of resources that are assigned to identical periods to the flight routes[4].

It is appropriate to mention the words of [7]: ‘In the case of amphibious airtankers, the air attack officer must decide from which water body each airtanker will pick up water and when and where each airtanker will drop its load’.

In [12], a mixed integer linear programming model was introduced to automate this task. The notations P and K are used for the sets of water recharging points and fire fronts, respectively. Moreover, P_i, G_i, and K_i are the set of water points, group of aerial resources, and fire fronts that are assigned to resource i.

Subsequently, given a resource $i \in I$, a resource group $g \in G$, a water recharge point $p \in P$, and a fire front $k \in K$, new parameters are introduced:

CAP_i	**The carrying capacity**.
DOI_{gpk}	The number of **downloads** per hour performed by an aerial resource of group g in the flight route, given by the fire front k and water point p.
DIS_{ik}	**The distance** from the current position of aerial resource i to fire front k.

Taking into account the new decision problem to be solved, the following variables are used:

a_{ipk}	Binary variable that takes a value of 1 if the aerial resource is **assigned** to a flight route given by water point p and fire front k.
m_k	Real variable that measures the **lack of water** used on the fire front relative to the amount initially assigned.
f_k	Binary variable that takes a value of 1 if fire front k is left **unattended**.

In this allocation problem, the objective is to maximise the discharged water/retardant per time unit. This criterion can produce ties when selecting the resources, in which case the closest resources will be prioritised. Moreover, a front

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[4] A flight route is a circular path that follows a set of air resources and is associated with a certain point of water loading and a fire front on which water is discharged.

being left unattended and/or receiving fewer downloads than those planned will result in a penalty. Thus, the objective function is formulated as follows:

$$\max \sum_{i\in I}\sum_{g\in G_i}\sum_{p\in P_i}\sum_{k\in K} DOI_{gpk}\cdot CAP_i\cdot a_{ipk}-\sum_{i\in I}\sum_{k\in K_i}\sum_{p\in P_i}\frac{DIS_{ik}}{\max\limits_{i'\in I,k'\in K} DIS_{i'k'}}\cdot a_{ipk}$$
$$-\sum_{k\in K} M\cdot(m_k+f_k)$$

The main restrictions of this model are that the maximum number of air resources on each flight route should not be exceeded and that no front should be disregarded. The remaining restrictions refer to the logical relationships among the variables.

The model ([12]) was programmed using the `AMPL` language and solved with `gurobi`. Part of the corresponding computational study is presented below. Different potentially realistic instances were designed (from 1 to 11) considering a different number of air resources, water[5] recharging points, and fronts in each case. The model was solved, and the average and maximum times obtained for 100 samples from each instance were recorded.

Table 1 Several instances considered in study of model for allocation of resources to flight routes

Instance number	1	2	3	4	5	6	7	8	9	10	11
Number of aircraft	3	3	3	3	3	6	6	9	9	12	15
Number of water points	3	6	6	9	9	3	6	3	9	6	6
Number of fire fronts	3	3	6	3	6	3	3	3	3	6	6

Table 1 describes the instances and Fig. 2 presents the computation times (s). The execution times (top line) were less than 5 min in each case, with most of these executions being less than 1 min. The average times were always less than 20 s and reached a value of 1 s only with a number of aircraft equal to 12 or 15.

5 Model for Allocation of Aerial Resources to Re-fuelling Points

As also mentioned in Section 1, once the resources that will participate in the extinction during a set of periods have been selected, a task of the terrestrial coordinator of aerial resources involves the allocation of air resources to the re-fuelling points in periods when the air resources are not indicated to work on the fire.

Therefore, a second model was introduced in [12]. In this case, it is a binary linear programming model to automate this other tasks. Accordingly, it becomes necessary to consider new sets:

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[5] In this paper, the term water is used for simplicity, but in general reference will be made to any kind of retardant used in extinguishing a forest fire.

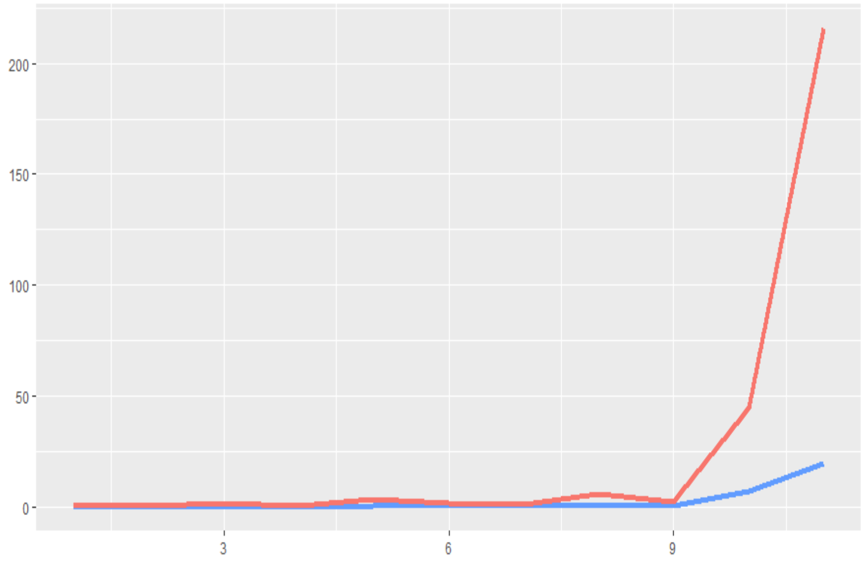


Fig. 2 Average and maximum computation times (s) of model for resource allocation to flight routes in several instances

B	Set of **re-fuelling bases**.
B_i	Set of re-fuelling bases **assigned to resource** $i \in I$.

Given a resource $i \in I$, base $b \in B$, and period $t \in T$, new parameters are introduced:

LOI_i	Fuel **load** of the aerial resource.
REF_i	Re-fuelling **time** of the aerial resource.
FUE_b	Current quantity of the **fuel available** in the base.
NUM_b	Number of aerial resources that **can refuel simultaneously** at the base.
TIM_{ib}	**Time** required to move an aerial resource from its current location to the base.
ATI_t	**Accumulated time** since the start of the re-fuelling planning process up to the period.

Two new sets of decision variables are also used:

s_{ibt}	Binary variable that takes a value of 1 when the aerial resource **starts re-fuelling** at the base in the corresponding period.
e_{ibt}	Binary variable that takes a value of 1 when the aerial resource **ends** re-fuelling at the base in the corresponding period.

In this allocation problem, the objective is to allocate the air resources to the different re-fuelling points in such a manner that the time spent in the operation is minimised, taking into account the re-fuelling itself and the round trip displacements from the work point to the re-fuelling base.

$$\min \sum_{i\in I} \sum_{b\in B_i} \sum_{t\in T} (ATI_t + TIM_{ib}) \cdot e_{ibt}$$

Regarding the restrictions, the fuel availability at each base, number and type of resources that can be used at each base simultaneously, re-fuelling times of the different resource types, and various logical relationships between the variables and parameters must be considered. The waiting times in the bases can be tackled in this manner.

The model was programmed using `AMPL` and solved with `gurobi`. Different realistic instances (from 1 to 11) were designed, with a different number of air resources and re-fuelling bases considered in each case. The model was solved, and the average and maximum times obtained for 100 samples from each of the instances were recorded.

Table 2 Several instances considered for allocation of resources to re-fuelling points

Instance number	1	2	3	4	5	6	7	8	9	10	11
Number of aircraft	3	3	3	3	3	6	6	6	6	9	12
Number of re-fueling bases	3	6	9	12	15	3	6	9	12	6	9

Table 2 describes the instances and Fig. 3 presents the corresponding computation times (s). The execution times (top line) were less than 10 min in each case, with most of these executions being less than 5 min. The average times never exceeded 3 min, and the maximum times did not exceed 3 min, provided that the number of aircraft was less than 9.

6 `Wrm` in Practice

In this section, the Wildfire Resources Management (`wrm`) package ([11]), created using the `R` software, is explained. It is a decision support tool created to solve optimization models in logistics for fighting forest fires. The `shinydashboard` library ([1]) provides an interface for friendly use of the model presented in Section 3. `wrm` is an open-source package stored in the `GitHub` repository. The main libraries are the following:

`Shiny`	This library enables easy construction of interactive web applications.
`Shinydashboard`	This library creates dashboards with ‘Shiny’.
`Plotly`	This library translates ‘ggplot2’ graphs into an interactive web-based version.
`Shinyjs`	This library performs common `JavaScript` operations in the `Shiny app`.

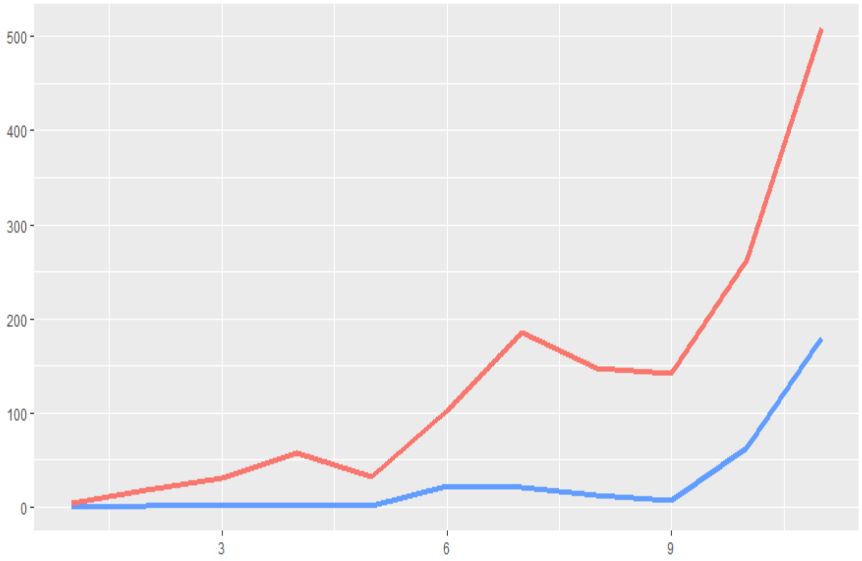
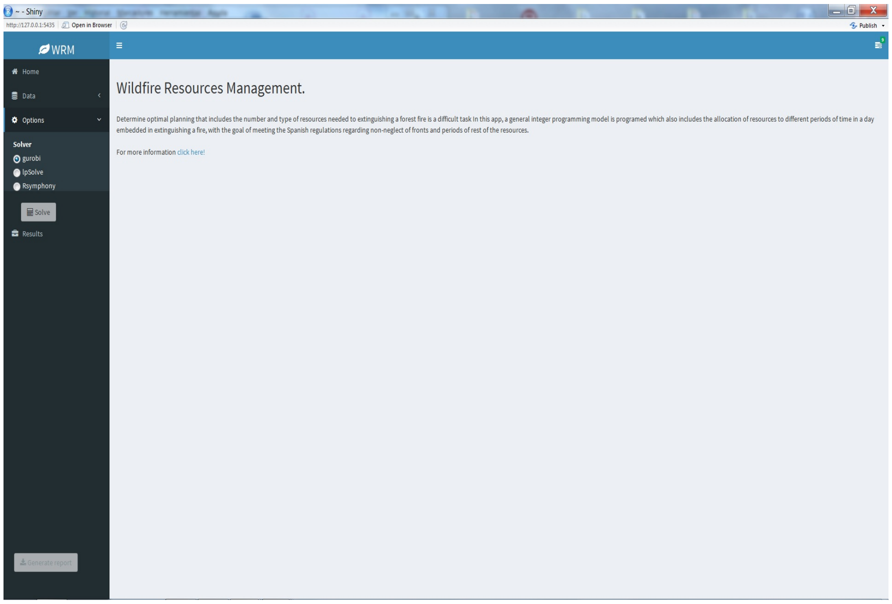


Fig. 3 Average and maximum computation times (s) of model for the resource allocation to refuelling points in several instances



Wildfire Resources Management.

Determine optimal planning that includes the number and type of resources needed to extinguishing a forest fire is a difficult task In this app, a general integer programming model is programed which also includes the allocation of resources to different periods of time in a day embedded in extinguishing a fire, with the goal of meeting the Spanish regulations regarding non-neglect of fronts and periods of rest of the resources.

For more information click here!

Solver
● gurobi
○ lpSolve
○ Rsymphony

Fig. 4 `wrm` interface appearance

6.1 Installation and Input Data

It is recommended to install the `wrm` package from the `GitHub` repository. For this reason, the first step is to install the ‘devtools’ package of `R`. Thereafter, it is necessary to install the below packages by using the following commands in the `R` console:

```
devtools::install_github('jorgerodriguezveiga/romo')
devtools::install_github('jorgerodriguezveiga/WildfireResources')
devtools::install_github('jorgerodriguezveiga/wrm')
```

Once the installation is complete, the following command line statement loads the interface:

```
wrm::shinyapp().
```

The interface automatically offers the appearance illustrated in Fig. 4.

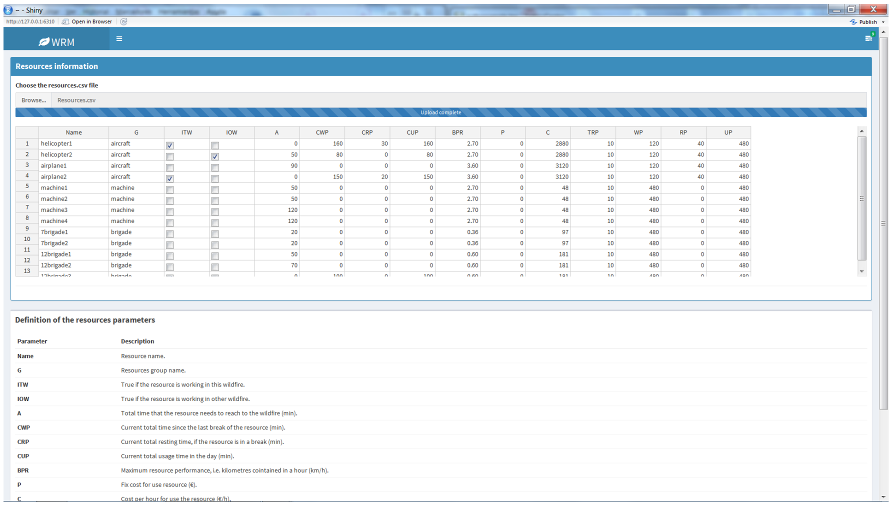
To verify the installation, an example dataset can be downloaded from the example folder. Firstly, it is advisable to use the example from the feasible subfolder.

Regarding the input data, the following information (parameters and corresponding descriptions) for each of the available resources should be provided:

Name	Resource name.
G	Resource group name.
ITW	True if the resource is working on the wildfire.
IOW	True if the resource is working on other wildfires.
A	Total time required by the resource to reach the forest fire (min).
CWP	Total current time since the last resort break (min).
CRP	Total current rest time if the resource is on a break (min).
CUP	Total time of the current use in the day (min).
BPR	Maximum performance of the resources; that is, kilometres maintained in one hour (km/h).
P	Fixed cost per use of the resource (Euros).
C	Cost per hour of the use of the resource (Euros/h).
TRP	Time required by the resource to travel to the fire from the rest area and vice versa (min).
WP	Maximum working time without interruption (min).
RP	Required rest time (min).
UP	Maximum daily working time including breaks (min).

The input data can be written to a `.csv` file. Fig. 5 presents an example of the interface appearance after entering the input data of the resources in `wrm`. In this example, two helicopters are considered, together with two aeroplanes and nine ground resources, among which six are brigades.

Furthermore, the following information for the fire should be provided:



Resources information

Choose the resources.csv file

Browse... Resources.csv

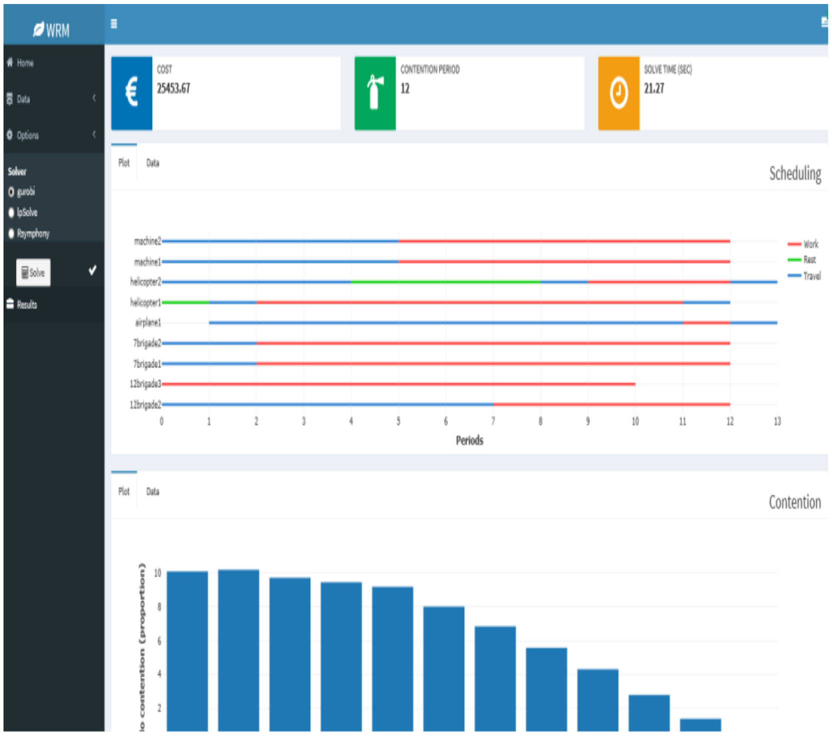
Upload complete

	Name	G	ITW	IOW	A	CWP	CRP	CUP	BPR	P	C	TRP	WP	RP	UP
1	helicopter1	aircraft	☑	☐	0	160	30	160	2.70	0	2880	10	120	40	480
2	helicopter2	aircraft	☐	☑	50	80	0	80	2.70	0	2880	10	120	40	480
3	airplane1	aircraft	☐	☐	90	0	0	0	3.60	0	3120	10	120	40	480
4	airplane2	aircraft	☑	☐	0	150	20	150	3.60	0	3120	10	120	40	480
5	machine1	machine	☐	☐	50	0	0	0	2.70	0	48	10	480	0	480
6	machine2	machine	☐	☐	50	0	0	0	2.70	0	48	10	480	0	480
7	machine3	machine	☐	☐	120	0	0	0	2.70	0	48	10	480	0	480
8	machine4	machine	☐	☐	120	0	0	0	2.70	0	48	10	480	0	480
9	7brigade1	brigade	☐	☐	20	0	0	0	0.36	0	97	10	480	0	480
10	7brigade2	brigade	☐	☐	20	0	0	0	0.36	0	97	10	480	0	480
11	12brigade1	brigade	☐	☐	50	0	0	0	0.60	0	181	10	480	0	480
12	12brigade2	brigade	☐	☐	70	0	0	0	0.60	0	181	10	480	0	480

Definition of the resources parameters

Parameter	Description
Name	Resource name.
G	Resources group name.
ITW	True if the resource is working in this wildfire.
IOW	True if the resource is working in other wildfire.
A	Total time that the resource needs to reach to the wildfire (min).
CWP	Current total time since the last break of the resource (min).
CRP	Current total resting time, if the resource is in a break (min).
CUP	Current total usage time in the day (min).
BPR	Maximum resource performance, i.e. kilometres cointained in a hour (km/h).
P	Fix cost for use resource (€).
C	Cost per hour for use the resource (€/h).

Fig. 5 Appearance of interface after entering input data corresponding to resources



COST
25453.67

CONTENTION PERIOD
12

SOLVE TIME (SEC)
21.27

Fig. 6 Appearance of `wrm` results

Period	Time period.
PER	Increased perimeter of the forest fire (km) in the period.
NVC	Increased costs of the forest fire (costs of the affected area, reforestation, and urban damage) in the period.
$EF.r$	Resource efficiency in the period (a number in [0,1]).
$nMin.g$	Minimum number of resources of the ‘g’ group working on the forest fire in the period.
$nMax.g$	Maximum number of resources of the ‘g’ group working on the forest fire in the period.

The appearance of the data files corresponding to a fire in the interface following its incorporation is similar to that for the resources.

6.2 Performance and Results

After loading the data files for the resources and fire, the solver used to solve the model should be selected: `gurobi`, `lpSolve` or `Rsymphhony`. The solver is executed by selecting ‘Solve’ in the interface and then waiting several seconds until the model is resolved, following which an ‘OK’ message will appear.

The results are obtained by selecting ‘Results’ in the interface. The obtained results include the cost, period in which the fire is contained, execution time, planning for the periods and resource type, and percentage of containment by period, as can be observed in the example of Fig. 6.

It can be observed from Fig. 6 that the computation time was 21.27 s and the fire was contained in period 12. Regarding the temporal planning of resources, the first terrestrial resource required five time periods to move from its current location to the fire, and the remaining time was spent working. The first helicopter required the four initial time periods for its displacement, rested for the following four periods, moved during another period, and worked for three periods until the extinction of the fire, at which point a new displacement began. Regarding the containment speed, it was possible to contain 10% of the fire in the first period.

Moreover, an alternative description of the number and type of resources used in each period is obtained, as illustrated in the case of Fig. 7. For example, one air resource, five brigades, and two other land resources were operating in period 8.

6.3 Computing Results

To illustrate the costs and time required by `wrm`, a simulation study with potentially realistic data was performed.

We created 24 cases by combining the resource groups indicated by Air.(aircraft), Mach. (machines), and Brig. (brigades) with 5 or 10 members for 20, 30 or 40 time periods. A total of 50 realistic instances were randomly constructed from each case.

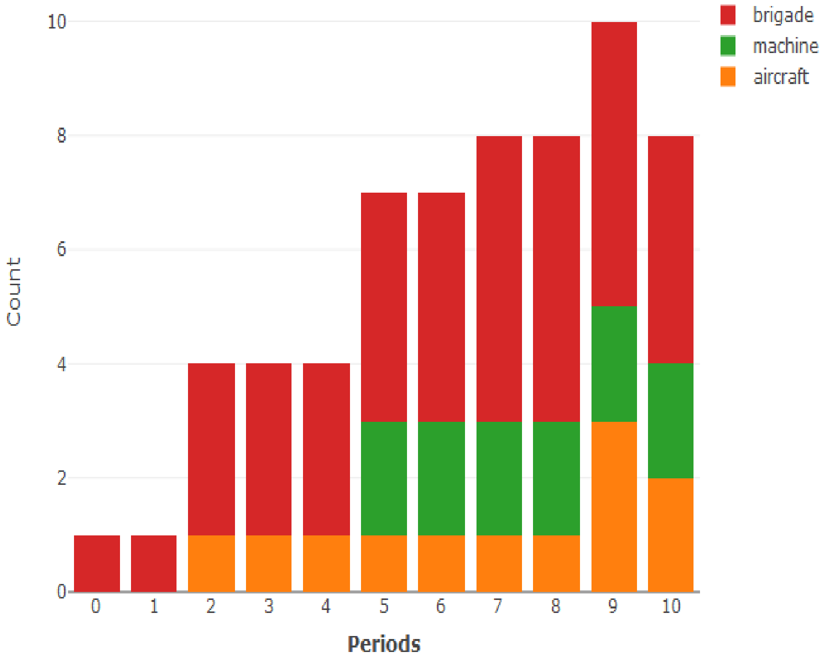


Fig. 7 Appearance of results corresponding to number of resources used

All of the computations included in this paper were performed on a personal computer with an Intel(R) Core(TM) i7-7700HQ 2.80 GHz CPU processor and 8.00 GB of memory.

In Table 3, the average information of the selected resources is displayed, distinguished by cases. The table presents the costs (Euros) of the operation, differentiating the costs of the use of resources and those for the hectares of land affected by the fire. It can be observed that the cost increased considerably when the number of periods increased.

Moreover, Table 4 indicates that the runtime was shorter for a smaller number of periods. In particular, if the number of time periods was as high as 30 (equivalent to 5 h), the execution times were short, with all of the instances resolved in less than 2 min.

Table 3 Mean operating costs obtained with `wrm`

Case	Air.	Mach.	Brig.	Periods	Resources	Fire	Total
1	5	5	5	20	895869.0	319879.8	1215748.8
2	10	5	5	20	1486565.4	314567.3	1801132.7
3	5	10	5	20	865444.4	287148.5	1152592.9
4	10	10	5	20	1564649.0	299793.1	1864442.1
5	5	5	10	20	854955.4	258997.2	1113952.6
6	10	5	10	20	1388193.4	281408.7	1669602.1
7	5	10	10	20	944578.4	281366.4	1225944.8
8	10	10	10	20	978959.6	246404.0	1225363.6
9	5	5	5	30	1707375.6	521991.5	2229367.1
10	10	5	5	30	2470270.2	381142.7	2851412.9
11	5	10	5	30	1677948.4	481234.3	2159182.7
12	10	10	5	30	1958495.8	346409.7	2304905.5
13	5	5	10	30	1651833.8	417261.5	2069095.3
14	10	5	10	30	3283654.6	436526.0	3720180.6
15	5	10	10	30	1392073.6	416127.4	1808201.0
16	10	10	10	30	3194804.2	406712.3	3601516.5
17	5	5	5	40	2441557.9	655377.6	3096935.5
18	10	5	5	40	3059774.8	347869.5	3407644.3
19	5	10	5	40	3750399.6	933170.7	4683570.3
20	10	10	5	40	2830142.6	389734.8	3219877.4
21	5	5	10	40	2648602.7	496788.5	3145391.2
22	10	5	10	40	2328978.2	256745.1	2585723.3
23	5	10	10	40	3362878.8	756016.1	4118894.9
24	10	10	10	40	5173332.1	452019.8	5625351.9

7 Conclusions

The first conclusion that can be rapidly drawn from this work is that operational research produces useful techniques for the optimal management of resources in fire-fighting problems. In particular, the model introduced in [2] is extended to meet the requirements of the partners in the company dedicated to fire-fighting. In this manner, academic advances can create powerful tools that are capable of producing results that can be transferred to industry.

For the specific problem studied, the results offer economic benefits and, importantly, enable an improvement in the efficiency of extinction tasks, thereby making the tasks safer and more powerful for the defence of the natural environment.

The models of Sections 4 and 5 are less complex than that of Section 3. The introduction of the data, modelling, and resolution have been addressed with `AMPL` and `gurobi`. However, the greater complexity of the model in Section 3 motivated the creation of an interface using `R`, which facilitates the introduction of data and displays the results graphically.

It should be noted that tools are required that provide adequate values for the model parameters. Historical fire data are also necessary to obtain useful research

Table 4 Mean execution time obtained with `wrm`

Case	Air.	Mach.	Brig.	Periods	Total time (s)
1	5	5	5	20	5.0
2	10	5	5	20	18.1
3	5	10	5	20	11.3
4	10	10	5	20	19.1
5	5	5	10	20	10.3
6	10	5	10	20	27.5
7	5	10	10	20	15.2
8	10	10	10	20	20.3
9	5	5	5	30	61.3
10	10	5	5	30	107.9
11	5	10	5	30	91.6
12	10	10	5	30	99.1
13	5	5	10	30	85.7
14	10	5	10	30	155.3
15	5	10	10	30	104.2
16	10	10	10	30	167.4
17	5	5	5	40	210.9
18	10	5	5	40	357.6
19	5	10	5	40	289.0
20	10	10	5	40	340.9
21	5	5	10	40	232.3
22	10	5	10	40	359.5
23	5	10	10	40	253.3
24	10	10	10	40	424.1

results. Of course, a tool to support the decision making of extinction coordinators is provided, but the experience of the pilots and brigades as well as their knowledge of the terrain is essential for appropriate extinguishing operations in a safe environment.

Regarding the work in progress, it is worth mentioning the interest in improving the graphic interface designed, including new utilities. Moreover, its correct integration with other tools for different project requirements is important. Finally, from the perspective of current academic findings that are potentially transferable to industry, it is worth studying the application of modern decomposition techniques to solve large problems involving resource selection and time planning. Moreover, the incorporation of uncertainty into the problem (stochastic programming) via modelling uncertainty (two-stage problem/multistage problem), the use of algorithms to solve integer stochastic problems, and possible parallel programming should be investigated.

Acknowledgements The authors are grateful for the interesting comments made by Alfonso Lorenzo and José Luis Sáiz Díaz, from the Spain Babcock International, as well as Manuel Febrero Bande, Wenceslao González Manteiga, and Beatriz Pateiro López from the University of Santiago de Compostela. This work has been supported by ITMATI, the ERDF (MINECO/AEI grants MTM2016-76969-P and MTM2017- 87197-C3-3-P), and Xunta de Galicia (Competitive Reference Group ED431C 2017/38).

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