Algorithms for Semi-Automated Dispatching in FOMFIS System

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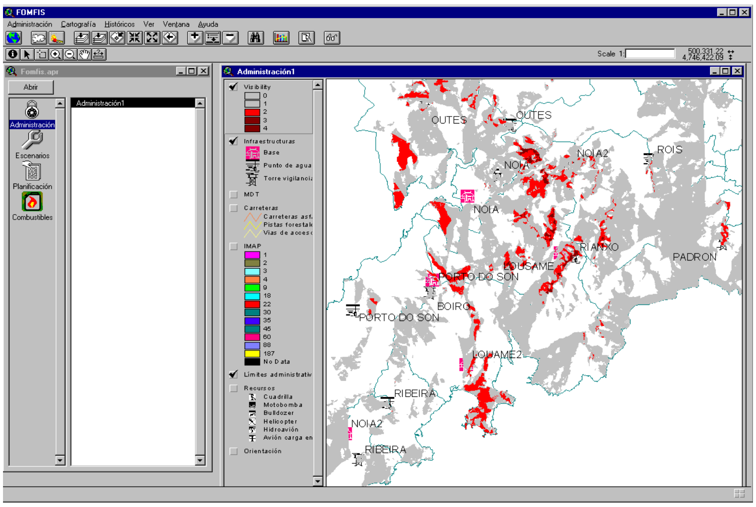
FOMFIS The Project

Allocation of budget for forest fire prevention and extinction operations is something that forest fire planners and managers have to face every fire campaign. Frequently resources are assigned under budgetary restrictions hence barely covering the basic fire service needs for a region. Planners and managers have to skilfully manage all the information pieces, such as historical fire and weather databases, to accurately distribute fire fighting resources in the territory and give coverage according the predicted fire occurrence.

Nevertheless, straight statistical analysis of databases is not enough in most of cases to exactly determine which are the required forest fire defence resources and infrastructures and the needed budget to cover such needs. Besides, geographic information not always is available or updated, thus forest fire prevention planning and management become a difficult task. FOMFIS system has been conceived to give an integral solution to the subjects give above.

FOMFIS project (Caballero, 1998, 1999) was an initiative partially funded by the European Commission through the 4th Framework Program of R+TD. This project was classified in the area of Natural Hazards-Forest Fires, one of the key actions of the Environment and Climate Programme.



The acronym FOMFIS stands for '**FO**rest fire **M**anagement and **FI**re Prevention **S**ystem', which is self-explanatory. Main objective of the project is to integrate information technologies in a single system to help planers take appropriate decisions regarding forest fire pre-suppression activities.

The project has focused on several research areas, namely:

- Forest fuel mapping
- Socio-economic risk analysis
- Forest fire behaviour and fire fighting simulation
- Probabilistic planning

In order to cover such developments a set of technological areas have been considered:

- Remote sensing and automated cartography
- Geographical information systems
- Knowledge based systems
- Fire behaviour simulation
- Statistical and probabilistic analysis
- Data and user interfaces software engineering
- Risk analysis

Simulation of Forces dispatching and operation

FOMFIS Planning Analysis Engine (PAE) performs the analysis of the evolution of the fire scenarios together with the resources dispatching, fighting efficiency and fire behaviour over a period of time.

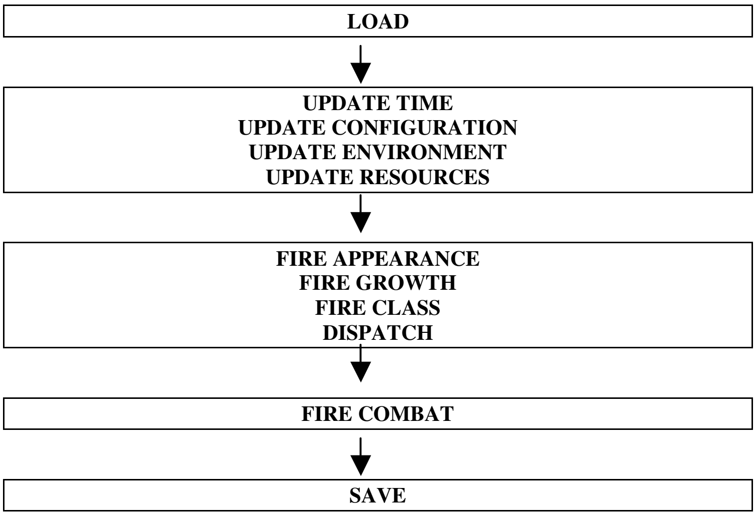
This module acts as a self-contained black box and deals with all the information regarding the planning of the resources, that is, the number, type, distribution, work shifts, costs, performance, defence criteria and associated infrastructures; the evolution of the atmospheric conditions including the air temperature and relative humidity changes, and the wind conditions characterised by the general surface component for each situation; the fire appearance and evolution, in space and time, embracing the fire risk due to socio-economic and natural causes and the fire behaviour modelled using a cellular automata which gives the size, shape and characteristics of every considered fire outbreak.

User interface is reduced to its minimum in the PAE, as it is acting as a calculation and simulation tool mainly. Nevertheless, the algorithms underlying the module could be arranged to give service as real-time planning tools through the use of an adapted user interface. This version gives the outputs as numbers, graphics and tables regarding the simulation.

The PAE procedure follows a parallel working structure as it performs the control over the forest fire spread simulations and the updating of the conditions (resources, wind, meteorology, etc.). This leads to consider two program threads holding the procedure control and data required for the calculations.

The main thread of the procedure is presented below as the general scheme of the procedure. This outline explains most of the procedure, although there is a close link with the Fire Behaviour Model (FBM).

The procedure of coupled simulation can be schematised using the following flow chart:



Forces Status Updating

The process of simulation of fire fighting resources operations is, in essence, the accounting of the resources status and their changes over time. In the real world there are a large number of situations into which the airborne and ground fighting units could be classified. Nevertheless, in order to simplify the process, it is required to reduce the number of such status classes.

The operative status of every fighting resource is assumed to fall in one of these five situations:

Ready (R), the unit is waiting for action in alert mode. It is supposed that the element is completely prepared to take action and, consequently, located at its assigned base.

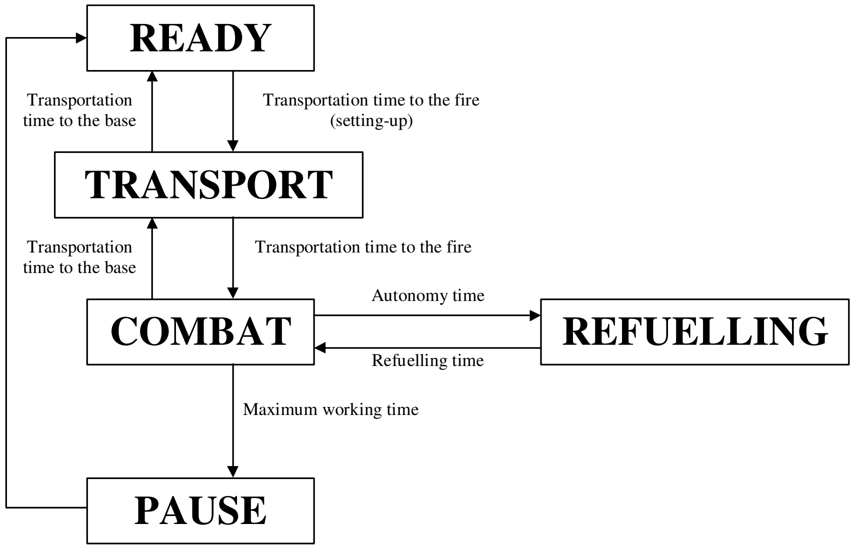
Transportation (T), the unit is changing its location heading to the assigned fire or returning back to the base. The water tank refilling transportation, to and from the nearest available water point, is considered within the combat status.

Fuel Refilling (F), the unit has run out the fuel tank capacity, saving the fuel required to return back to the base, and is not operative but to refill. It is assumed that the fuel refilling is performed at the base.

Combat (C), the unit is taking active part in the operations of fire extinction, either in direct or indirect attack. Some simplifications must be done to make the system to be easily implemented. These limitations are explained in the next points.

Pause, (P), the unit has reached the maximum work time permitted, or that work time belonging to the working schedule for every resource. The working timetables are defined previously and belong to every planning configuration. The units under this status are not operative for any operation.

This procedure block, essentially, keeps control on the status of every active fighting element taking part in the simulation. For that purpose a control scheme is followed and, again, some, simplifications and limitations must be considered. The scheme is presented below:



The initial status of a fire fighting unit is the READY status. It is supposed that the unit is prepared to a fire fighting sortie, the water tanks are filled-up and the fuel tanks are at their maximum capacity. It is obvious that READY status belongs to the operative and active units (those selected to take part in the forest fire defence for each planning configuration).

Once a dispatch is performed for a fire, some units are assigned to it. In this moment the fire fighting time accounting starts for every selected unit, taking into account the start-up time (that is considered within the transportation status). The status changes to transportation to the fire mode. At this point it is assumed that the unit is locked in this status until it reaches the fire; this simplification avoids certain infinite loops observed in the procedure. The system checks the amount of fuel availability and working time remaining prior to the activation of the selected unit, so ensuring that it has enough time to perform the transportation and start the fire fighting.

The transportation time is calculated using the access time maps, obtained separately for airborne forces and ground based ones. This map is extensively used for other transportation operations, including the water tank refilling. Once the unit reaches the fire location, it turns its status to COMBAT, and it is locked again until the fire is extinct. These simplifications avoid logical collisions in the computer code, but must be observed in detail in the verification process to test how much these assumptions divert results from reality.

In fighting time it is included all cycles regarding the possible water tanks refilling processes. This is more notorious for the airborne fire fighting units, namely the helicopters, air tankers and water bombers. This simplification in the design of the procedure has supposed an important saving in computation time, and operatively it has almost no impact in the final accuracy of the simulation. It is important to highlight that the time spent in accessing the different water refilling points is actually computed, but they do not suppose a new status type for the simulation process.

In the other hand the fuel tank autonomy is considered for every fighting unit type, namely the fire trucks, the heavy machinery, the fighting helicopters, the water bombers and the air tankers. Average fuel consumption is used in the calculations, where these figures have been consulted and contrasted with the fire fighting experts. Nevertheless, the system is open for new adjustments according to other forest fire defence services reality.

Working time schedule belongs to every planning configuration the user has defined. For such purpose the duty shifts are described and the system is accounting the current time spent in all the operations for every unit. When this time reaches its maximum, the system automatically changes the status to PAUSE. Obviously, this is an ideal behaviour but simplifications must be done to make the system to be possible while explaining most of the real world.

But in the real world, in the case of extreme demand, the fire fighting units must be forced to override such limitations and work to extenuation until the danger decreases or the forces presence is not required. This is a reality in most of the Mediterranean countries when large fires destroy valuable areas over extended periods of time. In these cases other rules must be applied. The system, nevertheless, is open to consider such extreme conditions by defining a special working timetable, that is an extreme demand working table, for which working conditions are tougher in terms of sustained work endurance.

The pause period belongs to fighting unit rest, whether it is physical rest of the crewmembers or the machinery and vehicles on-the-field maintenance. The pause periods are also defined in the working timetables for every planning configuration. It is assumed that no unit is operative when in PAUSE status.

A new simplification has been proposed in the design of the status control routine regarding to the status into a unit enters once it leaves the PAUSE status. To maintain track of the status into it was when it leaves the activity and entered the PAUSE status made the model too complex, whereas the end of the pause period leads to READY status most of the cases, as it is assumed that the units return back to the correspondent base.

Thus, leaving the PAUSE status is interpreted automatically to enter the READY status in the location of the actual assigned base. It is important to consider that all these simplifications have less impact in the accuracy of the system in the case of small to medium fires. In the opposite, for large fires things are quite different and these considerations, among others, should lead to unacceptable errors. The cycle for each unit assigned to a fire ends when the fire is completely extinguished.

Other implicit control times are taken into consideration also, as the day light period is for airborne forces and, literally in every case, for the ground forces. FOMFIS-PAE procedure assumes there is no fighting activity during the night, and this assumption is almost true in most of the real situations. The difficulty of fighting and the danger due to the lack of visibility is unacceptable for night operations, saving certain extreme cases.

The conditional expressions underlying the forces status control routine are presented in the following table, where t is the current simulation time:

CONDITION	FROM STATUS	TO STATUS
t >= time of end of activity (reaches working time end)	Any	Pause
t >= time of end of transportation	$Transport_{FIRE}$	Combat
t >= time of end of fuel tank autonomy	Combat	Refuelling
t >= time of end of refuelling operation	Refuelling	Combat
t >= time of unit pause (end of continuous work period)	Combat	Pause
t >= time of re-activation (unit ends the pause period)	Pause	Ready
t >= fire complete extinction time	Combat	$Transport_{BASE}$
Unit is assigned to a fire	Ready	$Transport_{FIRE}$

For the values for the different times implied in the calculations it is experience and direct observations that must be considered. These values change greatly depending on the conditions and the type of unit involved in the activity, nevertheless a default table is proposed with average values on it gathered from the experience of the forest fire services involved in the project (Spain, France and Greece):

Code	TYPE	XFT h	PT h	RFT min	AUT h	SUT min	ASP Km/h
FC	I	3	6	15	8	10	40
FT	II	8	6	15	8	10	40
HM	III	No limit	-	20	8	30	30
FH	IV	No limit	-	30	6	10	150
AT	V	No limit	-	30	6	15	160
WB	VI	No limit	-	30	4	30	300

where

TYPE is the type of fire fighting resource according the following code table:

FC Fire fighting crews. (I).
FT Fire fighting trucks. (II).
HM Heavy machinery (bulldozers). (III).
FH Fire fighting helicopters, they also could transport specialised helicrews. (IV).
AT Air tankers. (V).
WB Water bombers. (VI).

XFT Maximum continuous fighting time (safe physical/mechanical endurance limit).
PT Pause time. Prescribed time spent for physical/mechanical recovery.
RFT Refuelling time.
AUT Fuel tank autonomy time.
SUT Setting-up time in a fire fighting sortie.
ASP Average transportation speed for the unit type.

Again these values should be adapted to the particular conditions and requirements of every location and forest fire service.

New Fires Generation

The procedure keeps track of the fire matrix that is generated by the Probabilistic fire Scenario Generation (PSG), checking the current time t with the fire appearance time t_f. If such value is reached the PAE tells FBM to start up a new fire spread simulation at the given position. Several fire outbreaks could appear within every time interval of the simulation (5 minutes).

Fire Growth

The PAE procedure passes the METEO type, WIND type and the time interval of next simulation cycle to the FBM module that performs the fire spread modelling of every fire in the scenario. It returns to the PAE the fire growth, classified into four intensity classes and the number of EGU for each class. These numbers are used to estimate the actual fire fighting demand for each fire.

The Fire Behaviour Model (FBM) is called from the PAE module, and several values are consulted namely the increment of cells (Elementary Geographical Units or EGUs), due to fire spread, classified into four classes according their fire line intensity; and the fire importance according the current status of the fire and the first defence criteria and other fire fighting criteria to re-organise the dispatching configuration accordingly.

That means that PAE and FBM work in tandem continuously, as the fire spread changes the fire fighting demand (that increases or decreases over time) and, conversely, the fire fighting activities changes the fire growth and importance. This dynamic approach of re-adjusting the forest fire units involved in the fighting of every fire is performed taking into account also the fire growth of all the existing fires.

Fire Importance Classification

The procedure classifies the existing fires according their importance. The importance of a single active (burning) EGU of a fire line is calculated by:

$$w_i = 0.6\alpha_1 + 0.3\alpha_2 + 0.1\alpha_3$$

The values α_1 , α_2, and α_3 explain the most relevant criteria of fire severity classification by grouping them into three categories: the primary criteria of immediate defence, the fire potential spread danger and the fire fighting feasibility. The factors used in the formula are weighting values for the importance of each criteria.

The procedure assigns the value of α_1=10 when some or several of these criteria are found, and α_1=0 none of them are observed. The values are calculated using the following procedure:

$$\alpha_2 = \frac{ROS^2}{250}$$

where ROS is the forward maximum rate of spread of the fire in the analysed EGU expressed in meters per minute.

$$\alpha_3 = 0.6\gamma_1 + 0.2\gamma_2 + 0.2\gamma_3$$

where γ_1 explains the feasibility of fire fighting depending on the power of the fire front at each analysed EGU, and is obtained using the following table:

Fire Intensity Kcal/m/s	**γ_1**
< 80	10
80 – 400	6
400 - 800	3
> 800	0

The terrain roughness could be estimated by considering the slope of every analysed EGU giving a value according the following expression:

$$\gamma_2 = \frac{120 - Sl\%}{12}$$

where Sl% is the slope value found in the EGU expressed in percentage.

The sum γ_3 expresses the feasibility of fire fighting depending on the accessibility, and is calculated through the expression:

$$\gamma_3 = \frac{10 \cdot (t_h - t)^2}{(t_h - ATT)^2}$$

where t_h is the threshold time (beyond which the action is considered useless), ATT the Access Target Time (fixed by the user) and t the current access time of the nearest fighting unit to the analysed EGU. Nevertheless this sum could be overridden in the case the PAE procedure is analysing the feasibility of fire fighting of all the available resources in the nearby of the fire. In this case the sum γ_3 should be fixed to 10 as there is no consideration of the local fighting feasibility for each EGU for the fire importance classification.

To estimate the total importance of a fire the calculation is repeated for each EGU marked as 'burning' found in the fire. The resulting value should be used for fire classification in a given scenario for a certain time.

Examples

In order to understand the procedure an example is given below for two fires embracing several EGU each. For this example, the sum γ_3 is considered to be 10.

Fire 1
Total EGUs =10
Total fire importance $= \Sigma\omega_i = 35.1$
Calculation table:

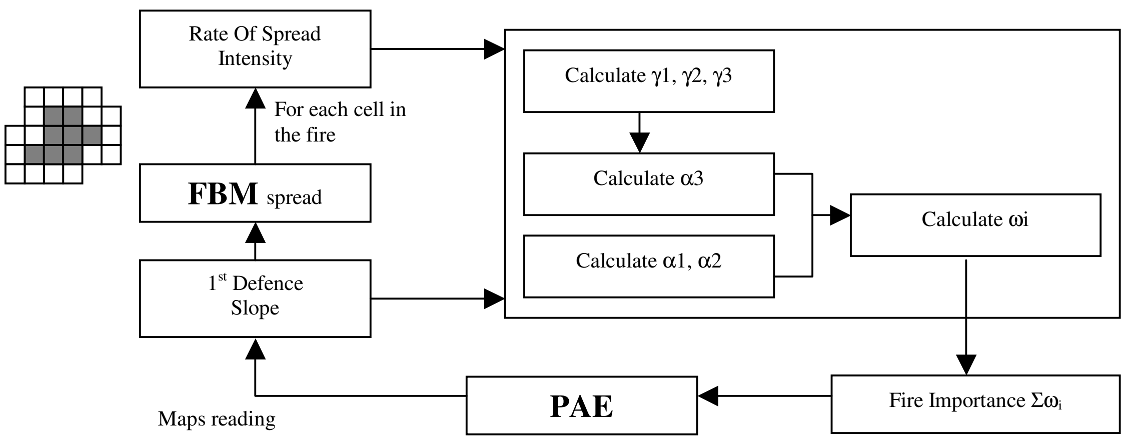
EGU#	DEF1st	ROS	SL	INT	α_1	α_2	α_3	γ_1	γ_2	γ_3	ω_i
1	Yes	20	15	650	10	1.6	5.6	3	8.8	10	7.0
2	Yes	10	5	450	10	0.4	5.7	3	9.6	10	6.7
3	No	15	10	250	0	0.9	7.4	6	9.2	10	1.0
4	No	5	5	100	0	0.1	7.5	6	9.6	10	0.8
5	Yes	5	0	100	10	0.1	7.6	6	10.0	10	6.8
6	No	2	0	80	0	0.0	7.6	6	10.0	10	0.8
7	No	2	0	80	0	0.0	7.6	6	10.0	10	0.8
8	No	10	5	150	0	0.4	7.5	6	9.6	10	0.9
9	No	15	15	200	0	0.9	7.4	6	8.8	10	1.0
10	Yes	60	30	900	10	10.0	3.5	0	7.5	10	9.4

Fire 2
Total EGUs =8
Total fire importance $= \Sigma\omega_i = 63.5$
Calculation table:

EGU#	DEF1st	ROS	SL	INT	α_1	α_2	α_3	γ_1	γ_2	γ_3	ω_i
1	Yes	20	15	650	10	1.6	5.6	3	8.8	10	7.0
2	Yes	30	25	750	10	3.6	5.4	3	7.9	10	7.6
3	Yes	45	40	350	10	8.1	6.9	6	6.7	10	9.1
4	Yes	50	50	1000	10	10.0	3.2	0	5.8	10	9.3
5	Yes	50	50	1030	10	10.0	3.2	0	5.8	10	9.3
6	Yes	20	30	680	10	1.6	5.3	3	7.5	10	7.0
7	Yes	20	10	380	10	1.6	7.4	6	9.2	10	7.2
8	Yes	10	5	150	10	0.4	7.5	6	9.6	10	6.9

Fire importance will drive the way fighting forces are assigned. It has relevance in the case that limited accessing resources are available, so they are firstly assigned to the top most important fires.

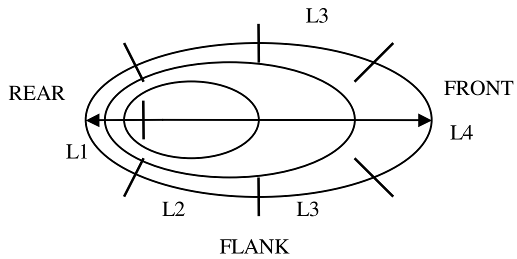
Summing-up, the procedure of fire importance calculation could be schematised as follows:



Fire Fighting Demand Calculation

The FOMFIS-PAE procedure deals with each particular fire in terms of fire fighting. To understand the type, size, importance and fire fighting demand of each fire front the system takes into consideration all the raster cells that configures each fire perimeter. These EGUs position and characteristics are obtained through the Fire Behaviour Model Spread Engine (FBM-FSE) cellular automata.

The cornerstone of the dispatch and fire fighting computing in FOMFIS-PAE is the consideration of four different fire intensity classes, depending on their value, according the following table:



Natural distribution of the fire line intensity for uniform fire spread fire fronts.

FIRE LINE INTENSITY Kcal/m/s	
L1 -	>0 to 80
L2 -	80 to 400
L3 -	400 to 800
L4 -	>800

The system will classify each burning EGU into one of such classes. The class 0 means an extinguished cell. The natural evolution of the fire, that is the consumption of the forest fuel over time, gives intensity changes hence the distribution and number of EGUs of every intensity class evolves over time. Besides, each fighting operation has effect over the intensity of the EGU onto which it takes place. Ground direct attack over the cells ranging from 0 to 80 Kcal/m/s could reduce or even suppress the fire in such cell. Water bombing and fire truck activity reduces the intensity of the front line thus changing the distribution and number of EGUs of each intensity class.

This approach allows considering the fire fighting operations as activities that either reduces the fire intensity and/or suppresses the fire. In these terms, the FOMFIS-PAE acts over the burning EGU in a progressive fighting scheme. Some operations, such as water bombing, should reduce the fire front intensity and other, such as ground fighting, will suppress the fire where it is possible.

The combined airborne and ground attack can be easily modelled in this way, where the helicopters and water bombers reduce (or even suppress in some cases) the fire line intensity to values that ground forces can manage, thus extinguishing the fire. This design has been conceived trying to mimic the real world and the actual fighting operations dynamic, but simplifying it in such way it is easily implemented as computer code.

All the calculations here exposed are referred to the perimeter length unit, but they can be easily reduced to number of EGU considering that a length of L, where L is the dimension of the EGU side, is equivalent to an EGU.

The fighting demand for each fire is calculated according the fire perimeter growth balance (Xanthopoulos, 1994), but instead of considering the fire perimeter as a whole, the FOMFIS-

PAE procedure considers this balance separately for each of its sections of different intensity classes.

The increment or decrement of number of EGU for each intensity class is the result of the balance between the perimeter growth incoming (number of EGU of each intensity class that appear due to fire expansion or intensity changes of upper intensity levels) and the number of EGUs leaving such intensity class (due to fire fighting and/or the natural intensity reduction as the fire reaches different fuel, topography or wind EGU conditions).

Thus, the balance (number) of EGU of intensity type **1** (F_1) results from the consideration of the following sums:

Positive:

- G_{11} The number of EGU of intensity type 1 that appears due to fire expansion of EGU type 1.
- G_{21} The number of EGU of intensity type 2 falling to type 1 due to spread conditions change.
- E_{21} The number of EGU of intensity type 2 that jump to class 1 due to fire fighting operations.

Negative:

- G_{10} The number of EGU of intensity type 1 that naturally extinguish to type 0.
- E_{10} The number of EGU of intensity type 1 that are suppressed due to fire fighting operations.

The balance of EGU of the intensity class **2** (F_2) is obtained considering the following sums:

Positive:

- G_{22} The number of EGU of intensity type 2 that appears due to fire expansion of EGU type 2.
- G_{32} The number of EGU falling from intensity class 3 due to spread conditions change.
- E_{32} The number of EGU of intensity type 2 that jump to class 1 due to fire fighting operations.

Negative:

- G_{21} The number of EGU that diminishes their intensity from class 2 to class 1.
- E_{21} The number of EGU that reduce their intensity to class 1 due to fire fighting activities.

The same procedure is applied to classes **3** and **4**, saving that for class 4, obviously, there is no sum due to upper intensity classes inputs.

Considering all these expressions the initial fire fighting demand could be estimated by the following set of equations:

$$
\begin{aligned}
F_4 &= (G_{44} - G_{43} - E_{43}) &&= G_4 \\
F_3 &= (G_{33} - G_{32} + G_{43} - E_{32}) + E_{43} &&= G_3 + E_{43} \\
F_2 &= (G_{22} - G_{21} + G_{32} - E_{21}) + E_{32} &&= G_2 + E_{32} \qquad (1) \\
F_1 &= (G_{11} - G_{10} + G_{21} - E_{10}) + E_{21} &&= G_1 + E_{21} \\
F_0 &= G_{10} + E_{10} &&= G_0 + E_{10}
\end{aligned}
$$

where

F_i is the total increment of EGUs for every intensity class (i = 1 to 4).
$G_{i,i}$ is the fire line growth rate due to fire spread for each class.
$G_{i,\ i-1}$ is the total change number of EGUs decreasing their intensity to the immediate lower class.
$E_{i,\ i-1}$ is the increment of EGUs due to fire fighting over the immediate upper intensity class.
$E_{i+1,\ i}$ is the decrement of EGUs changing due to fire fighting to the immediate lower intensity class.

The balance of total growth rate $G_i = G_{i,i} - G_{i,i-1} + G_{i+1,i} - E_{i,i-1}$ is obtained directly from the computation of the difference between the number of EGUs at each simulation time interval k. It includes also the effect over the total number of EGUs due to the fighting activities made in the time interval k-1, represented by the value $E_{i,i-1}$.

This computation belongs to the FBM that counts all the existing EGUs at each intensity class in the iteration k including the effect (reduction) due to the fire fighting in the iteration k-1.

The balance of fire fighting activities considers the effectiveness of the fighting chain from higher intensity classes to lower ones. In that sense the difference between the number of EGU incremented in a class i due to the fighting actions in the immediate upper class i+1 and the number of EGUs that decrement their intensity class to the next lower one i-1 must couple to effectively and progressively suppress the fire, and give positive fighting rates.

This consideration is exemplified in the case of combined attack of airborne forces with ground ones. Water discharges over EGUs belonging to intensity class 3 could reduce their intensity to class 2, to class 1 or even to class 0 (total suppression). If there is a reduction to class 1 and there is no other fighting action carried out by ground forces, in charge to suppress the fire down to class 0, the EGU will remain in the current class, so the fire could continue spreading.

It could happen that the efficiency of forces lowering the intensity from upper classes down to class 1 is higher than the capacity of ground forces to extinguish those EGUs of class 1, now with lower intensities, to be attacked effectively and suppressed down to total extinction (class 0). It is the ability and experience of the dispatcher to dimension the combined action to be successful accomplishing its objectives.

FOMFIS-PAE dispatch procedure includes this consideration and dimensions the combined forces to effectively cope with these chained fighting requirements. In this way the dispatch is re-assigned dynamically depending on the fire evolution (variation of number of EGUs at every intensity class) and the number, type and efficiencies of the resources assigned to it.

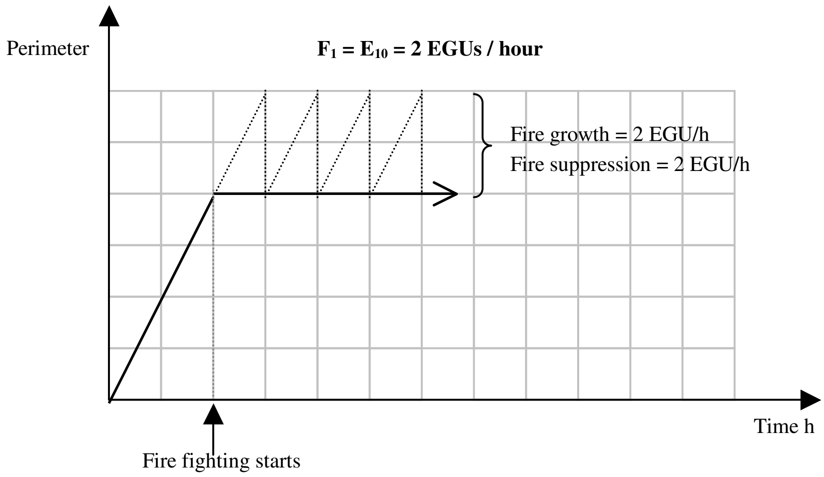
The resulting numbers F_i explain the dynamic of the fire perimeter, in terms of number of EGUs increment, considering the natural evolution together with the suppression activities at each fire line intensity class. This balance is the starting point for the dimension of the required fire fighting forces (see next point).

Forces Dimension Estimation

Once it has been estimated the increment of fire perimeter, expressed as increment in number of EGUs (cells) for each intensity class, it is possible to formulate the actual fire fighting requirements to suppress the fire. The initial consideration is to formulate the direct equivalencies between the fire perimeter growth, expressed through the F_i numbers, and the suppression power required for each intensity class, expressed by the numbers $E_{i,\, i-1}$ as follows:

$$F_1 = E_{10}$$
$$F_2 = E_{21}$$
$$F_3 = E_{32}$$
$$F_4 = E_{43}$$

Nevertheless these expressions just do balance evenly the fire growth versus the fire suppression, thus the size of the fire is not reduced, just contained as the graph shows below:



To effectively suppress the fire in shorter times it is proposed to augment the requirements of the fire fighting forces in terms of fire suppression capacity. To do this a set of factors f_i are considered and a new set of equations are proposed:

$$
\begin{aligned}
F_1 &= E_{10} / f_1 \\
F_2 &= E_{21} / f_2 \\
F_3 &= E_{32} / f_3 \\
F_4 &= E_{43} / f_4
\end{aligned}
\qquad (2)
$$

where $f_i>1$ is a factor that explains how much extra power, over the exact balance between fire growth and fire suppression rate, is required in each section of fire line intensity to meet the fighting requirements. These values are deduced from the operational databases and experience of fire services, providing and default set of values:

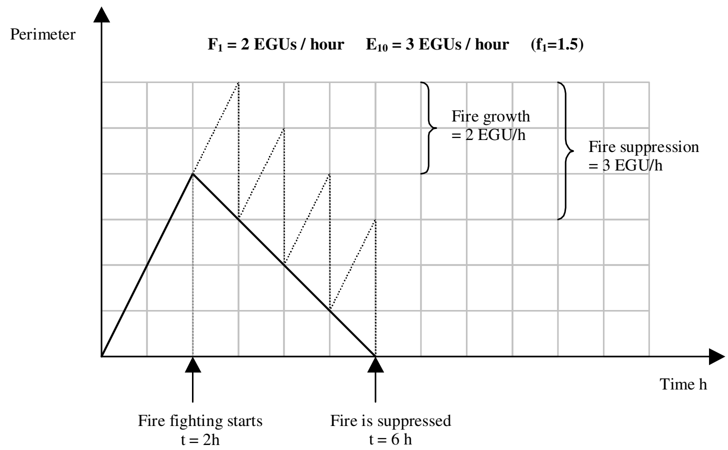
Intensity Class	f	f_o
1 (>0-80Kcal/ms)	1.8	2
2 (80-400 Kcal/ms)	1.4	1.8
3 (400-800 Kcal ms)	1.1	1.4
4 (>800 Kcal/ms)	1	1

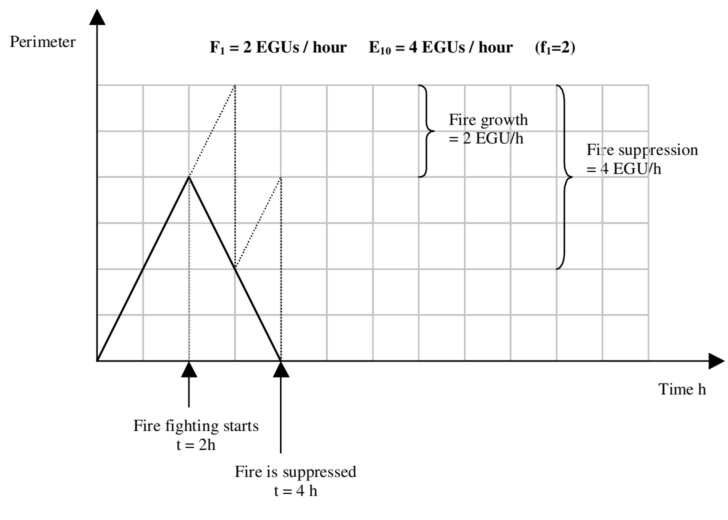
where

f is the value for the dispatching that is performed without first defence criteria,
f_o for those cases where immediate defence criteria is applied.

These values represent the fire fighting power that is applied in the dispatching criteria by augmenting the total fire growth rate hence the required fire fighting forces, and they are strongly based on the experience and objectives of every forest fire defence service, so they must be adjusted according the requirements of planners in their decision making process.

Two graphical examples are given below in the case of F_1 = 2 EGU per hour, E_{10} = 3 EGU per hour (f_1=1.5) and in the case of F_1 = 2 EGU per hour, E_{10} = 4 EGU per hour (f_1=2) :





Coupling the two equation sets (1) and (2) it is possible to estimate the global required efficiency (suppression rate) for every intensity class. The resulting expressions are:

$$
\begin{aligned}
F_4 &= G_4 \\
E_{43} &= F_4 \cdot f_4 \\
F_3 &= G_3 + E_{43} \\
E_{32} &= F_3 \cdot f_3 \\
F_2 &= G_2 + E_{32} \\
E_{21} &= F_2 \cdot f_2 \\
F_1 &= G_1 + E_{21} \\
E_{10} &= F_1 \cdot f_1 \\
F_0 &= G_0 + E_{10}
\end{aligned}
\qquad (3)
$$

thus resulting the following simplified expressions are :

$$
\begin{aligned}
E_{43} &= G_4 \cdot f_4 \\
E_{32} &= (G_3 + G_4 \cdot f_4) \cdot f_3 \\
E_{21} &= (G_2 + (G_3 + G_4 \cdot f_4) \cdot f_3) \cdot f_2 \\
E_{10} &= (G_1 + (G_2 + (G_3 + G_4 \cdot f_4) \cdot f_3) \cdot f_2) \cdot f_1
\end{aligned}
\qquad (4)
$$

From the expressions (4) the estimation of global efficiencies $E_{i,\ i-1}$ are obtained and belong to the total effect of all the fighting units that are operating over such intensity class. From these values a second step must be performed to obtain the distribution of forces that are coping with such efficiency requirement.

The total efficiency $E_{i,(i-1)}$ is computed by adding every particular fire fighting unit efficiency, that is the number of EGU of a certain type of intensity that changes to lower classes due to fire fighting, for the resources. Thus:

The total extinction capacity $\mathbf{E_{10}}$ per time unit, for EGUs of intensity class 1 (ranging from >0 to 80 Kcal/m/s) results from the consideration of the following sums:

$EE_{I1\text{-}0}$ Number of resources of type I (fire crews) n_I by the number of effectively extinguished EGUs (efficiency type I, turning intensity class 1 into class 0).

$EE_{II,1\text{-}0}$ Number of resources of type II (fire fighting vehicles) n_{II} by the number of effectively extinguished EGUs (efficiency type II, turning intensity class 1 into class 0).

The total extinction capacity $\mathbf{E_{21}}$ per time unit, for EGUs of intensity class 2 (ranging from >80 to 400 Kcal/m/s) results from the consideration of the following sums:

$EE_{II,2\text{-}1}$ Number of resources of type II (fire fighting vehicles) n_{II} by the number of effectively extinguished EGUs (efficiency type II, turning intensity class 2 into class 1).

$EE_{III,2\text{-}1}$ Number of resources of type III (heavy machinery, bulldozers) n_{III} by the number of effectively extinguished EGUs (efficiency type III, turning intensity class 2 into class 1).

$EE_{IV,2\text{-}1}$ Number of resources of type IV (fire fighting helicopters) n_{IV} by the number of effectively extinguished EGUs (efficiency type IV, turning intensity class 2 into class 1).

The total extinction capacity $\mathbf{E_{32}}$ per time unit, for EGUs of intensity class 3 (ranging from >400 to 800 Kcal/m/s) results from the consideration of the following sums:

$EE_{IV,3\text{-}2}$ Number of resources of type IV (fire fighting helicopters) n_{IV} by the number of effectively extinguished EGUs (efficiency type IV, turning intensity class 3 into class 2).

$EE_{V,3\text{-}2}$ Number of resources of type V (air tankers) n_V by the number of effectively extinguished EGUs (efficiency type V, turning intensity class 3 into class 2).

$EE_{VI,3\text{-}2}$ Number of resources of type VI (water bombers) n_{VI} by the number of effectively extinguished EGUs (efficiency type VI, turning intensity class 3 into class 2).

The fighting forces dimension problem, then, is reduced to find the numbers $n_{i,j(j-1)}$ of each fighting resource type operating over each fire line intensity class. To obtain such numbers the following set of equations should be used :

$$
\begin{aligned}
E_{10} &= n_{I,10}\, EE_{I,10} + n_{II,10}\, EE_{II,10} \\
E_{21} &= n_{II,21}\, EE_{II,21} + n_{III,21}\, EE_{III,21} + n_{IV,21}\, EE_{IV,21} \\
E_{32} &= n_{IV,32}\, EE_{IV,32} + n_{V,32}\, EE_{V,32} + n_{VI,32}\, EE_{VI,32} \\
E_{43} &= 0
\end{aligned}
\qquad (5)
$$

where $EE_{i,j(j-1)}$ are the particular efficiencies for each resource type (i) operating over each fire line intensity class (j). These values are estimated depending on the fire fighting conditions (see next point).

The last expression $E_{43} = 0$ is interpreted as there are no means to effectively reduce fire intensity for the EGUs with such high values to lower ones. In fact this leads to consider that no action, either airborne discharges or ground activities, could reduce such high line intensities. In particular, this embraces the fact that for such intensities even the fighting forces cannot even reach the fire front closer than several dozens or even hundreds of meters.

This expression, nevertheless, could be confusing, as if there were only intensity line type 4 the algorithm, theoretically, should not dispatch any force, neither ground based nor airborne, due to their potential inefficacy to reduce such high intensities. In the real world this rarely occurs, as there are a complete range of intensities from 0 to the maximum reached. Nevertheless, in real world big fires with high intensities in a large portion of fire front hardly can be attacked with the considered fighting resources, so dispatching of forces are made following other criteria rather than their effectiveness controlling the fire front.

Forces Efficiency Calculation ($\mathbf{EE_{i,\,j\,(j-1)}}$)

Fire crews on direct attack

The efficiency of direct attack is supposed to take place over fire line intensity class 1 (<0 to 80 Kcal/m/s). The efficiency expressed in number of EGU suppressed per unit time could be derived from the extinction rate tables, expressing the suppressed fire front in meters per hour, considering that one EGU corresponds to L meters of fire front, where L is the EGU edge length.

The efficiency of fighting operations in direct attack of fire crews ($EE_{I,10}$) for EGUs falling within the intensity class 1, depend on the local conditions such as fuel model and topography (slope). The suggested table (in meters of suppressed fire front per hour per person) for fire crews are:

	Productivity in meter/hour/person
NFFS Fuel Model	**Initial Attack**
1,2,3	53
4	13
5	53
6,7	40
8,9	26
10	5
11,12	13
13	5

Fire trucks on direct attack

The fire fighting trucks efficiency in direct attack operations ($EE_{II,10}$) is calculated using the following table :

NFFS Fuel Model	**Productivity m/h**
1,2,3,8,9	$nc \cdot Q \cdot t_r /(0{,}50 \cdot R)$
4,13	$nc \cdot Q \cdot t_r /(1{,}50 \cdot R)$
5	$nc \cdot Q \cdot t_r /(0{,}75 \cdot R)$
6,7,10,11	$nc \cdot Q \cdot t_r /(1{,}00 \cdot R)$
12	$nc \cdot Q \cdot t_r /(1{,}25 \cdot R)$

where

Q is the fire truck tank capacity (litres)
R is the fire propagation speed at that point (m/min) (XRATE)
t_r is the residence time of fire at that point (min)
nc is the number of fighting cycles per hour

The residence time is an intrinsic value that depends on the fuel model considered ($t_r = 384/\sigma$).

The efficiency of the resources using water depends on the distance to the nearest available and suitable water point.

Fire fighting helicopters

For fire fighting helicopters it is assumed that the total water load is distributed over an effective area of 15x15 m, so the concentration expressed in litres per square meter is:

$$C=Q/15x15$$

The intensity reduction could be estimated through the following expression:

$$I'_B=(C+0.0563)/0.0102613$$

From this value it is an easy task to obtain the intensity class jumps knowing the initially affected intensity. If the reduction is strong enough it can even quench totally the affected area.

The affected area is 15^2 squared meters, so if $A_{EGU} = L^2$ is the area of an EGU a proportion could be applied to estimate the number of affected EGU in terms of intensity change:

$$N_{EGU} = 15^2/A_{EGU} = 15/L$$

thus the total number of affected EGU can be obtained by multiplying this figure by the total number of discharges in the considered time interval. It is important consider that subsequent attacks should reduce the intensity cumulatively.

Air tankers & water bombers

For air tankers and water bombers a quite different approach is proposed (Martínez-Millán, 1991; Caballero, 1994). The discharge spot is divided into seven parallel straps following the direction of the plane flight. Each of these straps contains a concentration of water according to the reological curve, the flight speed, the flight altitude and the total amount of water that is thrown in the bombing.

A series of expressions lead to obtain the average concentration and, consequently, the intensity reduction due to the water bombing:

C= f(Q, H cte.)
Q= water tank capacity in litres
H=75 m. (discharge flight height is 30 to 120 m.)

$$C=1.202+0.00012188Q-12.33294H/Q+2.44962(\ln Q)/H$$
$$C2=(C+0.4)/3$$
$$C3=(C+0.4)/3$$
$$Cm=(C+2C3 +2C2+2x0.2)/7$$

$$I'_B=(Cm+0.0563)/0.0102613$$

The area affected by the water throwing is A = Q Cm and the same considerations that in the case of helicopters are applied, so:

$$N_{EGU} = A/A_{EGU} = Q\,C_m / A_{EGU}$$

These calculations correspond to single air discharges. The total number of discharges per unit time could be obtained knowing the distance to the nearest water point, the water refill time and the average speed of the plane or helicopter.

Forces Selection & Dispatching

This point is answering how to select the particular ground and airborne forces that are assigned to a particular fire. The assignment of resources for the existing fires within the analysed area are performed in order, according the fire importance classification, so available resources go first to the top most important fires at a certain time. Initially, every fire fighting force existing in the simulation scenario can potentially be assigned to a particular fire.

Nevertheless some constraints are applied in the selection process:

- The analysed fighting unit must be available (READY status).
- The fighting conditions must accomplish the given constraints (wind speed, fire line intensity etc.).

The dispatching procedure assigns forces progressively till the extinction requirements for each intensity class are covered. Depending on the constraints, availability and other operative criteria it could happen that the fire fighting requirements are not completely covered. For such cases the fire dimension is defective and the system simulates such condition (it could even result the fire escapes out of control, as it happens in real world).

Nevertheless, as soon as the constraints or the availability of the forces changes the system will attach new resources to the fire automatically. The criteria of selection comprises three sequential steps that are acting as imbricated filters:

- Availability, the fighting unit must be in READY status.
- Administrative dependence, the fighting unit must belong to the administrative boundary where the fire outbreak has appeared. This rule could be overridden if there is not enough fighting power at first instance (fire fighting resources assigned to the administrative unit).
- Distance to the fire area, in terms of access time. This value will classify the different resources and could be overridden if there is not enough fire fighting power.

Besides a threshold time is considered beyond which the dispatch of that unit is considered useless.

If the fighting requirements for a particular fire are covered applying these criteria then no extra forces are assigned. If the requirements are not covered then the last two criteria are subsequently overridden, that is the access time and the administrative dependence.

Every fire fighting resource has an entry in a table sorted by increasing access time. Together with this information there is the administrative dependence information and the calculated efficiency for the corresponding force type. This table belongs to each fire and is calculated as soon as the fire starting point location is known. Consequently, the access time becomes a major dispatching decision parameter. If the analysed fighting unit access time to the fire is greater than the threshold time then the next suitable element in the table is considered. The threshold time is initially set-up by experts at each location, but a default table is proposed.

Description	Type Code	Threshold time (min)
Fire crews (FC)	I	10
Fire trucks (FT)	II	15
Heavy Machinery (HM)	III	60
Fight Helicopter (FH)	IV	10
Air tanker (AT)	V	20
Water bomber (WB)	VI	30

The assignment is done automatically reading the table above and applying the mentioned constraints, adding more resources of each type until the required extinction power is reached for each intensity class.

The resumed dispatch procedure is as follows:

1.- Dimension of fire fighting units efficiency.
2.- Fire fighting units classification (distance)
3.- Assignment of fire fighting forces.

It is performed according the fire importance value, starting with the most important first. The calculation is done starting with the intensities of class 3 and ending with class 1.

The fire fighting forces that can be assigned to each intensity class are:

Class 1	Fire crews and fire trucks
Class 2	Fire trucks, bulldozers and fighting helicopters
Class 3	Fighting helicopters, water bombers and air tankers
Class 4	No resources are able to effectively reduce the intensity

The followed criteria are:

a.- Initially no aeroplane dispatch is considered for any intensity class.
b.- The resources with lower access time are selected first.
c.- They are selected first the resources belonging to the same administrative unit.
d.- Once the initial dispatch is done following these criteria, if the suppression rate is not covered for such intensity class the constraint of administrative dependence is overridden, and the dispatch is re-arranged for the remaining resources.

Some special considerations are applied:

e.- The dispatch is performed starting with the higher intensity classes due to the fact that the helicopters could have a fighting crew associated to them. If a helicopter is assigned to a fire, and it has a fighting crew attached and it is required for fire fighting, the fire crew is automatically assigned to the fire using the access time belonging to the helicopter transportation speed.
f.- Once assigned the fighting forces according to the intensity class 3 requirements it could happen that the remaining increment of the fire front in this class 3 is still greater than a maximum (threshold) fixed by the dispatcher and according the other defence criteria, the a

dispatch for the air tankers and water bombers is performed, following the same procedure explained above.

Forces Fire Fighting

The fire fighting operations lead to consider two generalised actions over the fire :

- **Direct attack** over flames of fire front EGUs of intensity class I (>0 to 80 Kcal/m s) to type 0 (completely extinguished).
- **Water throwing** over flames reduces values of fire front intensity, so it progressively changes the intensity of EGU to lower intensity classes.

To unify the algorithm, change rates for each EGU intensity classes are applied due to fighting operations. These changes are returned to the FBM, which is responsible to re-arrange the EGU matrix by performing the changes according the fire front EGU modification or reduction.

When a fire fighting resource is assigned to a fire, the procedure calculates firstly its efficiency for every intensity class, depending on the intensity line that it has been assigned to and the distance to the nearest water point (when it applies). This efficiency could be interpreted as the number of EGUs (cells) that a fire fighting force passes from an intensity class to the next lower one.

Once the fire fighting is computed the procedure gives to FBM the amount of efficiency, for every intensity class, that is subtracted from the total fighting demand. In this way, the fire fighting accounting for each fire takes into consideration the number of EGUs, belonging to each intensity class in the fire, that are reduced due to suppression activities.

The system keeps track of the fractionary attacks over every EGU (that is, an EGU could be large enough that its suppression must be completed in various cycles) that should be added to the next cycle and passes the number of completely suppressed EGU to the FBM. In turn, the FBM gives notice about the status of the whole fire, in particular if the total suppression has been completed.

Conclusions

A number of conclusions can be derived out of the practical use of FOMFIS dispatching algorithms presented:

- A simplified but practical method can be applied to estimate resources demand for a fire
- It is required to analyse all active points in a fire in terms of fire behaviour. Smoldering has to be considered as well
- Classification of fire front into intensity classes is an easy, practical way to estimate instantaneous fighting demand
- Fire front changes in time, observation growth rate in each line is required
- Coupling resources operating on different intensity lines is fundamental for an effective suppression
- Spatial analysis techniques help noticeably in synthesising fire fighting demand

- Simulation models help to estimate fire behaviour and fire importance. Nevertheless this must be coupled with real observation and monitoring
- Information Technologies help to automatise / objetivise decisions regarding fighting forces dispatching

References

CABALLERO, D. XANTHOPOULOS, G. KALLIDROMITOU, D. LYRINTZIS, G. BONAZOUNTAS, M. PAPACHRISTOU, P. PACIOS, O. (1999). "FOMFIS: Forest Fire Management and Fire Prevention System". En proc. DELFI Intl. Symp. Forest Fires Needs and Innovations, Atenas, Grecia. pp. 93-98.

CABALLERO, D. (1998). "FOMFIS: A Computer-Based System for Forest Fire Prevention Planning". En proc. del 3rd Intl. Conf. on Forest Fire Research. Coimbra, Portugal.

CABALLERO, D.; MARTÍNEZ-MILLÁN, J.; MARTOS, J.; VIGNOTE,S. (1994). CARDIN 3.0, a model for forest fire spread and fire fighting simulation. Proceedings of the 2st International Conference on Forest Fire Research. Coimbra, Portugal, Vol.1: 501.

MARTÍNEZ-MILLÁN, F.J. MARTOS, J. VIGNOTE, S. CABALLERO, D. (1991). "CARDIN, Un Sistema para la Simulación de la Propagación de Incendios Forestales" MAPA-INIA. Investigación Agraria Serie Recursos Naturales Vol. 0

XANTHOPOULOS, G. (1994). "Development of a decision support system for water bomber dispatching in Greece". Proceedings of the 2nd International Conference on Forest Fire Research. Coimbra, Portugal, pg. 139-149.