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Forest Fire Fighting Resources Planing: FOMFIS System

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Background

Forest fire defence planning tackles with a number of factors which are time and space dependant. Some of them are modifiable factors on which planning can directly act, and others are non-modifiable factors which must be predicted and modelled to complete planning on possible scenarios. May I remark that, although we are dealing with a large number of variables, in the practical realm we will focus first on those that explain most of the forest fire landscape and its evolution.

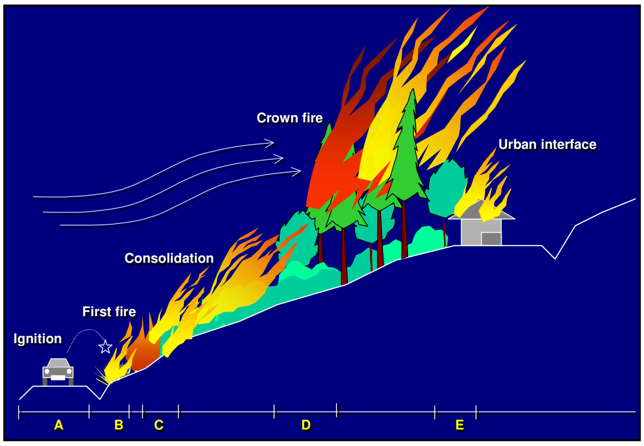
Among non-modifiable factors may we focus on topography, weather and wind, these are components that can be inventoried or predicted. For the modifiable factors we are limited to act on the forest fuels, either on the type and composition and the spatial distribution, and on some of the causes of fires, in particular those which have human origin. To complete the components, and in the side of forest fire defence, we will focus on the infrastructures, such as access roads, vigilance towers, water points and bases, and the aerial and ground means for forest fire fighting.

All the mentioned components are not independent. In fact they are linked by their position in space and time, and it is the matching of the moment and place of action that entails fire events and conditions their evolution.

Information systems, throughout spatial analysis, will help us noticeably in finding such combination of hypotheses and to simulate actions on the modifiable factors to see the consequences. Typically, this analysis of territory has focused on the values obtained for every cell in the raster map, assuming uniform conditions for every one.

Instead, and as a result of practical application, it is proposed the use of cross-sections of the territory, obtained from every point and along all the surrounding directions. Thus, the fire potential class of every point will be ranked depending on the fire intensity and spread rate values found along the analysed profile, and not just because of its own point-wise values. In this way every point will be typified by its potential to initiate, consolidate and propagate the fire.

In the analysis of profiles it has been found a number of transition areas (TA) which will drive the main criteria of forest fire defence planning:



- Zone A. Ignition
- Zone B. Initial fire
- Zone C. Consolidation
- Zone D. Jump to crown fire
- Zone E. Interfacing with urban areas and areas of ecological value

The occurrence and evolution of such transitions have to deal with the matching in time and space of the governing factors and, as part of the fire landscape, infrastructures and fire fighting resources which will meet defence demand in time and space.

Together, the occurrence of fire in every transition has an associated elapsed time, which will be the main link with the evolution of fire fighting operations. To put it in a single way, in the end, planning of fire extinction operations is the analysis and co-ordination of such times to avoid transitions of B, C, D and E zones, while preventive operations will deal also in avoiding A zones.

In this point it is interesting to notice that before a fire starts, and under certain weather and wind conditions, planning and preparedness of fire defence is based on the discrimination of such transition areas of all territory. But also, and particularly, after a fire has started, such zones are found progressively along fire front during its evolution. In the first case the method will be applied for preventive strategies, while in the second situation the method will help to plan specific fighting operations.

Proposal of method for integrated planning

In light of the above, it is proposed a combined analysis of factors to co-ordinate defence criteria and apply the results in the final planning. Information systems will help us noticeably in this task, which is intrinsically complex due to the spatial and temporal variability of factor

In order to simplify the approach, it is proposed to identify which parts of the territory could entail transition areas A, B, C, D and E and how to tackle with it by programming preventive actions and forest fire fighting capacity.

To identify such parts it is proposed a simplistic but meaningful approach by merely comparing spatially the values of forest fire defence offer and forest fire defence demand. From the nature and amount of such difference a list of defence actions and priorities can be easily identified.

Forest fire defence demand

Fire defence demand can be understood as an index which embraces the main factors of territory and that can be particularised for every point. For the calculation of forest fire defence demand it is proposed, first, to make a detailed inventory on the mentioned factors and store the information in raster, cell-based maps.

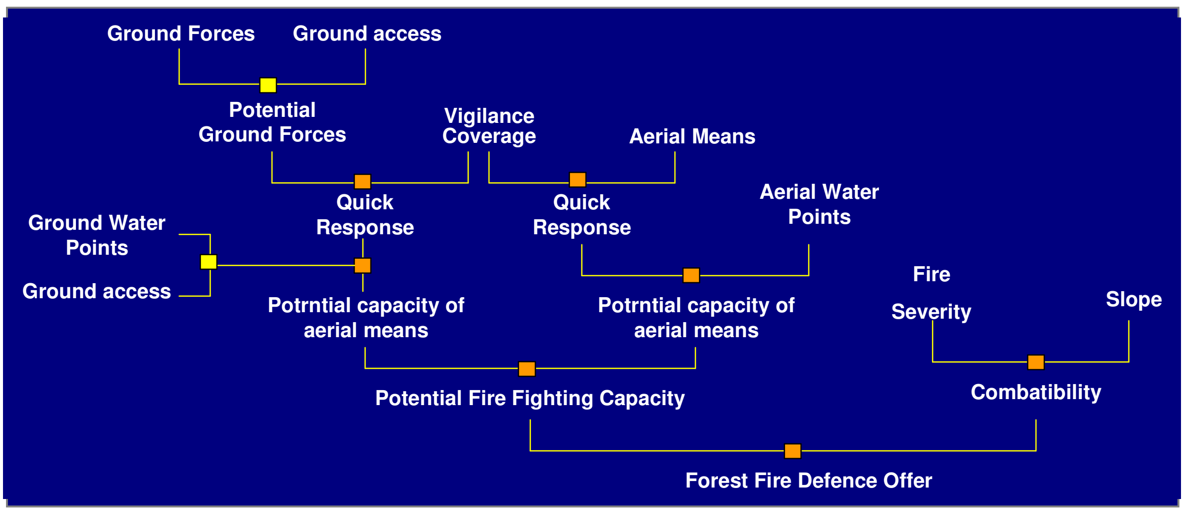
For every resulting cell, a number of calculations are made, namely:

- Fire intensity and fire spread rate, which combined give an idea of the destruction potential of a fire. This has to do with the identification of B, C and D and E zones.
- Ignition probability and historical pressure, which combined gives an idea of how prone a point is to ignite. This has to do with the identification of A zones.
- Both combined components, fire potential and fire prone likelihood, can be re-combined thus obtaining an integrated index of fire effect
- In the other side, ecological value and social use of territory can be combined into an index embracing a simplified expression of terrain value. This has to do with D zones.
- Finally, by combining forest fire effect and terrain value a final, simplified index is obtained that could be understood as forest fire defence demand, which explains, for a certain weather and wind conditions, how much fighting capacity is asking the territory for.

The combination of values are done using re-classification matrixes. Broad ranges such as Low, Average, High and Very High are used instead of numerical values in the matrixes. Re-classification rules are obtained by consulting a representative number of experts and managers who have to deal with all the implied factors in the analysis.

Forest fire defence offer

A similar approach of re-classification of maps using matrixes can be followed for the calculation of forest fire defence offer. In this case the components which are considered are shown in the following scheme:



As seen above, ground accessibility is a key factor in the whole scheme. In fact, road and access lane network has a double effect in the sense it provides access both to the fire area and the water points. In case of E zone, roads give essential support in the evacuation and rescue operations.

The spatial distribution of ground forces, that is, the typpe, number and location of bases, is weighted for every according the accessibility to such point for every type of vehicle. It has been observed that almost any fire fighting vehicle can access through the lanes to the fire area, but what discriminate ground mobility is the movement of forces within the fire area, particularly by cross-country and through mechanised lanes. In such cases, just a number of specialised vehicles, and in certain conditions of slope, firm and rock presence, can actually move.

The potential fire fighting capacity has taken into account the combined operations of aerial means and ground forces, each one with own restrictions and accessibility to specific water points.

Consideration about combatibility, that is, the degree of easiness and effectiveness in the fighting operations due to local conditions and fire severity, is a key component in the evaluation of final values of forest fire defence offer.

Identification of actions and priorities

The spatial, direct comparison of fire defence demand and fire defence offer will have a positive or a negative value between –3 and +3:

		OFFER			
		L	A	H	VH
DEMAND	L	0	+1	+1	+3
	A	-1	0	+1	+2
	H	-2	-1	0	+1
	VH	-3	-2	-1	0

Final comparison matrix Offer vs. Demand

L Low
A Average
H High
VH Very high

1	-3	VH	L	ZONE 1
2	-2	VH	M	
3	-2	H	L	
4	-1	VH	A	
5	+3	L	VH	ZONE 2
6	+2	M	VH	
7	+1	H	VH	
8	+1	M	H	
9	-1	H	M	ZONE 3
10	-1	M	L	
11	+1	L	H	
12	+1	L	M	

This process is applied to every cell in the territory, hence it can be identified a number of areas and associated actions which are prioritised according their impact on the territory, namely:

- Zone 0. Very low priority. Well covered area. It is equilibrated area, nevertheless it has to be characterised the nature of equilibrium (stable, unstable)
- Zone 1. Defective offer. Actions: Reduction of fuel load or change fuel type. Improve road network. Improve number and position of ground and helicopter bases. High priority
- Zone 2. Excessive offer. Actions: Move resources to Zone 1 where it is possible. Change budget and reallocate it. Average Priority
- Zone 3. Less impact. Act in the sense as shown in ZONE1 and ZONE 2. Low priority

FOMFIS The Project

FOMFIS project is an initiative partially funded by the European Commission through the 4th Framework Program of R+TD. This project is 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', and explains itself most of project objectives.

Allocated 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 and roughly cover the basic fire service needs for a region. Planners and managers have to skilfully manage the information pieces, such as historical fire and weather databases, to accurately distribute fire fighting resources in the territory thus giving 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 hence the budget to cover such needs. Besides, geographic information is frequently poorly available or updated, thus the forest fire prevention, planning and management is scarcely covered.

FOMFIS system has been conceived to give an integral solution to the mentioned issues. The project has focused on several research areas, namely:

- Forest fuel mapping
- Socio-economic risk analysis
- Forest fire behaviour 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

Objectives

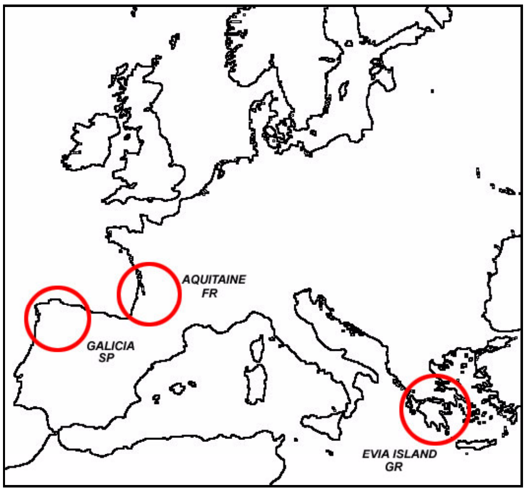
The project has covered the following main objective:

to integrate a computer-based application to give help in the decision making process to planners and managers of forest fire services willing to co-ordinate budget availability, resources efficiency, fire risks and environment factors evolution in the planning of a fire campaign.

Project Scope

Geographical Scope

FOMFIS project has been devised to be implemented and tested in three separate areas in the Mediterranean basin. Those areas are representative of most of forest fire planning and management scenarios, covering from strong Atlantic influence to typical Mediterranean climate territories. The considered regions are:



GALICIA, (SPAIN), located at NW of Iberian peninsula this region is considered having one of the most challenging problems on forest fires in Europe. A rapid biomass regeneration due to high humidity and relative mild temperatures leads to great fuel loads either at shrub level and at canopy level. Highly fragmented terrain property pattern gives socio-economic forest fire risk special relevance where most of 80% of fire occurrence has its origin in human activities. Regional Forest Fire Prevention and Fighting Service has to deal with large number of small fires, up to 8,000 fires per year, leading to severe conditions that test fire fighters endurance and fire managers expertise to the limit.

EVIA ISLAND, (GREECE), this particular area represents most of the fire conditions within Mediterranean basin, namely xerophytic vegetation and dry seasons when temperatures are high. Maquis vegetation formations together with pine stands over large areas leads to complex fire behaviour where high propagation speeds and fire line intensities are developed. Fire fighters has to deal with large fires in places where accessibility is reduced by topography and vegetation and, for most cases in Greece, located in islands.

AQUITAINE, (FRANCE), this particular region of the SW France has been considered for years as reference of forestry vocational area. Holding one of the most impressive continuous exploitation pine forest at Les Landes, the omnipresent sand soil and the ground water level marks the type and size of forest fires. Private ownership of lands favours forest fuel control and infrastructures maintenance, such as access roads, water supplies and silvicultural activities, by means of landowners associations. Due to forest canopy continuity big fires are prone to occur so fire prevention and fighting management and planning is aimed to shorten detection and extinction time for incipient fires. Lightning, linear structures, such as railroads and roadways, and tourist human pressure are the main causes of fire occurrence.

Consortium Partners

Nine partners have taken part in the projec development, which are listed below:

- Iberinsa (SP), as Project Co-ordinator
- Software AG (IT), as systme developer
- SEMA Group sae (SP), as system developer and integrator
- EPSILON (GR), as consultant in GIS and system developer
- IBERSAT (SP), as consultant in remote sensing and system developer
- SESFOR (SP), as consultant in socio-economic risks
- Xunta de Galicia (SP), as main user in Spain
- NAGREF – Ministry of Agriculture (GR), as main user in Greece
- CPFA- Maison de la Fôret (FR), as main user in France

User Profile

FOMFIS system is aimed at forest fire defence planners and managers dealing with geographical data to better distribute budget and allocate resources according fire defence needs. This figure is not clearly stated in several forest fire services and actually it embraces the decisions of several responsibles instead of a single person.

FOMFIS users are specialists on forest fire defence with mid computer-knowledge which make use of digital mapping systems routinely to accomplish most of their duties. Nevertheless these persons are not GIS specialists and perform simple operations such as data querying and basic spatial analysis. As it has been observed, FOMFIS users are giving support to chiefs and officers in charge of critical decisions about fire fighting forces depletion, instead of taking such responsibilities themselves, although close collaboration between the two specialists is essential.

For both test sites, in Galicia (Spain) and Evia (Greece), the FOMFIS specialists figure must be created and trained to really implement the system in the day to day operation. This job is currently undertaken by forest fire specialists who have literacy in computer systems but they are assuming many other critical roles in the forest fire service. This keeps apart users from continuous and expert FOMFIS system usage.

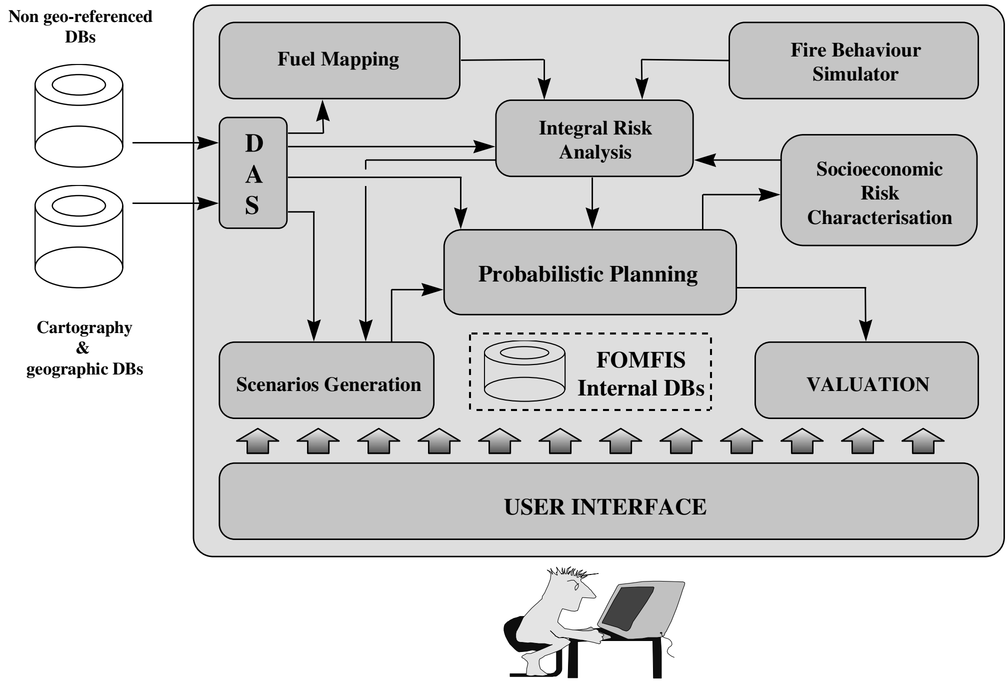
Applications and modules constituting FOMFIS system have been designed aimed to such a mid computer-knowledge user, focusing attention on forest fires resources planning and management. User interfaces for FOMFIS normal operation constitute the corner stone for application real use success. In fact. for such purpose a graphical user interface (GUI) supports system functionalities regarding user interaction.

Integration has been carried out over a common platform for ever FOMFIS constituting module taking into account common variables and following similar interface design for each module. In this way user feels comfortable changing from one module to other without loosing the attention over the studied area due to GUI inconsistencies.

System Description

FOMFIS General Scheme

FOMFIS system has been conceived modularly. A set of modules, which have definite functions, are integrated within the same GIS platform. All the modules share common databases and maps, wich are linked together following the scheme presented below:



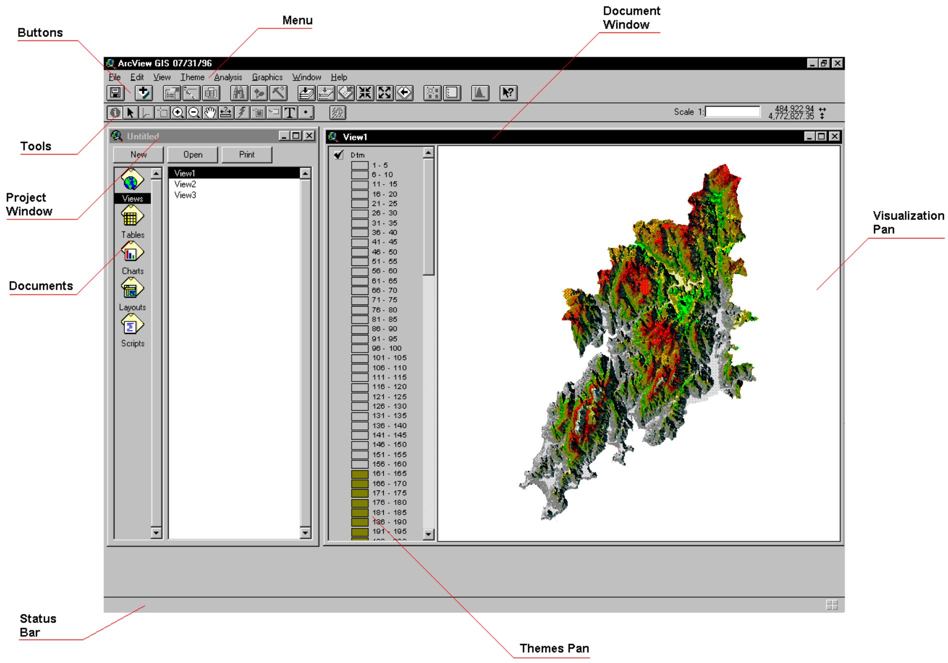
GIS Platform

FOMFIS is running as a program under Arc View 3.0 platform. The GIS platform offers most of the procedures of map handling, map representation, querying and spatial analysis. As far as it is possible, embedded functionalities have been chosen to perform most of FOMFIS operations. Nevertheless, FOMFIS counts on external, specific programs connected to the main platform that perform operations demanding high computer performance.

User Interface

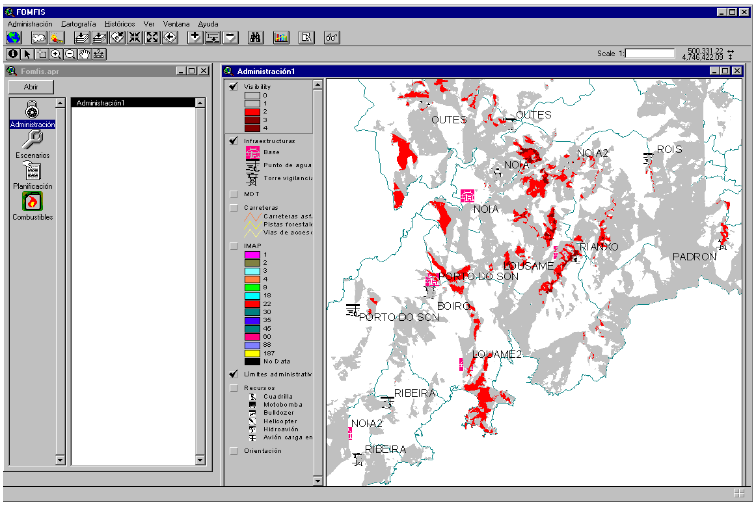
The integration of all pieces under a common interface allows fluent transfer among modules and the data handling. Although FOMFIS is composed of several modules, users feel they are using a single program.

FOMFIS appears as an extension to Arc View GIS application. New projects are treated as views, and all FOMFIS components are fully integrated in the Arc View philosophy.



Each of the FOMFIS module has got its own menu commands, tools and buttons, and the user will be able to access to each document functionality through them. In this way, the user interface is divided in a intuitive way and the user will be able to perform every moment, the operations corresponding to the document that is working with.

The following picture illustrates the final user interface appearance:



Data management

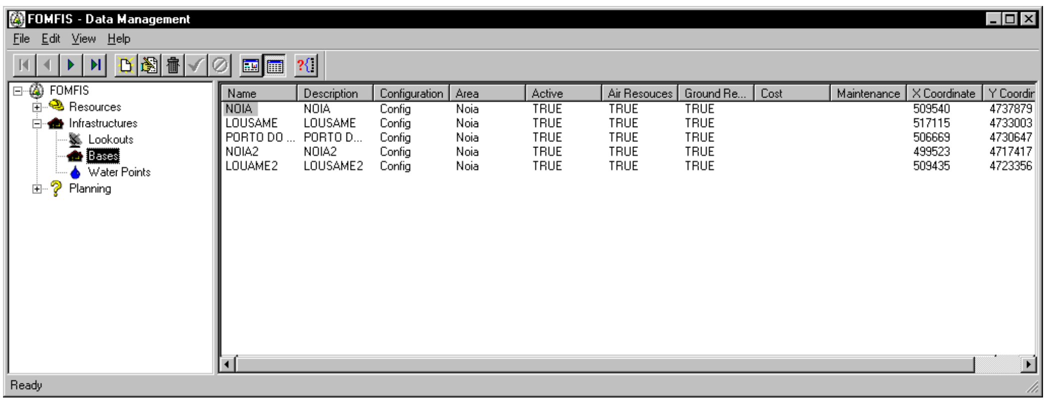
The Data Acquisition module (DAS) is responsible for the management of data used by FOMFIS. These data can be divided in two main blocks, with different usage: Alphanumeric Data and Cartographic Data.

Alphanumeric Data

The Data Acquisition Module allows the user to manage the alphanumeric data stored in the FOMFIS database. These data are actually limited to resources and infrastructures management, in order to allow the user to manage the elements that wants to activate in each planning.

The objective of this module is to allow the user to manage these data in a intuitive manner. In order to achieve this requirement, the user interface of this module becomes very important to ensure the module usability. This module user interface has been developed using the Windows Explorer style. In this way, the user can manage its data in a intuitive and easy-to-use way.

The following picture presents the DAS interface for alphanumeric data management.



FOMFIS works fundamentally with cartographic or geographical data, so the management of this type of data takes more importance.

The data acquisition module allows the user to update the maps with which FOMFIS operates. These maps can be divided in two main groups:

- *Primary maps*, or maps that the user provides and are not generated by the system.
- *Generated maps.* Generated by FOMFIS based on one or several primary maps or previously generated maps.

As described above, one map can be generated based on one or several maps. It generates a dependence relationship between maps. This relationship is very important when attempting to update, delete or change a map, because to change a map implies that every map based on that is now invalid.

Forest Fuel Mapping

A module has been built to deal with classification of remotely sensed data and render forest fuel maps accurately.

Data-sets of three districts of Galicia and one district of Greece were acquired and consisted of: Landsat TM (Spring 1995 Galicia, Summer 1997 Greece), SPOT-Pan (same dates), Digital Terrain Models, topographic maps, and digital copies of existing forest and land use maps (Galicia only). In Greece, NAGREF provided a stylised fuel modelling scheme that allows fuel loads to be developed from vegetation height and cover (Xanthopoulos 1997)

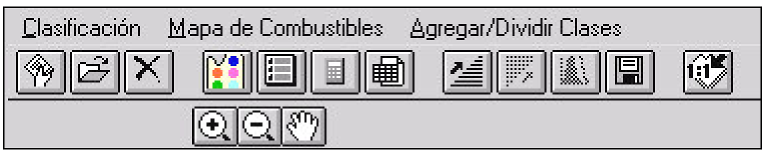
Two classification schemes were designed: a convergent scheme and a divergent scheme. The first starts with a large number of classes and sub-classes of fuel types (e.g. divided by species, age, soil type, altitude, etc.) and all available image bands and a number of auxiliary bands (texture, elevation, slope, etc.). A multi-spectral maximum-likelihood classifier uses these inputs to produce a thematic map with a large number of classes but a (usually) large degree of confusion between them. These classes are subsequently aggregated until errors are reduced and meaningful forest fuel classes are produced.

A multiple regression analysis of the Greek image data (Landsat TM NDVI and SPOT high-pass texture band) and the field data (active load) produced an empirical relationship between Active Load (AL) and observed vegetation index (NDVI) and texture (TX):

$$AL = 0.4 \cdot NDVI - 0.22 \cdot TX + 9.8$$

After classifying the area of Limni into Forest - Non-forest strata, this relationship was applied to the forest strata to produce a fuel load map which was evaluated by the Greek user.

The functionalities have been coded using Avenue macro language and the resulting fuel mapping application has been integrated in FOMFIS system through a common User Interface.



Socio-Economic Risk Model

An essential part of the preventive planning simulation is the characterisation of the forest fire risk due to socio-economic factors. In FOMFIS system this is taken into consideration through the design and implementation of a Socio-economic Risk Model (SER). This module is rendering expected number of fires by area unit, according the relationship between factors and forest fires, characterised through a set of expressions.

The main theoretical contribution of FOMFIS-SER is to substitute the traditional model of "the most probable attributed cause" that attributes most forest fires to arsons and offenders, by a socio-economic risk model based on an objective risk situation. Appropriate analytical categories were established and risk factors identified.

This approach is hardly present in forest fires research and in the users' strategies. By this reason and given the fact that the FOMFIS project paid a special attention to the design of a socio-economic risk model, it has been necessary to develop a well founded theoretical frame. To achieve this, two different ways were explored. On the one side, a microanalysis was conducted in four forest Districts within the Project's regions; on the other side, the insights of this qualitative work were statistically tested. As a result, five specific factors were defined for the Socio-economic Model.

IN FOMFIS-SER **primary data** (raw socio-economic data form different sources), **variables** and **indicators** are used. Variables are qualitative elements (without units of measure) that characterise the socio-economic setting of the forestry environment in a specific temporal or geographic unit. It has been selected a set of 156 variables that first thing, have an influence in the rise of fire risk. This set was classified in 10 groups (Forestry, Livestock, Agriculture, Land uses, Socio-demographic, ...) and 48 subgroups according to the area of study or subjects to which they belong. Indicators are functions that quantify the variable from the available primary data. Each variable can be quantified by more than one indicator, but among the available indicators, it has been selected those that offer greater accuracy and reliability in the representation of the variable

Socio-economic **factors** are the main components or aspects which are divided in the forestry environment, and contribute to the maximum causal explanation in the intensity and variation of fire risk. FOMFIS has defined and worked with 5 factors, namely :

- Forestry profitability (production and productivity in the forestry environment),
- demographic pressure (degree of human presence and evolution in forest areas),
- social tension (social strain level),
- forestry culture (level of forestry culture and public opinion), and
- organisational logic (prevention and fight model).

These 5 factors are supposed to be sufficient to explain the increase or decrease of fire risk. Three separate models have been designed, according the nature and geographical scope of the analysis.

Galician Spatial Model

It consists of a macro-model applicable to geographic units of middle extension, the municipalities or groupings of parishes with an average area of about 100 square km. The model has been obtained by means of spatial regression analysis of average FF data and socio-economic variables of the period 1991 – 1996. The result of its application is an estimate of the number of fires expected during a year per 100 km^2 of forest area for climatic conditions similar to those which average the period 1991 – 1996.

The equation works with seven variables for a start with a high degree of independence among them. All of them have a positive effect on the rise of the dependent variable. Then the above-mentioned variables are enumerated together with the impact coefficients (Standardised beta coefficients) that assess the specific weight of each of them: Agrarian Holdings Density (+0.41); Total Population Density (+0.29); Agricultural Land-Forest Interface (+0.21); Proportion of brushland (+0.18); Proportion of unemployed male population (+0.15); Disseminated Housing Density (+0.15); Sheep and goats Density (+0.14). The formula has been obtained by regression of 311 municipality with a 0.54 Adjusted R^2 and 60% Maximum Relative Error in 70% of the cases.

Greek Spatial Model

The development of this macro-model was based on the research done by Dr. Gavriil Xanthopoulos. It is applicable to large geographic units such as the nomos with an average surface of 2500 square km.

The model has been obtained by means of spatial regression analysis of average FF data and socio-economic variables of the period 1983 – 1993. The dependent variable is the number of fires expected during a year per 100 km^2 of total area for climatic conditions similar to those which average the period 1983 – 1993. The independent variables are two: The Municipality Density and A3GO (Complex variable related to Livestock). The Municipality Density is highly connected with the ratio of urban area and it is a clear essential component in the determination of the risk. A3GO is a complex variable. It combines two important factors related to goats grazing pressure: On the one side the Goats Density and on the other side the average grazing area per goat holding. The formula has been obtained by means of regression of 51 cases with a 0,73 Adjusted R^2, and 28% Maximum Relative Error in 70% of the cases.

Galician Temporal Model

It is a macro-model applicable to geographic units of large extension such as the Provinces. The formula has been obtained by means of temporal regression analysis of forest fires data and socio-economic variables determined per year for the whole of Galicia. 29 were the number of years used for the regression from 1968 to 1996. It is a model of temporal application that allows to explain the variation of risk from year to year.

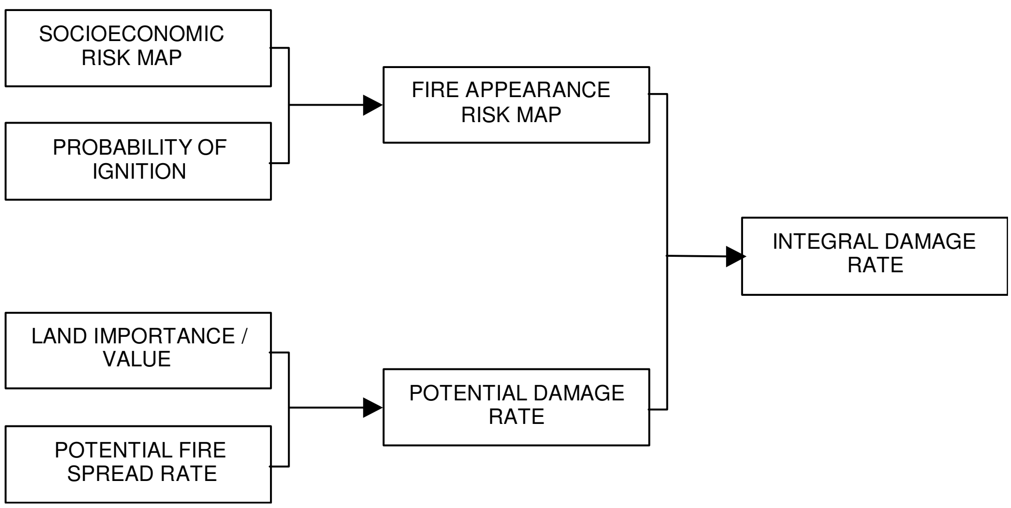
Besides to the models listed, two predictive, micro scale models have been developed for the Comarca of Noia (Galicia) and Dasarheio of Limni (Evia) which give number of fires per unit area (100 km^2). This micro-models give more accurate results than macro-models mentioned above.

Integral Risk Model

User is reported about the fire risk in every meteorological and socio-economic possible situation through the calculation and representation of a set of risk maps, which are combined together to render an integral risk map.

Besides, system is making use of **ignition probability** map, which is generated using forest fuel map and meteorological variables, together with socio-economic risk map to estimate the number, place and time of fire outbreaks in the simulations of fire scenarios.

The maps are generated progressively, according the following scheme:



Giving the resulting SER map as input, the system estimates the number of possible outbreaks according the distribution of socio-economic risk and the probability of ignition in each point. The resulting map, addressed as **fire appearance risk**, is used for the generation of fire outbreaks in the simulation process.

According the fire spread conditions found in every point of the analysis area, the system estimates the potential spread rate, taking into consideration every possible combination of meteorological conditions and wind situation. The resulting value is used to estimate the destruction capacity, addressed as **potential damage rate**, of fire in every point. This is expressed in terms of losses of terrain value per unit time.

Coupling the risk of fire appearance and the potential damage, a third map is generated, the **integral risk map**, which explains the total potential damage due to the appearance of all the expected fire outbreaks in the study zone.

Scenarios Generation

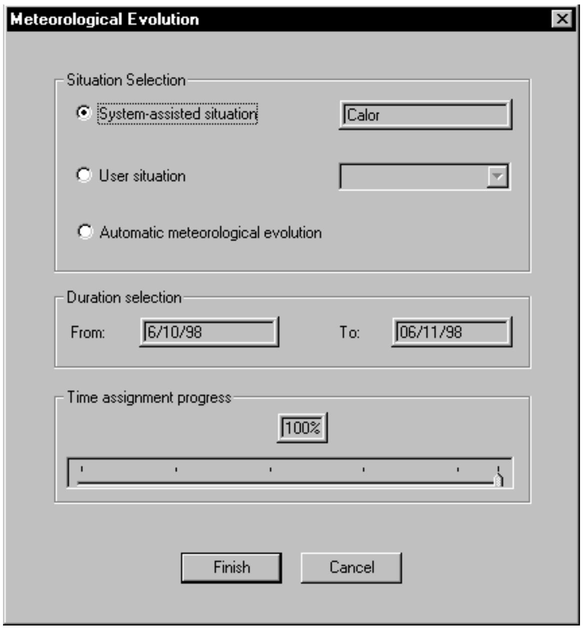
Prior to the simulation, the system allows to generate probabilistically a set of forest fire theatres to which fire defence planning must face in the simulation. To simplify analyses, FOMFIS considers a set of prescribed meteorological and wind conditions which are normalised according the study area data. Each situation points to a set of maps describing the weather and wind parameters.

The generation of forest fire scenarios comprises three parts:

Generation of meteorological conditions evolution. This is achieved through the study of historical data about meteorological factors, such as temperature, air humidity and cloud coverage. The system identifies patterns of change for every day in the week and every week in the year. The evolution of meteorology can also be forced to follow certain patterns according user's needs.

Generation of wind conditions evolution. Similarly, a probabilistic generation of wind patterns is achieved through statistical analysis of historical data.

Generation of fire outbreaks. The systems uses historical data of forest fires to characterise the distribution in time of fire appearance. Besides, and coupled with the above, makes use of fire appearance risk map to spatially distribute such outbreaks. Also, users are allowed to define particular fire distribution over time and space.



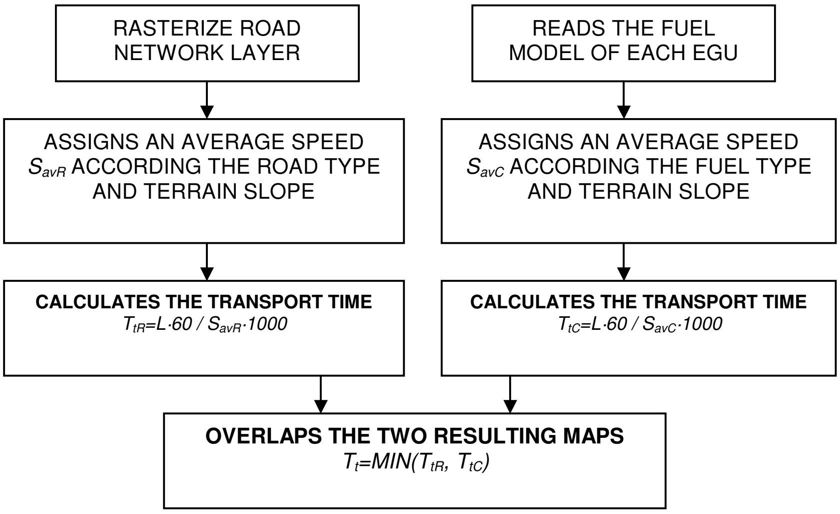
The resulting evolution of weather, wind and fires are stored and used in the planning simulation.

Efficiency Driven Planning

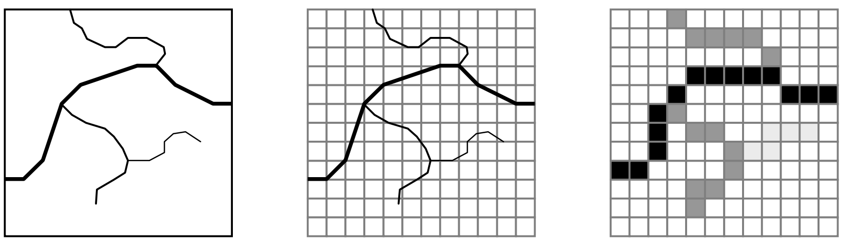
This module comprises a set of spatial analysis tools to help planners and managers to distribute their fire fighting resources and organise infrastructures works according at their efficiency in the prevention, vigilance and extinction operations.

Ground Transportation Impedance Map (IMAP)

This raster map contains the value for each CELL corresponding the average time spent to cross such CELL by ground vehicles. The time T_t in minutes is obtained by dividing an average distance, that equals the CELL border dimension L meters, by the average speed of transportation in km/h.



The procedure of IMAP calculation for ground based vehicles could be simplified by considering two coverages allowing access to every point within the analysed area: the road network and the cross-country displacement. These two layers are rasterised and then overlapped to obtain the final IMAP for ground vehicles taking the minimum access time value.



Ground Access Time Map

Based on the previously calculated impedance map (IMAP) the total accumulated transport time is obtained through the analysis of the time that is required to reach every CELL following the minimum path. A spatial analysis automata, included in the GIS supporting raster functions, performs this process.

This map belongs to a point, the starting position, so a new map should be obtained for every considered point (bases, water points, etc.) within the geographical area. Due to evident topological considerations, the resulting map is function depending on two variables with no local minimum points neither flat zones, hence there is a unique minimum path from the analysing point to the target point. For the spatial analyses regarding the TCMAP, FOMFIS assumes that the followed path is the minimum path. These procedures include the calculation of ground displacements efficiency, thus the coverage of fire fighting resources regarding:

- Bases
- Water Points
- Road network

The efficiency is expressed as percentage of points of a given area falling within the time range specified by user. Besides, this map is used in simulations to obtain displacement times between points (bases, fires, water points etc).

Aerial Coverage

To calculate the total access time for airborne vehicles it is assumed that they travel at a given average speed, so the time is obtained dividing the distance from the actual position (base, etc.) to the analysed CELL by the given speed. The resulting function will resemble a cone shape, where the apex corresponds to the base position. For airborne vehicles the isochrones are concentric circles which centre is the base itself.

Again, the calculation of aerial coverage is used in the study of airborne displacements regarding:

- Bases of airborne resources
- Water points for aircrafts

Lookouts Coverage

The lookouts efficiency is based in the analysis of potential viewsheds coverage. Given a vigilance network the process computes the number of lookouts that reach every cell in the analysis area. Depending on the obtained values, a final number giving the fraction of covered cells versus the total number of cells gives an estimation of the lookout network efficiency.

The process of viewshed calculation is based on the Digital Terrain Model (DTM) in raster format that explains the terrain relief of the analysis area. The process analyses every lookout once their position and height is known, and gives raster map containing their vigilance coverage, usually the number 0 is 'not seen point' and the number 1 is 'seen point'. By adding these values of all the existing lookouts a number is obtained that serves to estimate the total efficiency of the lookout network. Besides, this map is used to estimate fire outbreak detection time in the simulations.

Wind Field Simulation Module

The WIND module has been developed in order to provide end-users a tool which allows to generate wind maps for the FOMFIS environment. Two are the main functions provided:

With the first one, the user is able to introduce, through several dialog boxes, the generation parameters and the real wind measurements done in the work area. Then, the WIND module generates automatically the *.PAR* and *.OBS* input files for NUATMOS application. With these files, NUATMOS will generate a *.WIN* file that will comprise the wind data for the work area.

The second one allows to interpret the .WIN file and generates automatically the wind speed and wind direction maps for the FOMFIS environment.

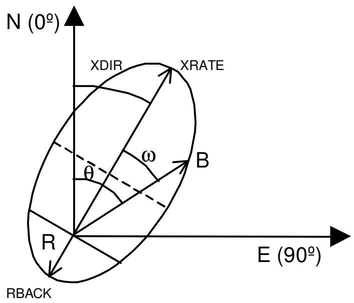
When the user is working in FOMFIS environment, he is able to click on the *Wind generation* button. Then, WIND module is called and displays a dialog box in order to allow the selection of one of the two main functions.

Forest Fire Spread Simulation

The FOMFIS Fire Spread Engine (FSE) is based in an adapted version of that found in CARDIN simulation system. The main modification is that FOMFIS FSE uses the elliptical shape as the fundamental spread law curve under uniform conditions, instead of the pseudo-cardioid proposed in the CARDIN model. all the other parts have been reviewed and implemented in the FOMFIS structure.

The engine bases its operation in a cellular automata that calculates the time spent by fire travelling from one EGU to the surrounding eight ones. Thus, the cells state, regarding the fire spread, could be one of these three: 1.- Intact; 2.- Flames burning; 3.- Quenched.
The process, essentially, is simple: the spread law is calculated using the values encountered in the analysing EGU relative to slope, aspect, fuel model, and wind direction and intensity. For each spread direction, corresponding to each of the eight neighbouring EGU, a projection of the spread law is obtained, giving the value of propagation for such direction. As distance among EGU is easily estimated by considering the centres position of each EGU, the time spent by the fire to travel from one centre to the other is obtained by dividing the distance by the projected speed.

For each analysed point B (regarding each of the 8 analysis directions) it is checked if the B EGU has been analysed yet; this can be detected reading its state value (as “burning”). This overlapping analysis is considered because fire could reach the same position from two different directions, each giving different access time; in such conditions, the engine calculates the new accessing time and compares it with the existing time, leaving the smaller time found.

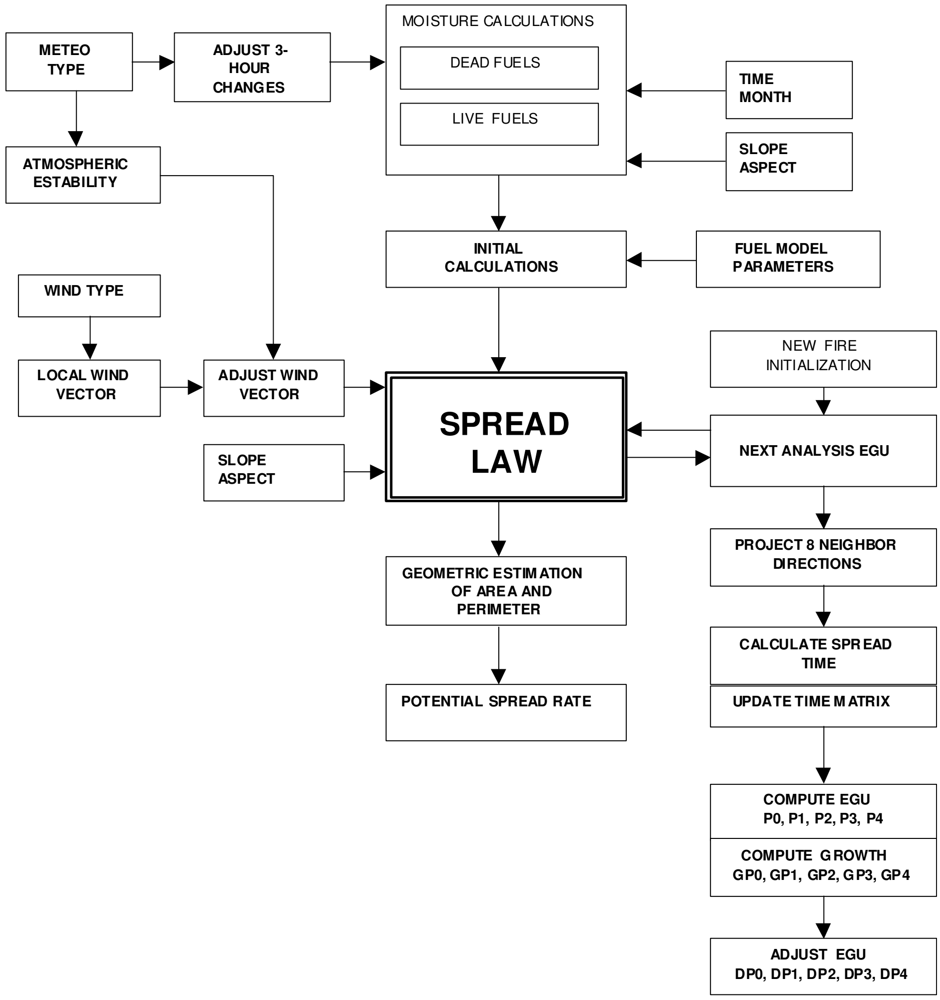


The total access time is the sum of the time to reach the reference point R (that is t_R) plus the time to travel from reference point R to the analysed point B, which is calculated using the local spread law regarding each reference point. To achieve such calculation it is required to know the spread rate in the direction ω_{RB}, obtained through the projection of the spread law belonging to the analysing EGU (A)

The spread engine integrated in FOMFIS system adds improvements to that found in CARDIN system in the following points:

- Improved elliptical functions for the calculation of local spread law
- Improved accuracy due to forest fuel moisture re-calculation and wind vector variation
- Improved connectivity with fire fighting model focused on fire line intensity classes
- Improved calculation of intrinsic spread values thanks to adapted fuel load estimations

The simulation procedure and its connectivity to other FOMFIS modules, can be synthesised in the following scheme:



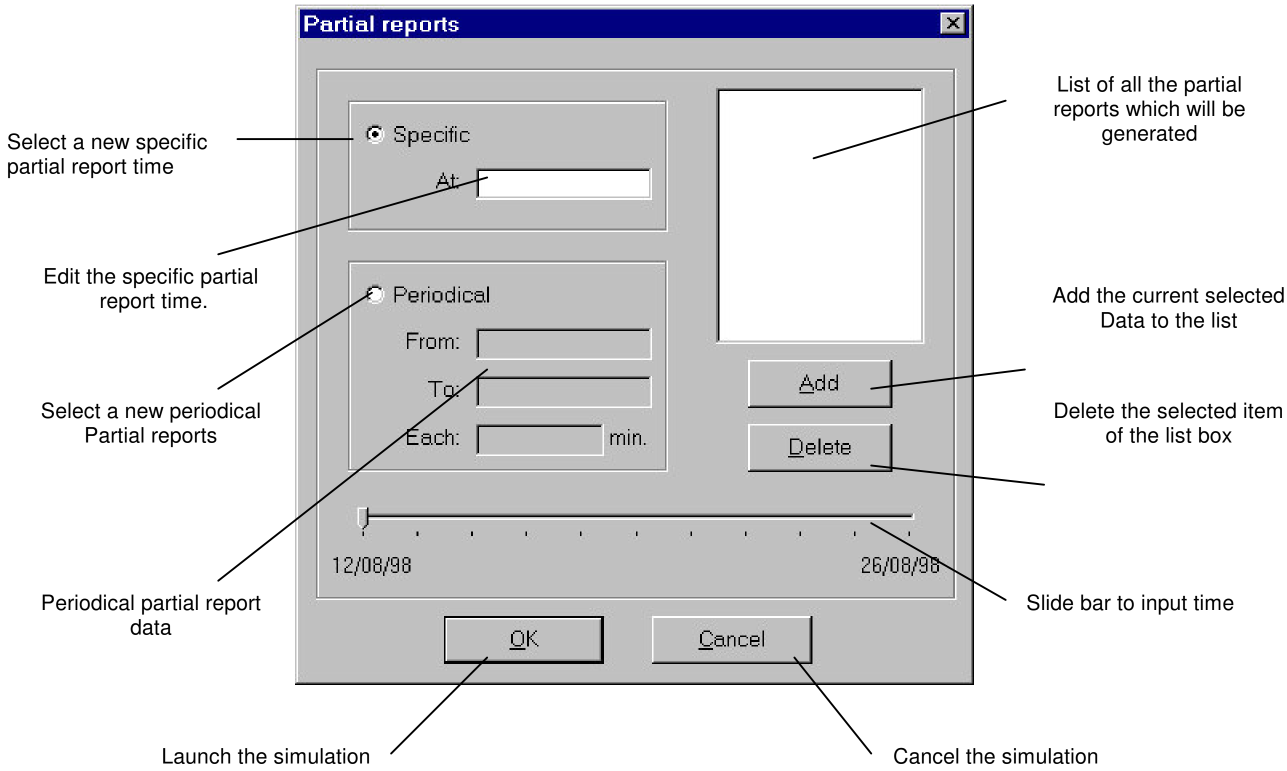
When the user is working in a scenario environment, he is able to select one or more fires and clicks on the *Simulate fires* button. Then the system check that there is at least one selected fire, marking them in database in order to FBM simulation function knows what fire must be simulated. In this moment FOMFIS launches the simulation process.

Planning Analysis Engine

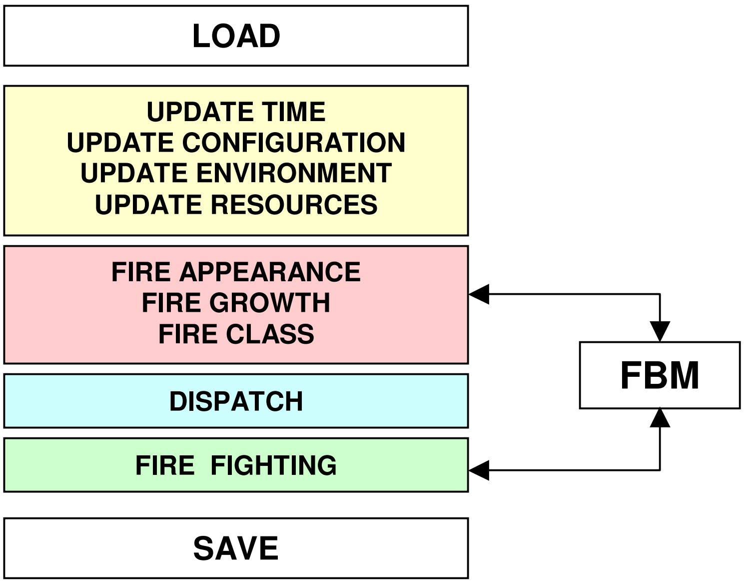
This module performs the analysis of the evolution of the fire scenarios together with the resources efficiency and the fire behaviour over a period of time. It allows to run a simulation of a complete fire campaign in every of its aspects and obtain in return reports about the changes that happen, the defence activities carried out, the resource implied and the cost and losses due to the fire burning and the resources usage.

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.

Users manage simulations done with PAE through the following interface:



The simulations comprise a set of procedures running sequentially, each performing a definite task in the simulation. The procedures are repeated during all the simulation in steps of 5 minutes (simulated time). These are:



Update time

The simulation runs until the current simulation time t reaches the specified maximum t_{max}, by increasing Δt each analysis cycle. The time increment is fixed in 5 minutes.

Update configuration

This procedure block reads the planning configuration evolution matrix and checks the initial time of every segment. When simulation current time is greater than this value the resources planning configuration is changed accordingly.

Update environment

The wind type evolution matrix and the meteorological evolution matrix are consulted. The simulation time is compared with the initial time of every evolution segment period, and if it is greater the change is performed. Every wind type points to a wind map containing the wind vectors. The same applies to the meteorological situation, which points to maps of temperature, humidity and cloud cloudiness.

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.

New Fires Generation

The procedure keeps track of the fire matrix that is generated by the Probabilistic 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 CELL 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, 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) cell of a fire line is calculated through:

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

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 criterion.

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

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.

The initial fire fighting demand could be estimated by the following set of equations:

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

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 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.

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:

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

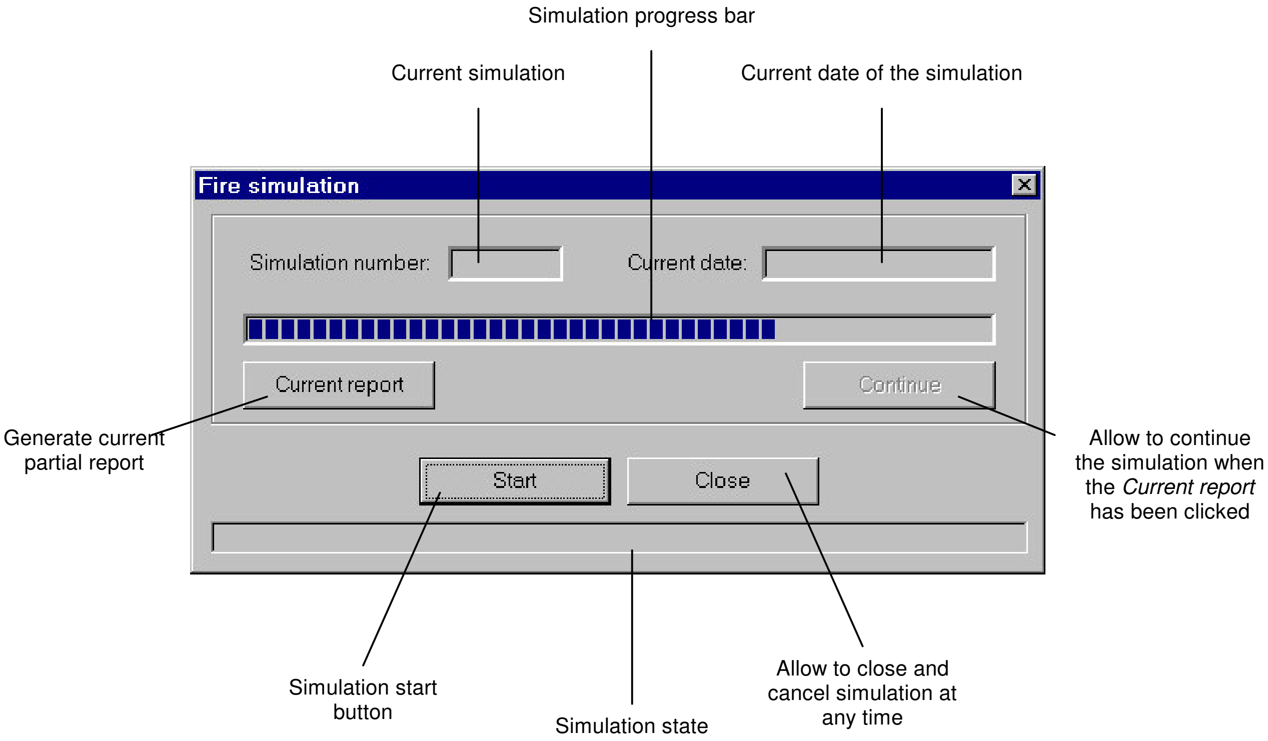
where $f_i>1$ is a factor that explains how much extra power, over the exact balance between fire growth and fire suppression rate, is required in each section of fire line intensity to meet the fighting requirements.

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.

Reports of Simulation

User is allowed to select the simulation times in which he wants to generate automatic partial reports. Later, during the simulation process, when one of this times is reached a partial report is generated automatically. This partial report compresses the burning fires, their characteristics, the resources states and theirs efficiencies at this time. Users manage reports using the following interface:



Verification and Validation Activities

A complete set of computer code verification has been carried out at the different offices of FOMFIS developers, and the results are satisfying giving high reliability for all the programmed modules.

Following, a complete set of validation activities have been carried out, starting with training sessions and checking the required data. Besides specific validation trips have been done to compare results of spatial analysis with the real world. The collaboration of experts has been very valuable. The results vary in accuracy, and some inconsistencies have found in the fuel mapping module and the total accumulated access cost map

In the first phase of the project, users have evaluated the design of system architecture. After development and integration of all components, first prototype was evaluated by users regarding its accuracy and adequacy meeting their needs. Users made comments about observed faults and inherent difficulties in the installation and training. Developers took into consideration these observations and modified or improved the affected software pieces. Users selected well-known areas within the FOMFIS three regions and performed exploratory excursions to evaluate system accuracy in forest fuel mapping, risk assessment and infrastructures and resources efficiency calculation.