Flexible Design of Wildfire Management Systems

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Abstract

There are few natural phenomena with the scope and complexity of forest fires [1]. These can be a major threat to the prosperity and well being of communities and, in fact, in Portugal they are a severe problem, accounting for more than half the fires in the EU Mediterranean region [2]. In recent years, their consequences have been severe, with 2.5% of forestland burned, 250 M€ of direct losses, and 120 M€ spent in prevention and suppression, every year, on average. Understanding how to mitigate these consequences with a finite budget is thus critical, especially given the current restrictive economic environment, and recent catastrophic fires (2003, 2005, and 2013).

Forest Fire Management (FFM) systems are complex systems involving environment, technology, people, and organizations, subject to large uncertainties, and whose design faces challenges that can benefit from an interdisciplinary approach. This research addresses one of those challenges – uncertainty management – by focusing on the use of flexibility, an important part of the Engineering Systems (ES) approach [3].

Starting from the study of waste in non-value-added FFM activities, we then proceed to examine the role of flexibility in designing integrated portfolios of diverse FFM alternatives, to allow these systems to perform better under uncertainty. Our results will reinforce the contributions of ES to the body of knowledge of FFM systems, and assist policymakers and fire managers in enhancing their design.

Decision makers must manage a portfolio of alternative FFM options under resource constraints. These alternatives include prevention (e.g., education, public campaigns, fuel treatments), pre-suppression (e.g., firefighter recruitment and training, maintenance of fuel breaks and water sources), suppression, and restoration [4]. The management of this portfolio requires an evaluation of how wildfires spread with and without suppression, and their impact in terms of the monetary value of destroyed or damaged assets [5].

In recent years, several authors have updated a number of reviews of the state of art in the FFM field: operations research methods [6], decision support tools and methodologies for wildfire risk assessment in face of uncertainty [7], applications of the economic efficiency analysis theory [8], wildfire simulators [9], surface fire spread simulation models [10], and the integration of wildfires into forest planning models [11].

Analytical solutions using standard mathematical methods are always a preferred approach, but when their application is not possible, as is almost always the case when working with complex systems [12], simulation is arguably the most robust method applied to model real-life stochastic systems that evolve probabilistically over time [6]. Since 1982 [13], and even though not considering the value of non-market resources (e.g., cultural heritage) [14], computer simulation, GIS, and the economic evaluation of losses and fighting costs have been successfully combined in integrated systems that provide the efficient economic choice of the fire suppression alternatives combinations. Behind these cost-benefit analyses, there are microeconometrics models such as [4, 15, 16].
However, studies including prevention and suppression in the same model are scarce [17] and the use of Mixed Integer Programming (MIP), as in Mercer et al. [18] and Minas et al. [19], is rare. MIP together with Discrete Event Simulation (DES) and System Dynamics (SD), two of the most used modeling approaches in the simulation field, are the approaches we have chosen, with microeconometrics methods in the background, to add a new ES perspective to the flexible design of FFM systems.

We started by studying (A) waste in non-value-added fire suppression activities, and now we are expanding our study to (B) the management of an integrated portfolio of FFM alternatives, at the operational and the strategic level, in the short (intra-annual) and in the long (inter-annual) term. These two stages of work have the following research questions (RQ):

1(A). How do rekindles and false alarms impact the behaviour of the suppression system?
2(A). How can suppression costs be reduced while maintaining safety levels?
3(B). What is the optimal mix of investment in prevention and suppression along the years?
4(B). Which conditions transform an ignition in a large fire?
5(B). How to manage an integrated portfolio of FFM options along the fire year, considering uncertainties in weather, economic conditions, and the impact of the different options?

Next, we focus mostly on the ongoing work (RQ3-5), but also briefly present work that has already been completed and published. For each RQ we provide motivation, materials and methods, and achieved/expected results.

**REGRESSION AND DES ANALYSIS [RQ1]**
Through regression analysis, we studied rekindle dynamics in Portugal [20]. We found that rekindle proportions increase in days with more occurrences, supporting the hypothesis of premature mop-up abandonment, due to pressure to attack starting fires. A detailed district level analysis provided further evidence of rekindle hazardousness.

We also developed a DES model addressing the impact of non-value-added activities, such as rekindles (defects, inappropriate processing) and false alarms (motion), on the suppression system [21, 22], and carried out a literature review on operational/strategic Decision Support Systems under uncertainty.

**SPATIALLY EXPLICIT OPTIMIZATION AND SIMULATION [RQ2]**
Combining optimization and simulation, we have developed a spatially explicit screening model that optimizes the allocation of firefighting vehicles to local dispatch centers, preserving security levels, while reducing investment and increasing vehicle utilization. To analyze the trade-off between proximity of vehicles to a fire, and number of vehicles required to put out such fire, under occurrence uncertainty, we use two-dimensional distributions (from historical data) of occurrences in a 20-year simulation. An Ornstein–Uhlenbeck process drives the weather and the model runs under four scenarios (“as-is”, Wildland-Urban-Interface expansion, surveillance policy, and law enforcement). The model confirms the safety of partial concentration, with a flexible design policy.

**SD OPTIMIZATION [RQ3]**
Appropriate allocation of a finite budget to suppression and prevention is complex. We have collaborated in a study [23] reporting that apparently sound management can have unintended consequences. Indeed, an instinctive response to worsening fire severity is to increase suppression investments, an approach with immediate appeal as it directly treats the symptom of devastating fires and appeases the public. However, the SD analysis indicates that a policy emphasizing suppression can degrade long-run effectiveness of FFM.

We will expand this model to a broader set of FFM alternatives, and use SD optimization to explore dynamical interactions between such activities under a finite budget in an inter-annual horizon.

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Resulting insights can help policymakers and fire managers to appreciate the impact and effectiveness of different resource allocations to these interconnected systems (reactive suppression and proactive prevention) and the dynamics that may undermine seemingly rational decisions.

**MICROECONOMETRICS ANALYSIS (RQ4)**

Using historic data from our merged Portuguese fires database (ICNF, ANPC, and UTAD), we will use a nonlinear panel model to study combinations of inputs that result in fire containment failure, i.e., initial attack giving place to extended attack, with larger burnt areas and more suppression means.

Such inputs can be purchased or free. Free (i.e., non-market) inputs include geographical surroundings, natural fuels (vegetation) and weather conditions. Purchased inputs include anything employed by fire managers to affect fire extent and intensity (suppression resources and training). Fire managers operate under finite budgets, so their decisions are typically choices among competing means of intervening in wildfire processes [16].

This production function model for escape probability, together with insights from the inter-annual studies (RQ2-3) and the suppression system model (RQ1) will be useful inputs to the next model.

**FLEXIBLE DESIGN (SPATIALLY EXPLICIT INTRA-ANNUAL MIP) (RQ5)**

With this model, we will study the relationship between different types of operational flexibility, to mitigate exposure to demand uncertainty, in FFM. Modeling intra-annual FFM as multistage capacity investment, we will consider a portfolio of FFM resources, enabling fuel treatment and suppression, with fires as demand.

Demand uncertainty has two origins: inter-annual weather variability (oscillations in fire season severity); and micro-scale factors (ignition, time, place, escape probability, and specific fire severity). We focus our analysis on mismatch risk (supply differing from demand): over-investment in FFM capacity will lead to unused capacity costs, whereas under-investment will lead to forest value losses (not satisfying demand). Inter-annual weather uncertainty will be modeled with scenario trees (considering winter, spring, and summer) and micro-uncertainty with spatial grids of forest districts (characterized by daily ignition probabilities).

We will address two types of flexibility, regarded as ability to adapt to change: postponement of the commitment to each capacity type (prevention/suppression), fine-tuning of the capacity mix as the year evolves (weather conditional probability changes); and spatial flexibility in trade-off with different resource type costs (helicopters and ground crews).

**References**


