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Flexible design of a cost-effective network of fire stations, considering uncertainty in the geographic distribution and intensity of escaped fires

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Abstract

This paper proposes an improved strategy for allocating fire-fighting vehicles to Local Dispatch Centers (LDCs) over a region. By considering the uncertainties in fire location and intensity, and a flexible design, it develops a plan more cost-effective than that from a traditional deterministic approach, reducing the number and cost of required vehicles.

While small fires occur regularly and call for 'first response' equipment to be available close to susceptible fire-prone areas, large fires occur rarely and take time to develop. Thus the 'extended attack' equipment needed for larger fires can be held in reserve over a larger area, serving in effect as insurance against rare events. A layered strategy removes specialized equipment from the front lines and locates it in strategic reserves located in some of the pre-existing fire stations. The proposed solution thus reduces specialized equipment.

Innovatively, the analysis applies simulation to the management of fire-fighting resources, in order to deal with uncertainty in the number of deployments and location of fires over time. The approach first uses location algorithms to calculate optimal sets of fire stations. It then uses simulation to determine the probability distributions of outcomes of several performance measures (e.g., distance run by vehicles, vehicle utilization, or fire access time). The simulation implements flexibility by considering decision rules to open and close LDCs, according to recent observations of leading parameters. The outcomes of the simulation allow decision-makers to evaluate the performance of the flexible design in four different scenarios: as-is, intensification through wildland urban interface expansion or climate change, and attenuation (i.e., surveillance investment and law enforcement).

Finally, we use data available from ANPC and AFN/ICNF to compare the current design with the proposed flexible design, in a case study of the district of Porto, in Portugal. The results show that this design (a partially centralized strategy) leads to a cost-effective allocation of equipment and could reduce investment costs up to about 68 percent.

Keywords: *forest fire suppression, flexibility, network design, capacity planning, operations strategy*

1. Introduction

Portugal has an old and hardly used fleet of fire-fighting vehicles. These vehicles have more than 34 years on average and their underutilization is reflected by the mere 80 km they travel every year on average. The main goal of this research is to define a flexible design for the location of this fleet, to improve vehicle utilization efficiency without compromising its effectiveness.

We propose the centralization in Local Dispatch Centers (LDC), located in pre-existing fire stations (*Corporações de Bombeiros*), of some of the vehicles used in extended attack, deployed well after the initial emergency call, when containment by initial attack fails. These vehicles do not need to be immediately close to potential fires to ensure current levels of protection.

The model carries out a simulation to compare the current design with a proposed flexible allocation of equipment to LDCs, which can adjust to the changing location and nature of the forest fires. To deal with the uncertainty in the number and location of fires, a flexible approach opens and closes LDCs, according to recent observations of leading parameters - some of the current fixed locations as the

LDCs are selected to be open each year, according to the severity of the past three seasons and the number of LDCs open in the previous year.
Using the district of Porto, one of the eighteen districts of Portugal, as a case study, four envisioned trends are also analysed in independent scenarios: business as usual, evolution of the Wildland-Urban Interface, increased forest surveillance and law enforcement.

2. **Methodology**

Our model combines optimization and simulation to assess the flexible design in each of the four scenarios, over a 20-year period, considering one-year time-steps.
First, for each possible number of LDCs in a given range, and using historical data, we determine the set of LDC locations that minimizes the total distance run by vehicles (Cooper 1963; Kotian *et al.* 2009; Aravind *et al.* 2010). The potential locations are the currently existing firehouses, to decrease the costs of implementing the new design.
Second, in the simulation component, the model uses the locations of LDCs and the uncertain XY coordinates of fires to calculate the distance run by vehicles. The main driver of uncertainty is the total number of deployments per year, which depends on fire weather, modeled as an independent mean reverting process (Chow and Regan 2011). Empirical data is used to obtain this parameter and generate grid-based spatial distributions of vehicle deployments for each scenario, i.e., specific 2D distributions for each time-step, accounting for the uncertainty in the location and intensity of fires (Figure 1).

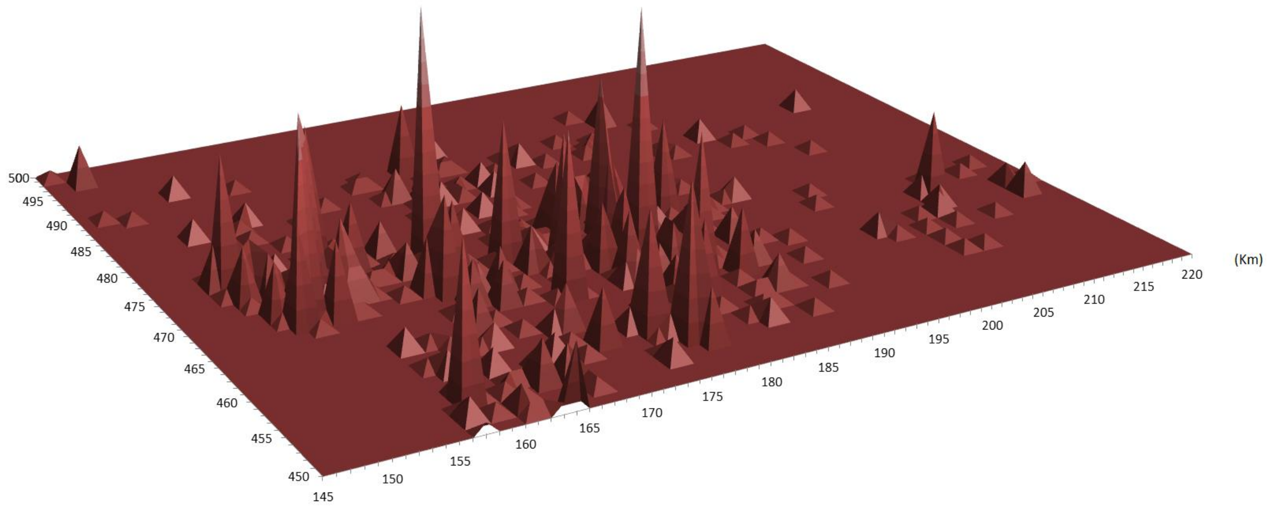

Figure 1. Graphical representation of a 2D distribution of escaped wildfires in the district of Porto, generated from a grid of one square kilometre

The model includes flexibility by applying, at each time-step, two decision rules to determine whether LDCs should be opened and/or closed given the new fire scenario conditions. Once the LDCs are fixed, the model calculates trip distance, time required to access fires, and thus extra time spent. The same procedure is repeated for the current network of firehouses, to compare the current and the proposed flexible design.

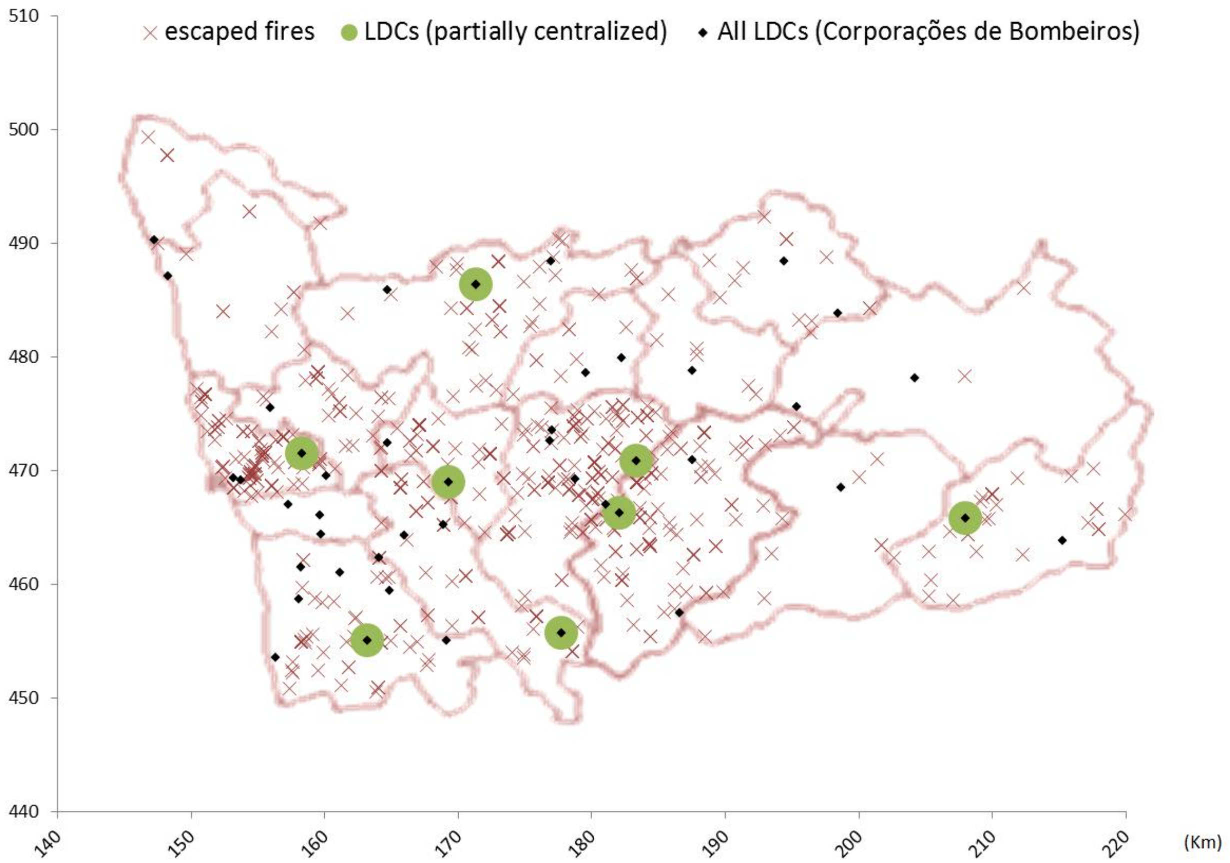

Figure 2. The best 8 (out of the current 45) LDC locations and randomly generated escaped fires, preserving the spatial pattern of historical forest fire data

For all the parameterizations, we use the Portuguese official fire databases, from ANPC and AFN/ICNF, the latter being the largest such database in Europe in terms of total number of recorded fires in the 1980–2005 period (Pereira *et al.* 2011).

3. **Findings**

Using one of the eighteen districts of Portugal as a case study (Porto, Figure 2), in the flexible design, the current fixed 45 locations were reduced to no more than 16 in the four scenarios. This design leads to a cost-effective allocation of equipment. Indeed, just in the case of the Porto district, it could reduce the investment in vehicles by about 6.5 M€, for a potential fleet reduction of up to 68%.
Additionally, the protection levels remain constant by keeping 90% of the potential fire-events within 10 km of the closest LDC and an average extra access time of sixteen minutes: these two indicators are reasonable given that they concern vehicles that are deployed after the fire escapes the first containment.

4. **Contribution**

This research tackles the issue of how to manage fire-fighting resources more cost-effectively. Analysis of empirical data of 2003 through 2005 provided by ANPC and AFN/ICNF, shows that Portugal has a very old and hardly used fleet of fire-fighting vehicles.
Our results show that a partial centralization by applying the proposed flexible design improves vehicle utilization efficiency while maintaining its effectiveness. The increased utilization reduces the number of vehicles needed and thus the cost of renewing the fleet (by about 100 M€). Policy makers might

consider using this new design as a strategy to address the lack of a management plan to procure equipment, since it eases the modernization of the current fleet.

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