# The Wildfire Risk Management System of Portugal:

## Using Decision Rules in a Simulation Model to Minimize Total Costs

## Abstract

This report attempts to model the wildfire risk management system of Portugal using Monte Carlo simulation and flexible decision rules to assess the value of flexibility in system design. Wildfire is a serious problem in Portugal, as the number of ignitions, the spread of the fires, and the damages caused are all increasing over time. While an increasing trend may be evident, it is uncertain how severe the fire season will be from year to year. Flexible designs help prevent the potential losses incurred from this uncertainty by exercising different options during the evolution of the system.

While there are many sources of uncertainty that complicate fire prevention and management, this report uses the demand for crew-hours of firefighting labor as the proxy for the level of fire activity in a given fire season. This is a simplified representation of the resources required to suppress an uncertain level of fire, but it makes the simulation model tractable.

Under this uncertainty, two fixed designs and three flexible designs are evaluated over a 20-year planning horizon. The first fixed design derives the optimal number of Portuguese crews required to minimize the NPV of costs. This design implicitly assumes an unconstrained budget at the beginning of the planning horizon to reach optimality. The second fixed design assumes a constrained budget throughout the planning horizon, and thus no additional crews can be hired at any time. The three flexible designs build on the latter fixed design in an effort to minimize the NPV of total costs. The first design allows Portuguese fire agencies to contract out foreign firefighting labor when demand for crew-hours exceeds firefighting capacity. The second allows expansion of the domestic Portuguese crew force, and the third is a combination of both flexibilities.

By implementing flexible decision rules into the simulation model, interesting insights can be gained into the nature of the system. All of the flexible options stochastically dominate the fixed design under limited budget. The contracting out and expansion options have advantages and disadvantages over each other, but the combined flexibility by far yields the lowest NPV of costs over the lifetime of the system. This option also performs better than the first fixed design, meaning that even if the Portuguese government can afford to increase their crew capacity to the optimal level in year 0, the combined flexibility still yields a lower NPV of total costs and does not require large upfront capital expenditures.

The model employed in this study is subject to many assumptions and arbitrary parameter values, so future work and data collection can improve on these limitations. Nonetheless, it seems evident that incorporating flexibility into the design of the wildfire risk management system of Portugal allows decision makers to minimize total costs under the variability of inter-annual fire activity and severity.

# Table of Contents

# 1. Defining the System

This report examines how incorporating flexibility into the design of a complex system can increase overall system performance. The system examined is the wildfire risk management system of Portugal, which is responsible for the prevention and management of fires in the country. The number of ignitions, fire spread, and severity in a given fire season are all uncertain, and flexible designs attempt to mitigate against this uncertainty by minimizing the losses and maximizing the gains of the fire risk management system. This section provides some context of the wildfire problem in Portugal and gives a simplified view of the system design concepts that will be evaluated in this report.

## *1.1 Context*

Wildfire is a serious national problem for the country of Portugal. The number of ignitions, number of hectares burned, and the subsequent damages to the ecosystem, property, and the economy have all been increasing (Beighley, 2009; Beighley & Quesinberry, 2004). In 2003, the damages from wildfire were particularly devastating, burning nearly 450,000 hectares (Trigo et al., 2006), which greatly strained the firefighting capacity for intervention and suppression activities. Figure 1 displays the burnt area of Portugal between 1980 and 2010; exceptional fire seasons of 2003 and 2005 are evident. A linear trend line was fit to the data, indicating a gradual increase in total burned area over the years. However, it is clear from the graph that the 2003 and 2005 fire seasons are the major cause of this increasing trend. Whether or not those two seasons were outliers, a function of global climate change, the result of organizational failure or social change, or some other set of factors is a matter of debate. Nonetheless, the Portuguese government declared wildfire to be a problem of national security following these two seasons, and it is the belief of various experts in the fire policy field that the next major fire season is right around the corner (Beighley, 2009).

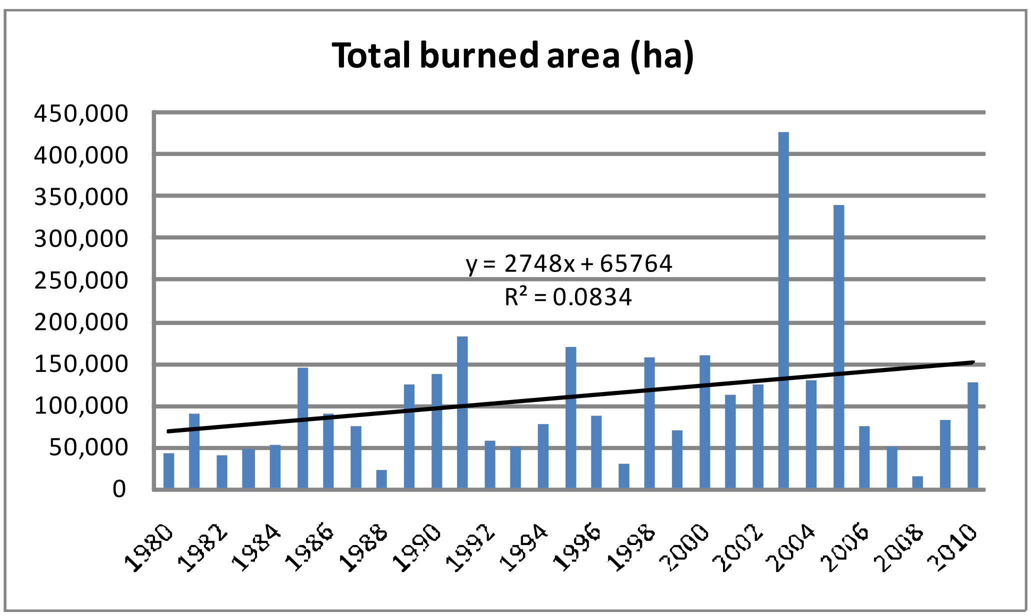


**Figure 1. Inter-annual variability of burnt area in Portugal, 1980-2010 (Oliveira, 2010).**

Preventing and protecting against wildfire is a difficult problem because many of the factors that affect ignition rate and fire spread are uncertain. There is also uncertainty around the responsiveness of firefighting crews to effectively detect a fire, dispatch resources, and ultimately suppress the fire. Finally, the budget for firefighting resources is variable from year to year, depending on the political climate, possible regime changes, and shifts of priority in government programs. The wildfire risk management system is therefore an example of a complex, engineering system with multiple sources of uncertainty, organizational responsibilities, and decision levers. The question, therefore, is how can Portugal dispatch resources most efficiently to cope with these uncertainties? This project examines flexibility in design through real options analysis in order to develop some preferred solutions to this problem.

## *1.2 System Concepts*

The wildfire risk management system of Portugal can be evaluated on many different temporal and domain-specific scales. For example, one can model the optimal timing schedule of prescribed burns in a forest stand in order to manage the flammable fuels accumulation. Another approach could look at the decision making structure of fire suppression (e.g. what resources to deploy and to what priority locations, where to plow fire lines, etc.) after a fire has been detected. These approaches look at two different aspects of the system with long and short planning horizons. To narrow the scope of decision making into a tractable model, this report evaluates how best to deploy firefighting "crews" during the fire season over a twenty year period. The author is not currently aware of the firefighting capacity of Portugal, so the term crew is used as a discrete unit of capacity in the model. These crews include various types of personnel positions (handcrew, hotshots, smokejumpers, rappellers), as well as the equipment and vehicles that these crews operate (fire retardants, fire engines, plows, helicopters). The size of each crew, in terms of personnel, equipment, and vehicles, is arbitrary (again because it is unknown), but they are assumed capable of an equivalent amount of work in the model.

It is also assumed that the fire agencies of Portugal have a certain capacity of crews available to fight fire at the start of year 0. This report examines fixed and flexible designs of how to manage and deploy these crews during 20 fire seasons, which occur yearly. The fixed designs do not allow adaptive decision making over the course of the 20 fire seasons. In other words, decision making occurs only at the beginning of year 0, and no subsequent decisions can be made over the course of the 20-year evolution of the system. The flexible designs incorporate decision rules over the lifetime of the system that allow decision makers to exercise various options if certain criteria are met. These options increase long-term system performance, and thus illustrate the value of flexibility in design. The designs are evaluated analytically using a Monte Carlo simulation model, discussed later in the report.

Fixed Designs:

- *Unconstrained Budget* – This design assumes that the government of Portugal has an unconstrained budget for training and deploying Portuguese firefighting crews. In other words, they can spend as much money as they want at the outset to ensure that total costs are minimized over the 20-year demand projection.
- *Constrained Budget* – This design assumes that the government cannot (or will not) spend any money on training and deploying Portuguese crews above the current capacity.

Flexible Designs:

- *Contract Out* – This design allows foreign firefighting crews to be contracted for additional labor (at a premium price) during seasons of high fire activity.
- *Expand* – This design allows for the expansion of the Portuguese firefighting labor force by training and deploying additional crews after seasons of high fire activity.
- *Do Both* – This design is a combined approach that includes contracting out to foreign labor and expanding Portuguese crews.

The first fixed design, while it seeks to minimize total costs, is unrealistic. It is unlikely that the Portuguese government will be able to make a large upfront expenditure to the fire budget at the onset of the 20-year planning horizon, especially given other budget requirements. The second fixed design is also unrealistic, as the government will likely have at least some money to spend on the firefighting infrastructure. Nonetheless, the fixed designs represent two important (and widely used) designs in decision modeling, the deterministic optimal design and the business as usual design, respectively. In addition, they provide a useful platform on which to incorporate the flexible designs, which will be shown later.

# 2. Defining the Uncertainties

There are many sources of uncertainty that characterize wildfire risk management. Including all of them into one model is not only unrealistic, but would make the results of such a model very difficult to meaningfully assess. This section discusses the two sources of uncertainty built into the simulation model, but also discusses other important sources of uncertainty that could be addressed in future work.

## *2.1 Demand for Crew-Hours of Firefighting Labor*

The major uncertainty in wildfire risk management is the behavior of all the fire that occurs during a particular fire season. The fire season occurs generally between June and September in Portugal, with peak fire activity at the beginning of August. Figure 2 displays the total monthly burnt area in Portugal between 1980 and 2003. The uncertainty in fire behavior each fire season can be modeled according to the number of ignitions that occur over space, the spread (spatial extent) of individual or multiple fires, the severity (often measured by flame length) and effects of fire, or some combination thereof. A quick search of the literature will reveal how varied the approaches are to modeling these uncertainties.

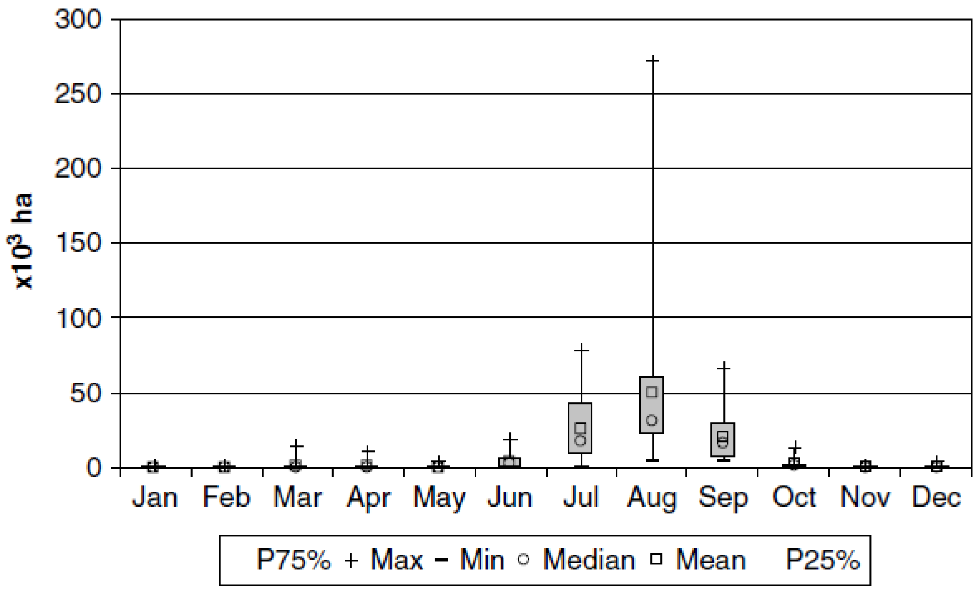


**Figure 2. Total monthly burnt area in Portugal, 1980-2003 (Trigo et al., 2006).**

This report uses the demand for crew-hours of firefighting labor each fire season as a crude proxy for all of these uncertainties. In seasons where there are many severe fires, the demand for crew-hours will be higher. When there are not as many severe fires (perhaps due to an unusually wet summer), the demand will be lower. Rolled up in this demand is yet another uncertainty, namely, the year-to-year variation in weather and climate. In one fire season the climate of Portugal could be exceptionally hot with multiple dry bouts due to abnormal weather effects, but the following year could be the opposite. Some posit that there could be an increasing trend in the demand for crew-hours (i.e. fire activity) due to the hypothesized warming effects of global climate change (Beighley, 2009). This potential effect would add validity to the increasing trend line of year-to-year burned area shown in Figure 1, and may also help explain the exceptional fire seasons of 2003 and 2005. While this trend has not been proven, it is assumed to exist within the model. Figure 3 displays this projected increasing demand for crew-hours starting at an arbitrary initial demand in year 0. The actual demand from year to year is uncertain, and thus fluctuates around the projection. It is important to note that the demand for crew-hours is assumed to be an exogenous variable, when in reality it is endogenous since demand in one season can be reduced by actions taken in previous years. The demand projections displayed in Figure 3 are entirely made up, but they are sufficient for meeting the objectives of this paper.

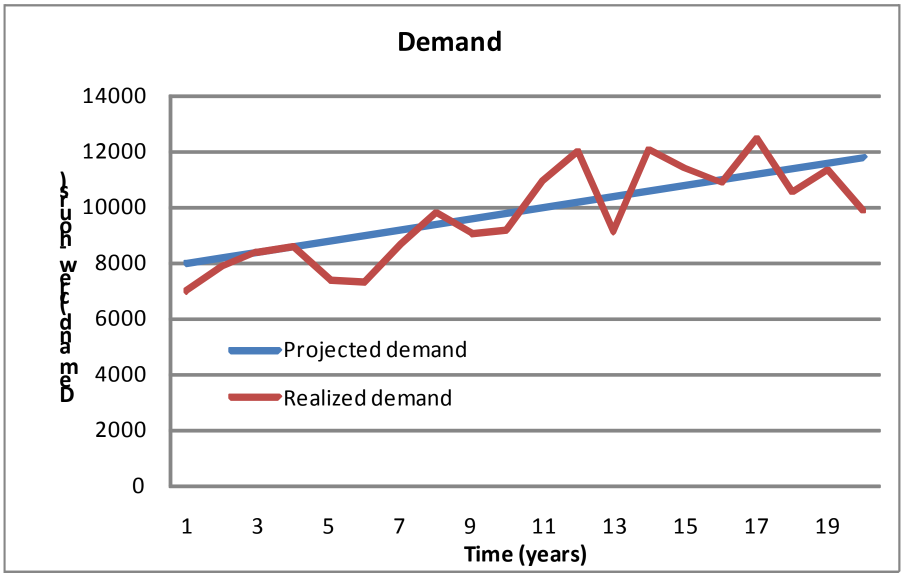


**Figure 3. Projected increasing demand for crew-hours and the uncertainty around this projection.**

## 2.2 Available Budget

The uncertainty surrounding the fire suppression budget is inextricably linked to the uncertainty in fire behavior (demand for crew-hours) from season to season. Historically, the United States Forest Service (USFS) has used the 10-year moving average of suppression expenditures in its annual budget request to Congress. But, given that fire activity and costs are steadily rising, the 10-year moving average budget formula has translated into shortfalls in available suppression funds nearly every year since the mid 90s (Holmes, Prestemon, & Abt, 2008). It is reasonable to assume that the Portuguese equivalent of the USFS has suffered from the same insufficiencies in budget, in particular during the devastating fire season of 2003. Fire agencies also typically develop budget requests 2-3 years before the start of the fiscal year in question (Holmes et al., 2008). Catastrophic fire seasons, political regime changes, and organizational failures, among many other rare events, can occur during those 2-3 years, which may substantially alter the budget required for fighting fire in subsequent fire seasons. While budget uncertainty is not directly incorporated into this model, readers should be aware of this uncertainty when evaluating different design options in the wildfire risk management system.

## 2.3 Other Sources of Uncertainty

Aside from uncertainties related to the behavior of fire, weather and climate patterns, and the available firefighting budget, other important sources of uncertainty pertaining to human action exist. In other words, the ways in which humans behave is not predictable, and their actions affect the performance of the fire risk management system. In Portugal, 97% of the fires that occur are caused by humans (Beighley, 2009). These human-caused ignitions can be accidental or on purpose (arson), but either way they are subject to the uncertainty of human action. There may also be variability in response effectiveness across the different firefighting crews. Certain crews may be managed and run more efficiently than others, or there may be poor communication in and across crews. The organizational uncertainty that results from these factors may limit the effectiveness of fire suppression efforts. Finally, there are socioeconomic conditions in Portugal that have led to rural abandon and subsequent migrations to the coastal cities (Moreira, Rego, & Ferreira, 2001). Fuels are accumulating rapidly in the rural inland areas where various properties (houses, barns, sheds, farms) are no longer occupied. Predicting these socioeconomic shifts is difficult, but the uncertainty needs to be acknowledged.

# 3. Designing the System

This section describes the model used to simulate evolution of the fire risk management system and evaluate the different design strategies. System parameters in the model are presented, as well as the measures used to assess system performance.

## *3.1 System Parameters*

Many of the system parameters in the model are arbitrarily assigned. Limited datasets and simplification (in order to increase tractability) of the model made it difficult to assign credible values to the parameters. However, given the user-friendly spreadsheet design of the model, it will be easy to add better parameter values as they become readily available. Table 1 displays the parameters used to determine the optimal crew capacity under the fixed design with an unconstrained budget.

**Table 1. System parameters for a fixed design.**

| | | | |
|---|---|---|---|
| 3 | Demand projections | | |
| 4 | Demand in year 1 | 8000 | crew-hours |
| 5 | | | |
| 6 | UNCERTAINTY ASSUMPTIONS | | |
| 7 | Realised demand each year within | 20% | of demand projection |
| 8 | | | |
| 9 | Average operating costs | $200 | per crew-hour (wages, equipment, etc.) |
| 10 | Average cost of escaped fire | $5,000 | per crew-hour (demand not met) |
| 11 | Fixed costs per crew (above 4) | $5,000,000 | per crew (training, facilities, etc.) |
| 12 | Fixed costs (total) | $20,000,000 | |
| 13 | | | |
| 14 | Capacity limit | 1500 | hours per crew |
| 15 | Initial capacity | 4 | crews |
| 16 | Optimal capacity | 8 | crews |
| 17 | | | |
| 18 | Time horizon | 20 | years |
| 19 | Discount rate | 3% | |

The initial demand for crew-hours at the beginning of the 20-year planning horizon is assumed to be 8000 (recall from Figure 3 that this demand is assumed to grow linearly from year to year). The uncertainty around each yearly demand projection is 20%. In the model, it is assumed that at the beginning of year 0, Portugal has an initial capacity of 4 crews. The initial capacity of 4 crews is made up, but it represents the state of Portuguese firefighting capacity at the beginning of year 0. As can be seen from Table 1, the optimal capacity under an unconstrained budget is 8 crews, so 4 additional crews were trained under the deterministic optimal design. New crews can be trained for a fixed cost of $5 million per crew, and average operating costs of each crew-hour is $200. Each crew has a maximum capacity of 1500 hours of labor in each fire season, and the assumed per-hour cost of escaped fire (i.e. when the demand for crew-hours exceeds the capacity of crew-hours available, and fire is therefore not suppressed) is $5,000. A discount rate of 3% is used since the opportunity cost of investing the money elsewhere is low. In other words, the

Portuguese government is unlikely to invest the money spent on wildfire risk management in high-return equity since fire is a problem of national importance, and the government has a responsibility to protect its people. Also, this is a problem of minimizing total costs, not maximizing profit, so highly discounting future costs will make the country feel safer under fire risk than it is in reality.

### *3.2 Assessing System Performance*

As mentioned above, the objective function of the Portuguese fire agencies is to minimize total costs. These costs manifest through operating expenditures, but also through escaped fire. Thus, optimal design strategies will minimize the sum of these costs. There are no revenue streams generated from suppressing fire in this model. Expected net present value (ENPV) is the primary metric used for assessing system performance. When evaluating different design options, the value at risk and gain (VARG) curve is also used to understand the distribution of outcomes that can occur under different designs. Specifically, extreme values $P_5$ and $P_{95}$ are used to understand the tail behavior of the VARG curves, also called cumulative distribution functions, or CDF. Using a simple maximum and minimum, while informative, should not be used exclusively, since it is unlikely that the simulation model will do enough random sampling to uncover these true values.

## 4. Modeling the System using Simulation

Monte Carlo simulation was used to model the evolution of the system over time. Simulation is a useful tool for incorporating multiple decision rules into a large decision framework. It is also useful for systems that are not easily modeled by other tools, such as decision trees or lattice models. This section evaluates the different fixed and flexible designs of the wildfire risk management system in Portugal. These designs stem from the system concepts discussed in Section 1.2.

### *4.1 Fixed Designs*

Two fixed designs are evaluated, one in which an unlimited budget is available in for investing in Portuguese firefighting crews, and the other in which there is no budget available for additional crews (and thus there are only 4 crews for the entire 20 year planning horizon).

#### 4.1.1 Unconstrained Budget

As mentioned previously, it is assumed that the fire agencies of Portugal are initially endowed with 4 well-trained firefighting crews and the facilities to support them. Given that there are no flexible options to exercise, the decision problem is a simple optimization that seeks to minimize total costs. The decision lever (or variable) is the number of additional crews to purchase and train. Figure 4 is a graph comparing crew capacity and NPV of costs given that there is no uncertainty in demand (i.e. the static case). As can be seen from the graph, there is a relative “sweet spot” at 8 crews where NPV is minimized (the peak of the curve is where costs are lowest). Under 8 crews, the NPV of costs is approximately $56 million. Some interesting insights can be gained from the shape of the curve. Referring back to Table 1, it is clear that operating expenses per crew-hour of labor is much less expensive than the potential per-hour damages of fire that is not managed or suppressed ($200 versus $5,000 respectively). That is why the curve starts at such a low NPV and rises sharply as new crews are added. After reaching the optimal level of 8 crews, the curve starts to decline again as operating expenses increase even though the additional crew-hours are not being utilized. But, since the unit operating expenses are so much less costly than escaped fire, the slope of the curve is much flatter after the optimum has been reached. The curvature of the graph is thus representative of the parameter values chosen, and as more credible numbers are inserted into the model, the curve shape will change.

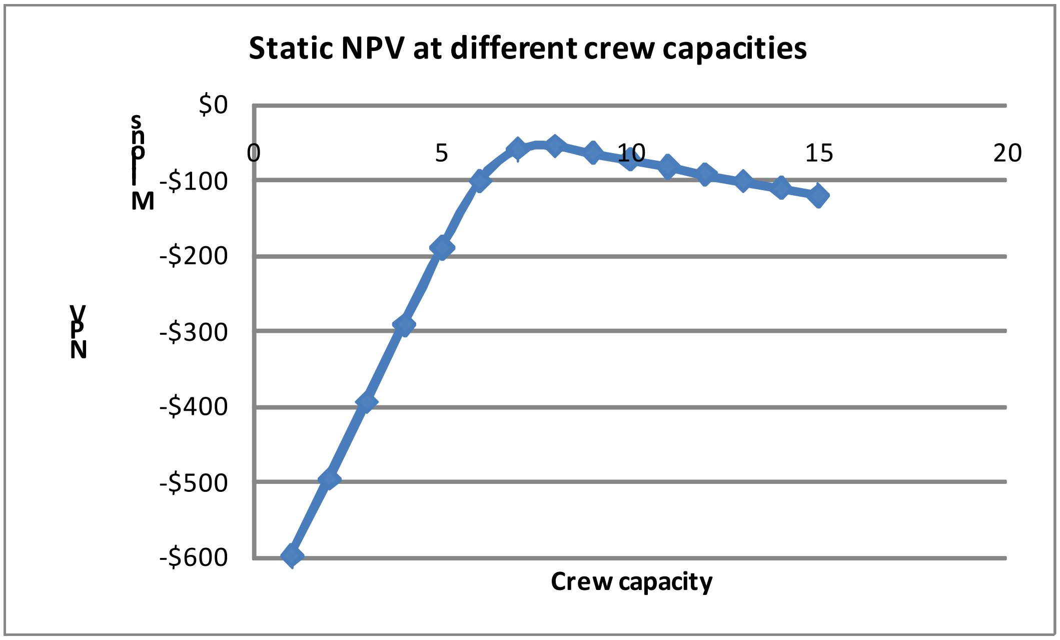


**Figure 4. Optimal crew capacity under no uncertainty in demand.**

Table 2 shows the last seven years of cash flows in the system under the capacity of 8 crews (12,000 crew-hours at 1500 crew-hour capacity per crew). It is important to point out that under 8 crews and with no uncertainty, capacity always exceeds demand. Again, this makes sense given the discrepancy in operating expenses and escaped fire costs. Thus, the costs of escaped fire under a deterministic 8-crew regime will never be realized. All of the costs instead stem from the operating expenses and the fixed costs of employing the additional 4 crews (on top of the initial 4).

**Table 2. Cash flows of the last seven years under deterministic fixed design with unlimited budget.**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 18 | Year | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 19 | Demand | 10600 | 10800 | 11000 | 11200 | 11400 | 11600 | 11800 |
| 20 | Capacity | 12000 | 12000 | 12000 | 12000 | 12000 | 12000 | 12000 |
| 21 | Revenue | $0 | $0 | $0 | $0 | $0 | $0 | $0 |
| 22 | Operating costs | $2,400,000 | $2,400,000 | $2,400,000 | $2,400,000 | $2,400,000 | $2,400,000 | $2,400,000 |
| 23 | Escaped fire costs | $0 | $0 | $0 | $0 | $0 | $0 | $0 |
| 24 | Fixed costs | $0 | $0 | $0 | $0 | $0 | $0 | $0 |
| 25 | Cashflow | -$2,400,000 | -$2,400,000 | -$2,400,000 | -$2,400,000 | -$2,400,000 | -$2,400,000 | -$2,400,000 |
| 26 | DCF | -$1,586,683 | -$1,540,469 | -$1,495,601 | -$1,452,039 | -$1,409,747 | -$1,368,686 | -$1,328,822 |

When uncertainty in the demand for crew-hours is included, the optimal number of crews is still 8, but the NPV of each capacity option necessarily decreases. This makes sense given that low activity fire seasons do not generate additional revenue, even though the entirety of the operating expenses is still realized. But, when there are high activity fire seasons, demand may exceed capacity and the costs of escaped fire will be incurred. Table 3 displays the ENPV of different crew capacity options under demand uncertainty. The ENPV measure is the result of 2,000 iterations in the Monte Carlo simulation model. Under demand uncertainty, the NPV of 8 crews is on average about $5 million more costly.

**Table 3. Crew capacity and corresponding ENPV under demand uncertainty.**

| Crew capacity | ENPV |
|---|---|
| 5 | -$193,278,978 |
| 6 | -$114,621,282 |
| 7 | -$72,416,823 |
| 8 | -$61,084,294 |
| 9 | -$65,357,136 |
| 10 | -$74,632,425 |

A simulation size of 2,000 iterations was deemed to be sufficient given computational limitations of the Excel-based model. Also, inspection of Table 4 shows that the summary statistics, including maximum and minimum, do not vary much across different simulation sizes. Since the statistics were relatively stable to simulation size for this fixed design, it was assumed that 2,000 iterations would be acceptable for the other designs as well.

**Table 4. Summary statistics for different simulation sizes.**

| Iterations | Mean | Max | Min | STD |
|---|---|---|---|---|
| 2,000 | -$61,004,184 | -$55,705,940 | -$74,583,608 | $3,569,186 |
| 5,000 | -$60,943,208 | -$55,705,940 | -$74,134,012 | $3,443,240 |
| 10,000 | -$60,956,476 | -$55,705,940 | -$78,120,302 | $3,469,020 |

### 4.1.2 Constrained Budget

While it is useful to think about the optimal value of Portuguese firefighting crews under a fixed design, it is unlikely that the Portuguese government will be able to allocate $20 million in upfront fixed costs to train the additional 4 crews and build the necessary facilities at the very beginning of the planning horizon. As mentioned previously, it is also unrealistic to think that the government will not have any budgetary dollars to spend on firefighting resources. However, this design (where the budget is effectively zero) is considered because it is a good base on which to build in flexible decision rules, and it represents business as usual, which unfortunately characterizes many government institutions. Thus, under this design, it is assumed that over the course of the 20 years, the Portuguese fire agencies have only the 4 initial crews at their disposal. This is a scenario that could in fact occur if poor economic conditions required the government to seriously slash funding in some of their programs. Regardless, it is no surprise that the ENPV of the costs incurred from this budget-constrained fixed design is approximately $293 million (as compared to the $61 million under the 8-crew fixed design).

## *4.2 Flexible Design 1: Contract for Foreign Labor*

Under this flexible design, understaffed fire agencies in Portugal can at any time exercise the option to contract out crew-hours from foreign countries (most likely Spain or France since both have similar dry fire seasons, and they are nearby). In other words, when demand for crew-hours exceeds the capacity, Portugal can hire labor from other countries at an elevated per-hour rate. This rate is arbitrarily set at $1,000 per crew-hour, five times the rate of Portuguese crews. This increase in expense can be associated with higher transaction, coordination, and planning costs that are required in order to get the foreign labor to Portugal in a timely manner so that the fires can be suppressed quickly and efficiently. It is assumed that when this option is exercised, exactly enough foreign crew-hours are contracted out to meet the capacity shortfall (i.e. make capacity exactly equal to demand). The model also assumes that the foreign crews have just as quick a response time as the domestic Portuguese crews. This is unrealistic however, and future work could develop a relationship between proximity of foreign workforce to the fire in Portugal, where longer distances result in higher escaped fire costs (due to longer response times).

Figure 5 displays the VARG curves for the fixed design with constrained budget (where only 4 Portuguese crews make up the entire firefighting labor force) and the flexible contracting option. It is evident that the flexible option stochastically dominates the fixed design (under existing assumptions), and by a sizeable magnitude. This makes sense given that instead of incurring $5,000 per hour of escaped fire costs, the Portuguese fire agencies are instead paying $1,000 per crew-hour of foreign labor. And, given the assumption of equal response times across Portuguese and foreign crews, this flexible design leads to substantial cost savings under demand uncertainty.

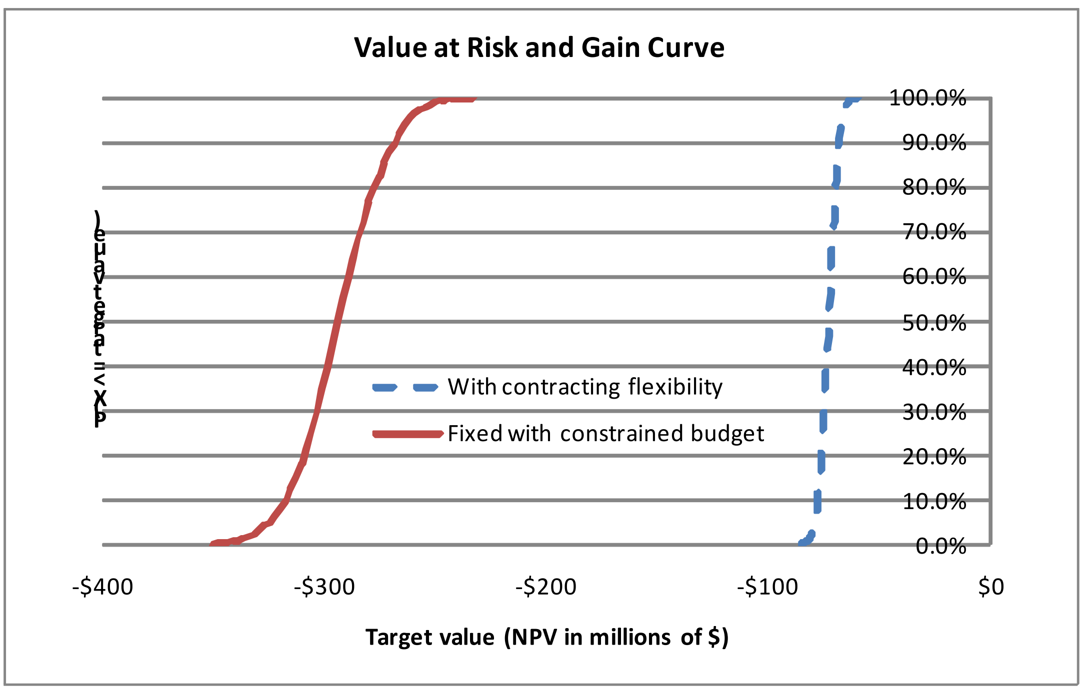


**Figure 5. VARG curves for fixed (no additional budget) and flexible contracting designs.**

## *4.3 Flexible Design 2: Expand Portuguese Firefighting Capacity*

Under this flexible design, the Portuguese fire agencies, initially endowed with 4 crews, are given the option to expand their number of firefighting crews by one crew after a year in which demand for crew-hours exceeded capacity. This expansion has a fixed cost of $5 million (this is the same parameter value used in Section 3.1). When the number of crews increases, operating expenses increase correspondingly. In the year in which demand exceeds capacity, the full effect of escaped fire costs is realized in that year. It is therefore assumed that capacity is increased at the end of the fire season for that year, and the newly trained crew is 100% available to fight fire in the following fire season. This flexible design is similar to the American call option, where some metric of capacity can be expanded given some criteria is met (i.e. a decision rule). There are some interesting features that distinguish the expansion option with the contracting out option discussed in the previous section. Figure 6 displays the VARG curves for the two options. The VARG curve for the fixed design under constrained budget is omitted given that it is stochastically dominated by both flexible design options.

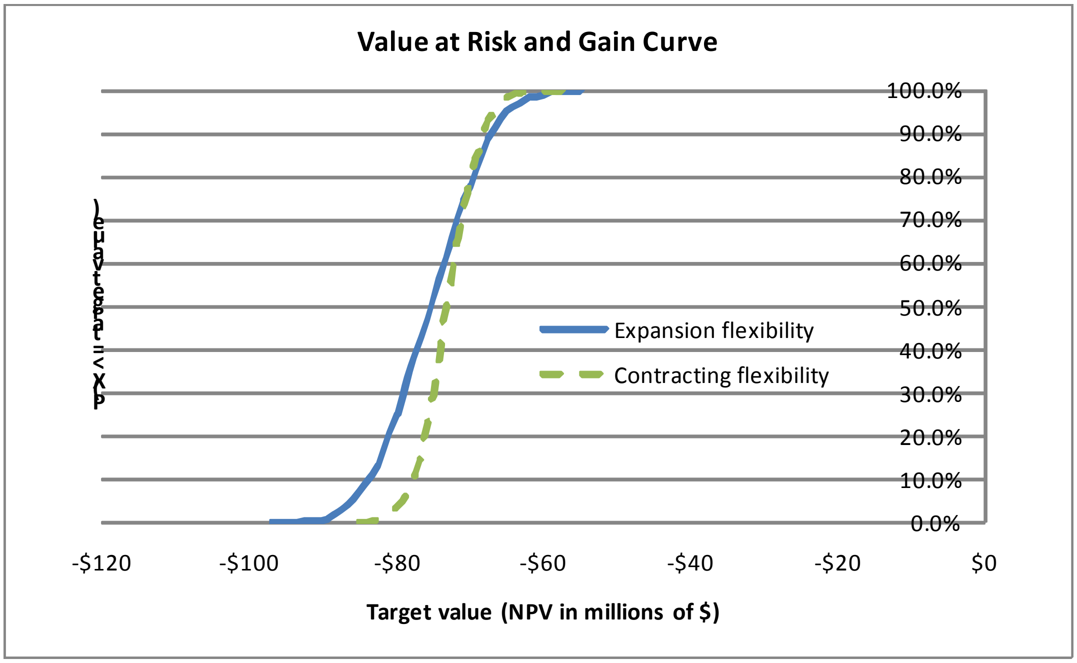


**Figure 6. VARG curves for the expansion and contracting out flexible designs.**

It is evident from the graph that neither of the curves is stochastically dominant, given that they intersect at around 80% probability. The contracting out option has a higher ENPV and a higher minimum, but the expansion option has the largest maximum. As mentioned previously, the goal of flexibility is to minimize the losses and maximize the gains in a system. With regard to the wildfire risk management system, the contracting out design minimizes the losses (smaller lower tail), but the expansion option maximizes the gains (larger upper tail). While the contracting out option has the highest ENPV, choosing exclusively between these two designs may ultimately depend on the risk preferences of the decision maker, or decision making entity. Table 5 provides some useful statistics comparing the two flexible designs against each other and against the fixed design with unconstrained budget. From the table it is clear that this fixed design still outperforms the two flexible designs, though the expand option does result in a larger maximum on average. Flexibility was shown to be very useful over the business as usual case (i.e. fixed design with constrained budget), but under an unconstrained budget the fixed design is still better. The combined flexible approach, discussed in the following section, outperforms them all.

**Table 5. Statistics comparing expansion and contracting out with the budget-unconstrained fixed design.**

| Statistics | Expand | Contract Out | Fixed Unconstrained |
|---|---|---|---|
| Maximum | -$55,265,188 | -$60,313,298 | -$55,705,940 |
| P95 | -$64,425,672 | -$66,894,288 | -$55,705,940 |
| Mean | -$75,287,684 | -$72,869,606 | -$60,850,949 |
| P5 | -$85,971,069 | -$79,019,172 | -$66,998,461 |
| Minimum | -$94,041,753 | -$85,484,768 | -$74,726,409 |

## *4.4 Flexible Design 3: Combined Approach*

Given that neither of the two aforementioned flexible designs were stochastically dominant, a third flexible design was evaluated, which allows the decision maker to exercise both options simultaneously. This combined approach allows the Portuguese fire agencies to contract out foreign firefighting crews during fire seasons where demand exceeds capacity, but then also expand their domestic crews by one crew immediately following that fire season. By expanding their domestic force, the Portuguese government will hopefully not have to rely as much on the expensive foreign labor in subsequent fire seasons. Figure 7 displays the VARG curves for the expansion and contracting out options, the fixed design with unconstrained budget, and the combined approach. It is clear from the graph that the combined approach stochastically dominates the two flexible designs and the fixed design. What is even more interesting is the magnitude with which the combined approach dominates each individual flexible design. The two individual designs are roughly similar in scale, and their ENPV of total costs are relatively similar (about -$75 million for the expansion option and about -$73 million for the contracting out option). However, the combined flexibility that is achieved through the interaction of the two individual flexibilities is much greater than the simple "sum of the two parts". In other words, there is some very interesting nonlinearity that occurs through interaction of the two individual flexibilities that lead to substantial gains when they are combined together. The result of this nonlinearity is not intuitively obvious through mere inspection of the expansion and contract out designs. It is therefore very important to be thoughtful and creative during the design process to uncover new and interesting designs that can increase overall system performance.

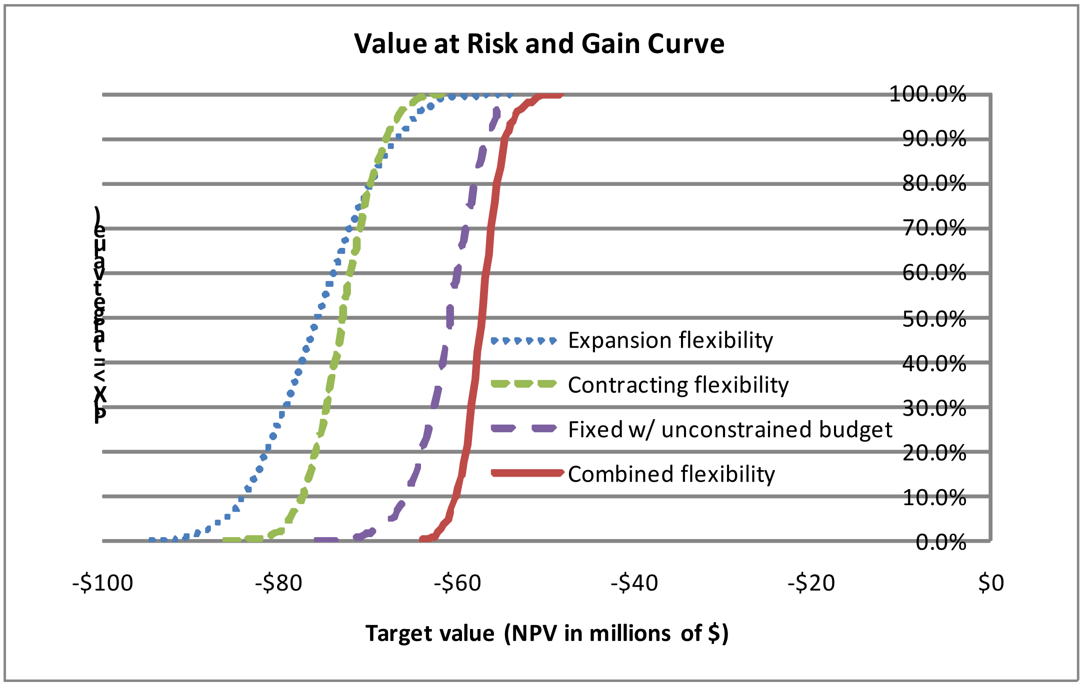


**Figure 7. VARG curves for individual and combined flexible designs.**

Recall that in Section 4.1.1, the optimal number of Portuguese crews (8) was derived based on the assumption that the Portuguese government had sufficient initial budget to front the capital required to train and house the new crews. Since the parameter values are arbitrary, this fixed design basically assumed that the government had an unlimited (or unconstrained) budget with which to train the optimal number of crews at the very beginning of the 20-year planning horizon. Under demand uncertainty, this design yielded an ENPV of about -$61 million in costs. Under the combined flexible approach, where a large upfront investment is not required, the ENPV of costs under demand uncertainty was only about -$57 million. Under this flexible design, overall system performance is better *and* it does not require large budget allocations at the beginning of the planning horizon. This result is important in light of the budgetary uncertainty discussed in Section 2.2. If budgetary uncertainty were incorporated into the model, then the gains of the flexible approach over the fixed design could be even greater. This could be an important avenue for future research.

# 5. Conclusion

This report built a Monte Carlo simulation model of the wildfire risk management system in Portugal in order to ascertain the benefit of flexible decision rules under demand uncertainty. In the model demand was defined as the number of crew-hours demanded each fire season, and it was assumed that this demand fluctuated within 20% of the projected estimate each year. It was also assumed that demand is increasing linearly over time due to the potential warming and drying effects of global climate change.

Using arbitrary system parameters, two fixed designs were constructed. In the first, the optimal number of crews was calculated under demand uncertainty assuming sufficient budget was available at the beginning of the planning horizon. The second fixed design assumed that the Portuguese fire agencies could rely only on their initial crew endowment given a scarce (or nonexistent) budget for additional crews. Three flexible designs, contracting out foreign crews, expanding Portuguese crews, and doing both, were built on top of the second fixed design in order to measure the value of flexibility. Combing the two flexibilities into one flexible design resulted in a stochastically dominant design that also resulted in fewer expected costs than the fixed design with unconstrained budget.

There are many limitations in the current model as it is based on several assumptions, but sacrifices to accuracy needed to be made in order to increase tractability of the model. Future work could produce better estimates of cost figures and a measure of demand for crew-hours that is functionally dependent on the predicted number of ignitions, fire extents, and severities. Improving these parameters will make the results more meaningful to decision makers in the Portuguese fire agencies, and it may even alter some of the conclusions. Regardless, this report showed that the nonlinearity present in complex and uncertain engineering systems lends itself to incorporating flexibility into design in order to increase system performance over the long-run.

# 6. Course Reflection

*Where do you see the most use for the flexible approach to design?*

The flexible approach to design is most useful when there are multiple uncertainties affecting the performance of the system being analyzed. These uncertainties are what create nonlinear outcome spaces from utilizing, or combining, different flexible approaches. Flexibility in design is therefore particularly useful in large-scale, complex, and socio-technical systems. These systems are often subject to large capital expenditures, multiple sources of uncertainty, and interactions with human designers and decision makers. If people are allowed to exercise options when the confluence of uncertainties and system evolution lead to particular system states, then the value of flexibility will be evident from the potentially substantial differences in NPV across designs. While the focus of this class has mostly been on large-scale infrastructure projects (e.g. mines, power plants, parking garages), I think there is application to major policy questions, such as the debate around climate change and investing in high failure rate emerging energy technologies. In the future, it would be nice to see examples such as these gone over in more detail during class and/or homework time.

*What do you feel that you have learned from the process of doing this application?*

Doing this application was a very valuable experience, especially since this work is the subject of my thesis. While designing this system was an imperfect process that still relies on many assumptions, each application forced me to be thoughtful about how I was going to model my complex system. I struggled quite a bit at first, since the nature of my system and its uncertainties were inherently different from the examples done in class and in the homework (again, here the focus was on infrastructure projects). But, with the help of the professors and the teaching assistants, I was able to model the wildfire risk management system of Portugal in a simple, yet tractable that can now be expanded upon in future work. Overall, I think the application portfolio is useful for getting students to think creatively about a system they'd like to model, and I think students should in the future be encouraged to tackle some of the more unorthodox engineering systems.

## References

Beighley, M. (2009, June). *Forest Defense against Fire in Portugal: Situation and Capability*. Beighley Consulting LLC.

Beighley, M., & Quesinberry, M. (2004). *USA-Portugal Wildland Fire Technical Exchange Project*. USDA Forest Service.

Holmes, T. P., Prestemon, J. P., & Abt, K. L. (2008). *The Economics of Forest Disturbances: Wildfires, Storms and Invasive Species*. Springer Verlag.

Moreira, F., Rego, F. C., & Ferreira, P. G. (2001). Temporal (1958–1995) pattern of change in a cultural landscape of northwestern Portugal: implications for fire occurrence. *Landscape Ecology*, *16*(6), 557–567.

Oliveira, T. (2010). *Totais Distrito (1980-2010)*. Portugal: Ministério da Agricultura.

Trigo, R. M., Pereira, J. M., Pereira, M. R., Mota, B., Calado, T. J., Dacamara, C. C., & Santo, F. E. (2006). Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. *International Journal of Climatology*, *26*(13), 1741–1757.