Simulation Analysis of a Wildfire Suppression System[1]

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Abstract

Rekindles and false alarms are unusually high in the Portuguese wildfire management system, representing a high burden on suppression resources in particular, and fire management resources in general. In 20,049 occurrences that the suppression system handled in the summer of 2010, 12.5% were false alarms and 15.0% were rekindles. We present a discrete-event simulation model of a wildfire suppression system, designed to analyze the joint impact of primary fires, rekindles and false alarms on system performance. The work contributes to fill a research gap concerning that impact, and features a novel application of simulation to suppression systems, as screening tools to support more holistic analyses. The model was implemented in ®ARENA, and used for a study of a Portuguese district. We found that reducing false alarms and rekindles to benchmark values would significantly reduce pressure on firefighting teams, enabling more effective suppression operations.

Key Words: Arson, Discrete Event Simulation, False Alarm, Hoax Calls, Rekindles.

Introduction

During the summer of 2010 Portugal registered 2,497 rekindles, a 17.2% increment to the 14,551 primary forest fires, leading to a total of 17,048 wildfires (Pacheco and others 2012). However, this figure may in reality be more extreme. Several authors indicate that the number of rekindled forest fires is higher than what is officially reported (ANIF 2005, Lourenço and Rainha 2006), and experts that we have interviewed point to the double. Even assuming that the reported data are correct, the proportion of rekindles is too high (Beighley and Hyde 2009). This situation has worsened over the years (ANIF 2005), and is mostly the result of ineffective mop-up operations (Lourenço and Rainha 2006, Murdock and others 1999, Lourenço 2007, ISA 2005, ANIF 2005, Beighley and Hyde 2009), despite an effective initial attack

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(ANIF 2005, Lourenço 2007, Lourenço and Rainha 2006). An ineffective mop-up and lack of surveillance (Lourenço 2007) lead to rekindles that often become large fires (ANIF 2005, Lourenço 2007, Lourenço and Rainha 2006). These are usually larger than the wrongly judged extinguished primary fire, with large burnt areas and considerable damage (ANIF 2005), even when the initial perimeter was just tens of meters (Lourenço and Rainha 2006).

In addition to rekindles, that are sometimes wrongly interpreted by the public as arson fires (Lourenço and Rainha 2006), the wildfire suppression system is also challenged by false alarms – malicious or good intent calls made to dispatch centers and fire departments. Because they cannot presume that a call is a false alarm and must respond as they would to a real fire (Ahrens 2003), hoax calls represent a waste of energy for the suppression teams. This means that 3,001 more events of this kind (20.6% of the primary fires) are added to the 17,048 wildfires, with rekindles and false alarms in total representing 27.4% of the 20,049 occurrences.

This huge proportion motivated us to analyze the joint impact of primary fires, rekindles and false alarms on the performance of the suppression system, using a discrete-event simulation (DES) approach.

The paper is organized as follows. In the next section, we explore the nature, sources and implications of rekindles and false alarms. The following section presents the data sources, describes the model, and briefly explains how the simulation was constructed. Subsequently, we present the results of the simulation and highlight the most relevant findings. The final section discusses the main points and offers conclusions.

Problem framing

In this section we use the literature and our interviews with experts, to suggest and describe three main sets of causes for rekindles: the characteristics of the physical site (soil and fuel type), ineffective firefighting technics (absence of use of tools, deficient fire line construction and patrolling), and the existence of a double-duty for firefighters. Next, we examine the nature and causes of false alarms, as well as strategies to decrease their number. Finally, we provide benchmark values for these two types of events, later used as targets in the DES study.

Bad mop-ups and rekindles

After establishing control lines around the fire perimeter, the fire crews start to solidify it working towards its interior (Martell 2007). When the fire is under control, mop-up begins, and later, the area must be patrolled before the fire may actually be declared extinct (Alexander 2001, Martell 2007, Murdock and others 1999). Performed along the fire control line, mop-up involves the detection and neutralization of all hot areas (Figure 1). The hot spots can be identified by smoke smell, visible signs (smoke, white ash, clouds of gnats, heat waves, steam), audible signs (crackling of embers, hissing of escaping steam) or by touch (almost touching the ground with the hand). Indeed, a small spark near a control line can cause a later rekindle (Murdock and others 1999). The mop-up stage may take several days, even weeks (Martell 2007) and can easily takes three times as long as the time spent until the fire was declared under control, in fires with more than 100 ha (ANIF 2005). Overall, it is a very time-consuming and costly stage (González-Cabán 1984).

Figure 1—Before and after a rekindle: signs of a bad mop-up (left) and holes caused by underground fire (right).

Rekindles, or reignitions, by definition, are fires that reburn an area over which a previous fire has passed, leaving fuel that later ignites due to latent heat, sparks, or embers (NWCG 2011). They can occur, for instance, in fuel complexes that exhibit heavy fuel loads and deep organic layers. Primarily under the decomposing leaf litter, lies a compact organic layer in which ground or subsurface fires will remain burning slowly (Lourenço and Rainha 2006). Areas near rivers, peat bogs, old forests, and large decaying logs are prone to such fire persistence, as a result of the dryness left after the passage of the main fire front. This arises especially in major dry spells or droughts (Henderson and Muraro 1968, Alexander 2001). Such underground burning (Figure 1) in a smoldering stage can erupt into flames when it gets to the surface exposing this heated fuel to air (NWCG 2005). Physical site characteristics, however, do not fully explain the observed variation in mop-up costs (Donovan and Brown 2005). Thus natural (weather conditions, spatial-temporal concentration) and organizational (human resources management and of equipment) factors must be considered (AFN 2011). This is the case of Portuguese mainland, where across the 18 districts the increment of rekindles beyond primary fires varied from zero to 85%, with half of the districts featuring proportions above 9.3% (Pacheco and others 2012).

The main reasons for many of these rekindles in Portugal are: inappropriate mop-up when the fires occur in inaccessible areas (Beighley and Hyde 2009); absent or deficient fire line construction using existing roads or near houses (Beighley and Hyde 2009, Lourenço and Rainha 2006); and the fact that mop-ups are performed almost exclusively with water, typically without hand tools that could safely consolidate the perimeter (Lourenço and Rainha 2006, ANIF 2005, Beighley and Hyde 2009, ISA 2005). Actually, it is critical to make a trench down to the mineral soil (Oliveira 2011), or regolith, where water does not penetrate (Lourenço and Rainha 2006) and create a discontinuity between burnt and unburnt areas (Lourenço and Rainha 2006) to prevent the rekindling of hot spots (Murdock and others 1999).

The need to address these problems was acknowledged in 2005 (ISA 2005, ANIF 2005) and officially assumed in 2006 (CM 2006) after the disastrous fires of 2003 (Fernandes 2008), repeated two years later. The government commissioned a technical strategy (ISA 2005) to address this problem, and in 2006 a modified version (shifting from an emphasis on prevention to an increase in suppression capability) was approved and published (CM 2006) as the national strategy for forest protection against fires (Beighley and Hyde 2009). Training for the use of hand tools by the firefighters was mandated, along with the acquisition of tools and the use of excavators. The use of handheld infrared scanners for hot spot detection (Alexander 2001) was also suggested later (Oliveira 2011). Additionally, it was officially recognized that mop-up and surveillance are an integral part of firefighting operations (ANIF 2005, Lourenço and Rainha 2006). The need to improve command and control structure (ISA 2005), establish procedures and assign responsibilities was also recognized (ANIF 2005, Oliveira 2011). Finally the plan recognized the impact of rekindles and established their mitigation as a priority, with a goal of 1% by 2010 defined as an acceptable value for the rate of rekindles (Oliveira 2011). This goal was not ever achieved (AFN 2011) and may in fact be considered too ambitious when compared, for instance, with the same statistic for the U.S. between 2004 and 2008, which varies between 2% and 6% (Ahrens 2010).

The fact that the observed high number of rekindles may result from inadequate post-fire management and active surveillance (AFN 2011) has led some experts to suggest the creation of specialized hand crew brigades, properly trained in mop-up operations (Beighley and Hyde 2009, ISA 2005). In fact, the crews responsible for the mop-up operations are the same that are needed for the suppression of new fires (primary or rekindled), and this “double-duty” weakens the system: firefighters often leave a fire too early in order to engage in new initial attacks (Beighley and Hyde 2009). Analyzing rekindle genealogies and using linear regression analysis across Portuguese districts, we found evidence supporting that hypothesis for six of the seven districts with a relevant number of rekindles (Pacheco and others 2012).

False and nuisance alarm calls

A false alarm (FA) may have its origin in a malicious or mischievous report (hoax call), or in a good intent call, e.g. when dust originated by some kind of heavy works is mistaken for distant smoke (AFN 2011). A key motive for the recent strong growth of FA in Portugal, suggested in our interviews with experts, is the change to a "muscled attack" dispatch policy since 2006: aiming to eliminate a fire in the first intervention, a helicopter is sent if available. The knowledge of this fact leads some adults and children to alert the fire department, in the hope of seeing a helicopter from close.

There is scarce research available with statistics on this type of calls (Flynn 2009). Additionally, it is not easy to perform international comparisons, due to the fact that in Portugal the alarm systems are not connected to dispatch centers. In fact, the unintended malfunctioning of automatic alarms is responsible for approximately one third of the false alarms reported in the U.S. (Hershfield 1995, Karter 2010, 2011), 42% in London (Tilley 1997), 50% in New Zealand (Tu 2002) and 62% in Tasmania, Australia (Killalea 1998). Even so, accounting for hoax and good intent calls, the rates found in the U.S. were 4.4% in 2009, and 4.1% in 2010 (Karter 2010, 2011), and between 4.6% and 5.4% in New Zealand (Tu 2002). In the United Kingdom, considering all emergency calls, the rates of hoax calls were 5.0% in Derbyshire (Yang and others 2003), and 6.2% in South Wales (Corcoran and others 2007).

These figures suggest the possibility of decreasing the number of false alarms in Portugal. For instance, the Dispatch Center of the District of Porto (CDOS Porto) implemented a policy of returning a call if it originates in a school, and asking to speak to a parent in case a child’s voice is recognized. According to our interviews, this policy enabled a reduction in the number of FAs and may explain the fact that the district rate is now 2/3 of the national rate (Pacheco 2011). Killalea (1998) also provides evidence of a similar reduction two years after the implementation of a policy to identify all the calling numbers. However, before considering concrete measures it is advisable to analyze and understand the specific local causes of this phenomenon. The differences found in various studies show the importance of not making premature assumptions about its causes (Corcoran and others 2011, Corcoran and others 2007). Only the collection of accurate information about FAs, namely their type and origin, allows authorities to identify risk areas and design policies and intervention strategies for their populations (Flynn 2009).

Data and Methods

For our study, we used data kindly provided by the Portuguese Forest Service (Autoridade Florestal Nacional in Portuguese) (AFN). This dataset has been stable for the last twelve years, and contains the fire location and time (i.e., alert, ignition and extinction), burnt area, event type (e.g. false alarm, agricultural or forest fire), its cause and nature. The distinction between single or rekindled fire (its nature) is recorded since 1984 (Pereira and others 2011), but 2010 is the first year for which it is possible to connect a rekindle to the specific fire whose bad mop-up originated it.

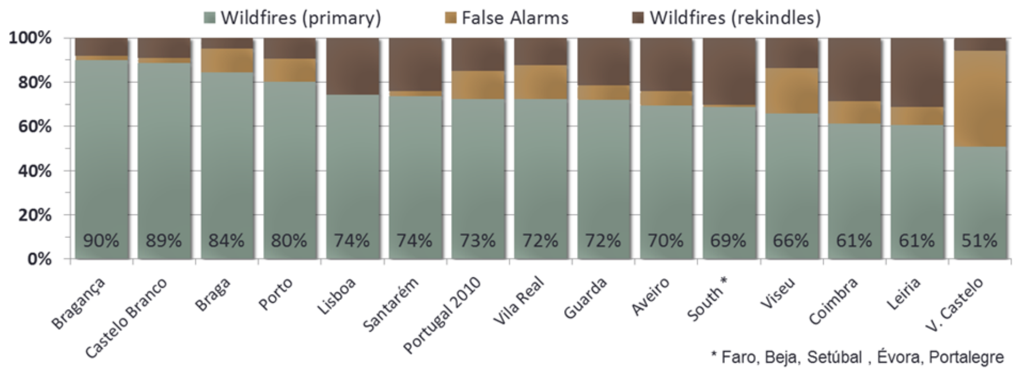

Figure 2—Share of primary fires, false alarms and rekindles (2010, summer).

The country mainland is divided in eighteen main districts (administrative regions) with their corresponding municipalities (278 counties). The significant geomorphologic, climatic and demographic differences along the country (Pereira and others 2011), and the heterogeneity of fire management policies, and suppression and prevention efforts (e.g. Figure 2), which are organized at the district level, justifies considering the district as a unit of analysis.

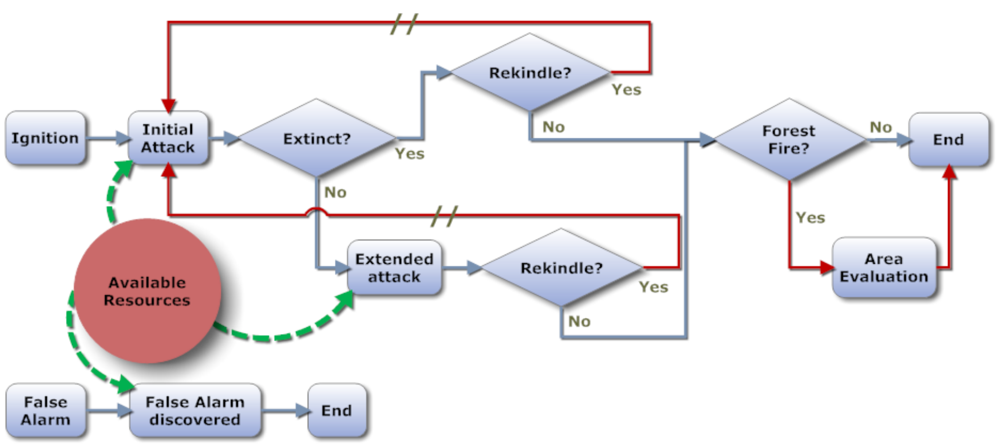

Figure 3—Conceptual model of a wildfire suppression system.

The design of our conceptual model for the wildfire suppression system (Figure 3) was based on literature review, fieldwork that included visits to firefighting dispatch centers, forest stands and wildfires, and informal and formal recorded expert interviews. To model explicitly the available firefighting crews, we used a second database (gently supplied by CDOS Porto) with the details of the fire suppression interventions. Finally the model was implemented in ®ARENA, and used for a study of the district of Porto between the months of July and September 2010.

There are four motives for the choice of this case study: Porto features a high number of fire occurrences, and available detailed data on deployed resources; the proportion of rekindles and false alarms is slightly below, but still in line with national figures; 84% of the ignitions, corresponding to 96% of the burnt area, occur in this three-month period (Pacheco 2011); and 2010 is the first year for which appropriate data on false alarms are available, providing (as mentioned before) the opportunity to reconstruct the chains of bad mop-ups and rekindles starting from the primary fire, for the first time (Pacheco and others 2012).

The databases of AFN and CDOS Porto were merged and used to parameterize and validate the model, which was subsequently used with sensitivity and optimization analyses to better understand the impacts of the factors under study.

Preliminary Results

In this section we briefly describe the implementation of our model (Figure 3) as a DES in ®ARENA, and how we used the results of the data analysis of the combined AFN and CDOS Porto databases to parameterize it (Table 1).

Table 1—*Essential parameters of the model (IA/EA: initial/extended attack).*

Arrivals	New Fire	A Class	24	parameters	(hourly)
		B Class	24	parameters	(hourly)
	Rekindle	A Class	24	parameters	(hourly)
		B Class	24	parameters	(hourly)
	False Alarm	A Class	24	parameters	(hourly)
		B Class	24	parameters	(hourly)
Durations	New Fire	A Class	1	parameter	Empirical Dist.
		B Class	1	parameter	Empirical Dist.
	Rekindle	A Class	1	parameter	Empirical Dist.
		B Class	1	parameter	Lognormal Dist.
	False Alarm	A Class	1	parameter	Lognormal Dist.
		B Class	1	parameter	Lognormal Dist.
Initial Attack (End)	New Fire	A Class	2	parameters	end, tuning
		B Class	2	parameters	end, tuning
	Rekindle	A Class	2	parameters	end, tuning
		B Class	2	parameters	end, tuning
Resources	New Fire	A Class	2	parameters	(IA / EA)
		B Class	2	parameters	(IA / EA)
	Rekindle	A Class	2	parameters	(IA / EA)
		B Class	2	parameters	(IA / EA)
	False Alarm	A Class	1	parameter	no EA
		B Class	1	parameter	no EA
Burned Area	Stands	A Class	1	parameter	regression
		B Class	1	parameter	regression
	Forest	A Class	1	parameter	regression
		B Class	1	parameter	regression

The ®ARENA simulation model (ASM) has three main sections, modeling primary fires, rekindles and false alarms. In a fourth final section we compute the total number of incidents, evaluate the forest and shrubland burnt areas as a function of the fire duration (including the waiting time), and compute value losses and CO_2 emissions (AFN 2011, Narayan and others 2007). Value losses are evaluated in two alternative ways: using the official guidelines of AFN (AFN 2011); according to the guidelines of the proposal for a National Plan for Prevention and Protection of Forest against Fires (ISA 2005), which includes non-timber (e.g. “recreational activities” and “indirect use”) value losses.

The three main sections of the ASM have in common two components: (1) the arrivals of primary fires, rekindles, and false alarms; and (2) the confirmation as primary fire or rekindle initial attack, or false alarm. A third (3) component is used to simulate the extended attack in the case of a fire escape, for the primary and rekindled fires. The latter two components also include resource allocation, namely for the false alarm verification operation (with an average duration of 62.8 minutes). Despite the separate modeling of primary fires and rekindles, we will simply call them "ignitions", and name the three abovementioned components as “arrivals” (1), “initial attack” (2) and “extended attack” (3), respectively.

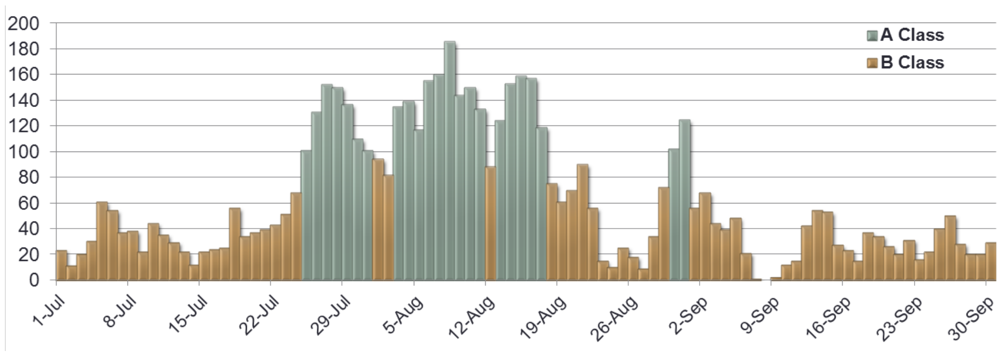

Figure 4—Day severity class along the 2010 summer in the district of Porto.

The “arrivals” component (1) distinguishes between two classes of severity for the days, which are related to the total number of occurrences (ignitions and false alarms) during the day. Studying the daily numbers of occurrences, we found a clear division around 100, and our interviews with CDOS Porto confirmed this threshold, i.e., up to 100 daily occurrences, resource allocation is easily managed and the response capability is clearly appropriate. We thus considered a severity “B class” below 100 occurrences/day, and a severity “A class”, above (Figure 4) that threshold.

Moreover, as the numbers of incidents change significantly along the day (Bookbinder and Martell 1979), we implemented the arrivals as a non-stationary Poisson process, considering rates of arrival that change hourly during the day. Using data from Bookbinder and Martell (1979), and analyzing the AFN database, in Figure 5 we show a comparison between the northwestern region of Ontario in Canada

(1967-69) and Portugal (2001-10), considering only the four coldest months (November to February), as well as the whole year. In the first two cases, the same camel-like shape is visible. As for the third case, the bell-like shape might be a result of the human footprint, since approximately 98% of the ignitions in Portugal were man-caused, in contrast with 65% for the first case (Cunningham and Martell 1973).

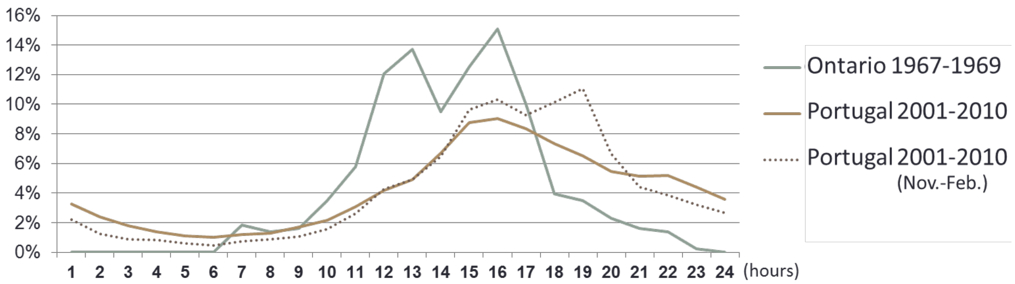

Figure 5—Arrivals as non-stationary Poisson process changing hourly along the day.

The "initial attack" component (2) starts by attributing to each arrival occurrence its duration and the resources needed (ground crews and, if available, a helicopter). In our model, the queue discipline is always FIFO and the resources have the same allocation priority. If the fire duration exceeds the maximum duration for an initial attack, it enters the extended attack component (3), otherwise the fire is considered extinguished and the resources are released.

Lognormal [#37]					
Kolmogorov-Smirnov					
Sample Size Statistic P-Value Rank	174 0.0555 0.63675 10				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.08134	0.09272	0.10295	0.11508	0.12349
Reject?	No	No	No	No	No
Anderson-Darling					
Sample Size Statistic Rank	174 0.67401 13				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	1.3749	1.9286	2.5018	3.2892	3.9074
Reject?	No	No	No	No	No
Chi-Squared					
Deg. of freedom Statistic P-Value Rank	7 3.2666 0.85929 12				
α	0.2	0.1	0.05	0.02	0.01
Critical Value	9.8032	12.017	14.067	16.622	18.475
Reject?	No	No	No	No	No

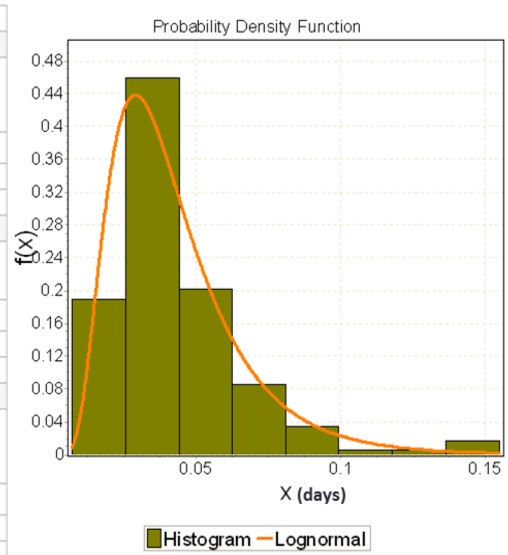

Figure 6—False Alarm duration in a B Class day (Porto, 2010, summer) and the lognormal distribution chosen: σ=0.51079, μ=-3.2822, LOGN(0.04278,0.02336).

The duration of the fire is modeled with probability distributions. Among the classic probability distributions available in ®Arena, we chose the one with highest fit and not rejected, at the $\alpha = .01$ level of significance. In half of the cases (Table 1), the lognormal distribution had the best fit and was chosen (e.g. Figure 6 for false alarms in B class days). When this was not possible we used an empirical distribution (Table 1) fitted with the ®Arena Input Analyzer. The lognormal distribution has the longest tail within the set of distributions offered by this software, and that could explain why it offered the best fit. We also tested our data with ®EasyFit and found that the Burr, Dagum, and Frechet distributions always proved to have better fit, but unfortunately none were available as an option.

To establish the threshold in the fire duration at which the transition between initial and extended attack occurs, i.e., distinguishing between fires suppressed in the initial attack and those that escaped, we used the merged datasets (AFN and CDOS Porto) and sensitivity analysis with this ASM to identify a value consistent with our field data for each type of ignition (primary fire or rekindle) and severity class.

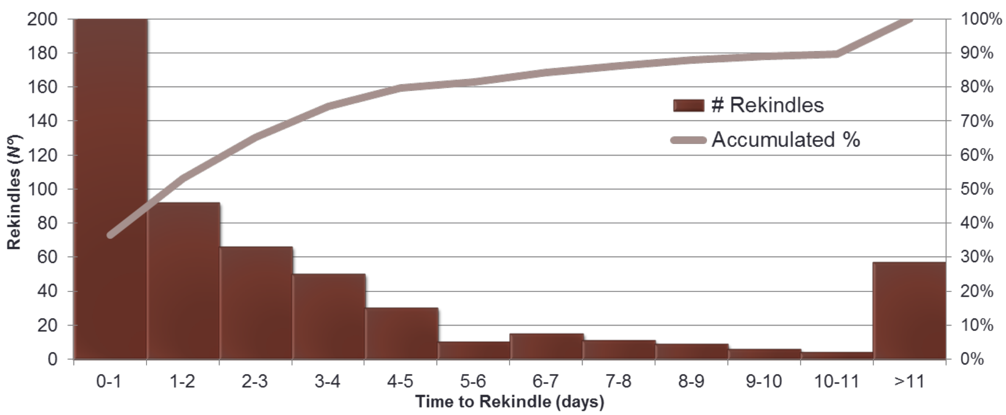

Figure 7—Rekindles as a function of the time to rekindle (Porto, 2010, summer).

We chose to model rekindles with the same logic as we modeled the primary fires, i.e., separately instead of as a result of bad mop-ups of primary fires, because the time to rekindle after a bad mop-up tends to be large – 3.96 days on average in the Porto district, during the summer of 2010 (Figure 7).

The fires that escape initial attack enter the "extended attack" component (3) and more resources are assigned to them for the remaining duration. Analyzing the abovementioned merged datasets, we were able to estimate the resources (number of crew teams) allocated to extended attack, again considering the two severity classes and for the two types of ignitions. As for the initial attack, we additionally considered the resources allocated to false alarms (under the two severity classes). In the six cases, we found evidence in the data, that the official rule of dispatching two crews for each initial attack is not being strictly applied in practice, a fact suggested in our interviews with experts, which could be attributed to insufficient resource capacity during the summer in the Porto district.

All the four main components described, are governed by a last (fifth) control logic component, which implements the change of day, its severity class, and the process of creation of new occurrences. The essential parameters of the ASM are listed in Table 1, and Figure 8 shows an example of the regional parameterization for the Porto district.

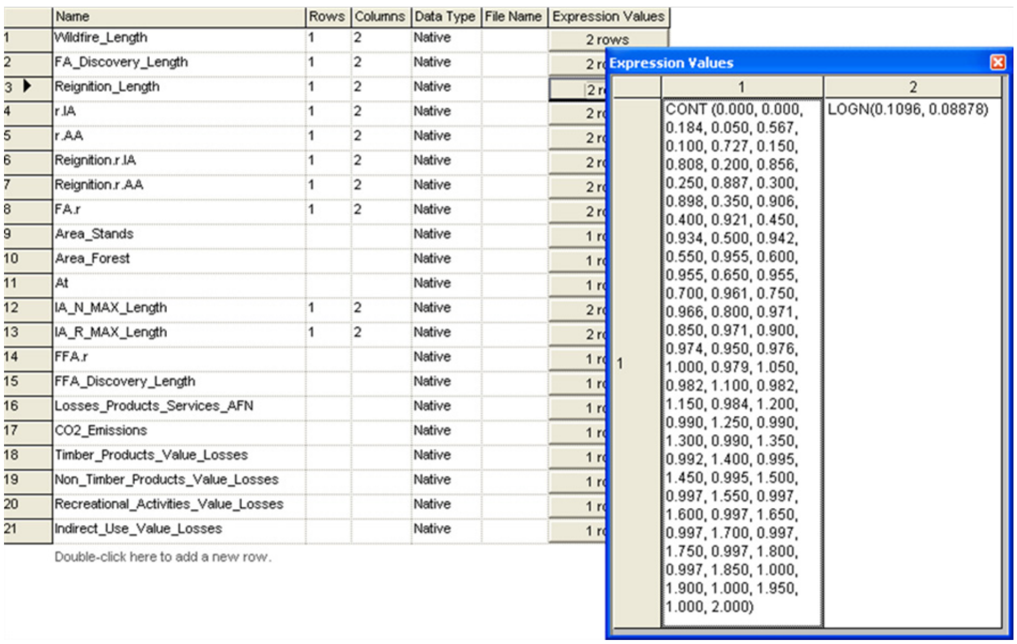

Figure 8—Expressions parameterization (detail of the ®ARENA implementation).

Discussion and Conclusion

Throughout the implementation and parameterization of the AMS, we made sure that the results of the model were consistent with the real data, which we consider our base scenario. For the alternative benchmark scenario under analysis, and according to the second section of this paper (Problem framing), we considered for rekindles the official target of 1% (AFN 2011, ISA 2005), and for false alarms half of the current level in the Porto district – a reasonable reduction according to international benchmarks (Corcoran and others 2007, Karter 2010, 2011, Tu 2002, Yang and others 2003).

We ran the ASM for the two scenarios, with 500 replications, for each resource level from 90 to 128, stable during the summer fire season of 92 days (with "days" as the simulation clock time step) and calculating the average waiting time over the 500 replications. The results are presented in Figure 9, and as in the case of the study of Podur and Martell (2007) on large forest fires in Ontario, this number of replications provided reasonable 95% confidence intervals.

False alarms deviate suppression resources from the real forest fires, and rekindles have much harder suppression operations. Our data analysis of forest fire resources management in the district of Porto during the summer of 2010 highlights the importance of addressing the phenomena of rekindles and false alarms. Jointly, they represented 27.4% of the occurrences: 5,498 out of 20,049 in the year. In other words, this addition of 5,498 to 14,551 primary fires brought to the fire suppression system an extra 37.8% of effort. Indeed, this additional pressure raises difficult challenges to the suppression system management. For instance, the fact that the average number of crews dispatched to initial attacks is much lower than the recommended (as we found in our data analysis), is an evidence of this pressure.

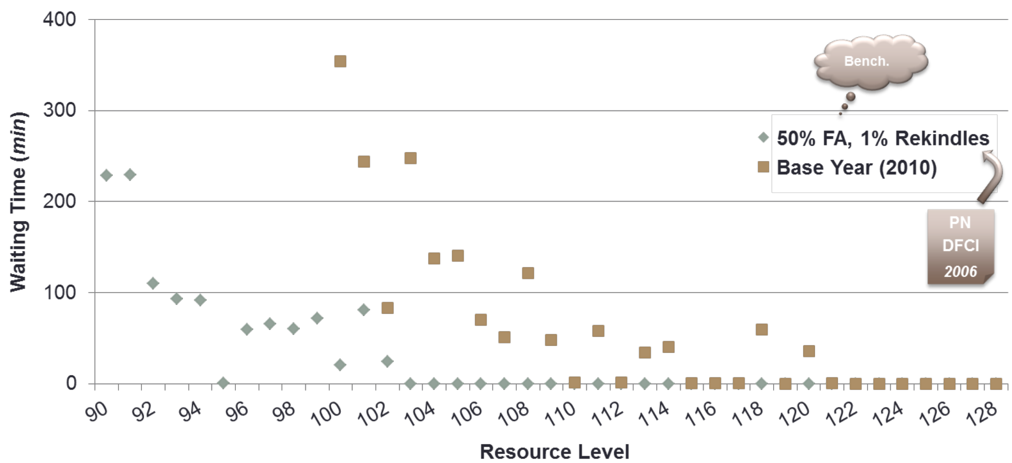

Figure 9—Average waiting times for different resource levels in the base and benchmark scenarios.

Our simulation study of the impact of rekindles and false alarms on suppression systems reveals that its reduction to target/benchmark values would release 14.9% of the resources, which would be available for effective mop-up operations. These results are more significant to the extent that 2010, within the first decade of this century, was an average year in terms of number of occurrences and burnt area (AFN 2011).

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