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A stochastic model for assessing bush fire attack on the buildings in bush fire prone areas

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Abstract: Bush fires are a major natural and socio-economic hazard in Australia. Under extreme fire weather conditions, bush fires spread very rapidly and are difficult to contain by firefighting services. When spreading on the rural/urban interface, they can cause significant damage to buildings or structures. The well known examples of such disastrous bush fire events include the bush fires which occurred in Tasmania in 1967, Victoria and South Australia in 1983, New South Wales in 1994, Canberra in 2003 and Victoria in 2009. The number of houses lost as a result of these fires is over 1300, 1500, 200, 500 and 2000 respectively (Leonard & MacArthur, 1999; Ellis et al., 2003; Blanchi & Leonard, 2005; Wikipedia 2009).

To minimize the risk of building loss from such devastating bushfires, many bushfire protection measures have been developed and implemented within each State in Australia. One of the most effective and commonly used measures is the application of construction and design standards to developments in bushfire prone areas. However, the appropriate application of this protection measure requires the use of a bushfire attack assessment model to determine the level of bushfire attack to which a development might be exposed based on the site specific variables associated with weather, fuel and topography.

At present, almost all the existing bushfire attack assessment models available for use are the so-called deterministic models (Ellis, 2000; Tan et al., 2005; SA, 2009), which are based on radiant heat flux modelling. The principles of these models are the same, i.e. taking deterministic values for all the input variables and producing the deterministic output of radiant heat flux. In situations where there exists a significant level of uncertainty with the inputs required by these models, it may be difficult to choose the appropriate values for them and therefore the risk level associated with the output on which a decision is made is usually unknown. This means that the safety levels of the decisions based on the deterministic models' outputs may be either more than adequate, due to the use of conservatively high values, or inadequate due to the use of the conservatively low values for the inputs with uncertainties.

In view of the above, a stochastic bushfire attack assessment model has been proposed by the Authors. The principle of the proposed model is that the model's output i.e. radiant heat flux is calculated repetitively with the randomly sampled values for the inputs with uncertainties using Monte Carlo sampling. The model output is not a single radiant heat flux but a radiant heat flux probability distribution reflecting the uncertainties with the model inputs. Based on the radiant heat flux probability distribution, the radiant heat flux for a given percentile or safety level and the corresponding standard construction requirements can then be determined. Therefore a risk based decision in relation to the application of appropriate standard construction requirements to a development in bushfire prone areas could be made.

The implementation of the proposed model makes use of a commercial software product called @Risk, which involves a number of steps like developing @Risk spreadsheet model, analyzing the model with Monte Carlo simulation, determining radiant heat flux for a given percentile or safety level and determining the level of bush fire attack and the associated standard construction requirements as per AS 3959 (SA, 2009). The use of the model has been demonstrated by an application example. As demonstrated in the example, the major advantage of the proposed model over the existing deterministic models is that the construction standard determined by this model for a given development could be based on a known minimum safety level. This approach provides construction standards for the proposed development which are likely to be more cost effective whilst providing for pre-defined safety levels.

Keywords: *Monte Carlo simulation, deterministic model, stochastic model, bush fire attack assessment, radiant heat flux*

1. INTRODUCTION

Bush fires are a major natural and socio-economic hazard in Australia and on average bush fires cost the nation approximately $33.5 million per year (McAneney, 2005). Under extreme fire weather conditions, bush fires spread very quickly and are difficult to contain by firefighting services. When spreading on the rural/urban interface, they may cause significant house losses. The expanding cities like Sydney and Melbourne are further compounding the existing serious situation with the number of houses and people in rural/urban interface in bush fire prone areas growing rapidly each year.

A variety of measures have been implemented to minimise the number of house losses from bush fires throughout Australia in recent years. The commonly used measures include reducing fuel load, prescribing Asset Protection Zones (APZ) and enforcing minimum construction standards. It is no doubt that the application of one or more of these measures will lead to the reduction of the number of house losses resulting from the devastating bush fires. However, it is usually uncertain whether or not the implemented measures are adequate due to the deterministic nature of the existing bush fire attack assessment models upon which these measures are selected and implemented.

In view of this, a stochastic bush fire attack assessment model has been proposed by the authors. Compared with the existing deterministic models, the proposed stochastic model is able to take the uncertainties associated with the model inputs into account explicitly by utilizing the so-called Monte Carlo sampling technique. Therefore a more confident and safe decision in relation to the bush fire attack level and the corresponding standard construction level required to commensurate this level of attack for an existing or new building could be made based on the modeling results of the proposed model. This paper describes the steps involved in implementing the proposed stochastic model and demonstrates its application with an example.

2. IMPLEMENTATION

2.1 Developing @Risk Spreadsheet Model

The proposed model is implemented by using a commercial risk analysis software product called @Risk. As shown in Figure 1, the implementation process involves the steps such as developing @Risk spreadsheet model, analyzing the model with Monte Carlo simulation, making decisions in relation to the radiant heat flux for a given percentile, the level of bush fire attack as well as the corresponding standard construction level.

In order to perform Monte Carlo simulation with @Risk, a spreadsheet implementing a deterministic radiant heat flux prediction model has to be developed first. The deterministic model was initially proposed by Tan et al. (2005) and later on adopted by AS 3959 - 2009 (SA 2009). It is developed for assessing bush fire attack under very high or extreme fire weather conditions.

As shown in Figure 2, the deterministic model consists of two types of sub-models, i.e. bush fire behavior sub-models and radiant heat flux sub-models. These sub-models are either the existing empirical models (e.g. rate of spread model) or the well established physical models (e.g. radiant heat flux model). Therefore the overall performance of the model is dependent on those of the comprising sub-models.

The inputs required by the model can be grouped into the following categories:

- Fuel: Vegetation Class, Fuel Loads, Fuel Height, Fuel Age and Fuel Moisture Factor;
- Weather: Fire Danger Index, Wind Speed, Ambient Air Temperature, Relative Humidity;
- Topography: Effective Slope, Site Slope;

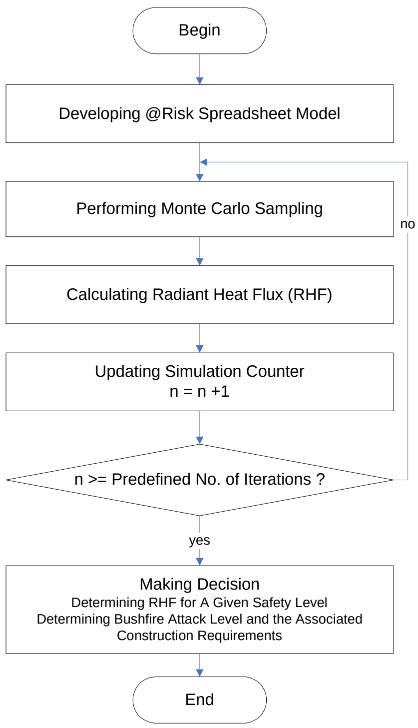

Figure 1. Steps involved in implementing the stochastic model

- Flame: Flame Temperature, Flame Emissivity, Transmissivity, Flame Length, Flame Width and Flame Angle;
- Configuration between flame and radiant heat receiver: setback distance and elevation of receiver.

In the spreadsheet model, both the input variables and output variables are represented by the spreadsheet cells references. The cells representing the independent input variables are entered with a single value or a @RISK (Palisade, 2002) probability distribution function. The cells representing the derived inputs and the desired outputs are entered with the formulas carrying out the desired calculations.

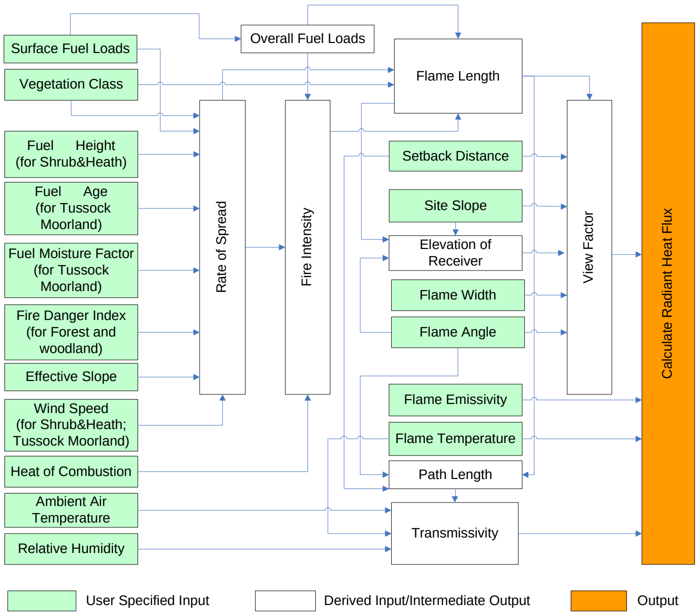

Figure 2. Radiant heat flux modelling process

There are two types of uncertainties, that is, things are that difficult to measure or unknown (e.g. flame temperature, emissivity) and things that vary due to environmental conditions (e.g. wind speed, relative humidity). The key difference between the two is that the first is due to the limitation of human being's cognitive ability while the second is due to the stochastic or chaotic nature of our ever-changing natural environment.

Whether an input variable is certain or not mainly depends on how much information a user may have when conducting the modeling. It is also influenced by the application objectives. This means that an input variable which is considered to be certain at one time for one specific modeling objective may become uncertain at another time for the same modeling objective. Similarly, a variable determined to be certain for one application objective may become uncertain for another different application objective. For instance, fuel load variables can be considered to be certain for a specific building site for the purpose of modeling the radiant heat flux exposure to which a house might be exposed for a short period while they are usually considered to be uncertain when modeling the potential radiant heat flux exposure to which a house might be exposed for a longer period of time due to the dynamic nature of the fuel accumulation process.

The uncertainty with an input variable is represented with probability distribution with @RISK (Palisade, 2002). Which probability distribution functions are to be used mainly depends on how much information users have at the time of conducting the modeling. If sufficient sample data for an uncertain variable are available, it is recommended that the distribution for use be derived through fitting these sample data. For instance, the distributions of weather variables could be derived by analyzing the historical climate data recorded in a given station. Otherwise uniform or normal distributions are the logic choices. Figure 3 shows four of the most commonly used probability distributions for risk modeling.

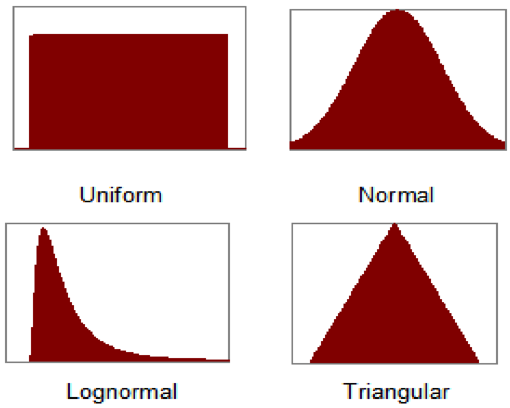

Figure 3. Frequently used distributions

Figure 4 shows a sample spreadsheet model for forest fire. In this sample, all the inputs except vegetation class, effective slope, site slope, setback distance and fire danger index are considered to be uncertain. A uniform probability distribution has been selected as the default distribution for each uncertain input variable. It should be noted that the use of uniform distribution as default is for the purpose of demonstration only.

SPREADSHEET MODEL USED FOR MODELLING RADIANT HEAT FLUX FROM FOREST FIRE				
Inputs				
Name	**Symbol**	**Value**	**Unit**	**Value or Distribution Entered into Cell**
Vegetation Type		Forests		Forests
Fire Danger Index	FDI	100		100
Effective Slope	slope	0	degrees	0
Site Slope	θ	0	degrees	0
Setback Distance	d	20	m	20
Surface Fuel	w	16.5	t/ha	RiskUniform(8, 25)
Heat of Combustion	H	17800	kJ/kg	RiskUniform(17000,18600)
Ambient Temperature	Ta	306	K	RiskUniform(298, 313)
Relative Humidity	RH	15%		RiskUniform(5%, 25%)
Flame Width	W_f	60	m	RiskUniform(20, 100)
Flame Angle	α	60	degrees	RiskUniform(30, 90)
Flame Temperature	T	1000	K	RiskUniform(800, 1200)
Flame Emissivity	ε	0.85		RiskUniform(0.7, 1.0)
Derived Inputs/ Intermediate Outputs				
Name	**Symbol**	**Value**	**Unit**	**Equation**
Overall Fuel	W	26.5	t/ha	W=w+10
Rate of Spread	R	1.98	km/h	R=0.0012 *FDI*w *exp (0.069*slope)
Fire Intensity	I	25944	kW/m	I = H*W*R/36
Flame Length	L_f	16.05	m	L_f= (13R+0.24W)/2
Elevation of Receiver	h	6.95	m	h = 0.5Lf sinα - d tanθ if 0.5 L_f sinα >= d tanθ; or h = 0
View Factor	Φ	0.378		Φ = 1 If d <= 0.5Lf cosα; or X1= (Lf sinα-0.5Lf cosα tanθ -d tanθ – h) / (d –0.5Lf cosα) X2= [h + (d-0.5Lf cosα) tanθ] / (d–0.5Lf cosα) Y1= Y2 = 0.5Wf / (d –0.5Lf cosα)
Path Length	L	15.99	m	L= d - 0.5L_f cosα if d >0.5Lf cosα or L= 0
Transmissivity	τ	0.851		$\tau = a_0+a_1L+a_2L^2+a_3L^3+a_4L^4$, where $a_n = C_{1n}+C_{2n}T_a+C_{3n}T+C_{4n}RH$
Outputs				
Name	**Symbol**	**Value**	**Unit**	**Equations**
Radiant Heat Flux	Rd	15.52	kW/m^2	Rd = τ * Φ *ε *σ * T^4 ($\sigma = 5.67 \times 10^{-11}$ kW m^{-2} K^{-4})

Figure 4. @RISK spreadsheet model for modeling radiant heat flux from forest fire

$$\phi = \frac{1}{\pi}\{\frac{X_1}{\sqrt{\cdots}}\tan^{-1}[\frac{Y_1}{\sqrt{\cdots}}] + \frac{Y_1}{\sqrt{\cdots}}\tan^{-1}[\frac{X_1}{\sqrt{\cdots}}]+$$

2.2 Analyzing the Spreadsheet Model with Monte Carlo Simulation

Once the @ Risk spreadsheet model is created, Monte Carlo simulation can be performed by the @Risk simulation engine. The simulation engine performs the simulation by utilizing the so-called Monte Carlo Sampling technique. Monte Carlo sampling technique is the traditional technique for using random or pseudo-random numbers to sample from a probability distribution. Therefore it is entirely random, that is, any given sample may fall anywhere within the range of the input distribution.

In the cumulative distribution shown in Figure 5, each Monte Carlo sample uses a new random number between 0 and 1. The simulation is carried out over and over until a predefined number of iterations are reached. Therefore the simulation results are not a single radiant heat flux value but the predefined number of radiant heat flux values which are usually expressed with a probability distribution curve.

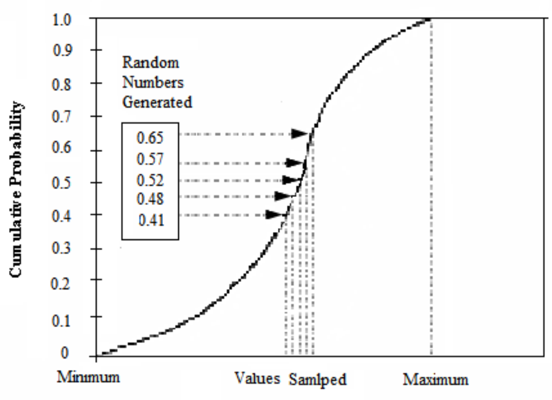

Figure 5. Monte Carlo sampling

In order to obtain a representative radiant heat flux distribution curve, the number of radiant heat flux calculations in the Monte Carlo simulation needs to be large enough. According to the authors' experiences, one million calculation iterations is normally considered sufficient in the majority of cases. This seems to be a very large number. However the simulation with this number of iterations will take less than 5 minutes to complete if it is performed on a PC with a CPU of 1.66GHz. If a smaller number of iterations is used, it can be determined by performing multiple simulations with the increased number of iterations. If the discrepancy between two adjacent simulations is small enough, the number of iterations used in the last simulation is one to be found.

2.3 Decision Making - Determining Bushfire Attack Level and Construction Requirements

Once the simulation is complete, a decision on the bushfire attack level and the applicable construction requirements of AS3959 (SA, 2009), for a development in bushfire prone areas, needs to be made based on the radiant flux simulation result. In order to make such a decision, the radiant heat flux for a given percentile or safety level needs to be determined first through analyzing and interpreting the radiant heat flux simulation result, that is, the radiant heat flux probability distribution.

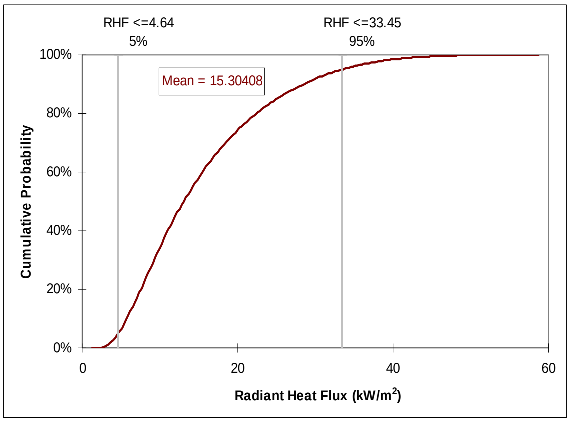

Figure 6. Sample output of radiant heat flux simulation

Figure 6 is a sample radiant heat flux probability distribution graph resulting from the simulation taking the inputs' values or distributions as defined in Figure 3. The graph shows the cumulative probability of the occurrence of a given radiant heat flux to which the development might be exposed in the designed fire weather scenario characterized by a nominal FDI value of 100. As shown in Figure 6, a radiant heat flux value of 33.45 kW/m^2 corresponds to a percentile or a cumulative probability of 95%. In other words, the probability of the predicted radiant heat flux value being less than or equal to 33.45 kW/m^2 is 95%. This means that if we know the safety level or the cumulative radiant heat flux probability for a development in bushfire prone areas, then the corresponding radiant heat flux used to determine the level of bushfire attack and the standard construction requirements could be determined from the radiant heat flux distribution graph. Once the radiant heat flux for a predefined safety level is determined, the level of bushfire attack can then be determined by comparing this radiant heat flux value with the radiant heat threshold exposure values for a given level of bushfire attack as defined in Table 1.

Table **1.** Bushfire attack levels and corresponding construction sections in the Standard (adapted from AS 3959 – 2009)

Bushfire Attack Level (BAL)	Heat flux exposure thresholds	Description of predicted bushfire attack and levels of exposure	Construction Section
BAL—LOW	See Clause 2.4.2 (AS3959-2009)	There is insufficient risk to warrant specific construction requirements	4
BAL— 12.5	≤12.5 kW/m^2	Ember attack	3 and 5
BAL—19	>12.5 kW/m^2 ≤19 kW/m^2	Increasing levels of ember attack and burning debris ignited by windborne embers together with increasing heat flux.	3 and 6
BAL—29	>19 kW/m^2 ≤29 kW/m^2	Increasing levels of ember attack and burning debris ignited by windborne embers together with increasing heat flux	3 and 7
BAL—40	>29 kW/m^2 ≤40 kW/m^2	Increasing levels of ember attack and burning debris ignited by windborne embers together with increasing heat flux with the increased likelihood of exposure to flames	3 and 8
BAL—FZ	> 40 kW/m^2	Direct exposure to flames from fire front in addition to heat flux and ember attack	3 and 9

For example, the level of bushfire attack and the applicable construction sections are BAL – 40 and sections 3 and 8. As can be seen in Table 1, the determination of bush the attack level is based on the predicted radiant flux the level. However, other attack mechanisms such as ember attack and flame contact have also been implicitly taken into account by defining a 100m ember attack cut-off distance and associating them with the corresponding radiant heat flux levels (SA, 2009).

APPLICATION EXAMPLE

To illustrate the application of the proposed model, an application example is given below. In this example, we need to determine the bushfire attack level and the corresponding standard construction requirements for a development in a bushfire prone area for a predefined safety level of 95%. It is assumed that the site specific inputs of the development take the following values:

- Vegetation Class = Forest
- FDI =80
- Effective Slope (degrees) = 5
- Site Slope (degrees) = 0
- Setback Distance (m) = 40

Other inputs required by the model are defined by:

- Surface Fuel (t/ha) = RiskUniform(8, 25)
- Heat of Combustion (kJ/kg) = RiskUniform(17000, 18600)
- Ambient Temperature (K) = RiskUniform(298, 313)
- Relative Humidity = RiskUniform(5%, 25%)
- Flame Width (m) = RiskUniform(20, 100)
- Flame Angle (degrees) = RiskUniform(30, 90)
- Flame Temperature (K) = RiskUniform(800, 1200)
- Flame Emissivity = RiskUniform(0.7, 1.0)

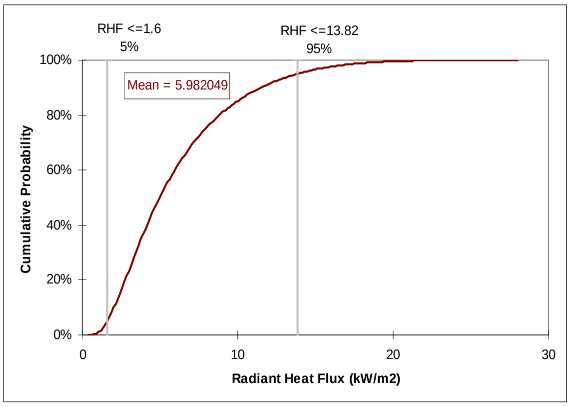

Figure 7. The radiant heat flux simulation result for the application example

The simulation result of this example is shown in Figure 7. Based on the simulation graph, the radiant heat flux for the predefined safety level of 95% is determined to be 13.82 kW/m^2. Therefore the bushfire attack level and the applicable construction sections of AS 3959 -2009 are BAL – 19 and sections 3 and 5 respectively. In other words, the safety level for the development constructed to these standard requirements in these sections will be not less than 95%.

What is the assessment result if a deterministic approach is used for the above example? To answer this question, a deterministic value has to be assigned to each of the variables with uncertainties. In this example, two extreme scenarios are used. The first represents an assessment with a low level of conservatism while the second represents an assessment with a high level of conservatism. Table 2 shows the values assigned to the variables with uncertainties in the two scenarios.

Table 2. Values Assigned to the Input Variables with Uncertainties in the Two Scenario Calculations

Input	Scenario 1	Scenario 2
Surface Fuel (t/ha)	15	25
Heat of Combustion (kJ/kg)	17000	18600
Ambient Temperature (K)	313	300
Relative Humidity	25%	5%
Flame Width (m)	50	100
Flame Angle (degrees)	90	75
Flame Temperature (K)	1000	1200
Flame Emissivity	0.85	0.95

The radiant heat flux and the corresponding bush fire attack level determined for the scenario 1 is 4.64 kW/m^2 and BAL – 12.5 respectively while those for scenario 2 are 27.78 kW/m^2 and BAL – 29 respectively. Compared with the radiant heat flux of 13.82 kW/m^2 and the corresponding BAL – 19 as determined by the stochastic approach for a given percentile of 95%, the building in the above example under scenario 1 will be under protected while it will be over protected under scenario 2.

4. CONCLUSIONS

To conclude, a stochastic bushfire attack assessment model has been developed and demonstrated with an application example. Compared with deterministic bushfire attack models, the proposed stochastic model is able to take the uncertainties associated with the model inputs into account by performing Monte Carlo simulation and therefore it allows a cost effective and safe decision to be made in relation to the determination of the bushfire attack level and the corresponding standard construction requirements.

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