

Fractal Characterisation of Forest Fire Evolution Using Sandbox

Tajudeen A. O. Salau¹, Olatunji O. Quadri², Yusuf Bodija³, Ismail O. Tella⁴

Senior Lecturer, Department of Mechanical Engineering, Faculty of Technology, University of Ibadan, Nigeria¹

P.G. Student, Department of Mechanical Engineering, Faculty of Technology, University of Ibadan, Nigeria^{2,3,4}

ABSTRACT: This research work investigates uncontrolled forest fire evolution for different occupation probabilities and lattice sizes using both average termination time and fractal characterisation of the fire front. The characterisation was effected using sandbox method for occupation probabilities ($0.000 \leq P_b \leq 1.000$) at constant step value of 0.001. The results show in general that the smaller the occupation probability the smaller the average termination time and vice versa for all studied cases. However at occupation probability of approximately 0.593 which is the theoretical percolation threshold, the average termination time curve surged as reported in literature. Likewise the variation of the average sand box dimension with increasing occupation probability shows four distinct regions. The fourth region with higher estimated sandbox dimension can be interpreted as indicator of aggressively dangerous forest fire front as $P_b \rightarrow 1$.

KEYWORDS: Sandbox dimension, Average termination time, Percolation threshold, Occupation probability, Fractal.

I. INTRODUCTION

A wildfire is an uncontrolled fire in an area of combustible vegetation that occurs in the wilds or non-urban environment [1]. The phenomenon can be described as forest fire in the case of a burning forest. There are many factors that can influence ignition, affect spread, and also determine the rate of occurrence of wildfire. These factors include: climate [7], forest type [8], wind [16], landscape [11] and human activities [15]. Humans start most of the fires whether accidentally or deliberately, however, weather is most crucial to the occurrence and growth of forest fires. In recent years, studies have shown that lightning-ignited wildfires pose the most serious threat because they are difficult to detect and quench early, as lightning fires often start in remote areas that can be difficult to reach [6].

There have been many studies in the field of wildfire behaviour with the primary aim of stopping the spread of wildfire or at least reduce its impact on life and property. Over the years, prediction systems or models have been developed to express in advance the likely danger posed by a particular fire. [13] Reviewed and classified wildfire models into three broad categories: physical and quasi-physical models; empirical and quasi-empirical models; and simulation and mathematical analogous models. The present study utilizes mathematical precept based on the concept of percolation theory to simulate the spread of wildfire.

Percolation theory is the simplest not exactly solved model displaying a phase transition [5]. It describes the attributes and properties of associated clusters in a random process, and can be applied to many systems such as forest fires, resistor network and biological evolution. Several studies have been performed in order to examine the main features of fire propagation and to model fire behaviour using percolation theory. [2] in 1986 investigated critical exponents of a propagating fire front and estimated its spread in terms of fractal dimension. Subsequently, [4] in 1990, compared values from mathematical model of fire propagation and that of a laboratory simulation of percolation using matchsticks. The most noticeable dissimilarity is that the mathematical model predicts that at critical percolation a fire front decelerates, whereas the experiments indicate acceleration.

The spread of forest fires in anisotropic conditions due to wind and/or topography is fractal [10]. Fractals refer to mathematical sets with a high degree of geometrical complexity which opens up new ways to analyse and model many natural phenomena such as river networks, lightning bolts and earthquakes [9,12]. All fractal shapes can be

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 6, Issue 1, January 2017

distinguished by fractal dimension – a measure of shape irregularity. Among popular estimation methods to determine fractal dimension is the sandbox method, a variant of the box method. The choice of sandbox over other estimators for this study lies in its simple procedures, and less complications in computing estimates.

The present study aims to examine the termination time and propagation of forest fire based on the concept of percolation theory for different occupation probabilities and lattice sizes. The fractal characterisation of fire front for various occupation probabilities—at constant step value of 0.001—was performed using the sandbox method.

In Section 2, procedures for generating square lattice sizes of different resolutions, and fractal characterisation of forest fire were described. Section 3 presents sandbox dimension estimates of burning trees across different forest lattice resolutions and occupation probabilities. Conclusions of this study were reported in Section 4.

II. METHODOLOGY

An algorithm for forest fire propagation and termination time on a random lattice was developed and coded in FORTRAN. The main features of the algorithm can be described as follows:

- Square lattice generation using Monte Carlo simulation.
- Fractal characterisation of forest fire front using average sandbox dimension method.
- Determine the termination time of a burning forest.

A. SQUARE LATTICE GENERATIONS

Square lattice described in an array with maximum size of 500 x 500 were generated at random with specified occupation probability and seed value using FORTRAN. A strip of square in the lattice is called a site. Filling each site with an integer is synonymous to planting trees in a particular location. The following outlines are steps to planting trees using the square lattice generation approach:

- Step 1.** Determine seed value (helps in generating random numbers), occupation probability (P_b) and size of the square lattice.
- Step 2.** At a fixed occupation probability (P_b), the program runs through the entire lattice and attaches a random number (N) to each site.
- Step 3.** If $N \leq P_b$, the site is tagged 1 and interpreted as occupied. Thus, a tree is planted.
- Step 4.** If $N > P_b$, the site is tagged 0 and planting is skipped.

B. FRACTAL CHARACTERISATION OF FOREST FIRE

Fractal characterisation of forest fire describes its propagation and the direction of fire spread over a period of time. It also illustrates the burning process of a tree, beginning from the time a tree is ignited till it is burnt down completely. Steps adopted to characterize the spread of forest fire front using the sandbox dimension are summarized below.

- Step 1.** Generate a square lattice using Monte Carlo simulation.
- Step 2.** Three stages were identified in the burning process of trees: un-burnt tree (tagged 1), burning tree (tagged 2), and burnt tree (tagged 3).
- Step 3.** The first row of the lattice is set on fire i.e. changing all 1s in the first row to 2.
- Step 4.** Subsequent burning of trees in other rows was implemented using von Neumann neighbourhood concept on a square lattice.
- Step 5.** Estimate the sandbox dimension at each time step as the burning of trees continues [3,14].
- Step 6.** Compute the average sandbox dimension for each occupation probability (P_b) in the range of $0.000 \leq P_b \leq 1.000$ at a fixed interval of 0.001.

[12] refers. The sandbox dimension can be computed using power related functions. Hence,

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Vol. 6, Issue 1, January 2017

$$Y = CX^d \tag{2}$$

$$\text{Log}(Y) = \text{Log}(C) + d\text{Log}(X) \tag{3}$$

Y = Number of covered burning site.

C = Constant of proportionality.

X = Box scale.

d = Slope (Sandbox Dimension).

C. TERMINATION TIME

Time is measured per unit step during characterisation of burning trees and when there are no burnable trees left, the termination time is obtained. In evaluating the fractal dimension, the time step helps to identify the stage of characterisation. To obtain the results of average termination time used in this study, ten (10) trials of simulation were conducted.

III. RESULT AND DISCUSSION

In this section, the results for the simulation process such as the effect of occupation probability on burning trees, average termination time across varying occupation probabilities and average termination time over different lattice sizes are presented.

A. EFFECT OF OCCUPATION PROBABILITY ON BURNING TREES

The sandbox dimension trend for occupation probability P_b in the range $0.000 \leq P_b \leq 1.000$ at an interval of 0.001 for forest square lattice resolution R of 100 by 100 is illustrated in Fig.1

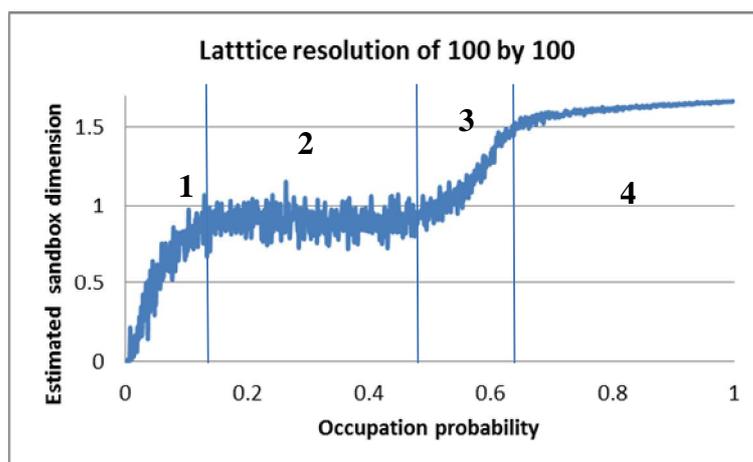


Fig. 1: Sandbox dimension of forest fire font in the range $0.000 \leq P_b \leq 1.000$

Four distinct regions exist in Fig. 1 as P_b increases from 0 to 1. It is noted that each region has a well-defined peak point where phase transition occurs. Taking a closer look at phase changes in the ambit of P_b , it can be observed that four regions exist from 0.000-0.100, 0.100-0.500, 0.500-0.650 and 0.650-1.000. They are tagged 1, 2, 3 and 4 respectively. Within the boundary of 0.000–0.100, an increase in the sandbox dimension is noticed and does so until it approached

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 6, Issue 1, January 2017

the P_b at point 0.100. This interprets the scanty number of burning trees captured per scale at low P_b . At 0.100-0.500, the horizontal progression indicates an equal magnitude of fire spread across burnable trees within the region. The third area bounded from 0.500-0.650 demonstrates a relative upsurge in the progression of sandbox dimension. This describes fire outbreak in vegetation with giant tree clusters. Finally, the fourth region of 0.650-1.000 yielded a slow rise in sandbox dimension as P_b approaches 1, and represents the most aggressive and dangerous forest fire front.

B. AVERAGE TERMINATION TIME ACROSS VARYING OCCUPATION PROBABILITIES

To examine attributes of termination time of a forest fire across different occupation probabilities (P_b), fixed values of P_b bounded below and above percolation threshold were selected and presented in Fig. 2.

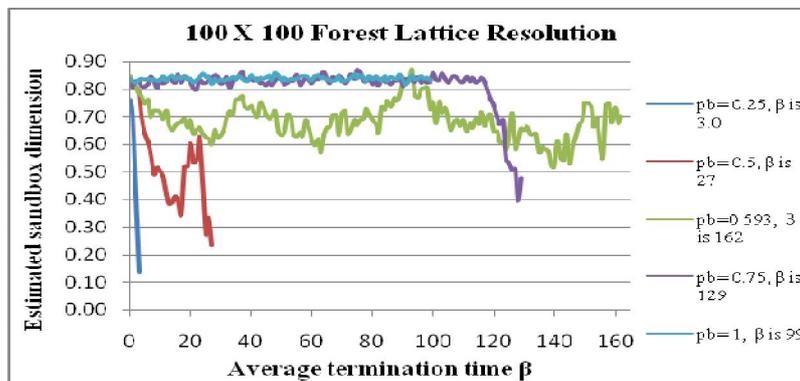


Fig. 2: Sandbox dimension against average termination time for 100 x 100 forest lattice

The values of P_b selected for the analysis include 0.250, 0.500, 0.593, 0.750 and 1.000. The value of 0.250 was chosen to visualize the result of average termination at a low P_b . Fig. 2 shows a steady decline in sandbox dimension for P_b at 0.250 due to decreasing number of burning trees as fire spreads in a widely dispersed tree arrangement. Subsequently, average termination time span is longer due to few tree clusters (which elongates burning time) available at a low P_b . Sandbox dimension decreases inconsistently at 0.500 P_b as it approaches the termination time. This indicates an uneven spread of burnable trees at P_b close to theoretical percolation threshold. In addition, average termination time increased.

Theoretical percolation threshold (0.593) yielded an upsurge in average termination time and a crooked progression of sandbox dimension due to fire spread through percolating clustered trees—the number of burning trees at each time step is irregular with respect to sandbox dimension. For P_b at 0.750, which is beyond percolation threshold, the sandbox dimension demonstrated a uniform burning progression horizontally exhibiting similar characteristics to the percolation threshold. This interprets increased burning rate due to accumulation of clusters at each time step. However, the sandbox dimension trend experienced a nose-dive as it approaches the termination time. Furthermore, analysis carried out on a forest lattice that is 100% occupied with burnable trees (where the value of P_b is 1.000) revealed that for each time step, an entire row burns completely as it progresses to the termination time. Thus, for P_b at 1.000, a direct relationship can be deduced to exist between the average termination time and lattice resolution, such that, as the lattice resolution increases the average termination time increases—fire spreads evenly across each lattice row.

A cursory examination of average termination time for the sequence of P_b values selected makes it evident that the average termination time increases with growing P_b values. However, the average termination time escalated at the percolation threshold which was the only anomaly found.

C. AVERAGE TERMINATION TIME OVER DIFFERENT LATTICE SIZES

Fig. 3 makes clear the outcome of sandbox dimension and average termination time at varying lattice sizes. A fixed probability of 0.750 and five (5) lattice resolutions including 100x100, 200x200, 300x300, 400x400 and 500x500 were picked for better illustration.

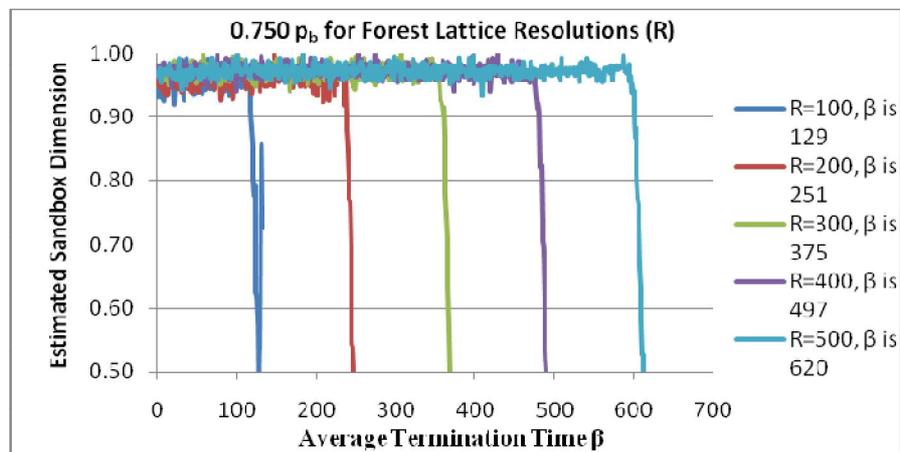


Fig. 3: Plot of sandbox dimension against average termination time for five lattice resolutions at 0.750 occupation probability.

Sandbox dimension progressed uniformly along average time termination for all lattice sizes considered. This interprets that at varying resolutions, the estimated sandbox dimension exhibits similar characteristics at all time steps just before terminating. Subsequently, the plot in Fig. 3 shows that the average termination time increases with growing lattice size. However, the sharp drop observed in the sandbox dimension trend indicates a fire spread approaching its termination.

IV. CONCLUSIONS AND RECOMMENDATIONS

Characterisation using the sandbox method was proposed to analyse the attributes of uncontrolled forest fire—such as the propagation and the termination time—for different occupation probabilities and lattice sizes. The effect of occupation probability (P_b) on burning trees shows four distinct regions. The fourth region with the highest estimated sandbox dimension indicates an aggressively dangerous forest fire front as P_b approaches 1. On the other hand, the study verified that the higher the occupation probability the higher the average termination time and vice versa for all studied cases. However at occupation probability of approximately 0.593 which is the theoretical percolation threshold, the average termination time curve surged. Furthermore, at varying resolutions, the estimated sandbox dimension exhibits sharp drop characteristics just before termination while the average termination time increases with growing lattice size.

This study recommends that tree spread on forest sites should be maintained at the percolation threshold. However, the model may not be completely reliable in preventing fire disasters in vegetation due to certain factors not considered which includes wind direction, leaf moisture and topography. Subsequently, the research work can be used as a safety tool in forest fire management, and can be applied to any medium that conforms to percolation theory.

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Vol. 6, Issue 1, January 2017

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