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ORIGINAL RESEARCH ARTICLE

DEVELOPMENT OF A MODEL FOR MITIGATING FIRE SPREAD IN MULTI-STOREY BUILDINGS

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ABSTRACT
In the developing nations that are located in the tropical region; there is a growing trend of fire incidence in buildings without adequate development of fire prevention and/or reduction protocol. Thus, this study addresses the growth and spread of fire in multi-storey buildings. The rooms are structured as cells in order to reduce the flame spread from a single fuel item, by heat release, to other neighbouring items or rooms (otherwise known as cells). The philosophy is to reduce the advent of vertical and horizontal fire spread. Thus, the mathematical model for the spread of fire in buildings over a solid fuel surface is therefore developed using the adaptation, development and simulation of cellular automata (CA) discrete model. The von Neumann neighbourhood cell configuration is adopted. Hence, the surface of the fuel is analysed using a regular square array (i.e. cells), while the flame spread is depicted as a series of ignitions of surface elements. In which case, ignition of an element is evaluated by a combination of critical surface ignition temperature and cellular automata discrete techniques. The work displays the movement of fire, from its origin of ignition to other fuel igniting elements around it. Consequently, this spread to other parts of the building. However, the technique presented in this work attempts to reduce the rate of growth of the fire spread using the predictive fire growth probability approach. In other words, the application of the cellular automata, using a multi-storey building, is herein presented. The study has potential to advance knowledge of technical approach to stop fire spread in multi-storey building. Thus it improves fire risk management as well as reducing magnitude of fire disaster and losses in the multi-storey buildings.

1.0 Introduction

One of the commonest emergencies that can occur in multi-storey buildings is fire outbreak. The occurrence of fires in multi-storey buildings pose a significant risk to building occupants (Kobes et al., 2010). The incidence of fire outbreak can be due to a number of reasons; most of which could be avoidable; if practice of due diligence and care are taken into consideration. In the modern society, the fire issues are becoming increasingly a significant subject matter due to several factors ranging from building materials to the building designs. It has been established that the bigger and increasingly complex buildings (together with the use of new materials such as respirable silica found in sand, concrete, brick, portland cement, ceramic tile, stone, and other materials made of stone or earth) can lead to more dangerous fires (Yi et al., 2019); whereby the enhanced hazards are difficult to predict. New risks arise due to the use of new chemicals, and also by transportation and handling of hazardous materials. Even unimportant incidents can gravely endanger life, assets and natural environment. In particular, fire and smoke spreading in large buildings represents an early warning with its terrifying threats (Zhou et al., 2019; Yi et al., 2019).

While it is an established fact that the phenomenon of fire and smoke spreading is extremely complex due to the intricacy of chemical reactions and physical processes involved, its spreading from one room to another inside a building is as a result of the transportation of heat and excess fuels that has been generated in the fire compartments. The heat that is generated is then transferred to adjacent buildings by radiation and convection of fire-induced plume to elevate ambient temperature. If the combustibles inside the building ignite and begin to burn due to the external heating, the building then becomes a new heat source to other buildings (Sime, 2001)

When fire starts to burn in a building, an ever-deepening layer of smoke is formed over the entire room space occurring from the rising of the smoke from the fire which becomes trapped within the volumes of room envelope. This is noticeably seen as the smoke hit by the ceiling and then spreads in all directions (Papinigis et al., 2010).

Thus, the smoke goes into other parts of the building through any hole or gap located vertically and horizontally between the walls, ceiling and floors. The building's temperature rises as a result of the heat transfer from the fire that gets trapped in the building. Some materials, such as metal/iron rods in the beams and columns of the buildings, then, absorb heat readily and transmit it to other rooms by conduction, where it can set on fire the combustible items that are in contact with the heated environment or material. Another means of heat transfer during fire events is the radiation; the radiation transfers heat in the air in the same manner that an electric bar heater heats a room. In essence the combustible material close to a fire will absorb the heat until such items start to smoulder which eventually then burn within few minutes (Papinigis et al., 2010). So, also the advent of convection cannot be under rated in building fire incidence. In which case, the hot masses of air move as the air gets heated, thus it expands which makes it much lighter than the surrounding air. This then makes the heated air column that develops to hot air currents that has capacity to ignite the combustible materials along its path of movement.

A great deal of loss is usually incurred from the occurrence of fire. In other words, the occurrence of fire not only destroys property, it is also a threat to the lives of the occupants that are trapped in the fire. These losses arise not only from the articles of things that are combustible within the ignition centre (which are initially ignited) but also the loss of combustible materials that are adjacent to the ignition source. Losses from these fires could be reduced drastically if fires are prevented from spreading to surrounding areas (Zalok and Hadjisophocleous, 2011). The cost of uncontrolled fires in multi-storey buildings in terms of both human lives and loss of properties is highly colossal. An estimate rate of a country's gross domestic product (GDP) shows that each year losses due to fires are between 0.1% and 0.4%. (Raubal and Egenhofer, 1998; Abolghasemzadeh, 2013). This shows that the annual economic and personal costs due to fire damage are immense. Since fires are random events which occur without notification; therefore, the goal of fire safety engineering is to reduce its risk to barest minimum (Ezeokoye, 2016). This will eventually reduce the expected losses. For a better

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evaluation, it is pertinent to understand and quantify the behaviour and consequences of building fires in multi-storey buildings (Architecture and Building Research Institute, 2004). In other words, the construction of building must devise an approach to overcome losses attributable to fire phenomenon.

This has led to the development of such technology places premium on the most important concern; which is to preserve an escape route with low temperature intensity and harmless levels of smoke concentration for the people caught within the fire accident area (Huang, 2010; Justra and Meacham, 2016). This clearly indicates the importance of a planning strategy that incorporates collaboration with the behaviour of the occupants of the building to achieve an effective fire spread mechanism. In general, the planning process requires enhancement of residents' propensity to participate in the process through increasing awareness of disaster risks and the need for improvement of the local environment (Huang, 2010). Even though precise and reliable mathematical models are still under development, the computer simulation represents the most efficient tool used to cope with this problem (Wang, 2015). Computer simulation techniques allow the replication of fire scenarios in virtual spaces with the perspective of discovering practical real-world solutions for dealing with accidental/deliberate fires (Zhang, 2016). In this line of thinking, the interest of this work is the simulation of smoke and fire spreading in enclosures such as buildings and tunnels, whereby the focus is set on the safety, as well as, on building design improvement.

The tremendous losses incurred by fire outbreaks are common knowledge (Chu and Sun, 2005; Kobes et al., 2010; Papinigis et al., 2010; Wang et al., 2015. A great deal of that loss arises not only from the articles or things which were initially ignited but to the loss of combustible materials adjacent to that igniting source. If fire occurrence could be prevented from spreading to surrounding areas, the losses from those fires would be sharply reduced (Hu, 2016). The prediction or analysis of fire spreading in an environment is one of the most challenging aspect of fire research since the effects of fire, of course, heavily affects the quality of buildings, personnel and the public safety. Since the impact of fire on buildings is critical, in the last few years the interest of researchers in models able to simulate the evolution of a fire front has increased significantly (Chu and Sun, 2005). Electrical fire in buildings is one of the most important factors enlarging the severe fatality and loss of materials (Wang et al., 2015; Tong et al., 2013; Yi et al., 2019). To explore the effective measures for reducing the loss, it is indispensable to have a means to rationally predict the behaviour of fires in buildings and some other facilities (Sime, 2001; Zhang, 2016; Ji et al., 2017).

Unexpectedly, fire outbreaks occur in multi-storey commercial buildings which, at times, could spread so rapidly, in such a manner, preventing individuals from escaping from the scene of the fire occurrence. This incidence could also lead to the destruction of properties. More importantly, the product of this combustion often results in hazards to both properties and occupants. It is essential to emphasize that; if the rate of heat generated as well as the fire spread is known, then there is a huge opportunity that lives and properties could be saved. From the aforementioned, it would only possible as long as there is simulation approach to identify source of ignition and the combustible materials within the buildings. Thus, a very close approximation model could be put in place to mitigate the extent of destruction during the ineffectuality of stochastic outbreak of fire. The volume of research in this area is quite significant and substantial (Shahama and Benenson, 2018; Cheng and Hadjisophocleous, 2009; Cheng and Hadjisophocleous, 2011; Yea et al., 2016). The effects of fire and smoke spread beyond the room of fire origin (burn room), on the other hand, have not been thoroughly investigated in the same extent, especially in the tropical region. In this respect, one interesting characteristic of fire is the way it spreads out of openings. Thus, the fire has the tendency to spread both vertically and horizontally (Cheng and Hadjisophocleous, 2011). The horizontal spread of fire could occur in four distinct ways namely: through the wall of partition connecting two compartments, through the closed or open doors, through the windows and through the corridors separating the compartments. However, in the case of vertical fire spread it could be undertaken in four ways that are: through the ceiling connecting compartments, through the stairwells connecting compartments, outside projection of flame through the windows during fire incidence and inside blow of air into the compartment through open windows. The appearance of flames through windows is caused by the venting of unburned gases from the burn room and their continued combustion beyond the opening where reservoirs of fresh air exist. Whereas the external flaming is a characteristic of fire that has undergone a transition to flashover and entered a ventilation-controlled state (Holborn et al., 2004).

It is noteworthy that accurate prediction of fire spread as well as its behaviour with potential changes in a specific time or place in respect of a real-time incidence in the buildings, is very crucial to ensure and mitigate losses and reduce extent of fire damage during its occurrence (Monedero et al., 2019). Thus, the essence of this research is to develop a model that can be deployed to predict and mitigate the spread of fire in multi-storey commercial buildings, using a typical commercial office in Lagos Nigeria as the case study. Succinctly, this goal is achieved firstly by developing a mathematical model for the analysis of the spread of fire in multi-storey buildings using a well versatile tools known as the cellular automata modelling technique. This is then followed by determining the building factors that can influence the spread of fire in a peculiar building as well as within the compartments of the particular building and finally by developing a mitigating measure to mitigate or stop the spread of fire from one room to another.

2. Materials and Methods

The data available for this study is partly secondary and partly primary. This is due to the limitations imposed on the garnering of statistical information relevant for the analysis to be conducted in this study. Towards the analysis of the data and addressing of the objectives of the study, the software adopted for the implementation of the design in this study is Mathematical Laboratory (MATLAB) software. From foregoing the study data include namely: fire sizes, fire growth rates, building sizes, building room/compartment sizes, nature of building materials such as concrete wall and slabs as well as the wooden structures in the building (Ezeokoye, 2016; Huang, 2010; Lahouar et al., 2019; Zhou et al., 2019; Jutras and Meacham, 2016).

2.1 Study Area

This study was conducted in Lagos Nigeria, using Oluwatobi House on Allen Avenue, Ikeja. The house is a six-storey building consisting of offices on the left and right wing of the building. It is located on the street of Allen Avenue, in Ikeja, Lagos State. It accommodates about 300 staff members. The study size has a space area which is about 10m in width and 25m in length within which there are 12 offices. Each office in the building has about 5 compartments demarcated with heat retardant materials (Ji et al., 2017; Lahouar et al., 2019; Yi et al., 2019; Zhou et al., 2019). Most compartments in each office are for 1 or 2 staff members only and are no wider than 3m,

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and rooms are linked by 2m wide long corridors. The various views of the building for this study is as shown in Figure 1a and Figure 1b.

Figure 1a. Front view of the building Figure 1b. Side view of the Building

Figure 1: The subject area

2.2 Research Method

As a prerequisite to simulating building fire spread, a dynamic model for fire spread in buildings is established using the philosophy of fire development in a compartment and its spread from that compartment to the adjacent compartments within the building.

Based on the data developed for the study area, the major work of this study is to propose a new cellular automaton modelling approach. Then the validation of its performance on simulating the fire spreading phenomenon. Therefore, the entire operations of the methodology are classified into three sections (a) development of basic cell size for fire spread model (b) philosophy of neighbourhood phenomenon in fire spread model, and (c) processing the fire spreading model and its validation.

The analysis adapted Cellular Automata (CA) as a tool for analysing fire spreading modelling in the building (Liu et al., 2018; Zheng et al., 2017). This represented how the building factors can influence the spread of fire to another building or within compartments of the same building. There were two main steps adopted in analysing fire spread factors. These are namely: (1) development of CA model and (2) simulation using CA model being developed. The development of the CA model was initiated with the formulation of equations with special consideration for the variables' formulation. It should be noted that there were seven variables that were deployed for the analysis of the analysis of the fire spreading probability factors in the simulated settlement. These were combustibility of materials, total envelope area covered with combustible material, distance between compartments of the buildings, width, building shape, total opening area, and wind speed (Fernandez-Gracias et al., 2019; Hansen, 2019; Lahouar et al., 2019; Raubal and Egenhofer, 1998)). Next step was to define the state of cell which consists of type of cell/object, flammability level, and cell value. For simplification, only the main object in a settlement was involved in the simulation, and that is building (Wang et al., 2015). The value of each cell/object was determined based on the ability to burn and probability to quickly spread the fire to the nearest objects. In this research, the value was calculated based on the flammability rate of the cell/object, total area of combustible material, distance between objects and width. However, the building shape, total opening area and wind speed were ignored because it was considered the same and fixed on each object (Zalok, 2016).

Note that the building is for office space, thus the load has been assumed to be that of a typical office; 25kg/m^2 of cellulose-type fuel (which is the combustible materials that are encountered by fire) with an effective combustion heat of fuel to be 16 kJ/g which results in an equivalent load of 400 MJ/m^2. Thus, the burning mass rate per unit area in typical office building fires ranges from 20 to 40 g/m^{2}s while the corresponding released heat rate per unit area ranges from 320 to 640 kW/m^2.

2.3 Development of Basic unit Cell Size for fire Spread Model

In the recent times, there is increasing capacity development in remote sensing, geographical information system and computing architecture development to ensure that simulation fire models are close to exact behaviour of and effects of fire spread. Thus basically, there are three common fire models that have attracted attention of engineers. This includes Consolidated Model of Fire Growth and Smoke Transport (CFAST), Fire Dynamics Simulator (FDS), and Building Research Association of New Zealand fire (BRANZfire). It should be noted that the fire spread models are interested in variables that influence the convection of fire perimeters through the cells.

Naturally, if the size of cell which is a basic unit of fire spreading model is small, the possibility of a more detailed simulation is evidently essential to ensure that mitigation of fire spread would take care of the microscopic elements of the fire chemical contents. (Abolghasemzadeh, 2013; Ahmed et al., 2019; Olawoyin, 2019). However, if the size is too small, there will be an increase in the time of calculations and volume of data. Since the aim of the simulation model proposed in this study is to identify and show fire spreading, the size of cell used needs not to be too small. An adaptation of the spread of fire in electrical distribution network put paid to this (Bagchi et al., 2013). Therefore, the size of cell used in this study is set at 3 by 3 meters using the following equation representing limit of distance between spread points or distance from source of fire spread (Murosaki et al., 1984; Bagchi et al., 2013). Hence the equation is expressed as (Ohgai et al., 2004):

$$D = 1.5(5 + 0.5v) \tag{1}$$

where: v is cumulative wind velocity in meter per second (m/sec) and D is the limit of distance by which fire can spread in metres (m). These are design vectors whose dimensional concept is developed in such a way as to provide needed information when the effect of one or more variables on the figure of merit is needed.

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2.4 Philosophy of Neighbourhood phenomenology in Fire Spread Model

Traditionally, there are two approaches of tessellating the buildings for this research, namely square- and hexagonal-lattice modelling procedures. However, the square-lattice was adopted. In order to simplify the process and reduce computational burden; the 2-dimensional regular square grids were employed as cells of the CA framework. However, each square-lattice cell at different discrete time steps was characterized by a number of discrete transition states.

This development is guided by a number of previous rese4arch on the subject matter. For instance, Bagchi et al. (2013) gave information based on the idea of the limit of distance that fire can spread, which has been brought out by previous researches (Murosaki et al., 1984).

In applying the neighbourhood phenomenon to the Cellular automata fire spread model; there are two school of thoughts. The cellular automata as a mathematical model was introduced in 1963 by von Neumann with the specific purpose of modelling biological self-reproduction. There are basically two common types namely von Neumann neighbourhood and Moore neighbourhood phenomena. While the former is expressed mathematically using the four orthogonal cells surrounding the central cell, the latter needs to consider the eight cells surrounding the central cell. This is as displayed in Figure 2. In this case the noticeable changes with time steps is recorded with respect to the wind velocity. For instance, from the diagram, consider that cell kl is the igniting source of the fire spreading while cell ij is the cell tagged the received one in the neighbourhood. In the CA framework, the state of each cell evolves in discrete time steps based on a finite set of local transition rules.

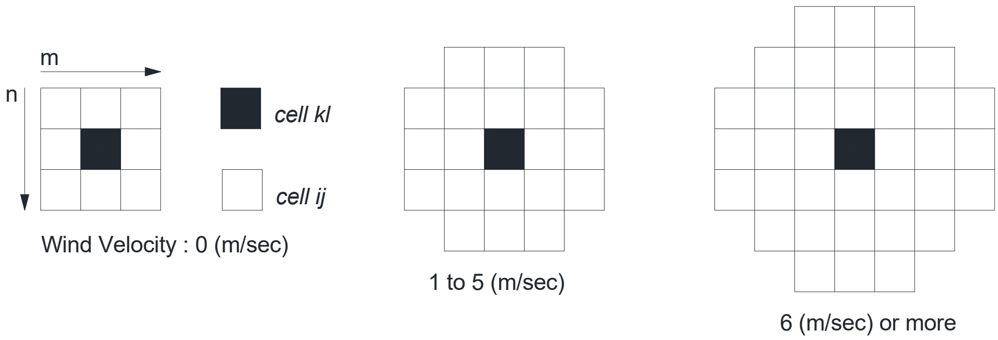

Figure 2: Neighbourhood used in the model

Thus, the basic model adapted for the study is the extended model developed for fire spread in two-dimensional linear cellular automata (Encinas et al., 2007; Yang et al., 2014). It relies on the transition principles of discrete dynamical systems using the finite number of identical objects (otherwise known as cells). This transition of cell states is set as shown in Table 1. Though there are several classes of neighbourhood in the analysis of fire spread, however for the sake of emphasis, this study adopted the extended Moore neighbourhood approach. Thus, at the start of the simulation; all the cells are either in the "Unburnable" state (i.e. 0) or "Not-Burning-Yet" state (i.e. 1). The cell with state 1 is not burning yet, but it has the potential of burning. However, during simulation, a cell can transcend from state-1 to state-2, either through a new fire occurrence or through spread of fire from the adjacent cell or cells (Ghisu et al., 2015; Encinas et al., 2007). In other words, once a cell catches fire the state of the cell changes to state 2. And then, according to the elapsed time after the outbreak of fire incidence, thus the state of the cell changes from state 2 to 4. But it is noteworthy to state that the cell with state 0 is unburnable; thus, it never changes during the simulation period.

Table 1: Transition State of a cell

State of Cell	Explanation
0	n_{mn} = 0 : Unburnable; Having nothing burning
1	n_{mn} = 1 : Not-Burning-Yet; Having the possibility of burning
2	n_{mn} = 2 : Catching fire; just catching fire, but having no ability to cause fire spreading
3	n_{mn} = 3 : On fire; having the ability to cause fire spreading
4	n_{mn} = 4 : Extinction

2.5 Process of the Fire Spreading Model

This model is built on the earlier work (Ohgai et al., 2004). According to Zheng et al. (2017); the fire spread model adapted the transition algorithms or steps under the CA framework. In which case, the cells evolved individually in discrete time steps on a set of discrete transition steps which are as follows:

Step 1: First of all, one cell kl of N_{kl}=3 is selected.

Step 2: One cell ij of n_{ij} =1 is selected at random from the neighborhood defined by a wind direction and a wind velocity externally given when simulation starting.

Step 3: Fire spreading judgment index F_{ij} of a selected cell ij is calculated. If F_{ij} is satisfied with the following requirements, the state of cell ij becomes n_{ij}= 2 (i.e. catching fire).

If

$$n_{ij}(t) = 1 \text{ and } F_{ij} > \text{ran; then } n_{ij}(t+1) = 2 \quad (2)$$

where: $n_{ij}(t)$ is the state of cell ij at simulation time t and ran is the random number which takes from 0 to 1., t_{cij} is an elapsed time after outbreak of fire in cell ij. The time count of t_{cij} starts when the state of cell ij changes from state 1 to 2 which is satisfied in equation (2). Steps 2 and 3 are iterated for all cells ij within the neighbourhood of cell kl. Furthermore, the process regarding cell kl is executed for all cells of state 3.

Step 4: The state of cell ij after catching fire changes according to the elapsed time after outbreak of fire, t_{cij}. In other words, if the value of t_{cij} takes more than t_1 = 2mins, cell ij changes from state 2 to 3. Namely, n_{ij}= 3. Moreover, if the value of t_{cij} takes more than t_2 = 10mins, cell ij changes from state 3 to 4. Namely; n_{ij}= 4.

Step 5: The simulation ends when the time, t, in minutes becomes the end time externally given in the model. The time, t, is counted from the simulation start to the end. When the time, t, does not reach end time, 1 is added to t_{cij} and t; then the process returns to Step 1.

Thus, the fire spread judgment index of each cell is expressed as:

$$F_{ij} = \alpha p_{(i,j)t} * \beta v(i,j)_t \quad (3)$$

where $p(i,j)_t$ is the cell's ignition probability; 0<α≤1 (i.e. this is the condition of slowing down fire spread without considering the wind velocity); β>1 and v is the wind velocity effect

thus the fire spreading time is obtained as follows:

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$$t_{i,j} = \frac{L}{ROS} \tag{4}$$

where:

L is the centroid distance between two adjacent cells ROS is the rate of spread (this is dependent on wind velocity and other accompanied factors)

t: Simulation time in minutes

t_{cij}: Elapsed time after outbreak of fire in minutes

end time: End time of simulation in minutes

F_{ij}: Fire spread judgment index of cell ij

ran: Random number given within the range from the maximum to the minimum of F_{ij} value.

As mentioned above, even simulation using the same conditions produce different fire spread results. Even if fire spread is not externally intercepted with respect to its extinction; yet the characteristics of a model with a probabilistic calculation process will naturally ensure that the number of cells in each state converges to a certain value as long as simulation is infinitely iterated. Accordingly, it is more appropriate to use a probabilistic expression as a means of offering information to the participants. Based on this perspective, primarily, the information on the numbers of completely burned cells as a product of 100 iterations were collected. Then, both the mean and standard deviation in each of these samples using 20 cases of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95 and 100 samples were thus evaluated, so as to evaluate the spread from the expected value. Thus, the mean or average fire growth is given by Eqn(5a)

$$\mu = 3\sqrt{\frac{3\mu_F A F_h}{\delta}} \tag{5a}$$

and thus; standard deviation of fire growth is given as follows:

$$\delta_F = \sqrt[3]{\frac{3AF_h}{\alpha(\mu)^2}\frac{\sigma}{3}} \tag{5b}$$

where:

α: growth coefficient of t_2 fire

σ: standard deviation of fuel load density

μF: mean duration for fire to grow from ignition initiation

A: Floor area of compartment

F_h: Floor to floor height or cell height

In line with the above stated algorithm, Figure 3 shows the flow chart of a fire spread model as presented. From this diagram, it can be explained that the outbreak of the fire is initiated in a cell, nij=3. The growth of the fire in this cell continues until the fire outbreak is spread after a period of graduated time steps (i.e. t+1) to other parts of the building. Thus, the fire spread, in a random manner, to other cells by the help of the von Neumann's protocol. Hence, this procedure extends the fire spread to all the other compartments in the building (von Neumann, 1966).

Thus the propensity that the fire will reach other parts of the building is built on the transition probability (i.e. Pi,j). This measures the likelihood of cell's state transition. In other words, it provides information on the cells that will be burning at the next discrete time step (t + 1). This rule implies that a cell containing combustible fuel will be burning. However, it is possible to have one or more than one burning cell in its von Neumann neighbouring cells and its state transition probability (i.e., Pi,j) is higher than a random probability threshold (Cheng and Hadjisophocleous, 2009; Cheng and Hadjisophocleous, 2011).

0	Pi+1,j	0
Pi,j-1	Pi,j	Pi,j+1
0	Pi-1,j	0

Figure 3: Adapted von Neumann Neighbourhood configuration for fire spread Model (von Neumann, 1966)

To model the fire spread from the perspective of the movement of fire and heat from one cell to the adjacent cells, this can happen in random manner however, Neumann developed an approach for evaluating the pattern of spread (Zheng et al., 2011). This is explained by the expression in equation (6)

So, the transition probability,

$$P_{ij} = N \frac{e^{(k_d D_{ij})} e^{(k_s S_{ij})}}{e^{(k_f F_{ij})}} (1 - \eta_{ij}) \xi_{ij} \delta_{ij} \tag{6}$$

where:

D_{ij} :dynamic floor field
S_{ij} : radiation intensity field
F_{ij} : Fire floor field
η_{ij} : whether cell ij is occupied by wall or obstacle (if occupied it is 0 and if not it's 1)
α : adjustment factor for Fij
ξ_{ij} : cell occupied by combustible material (0 when occupied; 1 when not)
δ_{ij} : whether cell occupied by danger (0 when it is; 1 when not)
$k_d; k_s$: two positive parameters for scaling Sij and Dij
k_f : scaling factor for Fij
N : Normalization factor

Hence, according to conduction property of fire, then the dynamic floor field expression can be obtained from the randomized movement of fire as follows;

$$D_{ij}^{(t+1)} = \frac{D_{ij}^{(t+\frac{2}{3})}}{\sum_i \sum_j D_{ij}^{(t+\frac{2}{3})}} \tag{7}$$

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Since the fire can spread by radiation hence, the variation of radiation intensity field with distance from the source could be defined as:

$$S_{ij} = \frac{1/D_{ij}}{\sum_i \sum_j 1/D_{ij}} \tag{8}$$

So, also since convection is the physical movement of hot mass of air. In other words, at heating there is density change in the boundary layer which cause the denser (cooler) air to rise so as to replace the cooler air which will heat and rise; this cyclical heat transfer phenomenon continues until the fire spread is further enhanced. Thus, in a building, during fire outbreak the hot air will always rise and float under the ceiling of a room thus spreading the heat from the fire. This can be expressed by modifying the Newton's cooling Law as follows:

$$F_{ij} = k_{h_{ij}} \left(\frac{\rho_{ext}}{\rho_o} \right)^{\frac{2}{3}} h_{ij} \tag{9}$$

Where the fuel bed the term inside the brackets and its coefficient is the convective heat transfer coefficient and hij is heat gradient that is exercised during fire outbreak. As an adaptation of the earlier research on the city-wide fire spread model, this work is situated within a building in a tropical region as depicted herein in this presentation (Ohgai et al., 2004). Thus, the flow chart presented in Figure 4 is a further explanation of the fire spread phenomenon as captured by the foregoing mathematical expressions.

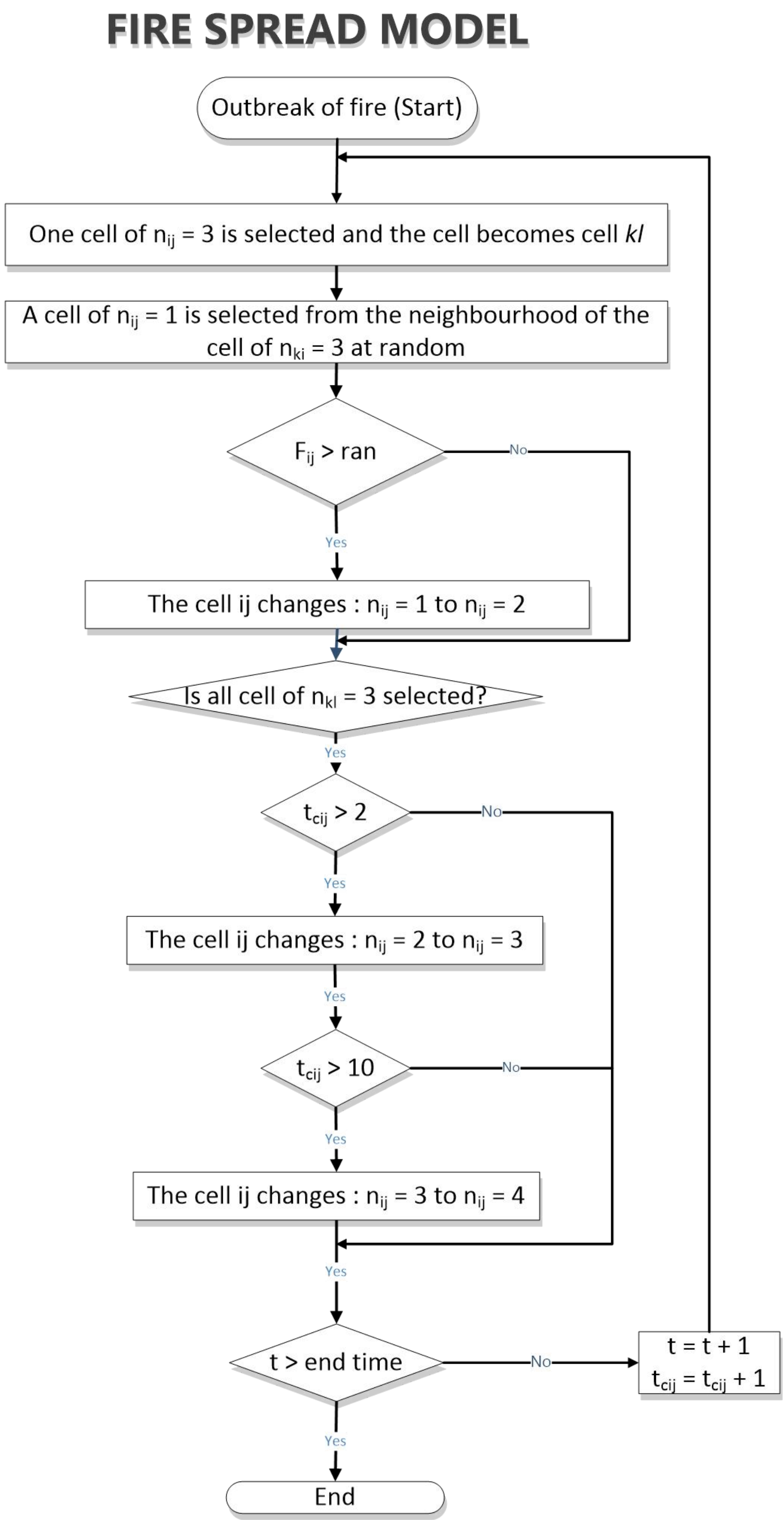

Figure 3: Flow chart of the fire spread model

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3. Results and Discussion

The model developed herein is applied to the subject area. Since fire is highly unpredictable, then the probability model is developed alongside to the simulation takes care of any ineffectuality. It should be emphasized that there are a number of variables that determines the fire spread rate. However, a number of them is assumed constant during this study thus the cause of fire outbreak in the building under study is assumed to be dependent on the fuel load in the building. With respect to the fuel load, then a typical cell may be unburned, partially burned or completely burned. It should be noted that the fuel load is inclusive of the individuals and things found within the building.

From the foregoing, therefore applying this to the cellular automata model developed for implementation on the subject area. The simulation was carried out using 100 iterations. The results of the simulation were subjected to test using the probabilistic assessment process which is built into this model. This thus yielded results that the fire spread depends on randomized occurrence of fire.

As depicted in Figure 3; even though the actual time required for calculation of the simulation of 100 iterations was about 26 minutes using a personal computer but the simulation end time was set at 180 minutes. This is calibrated in such a way that the trend was studied in three discrete time steps set as: 30minutes after ignition, 120 minutes after ignition and 180 minutes after ignition. The occurrence, spread and extinction of fire occurrence was studies over these set times. it was discovered that for the first 30 minutes of the ignition; the fire spread via heat transfer by combination of conduction, radiation and convection is such that mean is very close to the standard deviation. In other words, the standard deviation of the number of cells within the state transition of the fire incidence (i.e. from unburned to burning state) that converges to a mean value shows a close relationship which then suggests that the cells experience combustion. Furthermore, at 120 minutes the standard deviation to mean (average) values experience a wider gap which connotes that the fire spread is approaching extinction while the relationship between mean and standard deviation at 180 minutes clearly predicts the complete extinction of the fire spread. Furthermore, after the number of accumulated samples exceeds 50; it is found out that there is a fixed number of extinction cells due to the fact that the gap between a specific mean and its standard deviation becomes smaller.

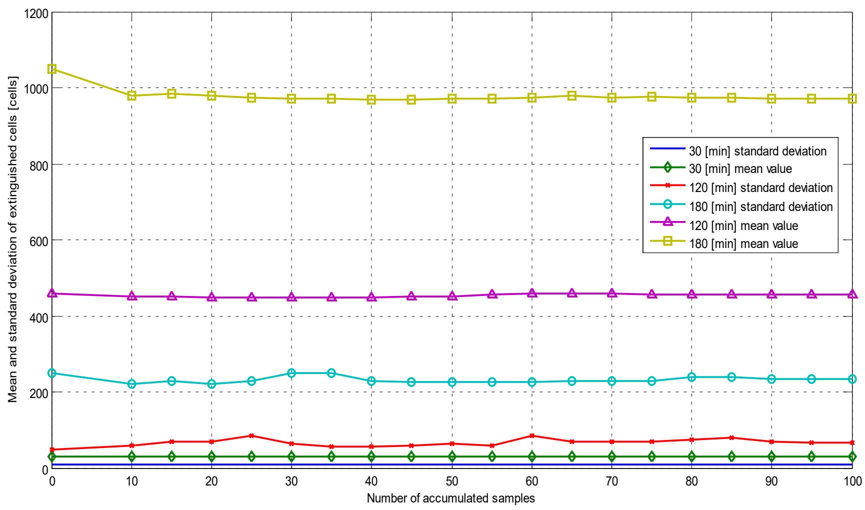

Figure 3: Mean and standard deviation values of the simulation results

So also based on the fire spread judgement index, it was quite essential to design a value-based analysis of judgement capacity, behaviours and stability. Figure 4 presented the relationship between the numbers of extinguished cells as against the time of fire spread. So by adopting the judgement index, it served to assist in enumeration, building and development of capacity to make good judgement on fire spread with time. Hence the relationship between the number of cells that had been extinguished and the time of fire spreading based on different types of fire occurrence. From the family of trend curves in Figure 4, the dotted line was based on the mean values of 50 samples for each simulation time; whereby the probability factor of fire spread excluding wind velocity (i.e.α) is taken as α = 1; while the probability of occurrence inclusive of wind velocity factor (i.e. β) is set as β = 1. At another instance, the dotted and dashed lines (displayed in Figure 4) were based on the mean values when α = 0.7 and β = 1. From the trend lines presented in Figure 4, it was found that the number of extinguished cells for the first scenario was about 70% of the estimated number of those cells obtained in the simulation when α = 1 and β = 1. This reduction can be considered to be due to the slowdown of fire spreading which is attributable to the restriction of air supply due to building after a period of time. Therefore, it can be seen that this plays the role of expressing an uncertainty situation that is synonymous of fire outbreak. Furthermore, it is still possible to suggest that the number of extinguished cells could be less than that of the others due to the propensity of intervention from the firefighting paraphernalia. Thus, the variations in the range and speed of fire spread (as well as its extinction) may therefore be explained to some degree by the stochastic nature of the fire occurrence as implemented in the model herein presented.

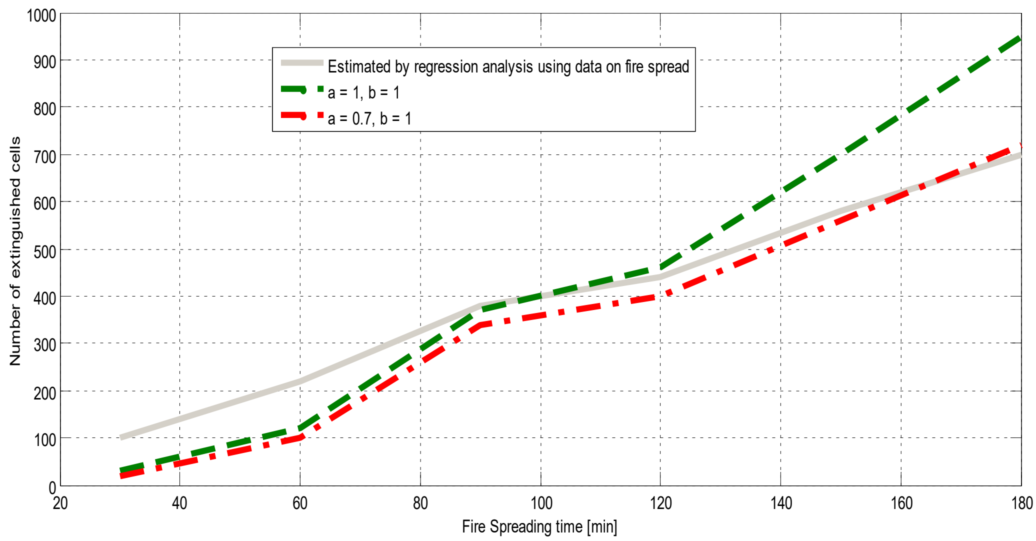

Figure 4: Comparison between actual fire records and simulations results

4. Conclusion

The study utilises cellular automata (CA) for the development of fire spread simulation model. It shows that fire spread is highly reliant on the fuel loads, wind speed and spread rate. Thus, any attempt to arrest the spread of the fire should be focused on these variables. From the results presented; it is quite clear that the time count from partial burning to complete burning may not be more than 30 minutes. However, the final extinction of the smouldering cells could extend till 180 minutes. This model is virtually simulated to understand the fire safety technology and principle of the spread of fire in detail. Thus, the developed framework has the capacity to deal

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with the process of fire spread in a building that the traditional models cannot efficiently arrest. Furthermore, from the study, the actual spread of fire varies distinctly with varying physical and/or planning circumstances such as the location or locality of building, fuel loads in the building, prevailing weather conditions, sizes of the room, building occupancy types and wind velocity. With the aid of the Neumann neighbourhood in the implementation of the CA model (which considered the fire transition in the four adjacent cells), it was discovered that fire can spread to the other cells through heat transfer promoted by the radiation and convection profile of the fire environment. So, the presence of fuel loads is essential to the conduction of heat to both vertical and horizontal adjoining cells while the availability of wind speed is crucial to the convection heat transfer process. This is then suggesting that the firefighting procedure needs to take the conduction and convection heat transfer into consideration in any event of the fire outbreak. In conclusion, the model shows great potential to predict the behaviour of fire spread, hence, it means that once the trend of spread of the fire is known; it becomes quite easy to avert its spread to other cells or buildings after the initiation of ignition process. Fire outbreak is stochastic; hence it cannot be outrightly eliminated but can be reduced. Thus, this study proffers procedures for mitigating the incidence of fire spread before the outbreak records disaster or causalities.

Reference

Abolghasemzadeh, P. 2013. A comprehensive method for environmentally sensitive and behavioural microscopic egress analysis in case of fire in buildings. Safety Science, 59, 1–9.

Ahmed, A., El-Kady, MF., Hassan, I., Negme, A., Pourrahimi, A.M., Munic, M., Selvaganapathy, PR. and Kaner, RB. 2019. Fire-retardant, self-extinguishing triboelectric nanogenerators. Nano Energy, 59: 336-345.

Architecture and Building Research Institute (ABRI). 2004. The evaluation manual of building fire prevention and escape ability. Taiwan: Taipei. Retrieved from

https://www.revolvy.com/page/Ministry-of-the-Interior-%28Taiwan%29

Bagchi, A., Sprintson, A. and Singh, C. 2013. Modeling the impact of fire spread on an electrical distribution network. Electric Power Systems Research, 100: 15–24.

Cheng, H. and Hadjisophocleous, GV. 2009. The modeling of fire spread in buildings by Bayesian network. Fire Safety Journal, 44: 901–908.

Cheng, H and Hadjisophocleous, GV. 2011. Dynamic modeling of fire spread in building. Fire Safety Journal, 46(4): 211-224.

Chu, G. and Sun, J. 2005. Decision analysis on fire safety design based on evaluating building fire risk to life. Journal of China University of Science and Technology, 26: 456–508.

Encinas, AH., Encinas, LH., White, SH., Martin dey Rey, A., Sanchez, GR. 2007. Simulation of forest fire fronts using cellular automata. Advances in Engineering Software, 38, pp. 372-378.

Ezeokoye, OA. 2016. Conduction of heat in solids. In Hurley, M.J., Gottuk, D.T., Hall Jr., J.R., Harada, K., Kuligowski, E.D., Puchovsky, M., Torero, J.L., Watts Jr., J.M., Wieczorek, C.J. (Eds.), The SFPE Handbook of Fire Protection Engineering (pp. 25-52). New York: Springer-Verlag.

Fernández-García, V., Miesel, J., Baeza, MJ., Marcos, E. and Calvo, L. 2019. Wildfire effects on soil properties in fire-prone pine ecosystems: Indicators of burn severity legacy over the medium term after fire. Applied Soil Ecology, 135: 147-156.

Hansen, R., 2019. Fire behaviour of multiple fires in a mine drift with longitudinal ventilation. International Journal of Mining Science and Technology, 29(2): 245-254.

Holborn, PG., Nolan, PF. and Golt, J. 2004. An analysis of fire sizes, fire growth rates and times between events using data from fire investigations. Fire Safety Journal, 39: 481–524.

Hu, YN. 2016. Research on the Application of Fault Tree Analysis for Building Fire Safety of Hotels. Procedia Engineering, 135: 524 – 530.

Huang, LY. 2010. Application of SIMULEX to simulate evacuation time in public building: Using Warehouses as Examples. MSc. Thesis, Chaoyang University of Technology, Taichung, Taiwan.

Jutras, I. and Meacham, BJ. 2016. Development of objective-criteria-scenario triplets and design fires for performance-based Fire Safety Design. Journal of Building Engineering, 8: 269–284.

Ji, Y., Li, Y., Chen, G. and Xing, T. 2017. Fire-resistant and highly electrically conductive silk fabrics fabricated with reduced graphene oxide via dry-coating. Materials and Design, 133: 528–535.

Kobes, M., Helsloot, I., Vries, B. and Post, JG. 2010. Building safety and human behaviour in fire: a literature review. Fire Safety Journal, 45(1): 1–11.

Lahouar, MA., Pinoteau, N., Carona, JF., Foreta, G. and Rivillon, P. 2019. Fire design of post-installed bonded rebars: Full-scale validation test on a 2.94 × 2 × 0.15 m3 concrete slab subjected to ISO 834-1 fire. Engineering Structures, 174: 81-89.

Liu, Y., Liu, H., Zhou, Y. and Sun, C. 2018. Spread vector induced cellular automata model for real-time crown fire behavior simulation. Environmental Modelling and Software, 108: 14-39.

Magaliea, C., Anne-Sophie, C., Rodolphe, S., Laurent, F., Emmanuelle, G. and Christian, L. 2018. Fire behaviour of electrical cables in cone calorimeter: Influence of cables structure and layout. Fire Safety Journal, 99: 12–21.

Monedero, S., Ramirez, J., Cardil, A. 2019. Predicting fire spread and behaviour on the fireline. Wildfire analyst pocket: A mobile app for wildland fire prediction. Ecological Modelling, 392: 103–107.

Murosaki, Y., Ohnishi, K. and Matsumoto, K. 1984. Research on spreading factor of an urban expansion fire. Journal of the City Planning Institute of Japan, 4: 373-378.

Ohgai A., Gohnai Y., Ikaruga S., Murakami M., Watanabe K. 2004. Cellular Automata Modeling For Fire Spreading As a Tool to Aid Community-Based Planning for Disaster Mitigation. In: Van Leeuwen J.P., Timmermans H.J.P. (Eds) Recent Advances in Design and Decision Support Systems in Architecture and Urban Planning (pp. 193-209). Springer, Dordrecht.

Olawoyin, R. 2018. Nanotechnology: The future of fire safety. Safety Science, 110: 214-221.

Papinigis, V., Geda, E. and Lukošius, K. 2010. Design of people evacuation from rooms and buildings. Journal of Civil Engineering Management, 16 (1): 131–139.

Raubal, M. and Egenhofer, MJ. 1998. Comparing the complexity of way finding tasks in built environments. Environment and Planning B: Planning and Design, 25(6): 895–913.

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https://doi.org/10.1068/b250895

Shahama, Y. and Benenson, I. 2018. Modeling fire spread in cities with non-flammable construction. International Journal of Disaster Risk Reduction, 31: 1337–1353.

Sime, J.D., 2001. An occupant response shelter escape time (ORSET) model. Safety Science, 38 (2): 109–125.

Tong, RT., Guo, LZ. and Cao, Z. 2013. The Analysis in Several Application Issues for Leakage Current Electrical Fire Monitoring System. Procedia Engineering, 52: 342 – 348.

von Neumann, J. 1966. Theory of Self-Reproducing Automata. University of Illinois Press, pp. 388.

Wang, SH., Wang, WC., Wang, KC. and Shih, SY. 2015. Applying building information modelling to support fire safety management. Automation in Construction, 59: 158–167.

Yang, Y., Deng, J., Xie, CC., Jiang, YT. 2014. Design and implementation of fire safety evacuation simulation software based on cellular automata model. Procedia Engineering, 71: 364-371.

Yea, X., Maa, J., Shena, YX. and Lin, LY. 2016. Suppression effect of sprinkler system on fire spread in large commercial buildings. Procedia Engineering, 135: 455 – 462.

Yi, J., Chen, W., Han, J. and Chen, D. 2019. Sensitive and selective detection of plasticizer vapors with modified-SnO2 hollow nanofibers for electrical fire warning. Sensors and Actuators B: Chemical, 287: 364-370.

Zalok, E. and Hadjisophocleous, GV. 2011. Assessment of the use of fire dynamics simulator in performance-based design. Fire Technology, 47(4): 1081–1100.

Zhang, Q., 2016. Scene design and simulation analysis of fire accident in underwater tunnel. Procedia Engineering, 166, pp. 337 – 346.

Zheng, Z., Huang, W., Li, S., Zeng, Y., 2017. Forest fire spread simulating model using cellular automaton with extreme learning machine. Ecological Modelling, 348, pp. 33–43.

Zheng, Y., Jia, B., Li, X.-G., Zhu, N., 2011. Evacuation dynamics with fire spreading based on cellular automaton. Physica A 390, 3147–3156.

Zhou, X., Xin, Y. and Dorofeev, S., 2019. Evaluation of an oxygen reduction system (ORS) in large-scale fire tests Fire Safety Journal, volume 106, pp. 29-37.