

Analysis of Architectural Building Design Influences on Fire Spread in Densely Urban Settlement using Cellular Automata

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Abstract. This study aims to determine the influence of architectural design on the risk of fire spread in densely urban settlement area. Cellular Automata (CA) is used to analyse the fire spread pattern, speed, and the extent of damage. Four cells represent buildings, streets, and fields characteristic in the simulated area, as well as their flammability level and fire spread capabilities. Two fire scenarios are used to model the spread of fire: (1) fire origin in a building with concrete and wood material majority, and (2) fire origin in building with wood material majority. Building shape, building distance, road width, and total area of wall openings are considered constant, while wind is ignored. The result shows that fire spread faster in the building area with wood majority than with concrete majority. Significant amount of combustible building material, absence of distance between buildings, narrow streets and limited fields are factors which influence fire spread speed and pattern as well as extent of damage when fire occurs in the densely urban settlement area.

1. Introduction

Fire risk in buildings not only from the inside but also from surrounding its location. This risk is unavoidable. Example case is from a case of fire that occurred in Indonesia not long ago, care of fire from densely urban settlement in Kampung Lio, RW 19, Depok Village. This fire started from ignition from kitchen stove, then spread and burned at least 60 houses (Anugrahady 2016). Although firefighters already came and try to extinguish the fire, but there is so many difficulty to stop the fire. Difficulty of fire trucks to access, building is too dense, and difficulty to find water resource is the main reason firefighting had difficulty to solve this fire disaster. Dense settlements area are highly heterogeneous with regards to population density and tree cover that population density never falls below 100 persons/km (Shankbone 2008). The beginning of densely settlement area is come from urbanization era. Because of economic crisis, people live in big cities is very hard and less of them can survive in this condition. Many communities cannot afford a proper house to stay. So they built themselves a settlement by ignoring regulations and building permits. This causes some area in big city become dense urban settlement area with no urban development control and building safety. If there is disaster happen in this area especially fire. It can be dangerous and have potential to causes large area of damage.



To prevent fire spreading in densely urban settlement area, an analyzed and comprehensive studied must be done. In architectural field, there are several factor that need to be study for fire disaster mitigation, such as building design includes type of material, area of building envelope, area of openings, and building shape. Through these architectural study, there are possibility to decrease fire spread by knowing its occurrence process and behavior. This concept of model is one of the views of “complex systems” called CA (Cellular Automata) that effective for being used as a tool to study spreads of fire (Takizawa, et al. 2000). Through fire spreading simulation by using CA, this research expect to identify patterns fire spread in high density area. So in the future there are solution, action, and mitigation could do to prevent fire spread in high density area by input to urban management guideline in Indonesia.

2. Fire Occurrence

2.1. Fire Behaviour

Fire is a phenomenon that is produced by a chemical reaction between things that can burn and oxygen, which is accompanied by heat, light (flame), smoke and gases onset from the burning material. There are three elements forming the fire: fuel, heat and oxygen. Fuel is categorized based on the minimum temperature which causes ignite (fuel temperature). The use of various construction materials, interiors, and furnishings in building can generate a collection of fuel with fuel temperatures ranging from low to high. Total content of the fuel is called the fire load (fuel load). The higher the volume of flammable material, the greater the possibility of fire occurs.

The fire started from the stage ignition. Fire will turn into a fire if ignition continues to combustion. Combustion required a fourth element, namely a chain reaction. Fire arising in a part of the fuel will heat and raise the temperature on the part of other materials, thus causing the entire fuel consumed, and can result in the objects around it burned. Conversely, if one of the three elements forming the flame is removed, the chain reaction does not occur, and the combustion process will stop. There are three ways of heat transfer, namely (1) conduction, (2) convection, and (3) radiation. Transfer by conduction occurs through a solid material, of a part with higher temperatures to the lower temperature. In buildings, conduction occurs through a partition wall where if a fire occurs on one side of the wall, then the wall behind it will receive the heat that can burn the surface of objects located on the wall. While the heat transfer by convection is heat and smoke spread of fire to the top of the building through an open staircase. Radiation occurs through empty space caused by heating or the air pressure / wind (Langdon-Thomas 1972).

Fire can grow and spread from one room to another room in the building, or from one building to another building in an area due to failure in the containment effort. According to Yung (2008), the fire spread probabilities in a building is a result of the failure of the boundary elements. The boundary element would fail if its fire resistance rating (FRR) is not high enough to withstand a fully developed compartment fire. The results of the analysis of the cause of the burning of large buildings show how the fire spread rapidly to all parts of the building as a room divider wall made of combustible material (Rasbash, et al. 2004).

There are five stages of fire development, namely: (1) Ignition, (2) growth, (3) flashover, (4) fully developed, and (5) decay. All burning must be having ignition stage, but after that it can continue to grow or outages. Fires can reach flashover, or the fire had subsided before reaching flashover. Ignition process is caused by the heat energy of the material that can be burned. The heat energy can be derived from the blast stoves, electric short-circuit current, cigarette butts, or others. Upon ignition, the fire began to grow, and if the air in the room is still sufficient and material that is burning still a lot, then the growth of the fire will continue, causing the temperature of the room rises. At this stage the fire can still be localized, hence the effort to control the fire is best done at this stage. Flashover is generally defined as a period of transition between stages of growth with a fully developed stage. The process is very fast, ranging from 5 minutes to 8 minutes. At the time of flashover objects that previously burned partially burned sudden entirely. Combustion speed rises quickly causing the fire

difficult to control. Flashover occurs when the flame has touched the ceiling and started to protrude out of the openings. The fire already difficult to extinguish, so that flashover can extend to full combustion stage. At this stage, the heat release is very large because of fires have broken out across the room. All materials in the room had been burned. At this stage fire development is influenced by the openings wide, because indoor air can no longer support fully combustion (Langdon-Thomas 1972). One attempt to do is localize the fire in the building of fire origin to prevent the fire from spreading to other buildings.

2.2. Conflagration

Conflagration is a large destructive fire, in the context of the settlement, usually involving tens or even hundreds of houses on fire. Losses caused by the Conflagration is very large, therefore these types of fires are classified into a major disaster. Conflagration frequently occurs in densely populated urban areas such as Jakarta. Based on the data, during January to March 2015 there were 177 fires with 74 cases or 41.8% were residential fires (Bayu 2015). Fire sources which occur in dense settlements are including electricity, stoves, candles, burning trash, cigarette butts. In many cases, electricity is the most frequent cause of fire. In terms of source of fire, dense settlements have very high vulnerability due to the use of electricity that exceeds the capacity of the equipment, the use of non-standard electrical wires, and illegal usage. Most of the building walls, roofs and also furniture are made of combustible materials such as wood so when ignition occur the fire easily enlarged if not immediately extinguished.

A number of researches that aims to determine the factors that cause the spread of fire through fire modelling have been done (Himoto and Tanaka, 2010; Lee and Davidson, 2008; Ohgai et.al, 2004). Wind speed and direction, location, thermal radiation, wide openings, construction materials, and the distance between the buildings are factors that are considered influential on the direction and speed of the spread of fire. High building density and building huddled together also can facilitate the flames move from one building to the adjacent buildings when fire occurs. Fire spreads very fast through wall and roof which are made of combustible materials. This was exacerbated by the narrowness of the road making it difficult for fire engines to reach the fire location. The absence of hydrants or water sources with sufficient volume for extinguishment making the fire more difficult to control, and eventually become conflagration. Research on urban fire spread is generally carried out abroad where the conditions are different to the settlement in Indonesia. Therefore the study of urban fire spread factors in densely urban settlement areas in Indonesia needs to be done and the results are used to develop strategies for mitigating fire.

2.3. Cellular Automata (CA) Model in Fire Spreading

Cellular Automata (CA) is a computer modelling that is usually used in social sciences and scientific fields. The reason behind frequent used of CA in analyzing many natural phenomena is that most physical processes are themselves local in nature—molecules interact locally with their neighbors, such as bacteria with their neighbors, ants with theirs, and people likewise (Schiff 2005). This is seen as potential to be used in modelling of fire spreading, especially in densely urban settlement. Some previous study even have experimented and research about simulations of spreads of fire on city site (Takizawa, et al. 2000). Ohgai (2004) in his research on using CA modelling of fire spread in built up areas define as a tool for simulation model that can offer resident clear information on how improvement in the local environment can enhance disaster mitigation performance as well as educating them on disaster risk and the need for improvement measures. Hongpo Wang (2014) on his research on using CA modelling of fire spread model in historic site which represent the commercial culture, academic culture, exotic culture and civilian culture building are usually made of wood and highly combustible materials. This simulation use CA rules and influence coefficient of the evacuation time were investigated and typical characteristic of space-time dynamic were analyzed. The numerical simulation show the modelling and use as tool to predict fire (Wang and Zhou 2014).

Implementation of CA in fire spreading is an opportunity for architects and planners both in building scale and city scale for various prediction in fire safety is important for solving fire risk that may not seem obvious in early phase of design. It represents not only in existing grid cell configurations, but also can be used to analyze and predict the possibility of fire spreading. The idea is to describe “ignition probability” in particular phenomenon that generated from some parameters in fire spreading. A case for fire spreading simulation in this research is densely urban settlement area. The benefits of using cellular automata in modelling natural phenomena lies on its ability to “simplify” a complex system (Ganguly 2003). CA employs decentralization

Spatial modelling that consist of cell component. Basically, the CA structure can be implemented by parallel and iterated recently (Ganguly 2003). So overall structure of CA can be seen as a device that works in parallel. But this seemingly simple structure that will generate a complex pattern by repeatedly iteration (Ganguly 2003). This section explains fire spread modeling and parameters used in the model and the process of simulation.

2.4. Cell Properties

Cell is the smallest unit in CA. Cell can be set in many shapes and size. Cell shape can be a rectangular, hexagonal, or other topology (Quartieri, et al. 2011) . These cells are all equal in size and size of cell can represent scale in real area. Each cell have state that define themselves in physical environment, such as building condition (material, floor area, height), weather condition (wind velocity and direction), and characteristic of built up area (vacant land, pitch of building and roads) (Ohgai, Gohnai and Watanabe 2007). Hamada (Jirou & Kobayahi, 1997 in Ohgai, et al, 2007) proposed the following equation representing the limit of the distance that fire can spread leeward:

$$D = 1.15(5 + 0.5v) \quad (1)$$

Where v is a wind velocity meter per second [m/sec] and D is the limit of distance which fire can spread [m]. These equation express optimum size of cell is 3 by 3 meter, because it can unsure visual expression and a degree of dynamics under the restriction of an appropriate calculation time for practical use. That size also is about half the limit of the distance of fire spread at $v = 0$.

2.5. State of Cell and Neighbourhood

One cell (n_{ij}) just can represent one state per iteration. State of cell can be define into several step: the cell with state [0] is cell that cannot burn. State [1] is cell that not burning yet, but have possibility of burning. Once the cell catches fire, the state of the cell changes to state [2], on fire. And then, when fuel already burnt, state of cell become state [3].

Table 1. State of Cell (A. Ohgai, et al. 2004)

State	Description
[0]	Non burnable; not fuel; having nothing to burn
[1]	Fuel, but not burning yet: having the possibility to burn
[2]	On fire; having the ability to cause fire spreading
[3]	Burnt;

This state can be change from influence by state and neighbour cell in their surroundings. These properties arranged to physical environment high densely area. When flammable cell put in surrounding flammable cell, then fire can spreading until there is no flammable cell in their neighbourhood. Rules act in changing conditions for a cell and its neighbours in one step discrete time to the next time step. Neighbourhoods in this case is a bunch of nearby cells around one cell. This relation neighbourhood to cells which will then be given state. Fire spreading in Cellular Automata from one cell to another can be done by two types, there are von Neumann neighbourhood and Moore

neighbourhood. Neighbourhood system that being used in this research is Moore neighbourhood with 8 adjacent cells in 8 ways. This is because this system much more alike with real site.

2.6. Physical Environment

Physical environment defines the universe on which the CA is computed. This underlying structure consist of a discrete lattice of cells. This study attempts to express the actual circumstances in the form of cells with a certain degree of reproducibility by employing method (Ohgai, Gohnai and Watanabe 2007). Overlaying physical environment can following this rules (Ohgai, Gohnai and Watanabe 2007):

- A layer cells is overlaid on map of an actual built-up area showing building structures (all material as in built-up area) and characteristics of the built-up area (open spaces, roads)
- Even if a cell is only partially overlaying a building of buildings, the cell attribute of building structure is defined by the building structure occupying the largest area among all types of cell. It can be material and other aspect.
- In the case of a cell that does not overlay any building, the attribute of open space or road as a noncombustible area is assigned to cell.

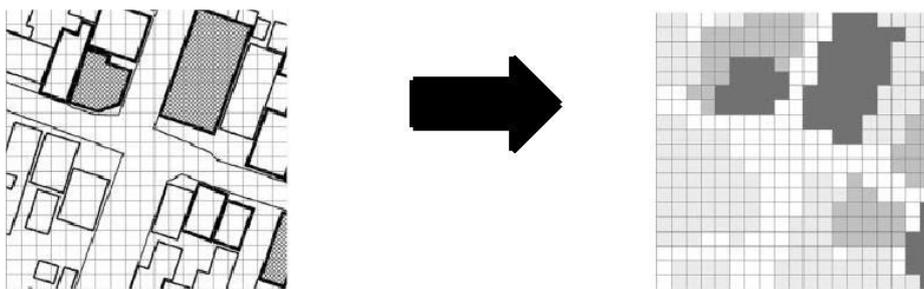


Figure 1. (a) Cells overlaid on map of an actual built-up area. (b) Results of expressing the built up area in the form of cells. (Ohgai, Gohnai and Watanabe 2007)

3. Methodology

This research uses Cellular Automata (CA) as a tool for analysing fire spreading probability which represent how building factors can influence the spread of fire to another building. There are two main steps in analysing fire spread factors: (1) development of CA model, (2) simulation using CA model being developed. CA model development starts with variables formulation. There are seven variables are used to analyse fire spreading probability factors in simulated settlement: combustibility of materials, total envelope area covered with combustible material, distance between buildings, road width, building shape, total opening area, and wind speed. Next step is 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 is involved in the simulation, i.e. building, field/park, and street/alley. Flammability level is determined based on the combustibility of materials used in the object. In this research, building with wood majority is more flammable than building with concrete majority, while field/park and street/alley are defined as non-flammable. Value of each cell/object is determined based on the ability to burn and probability to quickly spread the fire to the nearest objects. In this research, the value is calculated based on the flammability rate of the cell/object, total area of combustible material, distance between objects, and road width. Building shape, total opening area and wind speed are ignored because it is considered the same and fixed on each object. Determining the value of each object is done through simulation (Fig.2), and values obtained from the simulation are listed in the Table 2.



Figure 2. Simulation of Each Building Material and Stopped in 25 Iteration

Table 2. State of Cell

No	Cell/Object	Property	Value
1	Field/Park	Non-flammable	0
2	Street/Alley	Non-flammable	0
3	Concrete Building	Flammable	0.1
4	Concrete-Wood Building	Flammable	0.5
5	Wood Building	Flammable	1

The Cell/object developed to be used to simulate fire spreading in the simulated area. There are two spread patterns, (1) direct flame contact if flammable objects very closed or attached, (2) indirect contact if there is a distance between the buildings, or the buildings are separated by a street/alley or field/park. Steps of fire spread simulation are as follows:

- Step 1: defining all cell properties that already determined as fire spreading factors Step 2: tracing the simulation area into physical environment from cell properties Step 3: to run simulation, one or several cell n_{ij} selected as fire ignition.
- Step 4: the state of cell n_{ij} , after catching fire in more than $t-1$ (iteration 1), will be change from state 2 (on fire) to 3 (burnt).
- Step 5: the type of cell that could spread fire to its neighbourhood will change its surrounding cell's state (Type of cell that has value $0 < x \leq 1$). After cell with state 2 side by side to another cell with state 1 in its 8 direction, its neighbour cell will changes to state 2 and then these neighbour cell will influence its neighbour cells, and so on and so on.
- Step 6: the simulation ends when there are no more cells that can spread the fire. The time t (iteration) is counted from the start of the simulation to the end.

4. Analysis of Fire Spread Factors

In this research, Cibangkong District in Bandung city is used as simulated densely urban settlement area. Total simulation area is 500 m² which consists of houses, street/alley, and field. The area is divided into grid cells (simulation area) of 3 x 3 meter each. These grids will be traced. Cells properties are distinguished by colour, where green represents wood majority building, yellow represents concrete-wood majority building, orange represents concrete majority building, red represent on fire cell, brown represent burnt material, and white represent incombustible aspect such as road, field, and valley. Two fire scenarios are used to model the fire spread: (1) fire origin in building with wood majority building, and (2) fire origin in a building with concrete-wood majority building. Fire ignition starts in 3 cells. Figure 3 and Figure 4 shows result of fire spread simulation.



Figure 3 Fire Spreading Simulation Result for Wood Majority Building

In initial spreading at t=5, it shows that wood majority building cells are already influenced by fire on 114 cells. Meanwhile, concrete-wood majority building cells are influenced by fire on 41 cells. In the end of the simulation (t=58), it shows that wood majority building cell have burnt on 2414 cells and concrete-wood building cells have burnt on 679 cells. Simulation above shows that fire spreading in wood majority building is faster than concrete-wood majority building.





Figure 4 Fire Spreading Simulation for Concrete-Wood Majority

Initial spreading in concrete majority building shows that in $t=4$, the concrete-wood majority building cells are influenced by fire on 8 cells. Meanwhile, concrete majority building cells are 2 cells. Even concrete majority building cells are influenced by fire spreading only 4 cells for the rest of the simulation. It is just running from $t=0$ until $t=10$. However, concrete-wood majority building cells running until $t=70$ and has burnt cells on 1898 cells.

From these two simulations, it shows that wood majority building has ability to spreading the fire in 58 iterations and burning 2414 cells. Meanwhile in the same location of its fire ignition, concrete-wood majority building has ability to spreading the fire in 70 iterations and burning 1898 cells. Far from wood majority building and concrete-wood majority building, concrete majority building ability to spread the fire stop in 10 iterations and burning 4 cells. This is can be compared to same location of concrete-wood majority buildings in first simulation that can be spreading fire until burning 679 cells.

These results show that if fire occurs in a densely urban settlement where most of the buildings are made of combustible materials (wood majority building), fire will spread faster than most of the building made of non-combustible materials (concrete-wood or concrete majority building). This means that usage of combustible material in significant amount influence the speed of fire spreads. Area of wall opening also can be a factor of fire spreading probability since it provides way for heat radiation thus fire can move easily to building nearby. This process is also affected by wind speed in the area. Distance between buildings also influences the fire spreading speed, since fire can move by conduction through the wall. In this situation the presence of field or wide road will be very helpful because it serves as a separator thus fire could be confined or blocked in the fire origin area.

5. Conclusion

This research identifies architectural design factors that influencing fire spread in a densely urban settlement area using Cellular Automata as analysis tool. Cell attributes objects in the simulated settlement area along with their flammability level and capability to radiate and burn its neighbours. Two scenarios are applied to model fire spread pattern and speed which involved building material, building distance, building shape, road width, and total area of wall openings. It is observed that fire spread faster in the building area with wood majority comparing with building with concrete majority. Furthermore, absence of distance between buildings, narrow streets and limited fields are factors which influence fire spread speed and pattern as well as extent of damage when fire occurs in the densely urban settlement area. These factors need to be considered to be included to urban settlement guidelines to reduce fire spreading risk. On the other hand, CA has limitation to model fire spreading in a complex characteristics area such as densely urban settlement. For ideal results, wind, opening area, and building shape should be considered in the next CA model development.

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