Fire spreading in South African low-cost settlements
"A physics-based model"

by
"Ali Moradi"

Thesis presented in partial fulfilment of the requirements for the degree of Master of Civil Engineering at the University of Stellenbosch

Study Leader:
Prof. J. A. Wium

March 2016

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

March 2016

ABSTRACT

The risk of fire is increasing due to urbanization, industrialization and development of cities with dense buildings. Since *low cost settlements* are poorly serviced and are densely built urban areas with poor service delivery, they are the most vulnerable areas to fire. In recent years, urban fire-spread simulator models have commonly been used amongst more developed countries. However, in the case of South Africa, no fire-spread model has been developed/calibrated for low cost settlements in. Therefore, this study aimed to *develop*, *validate* and *verify* the first physics-based fire spread model, which is specifically calibrated for low-cost settlements in South Africa. The objective of this thesis was to apply the new model in a real life case study to illustrate the results of the model and prioritising the influential fire spread factors.

In order to provide a theoretical base for the development, the verification and validation of a new fire-spread model, a selected group of existing notable fire simulation models were reviewed in literature.

To develop a new model, first the scope, input and output of the model was defined and described. Next, the process of the fire simulation was divided into modules, their functionality were explained and thereafter an appropriate sequence of the modules were described. Finally, the entire fire spread process was programmed in C#.net. A geographical information system (GIS) was employed to pre-process the input data as well as to provide graphical output.

Verification and validation method were carried out in two hypothetical case studies. The new model was then applied to a low-cost settlement call? Imizamo Yethu which is a Metropolitan township of the city of Cape Town, South Africa, where fire is one of two top risks of the area. An area of this township was selected and input data for the new model were prepared through field measurement, information from Google earth and by determining parameters based on the environment of the area. The results were presented quantifiably and visually by a map series that showed fire spread progression across the area over time.

The findings of the analysis determined that in the area of Imizamo Yethu, wind speed and the separation distance between buildings were the first and the second most influential fire spread factors. In the building factor category, fire load has the highest impact while window orientation has the lowest impact on the total burnt area?? as well as the speed of fire spread.

Key words: Fire risk; Low cost settlements; Model development; Real life case study

OPSOMMING

Die ontwikkeling van stede met hoë digtheidsgeboue, industrialisasie asook die proses van verstedeliking, verhoog die risiko van brande. Aangesien lae-koste behuising gewoonlik baie dig beboude stedelike areas is met swak dienslewering, is sulke areas die mees kwesbare vir brande. In die afgelope paar jare, in ontwikkelende lande, word stedelike brand= verspreiding-nabootsende modelle of simulators, al hoe meer gebruik in die voorkoming van brande. In die geval van Suid- Afrika is daar egter nog geen so 'n brandverspreidings-model ontwikkel nie; verder is geen van die bestaande modelle al toegepas in Suid- Afrika nie in 'n poging om brande te verstaan of te voorkom nie. Met hierdie studie word beoog om die eerste fisika-gebaseerde brandverspreidings-model te *ontwikkel*, te *verifieer* en te *bekragtig*; 'n model wat spesifiek aangepas en gekalibreer is vir lae koste nedersettings in Suid-Afrika. Die doelwit van hierdie tesis was om die nuut ontwikkelde fisika-gebaseerde model toe te pas in 'n lewensgetroue situasie om die uitkomste van die model te demonstreer asook om die brandverspreidingsfaktore wat die grootste gewig dra, te prioretiseer.

In die daarstelling van 'n teoretiese basis vir die ontwikkeling, die verifikasie en bekragtiging van die nuwe brandverspreidings-model, is 'n geselekteerde groep brand nabootsingsmodelle (simulators) in bestaande literatuur bestudeer.

Om die nuwe model te ontwikkel is die strekwydte (scope), insette en uitsette van die data van die model eerstens gedefinieer en beskryf. Daarna is die proses van brandnabootsing (simulasie) verdeel in modules, waarna die funksionaliteit van die modules bespreek is; sodoende kon daar gekyk word na 'n toepaslike volgorde van die modules. Laastens is die hele brandverspreidingsproses geprogrameer in C#.net. Die geografiese informasie sisteem (GIS) is gebruik om die insette data te proseseer so wel as om grafiese uitset data te bekom.

'n Verifiërende en geldigheids-metode is uitgevoer in twee hipotetiese gevalle studies. Daarna is die nuwe model toegepas in a lae-koste nedersetting genaamdImizamo Yethu 'n nedersetting in die Kaapse metropool van Suid-Afrika. In hierdie omgewing is brande een van die twee hoogste risiko's van verstedeliking. 'n Spesifieke gebied van hierdie nedersetting is gekies en invoerdata vir die nuwe model is voorberei deur gebiedstudies en metings, 'Google Earth' en bepalende grense gebaseer op die omgewing. Die resultate is kwantitatief weergegee asook visueel deur 'n reeks kaarte wat die brand- verspreiding-stadia met tydsverloop uitbeeld.

Die bevindings van die toegepasde data analise bewys dat in die area van Imizamo Yethu, windspoed eerstens en dan tweedens, die afstand wat tussen geboue bestaan, die faktore is wat die grootste invloed het op brandverspreiding. In die geboue-faktor kategorie, het brandlading/vuurvrag (fire load) die hoogste impak op brandverspreiding; daarenteen het die vensteroriëntasie die laagste impak op totale gebrand sowel as op die spoed waarmee die brand versprei.

Sleutelwoorde: brandgevaar, lae-koste nedersettings, model ontwikkeling, lewensgetroue gevallestudie

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to my supervisor Prof. Jan Wium for the continuous support of my master study and related research, for his patience, motivation, and immense knowledge. His guidance helped me duringthe time of research and writing of this thesis.

Besides my supervisor, I would like to thank Dr. Ailsa Holloway not only for her encouragement, insight and helpful comments but also for the hard probing/challenging questions which motivated me to widen the scope of my research.

Last but not the least, I would like to thank my family: my parents and my sisters for supporting me spiritually throughout the process of writing this thesis and my life in general.

Nomenclature

A_P	open pool fire area	m^2
A_F	room floor area	m^2
A_w	window area	m^2
A_T	total area of interior and exterior walls, ceiling and floor minus total window area	m^2
B^*	dimensionless number defined in Eq. 47	
C_d	discharge coefficient	
C_p	heat capacity of gas	kJ/kgK
D	room depth	m
D_R	diameter of roof flame	m
dp	brand thickness	m
e	Euler's number	
E	the radiation intensity received at the target element	kW/m^2
E_s	emissive power of smoke	kW/m^2
E_{max}	equivalent black body emissive power	kW/m^2
F_H	configuration factor for horizontally-oriented target of roof flame	
F_V	configuration factor for vertically-oriented target of roof flame	
g	acceleration of gravity	m/s^2
H_R	visible roof flame height	m
h	window height	m
h'	height of radiator rectangle	m
$I_{Windows\ gas}$	received radiation by a target from hot gas	kW/m^2
$I_{window\ flame}$	received radiation by a target from window flame	kW/m^2
L	total room fire load	kg
L_R	distance between a receiver and centre of roof flame	m
L_T	percentage of total fuel loud that is burnt in time step t	kg
$\mathfrak{m}$	Mass burning rate per unit pool area	kg/m^2s
$\mathfrak{m}_0$	Mass inflow of air	kg
N	number of generated brands per m^2	
P	centroid of the receiving window	
P'	receiver point referring to figure 3.8	
Q	heat release rate	kW
r	stoichiometric air/fuel ratio	kg/kg
R	burning rate	kg/s
R_R	radius of pool fire	m
S	extinction coefficient	m^{-1}

S'	distance from P to P'	m
t	time	s
T_∞	ambient air temperature	°K
T_{gas}	room gas temperature	°K
T_{flame}	flame temperature	°K
u	wind speed	m/s
$u*$	modified wind speed	m/s
v_o	inflow velocity of air	m/s
W	width of wall containing window	m
W_{indow}	width of the window	m
W'	width of radiator rectangle	m
x	projection of the centreline of window flame	m
y	height above or below the neutral plane	m
y_{bot}	horizontal distance between ceiling and bottom of window	m
z	height of the projected flame from a window	m

Symbol

ε_f	emissivity of window flame	kW/m2
ε_f	emissivity of room gas	kW/m2
θ	angle between radiator and receiving window	rad
θ_R	roof flame tilt angle	rad
λ	window flame thickness	m
$\mu_{L,x}$	mean of downwind brand transport distance	m
σ	Stefan-Boltzmann constant	W/m2K2
σ_{LX}	standard deviation of downwind brand transport distance	m
ρ_f	density of compartment gas	kg/m^3
ρ_0	ambient air density	kg/m^3
ρ_P	brand density	kg/m^3
τ	atmospheric transmissivity	
∅	configuration factor of windows flame and room gas	

Table of Contents

List of tables

List of Figures

Chapter 1 Overview

1.1 Introduction

This chapter first discusses the effects of fire disasters on a global scale and in South Africa. Next, the aims and objectives of this study are presented in section 1.3. Section 1.4 describes the three significant contributions of this research. Finally, section 1.5 provides the chapter outline of the document.

1.2 Problem statement

Despite the benefits of fire as a source of energy and light, fire can also be seen as a hazard, resulting in death and destruction. Nowadays, a fire can ignite in urban areas because of various reasons, including electricity problems, overturned candles, gas flame contact on fuel in kitchens etc. (Scawthorn, Eidinger & Schiff, 2005).

Fire is the only disaster with multiple points of origin that can also be caused by other disasters such as earthquakes, storms and terrorist attacks. In addition, fire losses and fatalities can be exacerbated by the consequences of other disasters, for example, damaging the water-supply system and blocked streets due to debris.(Golmohamadi & Mohamadfam, 2014:57).

Furthermore, in many instances where a fire follows other disasters, it can be regarded as the dominant damage-causing factor. Fire followed the San Francisco earthquake in early 1906. As the fire department of the city of San Francisco reported, 80% of all losses and fatalities occurred because of the fire destroyed 492 houses and claimed the lives of more than 3000 people (Scawthorn, Eidinger & Schiff, 2005). Chung, Madrzykowski, Stone, Lew, Taylor & Hayes (1996) states that in 1996, 148 fires ignited in just three days after the earthquake in Kobe, Japan, claiming 500 lives and destroying 6 900 buildings.

From a global perspective, the average cost of fire losses for each country, annually, is estimated between 0.1% and 0.4% of the Gross Domestic Production. (Holborn, Nolan & Golt, 2004:481). In South Africa, which has 2628 informal settlements, and with a large portion of the population living in informal settlements (HAD, 2012), the situation is quite different. Figure 1 shows the percentage of residents living in informal settlements for each province. As illustrated in figure 1.1, 10% of households were living in informal settlements in 2011(HDA, 2015), and in this year 4 046 fire incidents were reported. Likewise, 49% of all residential fires occurred in those settlements and R 102,389,740 was lost because of these fires (FPASA, 2014:24).

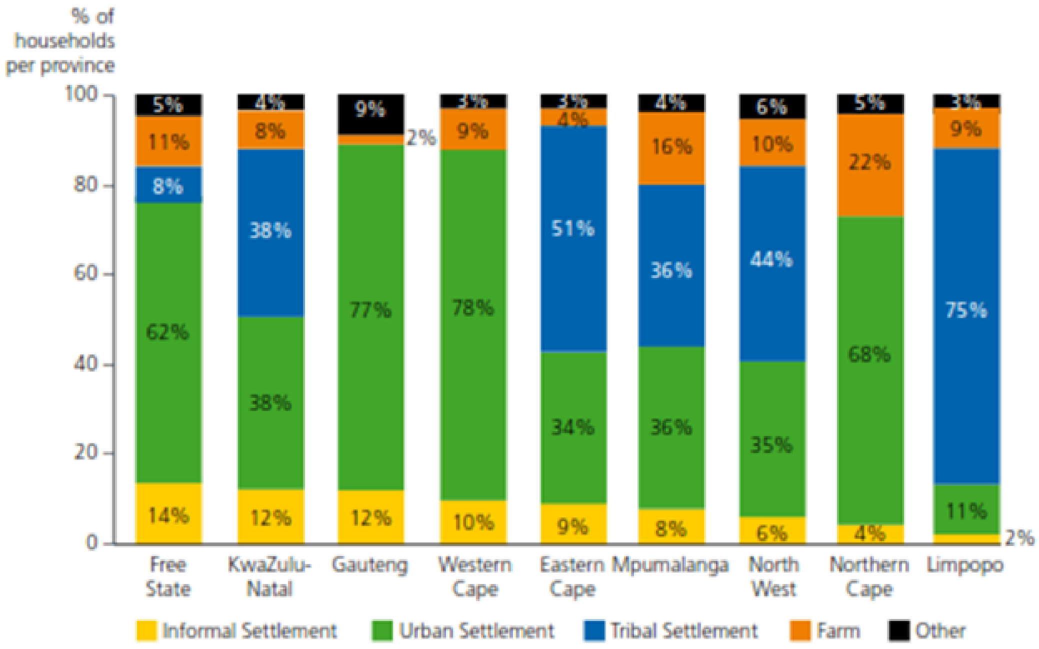


Figure 1-1: Type of accommodation area by provinces in South Africa (HDA, 2015).

Figure 1.2 presents an annual number of fatalities in the city of Cape Town from 2008 to 2013; in this period fire claimed 115 lives per year on average. Between2006 to 2012, figure 1.3 classifies fire loss into formal dwelling, informal dwelling, flats, and hotels and boarding houses from 2006 to 2012. For the same period, figure 1.4 compares the fire loss and the number of fire incidents. Appendix A presents a list of the number and causes of incidents occurring in different occupancy buildings during 2012 in South Africa.

All in all, looking at the above-mentioned data, together with figures 2-4 with regard to fire losses and the number of incidents, one can clearly see the catastrophic effects and impact of this phenomenon. Therefore, taking advantage of the most recent international methods and applying them to local conditions to deal with this disaster would be most beneficial.

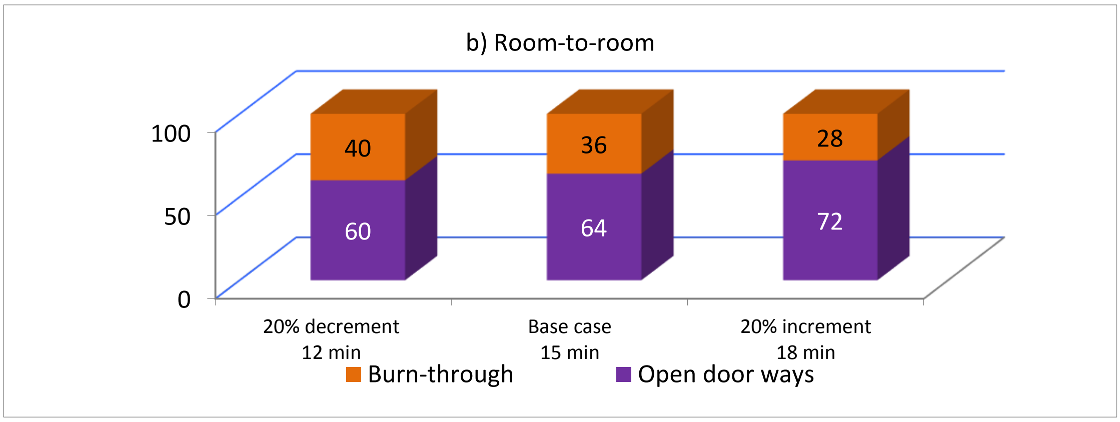


Figure 1-2: Statistic of fatalities in city of Cape Town (I Schnetler 2014, pers,comm., 5 September).

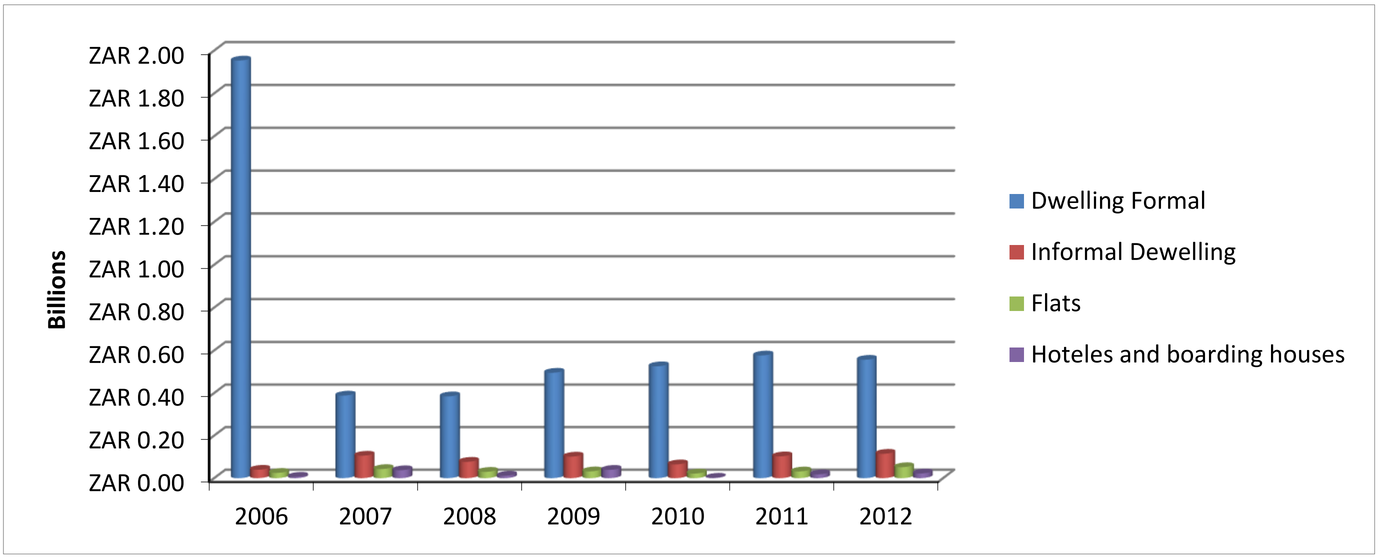


Figure 1 3: Residential loss in South Africa from 2006 to 2012 (FPASA, 2014:24).

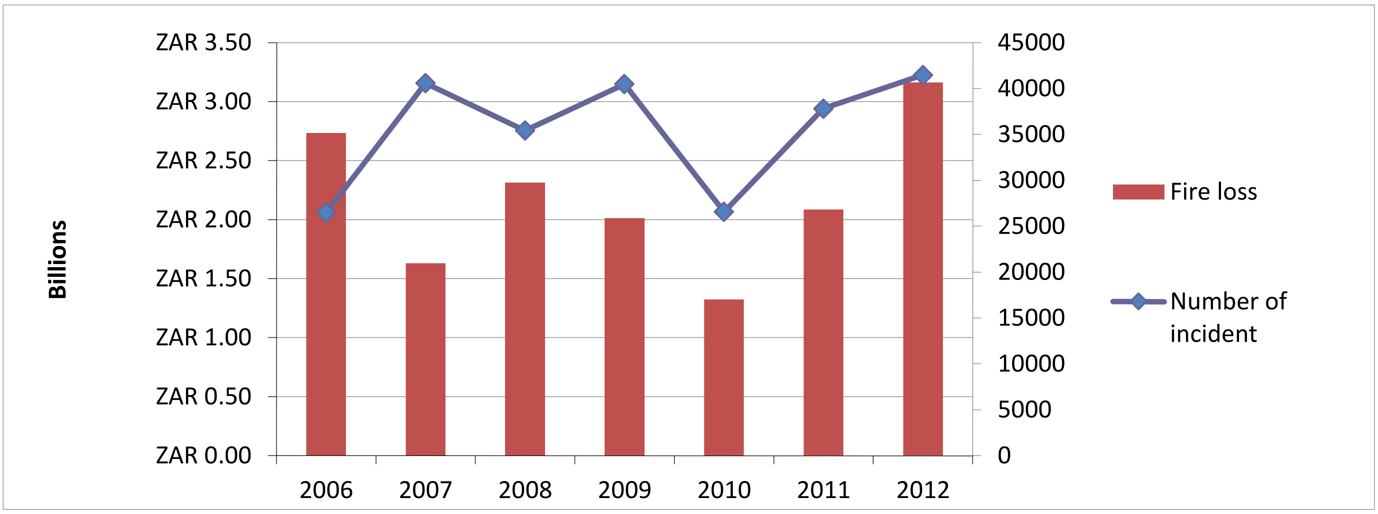


Figure 1-3: Compared loss by number of incidents in South Africa from 2006 to 2012 (FPASA, 2014:24).

1.3 Aims and objectives of the study

Fires in residential areas pose a significant risk to human life, infrastructure and the environment as a whole. The concept of fire has been studied across different disciplines ranging from the social and natural sciences to the field of engineering. A variety of studies exist that offer possible explanations and appropriate ways to mitigate fire risk.

The aim of this study is to *develop and validate a model* that simulates the process of fire spread inside of a building (room-to-room) and from a building in a burning condition to a neighbouring building (building-to-building). While the value of influential fire-spread factors/parameters vary through different regions (Hua, Wang & Kumar, 2005:99), the objective of this research is to apply the new model in a real-life case study to demonstrate that the required data is available, to calibrate the model and to illustrate what the model results look like and how they can be used.

From the perspective of civil engineering, this study is exclusively focused on prioritising the influential factors of fire spread, namely environmental, building and landscape factors. Although this model simulates the fire-spread process in great detail and other objectives can therefore be considered, they are not addressed in this study. These include:

- Evaluation of potential short-term and long-term risk-mitigation strategies
- Provision of support for the insurance industry
- Development of an evacuation plan for fire
- Planning for emergency response
- Significance of the study.

By achieving this study's objectives, some advanced improvements of fire mitigation planning, building and landscape designing are considered in two key statements:

Establishment of a physics-based model: The development of empirically-based models started many years ago. For example, in 1951, Hamada developed a revolutionary empirical model by making assumptions to simplify the fire-simulation process (Mohamadzadeh. 2011). Recently, there has been a shift towards models which use physics-based approaches and computer programming to obtain more accurate results.

The development of the first physics-based urban fire simulator model in South Africa: Although this study does not present a new technical method to conduct any task of fire spread simulation for urban areas, it is the first development of a fire-spread model for low-cost settlement in South Africa.

1.4 Research methodology

Section 1.2 discussed the catastrophic effects of fire on human life, the environment, the economy etc. In order to identify a contribution that civil engineering can make to solve this problem, two methods of research were utilized, namely interviews and literature study. First, several interviews with people in academia and the industry were conducted; secondly, a number of articles, books and other accredited publications were read to provide insight into the existing ways, relevant to the field of engineering, which have been developed and used to deal with this problem. Lists of interviewed people in academia and industry professionals are presented in Appendix A. After conducting these two methods and because there is no development of a fire-spread model in South Africa, it was decided to develop, validate and apply a new model that is specifically calibrated for low-cost housing in South Africa.

First, Literature of a selection of old and more recent fire simulator models was reviewed. This review was conducted in order to compare their basis and approaches, factor considerations, methods of validation and technical methods to conduct fire-simulation modules' tasks. The literature review was conducted to provide a theoretical basis for the next step in the research process.

Subsequently, the scope of the new model was determined. A suitable method was selected for each task and an appropriate sequence for these methods was planned. The new model was verified and validated by comparing its results against hand calculations and two other existing models' results.

Once the new model had been verified and validated, it was possible to apply it to a case study. In order to apply the new model in a real-life case study, Imizamo Yethu was chosen as the subject for a case study for this research, being a metropolitan township of the city of Cape Town. Input data preparation was conducted through three methods, namely:

field measurement

using Google earth (to provide the landscape map of the area)

making relevant assumptions based on the environment of the area and fire codes.

Finally, this research was concluded by summarising the entirety of the work and it was discussed whether and how comprehensively the aim and objective of the research were achieved. Recommendation were made to:

mitigate the fire risk of future events on/in the case study

further application of the new model in the current form

develop the new model based on limitations of the current study.

1.5 Research outline

This thesis consists of 7 seven chapters and 11 Appendixes. A short description of each chapter is as follows:

Chapter 2 consists of two sections. The first section conceptualises fire. The second section reviews and summarises a selected list of existing models based on three considerations: (1) approach and biases (2) factors considered, and (3) model validation methods and application.

Chapter 3 describes the development of this research's model. The first section defines the scope of the work and its assumptions. Therefore, it specified what should be included and why. It also describes what is excluded (all technical and non-technical methods, theories, etc.) to achieve the research objectives. The second section explains the input data and output results of the new model. The third describes the overall model simulation, breaks the fire-spread simulation into modules and describes the sequence of the simulation process. Lastly, section four provides a brief review of the available methods for each module, the reasons for its selection and an explanation of the functionality of each module.

Chapter 4 presents the verification and validation of the new model. Firstly, for the purpose of verification, the newly developed model will be applied in a small case study consisting of two buildings, and the results will be compared to hand calculations. Then the model is applied to a hypothetical case with 1 024 buildings. The new model's results are compared to two other models' results, found in literature that used the same case study.

Chapter 5 presents the application of the new model in a real-life case study. This chapter consists of three sections. The first section explains the reasons for the selection of Imizamo Yethu, provides a short history of the fire risk of the area and determines a suitable district of the area to which to apply the new model. The second section determine the input data thereby using the three considered methods. The third section includes a base scenario that reflects the real conditions in Imizamo Yethu and nineteen derived scenarios from the base scenario. Each scenario is discussed and its results are presented separately. Finally, all scenarios' results are analysed.

Chapter 6 first gives a comprehensive summary and conclusion of this research. Secondly, recommendations for using the proposed model of this study in practice and some suggestions for future work will be made.

Chapter 7 includes references and bibliography.

Chapter 2 Literature review

2.1 Introduction

This chapter consists of two sections. Section 2.2 reviews the definition of fire and related issues in the literature, both generally and in the case of urban areas. This section aims to provide scientific insight into fire and related aspects (the fire triangle's elements, heat transfer modes, fire classification and extinguishers) before reviewing fire-spread simulator models. Since the main aim of this study is to present and validate a suitable fire-spread model to simulate fire in low-cost housing and to study the effect of fire-spread inflectional factors, section 2.3 reviews approaches, considered factors and ways of validation based on a selection of previous fire-simulator models. Because of the complexity of the fire-simulation process, each model includes modules. Hence, with regard to the amount of information, to avoid confusion, section 2.3 only provides an overview of the above-mentioned aspects. A review of the available technical methods for each module will be provided in the next chapter.

2.2 Conceptualising fire

2.2.1 Combustion and fire:

Combustion is a chemical reaction that occurs between a fuel and an oxidizing agent that produces energy, usually in the form of heat and light. When the process of combustion accelerates rapidly, it is defined as fire and visualised with a flame (IFSTA, 2008:1100).

Figure 2-1: The fire triangle (Drysdale, 1998)

Oxygen, fuel and heat are known as the "Triangle of fire" (Arora & Boer, 2005:- G02008). The concept of the fire triangle was developed by scientists to gain better insight into the causes as well as extinguishing of fire and to gain better insight into prevention methods (Arora & Boer, 2005:- G02008). In fact, fire only starts when fuel, oxygen and sufficient heat are combined, and the fire keeps burning while the chain reaction between the fire triangle's elements are presented (Ma, Tingguang,Larrañaga, Michael, 2015:271).

2.2.2 Oxygen sources:

Approximately 21% of air is oxygen. However, depending on the type of fuel involved, fires can occur even with a much lower volume of oxygen present than the approximated oxygen content of air (Golmohammadi, 2010:456). Therefore, atmosphere is regarded as the source of oxygen for fire in most cases, especially in residential fires (Golmohammadi, 2010:456). As a fire occurs and the temperature rises, oxygen might generate as a result of the chemical composition of some materials, such a condition normally is not considered in the case of fire in residential areas (Golmohammadi, 2010:456).

2.2.3 Fuel sources:

Fuel sources include all types of combustible materials, although they differ based on the type of area such as commercial, residential, industrial, etc. (Ager, Vaillant & Finney, 2010:1556). "Most fires involve combustible solids, although in many sectors of industry, liquid and gaseous are also to be found" (Drysdale, 1998). Normally, wood, plastic, clothing, etc. are considered fuels in the case of residential areas (Golmohamadi & Mohamadfam, 2014:57).

2.2.4 Heat and ignition sources:

Any operation, equipment or material that emits a flame or a spark, or radiates heat, is regarded as an ignition or a heat source. These sources might be an obvious item, such as torches, or a less obvious item, such as static electricity (Golmohammadi, 2010:456). In the case of low-cost housing in South Africa, appendix B presents possible fire causes.

2.2.5 Heat transfer modes:

Thermal science defines that heat flux can be transferred from fire (or other sources of thermal energy) through three mechanisms being (1) conduction (2) convection, and (3) radiation (DiNenno, 2008). Figure 2.2 shows these heat transfer modes in a simple manner. With regard to the process of fire spread among buildings and while two of the fire triangle's elements (furniture, food, etc. as fuel and oxygen of air) are always available in buildings, heat flux is the critical element to complete the triangle and to ignite a new fire. The following subsections define the heat transfer mechanisms individually:

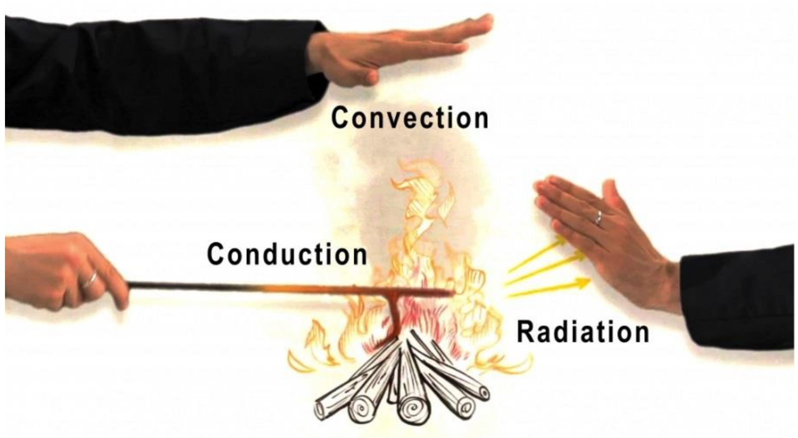


Figure 2-2: heat transfer modes (Dawn, 2011).

2.2.5.1 Conduction:

Heat conduction is defined as heat flowing from a hot object to a cold object when these two objects have physical contact (figure 2.2 simply shows how heat transfers by conduction mechanism). Sir Isaac Newton was the first scientist to study this mechanism, although in 1812 conduction was quantified by Joseph Fourier. He presented an equation to measure transferred heat from an area per unit of time (DiNenno, 2008). Fourier's equation (Equation 1) and a more accurate version of his work (Equation 2) are as follows:

$$q = -kA \, {}^{dT}\!/_{dx} \qquad (1)$$

A= Surface of the area T= Temperature

d = Differential operator x=Distance normal to the surface

k = Thermal conductivity

q = The rate of flowed heat

$$\frac{dQ}{dt} = -\int_A (K\,T)\,n\,dA \qquad (2)$$

Q = Heat content of surface A (Joules)

n = Outward directed vector normal to the surface element d_A

t = Time

T= Vector gradient of Temperature

k = Thermal conductivity

A = Integral taken over the whole surface

2.2.5.2 Convection:

In this mechanism, fluid motion transfers the energy from an object to the environment or from one place to another place. The direction of fluid flow may be directed by external forces. Depending on whether the flow of the fluid motion is directed by an external force or not, and depending on the cause of the force, convection is classified into 'natural convection' and 'forced convection' (Golmohammadi, 2010:456).

Natural convection: In the case of natural convection, gravity is the only force that has an effect on the convection process. In fact, as the air heats up, the air expands and the density of air decreases (i.e. a fire plume); therefore, gravity is the only force that influences a flowing fluid.

Forced convection: Forced convection happens when, in addition to gravity, another external force directs or forces direct the flow of the fluid. Wind, a pump or a fan are external forces.

2.2.5.3 Radiation:

Radiation is one of the three ways of heat transition. Energy radiates from a non-zero temperature solid surface, as well as liquid or gas. "Radiative energy propagation can be considered from two points: quantum mechanics and classical electromagnetic waves theory" (Howell, Siegel & Menguc, 2011). Unlike convection and conduction, energy can be transferred through radiation in a vacuum (Howell, Siegel & Menguc, 2011).

Fire Classification:

Based on the substance of fuel, fire is classified into four classes (Lynne, 2005:347):

Class A: Ordinary combustible materials such as wood, plastics, papers, trash etc. (residential areas fit into this fire class).

Class B: Liquids and flammable gases such as petrol and gasoline (oil derivatives), methane and propane (Petrol stations, industry etc.).

Class C: Energized electrical of components are involved (industry).

Class D: All kinds of metals ending with the suffix 'um', such as sodium, aluminum and beryllium.

Class K: Cooking oils, fats and vegetable etc.

Fire Extinguishers:

Based on fire classification, different methods have been developed to extinguish fire. Selecting an appropriate method is incredibly important, because using a wrong method may make a fire emergency worse (Golmohammadi, 2010:456). Different fires require certain extinguishing methods, for example, electrical fires will need to be extinguished with a non-conductive material in order to safeguard the lives of those responsible for putting out the fire.

Since fire suppression falls outside the scope of this research, table 2-1 succinctly presents the types of fire extinguishers without going into further detail.

Table 2-1: types of extinguishers based on fire classification (Mohamadzadeh. 2011)

Fire Extinguisher Type	**Class of Fire it extinguishes**
Dry Chemical (multipurpose)	A, B, C
Foam	B
Water	A
Metal	D,B,C

2.3 **Fire-spread models:**

Theoretical fire simulation in urban areas can be divided into three parts, namely fire ignition, fire spread and fire-suppression simulation (Golmohammadi, 2010:456). Regardless of the cause/causes of fire ignition, such as earthquakes, storms, etc. (Appendix B presents fire causes in the case of low-cost housing in South Africa), the ignition simulation includes an estimation of the number, location and time delay of ignitions. The firespread simulation includes the geographic fire spread and the status of buildings (e.g. burned and unburned buildings) over time, and fire suppression applies the effectiveness of suppression methods to stop fire.

While some models are specialised to estimate one of three parts of fire simulation (ignition, spreading and suppression), there are comprehensive models that are available which integrate all or more than one part of the fire-simulation process. Integrated models can be easily decoupled or adopt an extra part to be used by different users such as water supply agencies, fire departments, insurance industries and urban planners etc. (Lee & Davidson, 2010:688). The following examples of integrated models are notable: Scawthorn, (1987), SERA, TOSHO, HAZUS, URAMP, Cousins and Smith's model (2004), Ren & Xie (2004) and Zhao (2010).

With regard to the aim of this study, this research focuses exclusively on the spread simulation part. A group of prominent models are reviewed (fire spreading models or only the spread part of integrated models) from over 50 years ago. In order to have a clear understanding of these models, the following aspects of the models are reviewed:

- Basis and approaches
- Factors considered
- Validation and application

There is a table at the end of each following subsection to compare and summarise the models with regard to the above-mentioned aspects.

2.3.1 Basis and approach of fire-spread models:

Regardless of whether a fire is a wildland fire (fire in forest, jungle, etc.) or an urban fire, there are two bases for the simulation of fire (Lee & Davidson, 2010:688), namely empirically-based and physics-based models. Additionally, there are some empirical-physics-based models that exist that are a combination of both. Analysing observations of fire events provides the basis for empirically-based models to present equations for fire simulation (Mohammad Zadh 2009). On the other hand, "physics-based coupled fire–atmosphere models are based on approximations to the governing equations of fluid dynamics, combustion, and the thermal degradation of solid fuel" (Schadschneider, Klingsch, Klüpfel, Kretz, Rogsch& Seyfried, 2009:3142).

The most well-known urban fire simulator is Hamada's model (Himoto & Tanaka, 2008:477) that was developed in 1951. It has been updated until 1975 but the principle of the model stayed the same. He assumed an earthquake caused ignition in an urban area and then with the aid of the model he determined how the speed of the spreading fire is a function of wind speed (upwind, downwind and crosswind) in an elliptical shape. However, "[it] was found that none of geometric shapes could be mathematically explained based on simple variability in wind speed or direction" (Finney, 2004). Hamada's model also included the building size, location and material (Himoto & Tanaka, 2008:477). The latter was assumed to consist of three categories (Himoto & Tanaka, 2008:477): wood, protected wood and non-combustible material. Finally, an empirical equation for estimating the speed of fire spread was presented. This particular model's average building size was adopted as the standard for case studies of all other buildings and the same shape and distance was assumed. However, in reality, the building size, fire load and spacing between buildings in urban areas are not as homogeneous as Hamada assumed. Figure 2.3 shows how a fire spreads according to Hamada's model. Fire spreads in an elliptical shape in the direction of the wind (upwind and downwind) among buildings in different time steps.

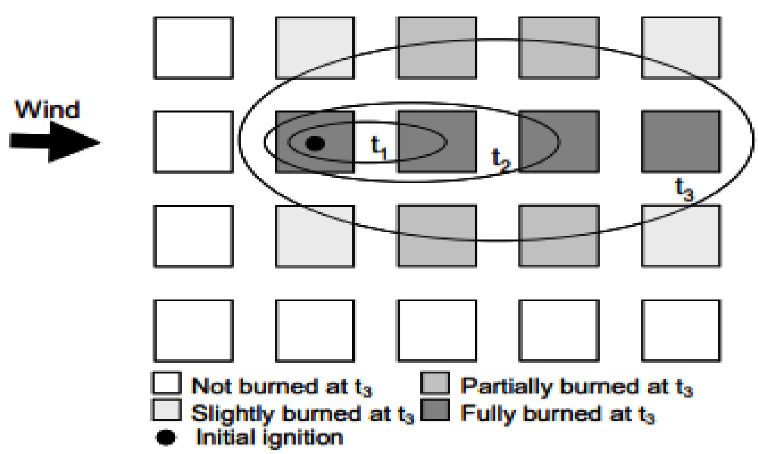


Figure 2-3: Illustration of Hamada's model, fire spreading in elliptical shape spread (Scawthorn, Eidinger & Schiff, 2005)

Despite all the assumptions in Hamada's model, the approach of his model is easy to understand and apply. In addition, in most cases it estimates the speed of a spreading fire with reasonable accuracy; although in some cases the speed is quite underestimated when compared with documented reports of data of previous hazards (Scawthorn, Eidinger & Schiff, 2005).

Hamada's model has been a basis for subsequent models. New models were developed with new methods but the principles of Hamada's approach and assumptions remained the same until 2000 (Scawthorn, Eidinger & Schiff, 2005). For example, Horiuchi, Kobayashi & Nakai (1974) and Scawthorn (1986) adopted the Hamada model's principles. Further description and the equations of the Hamada model are presented in Appendix C.

Previously, because of weaknesses in computational power and data availability, applying a model even with many assumptions to simplify the process (e.g. Hamada model) was a great challenge and human errors always had to be considered (Mohamadzadeh. 2011). Recently, because of the rapid growth in computer sciences, there has been a shift from the empirical to physics-based approaches with a greater emphasis on detail and less reliance on assumptions. Thermal physics identified certain ways to transfer heat which were explained in section 2.2.5 (convection, conduction and radiation). Physics-based fire-spread models translated the heat transfer ways into different modes that fire can spread through them in a building (room-to-room) or among buildings (building-to-building). Lee & Davidson, (2008) reviewed the fire transfer modes used by fire simulator models in the case of urban areas. The modes are as follows:

Room-to-room fire spread modes are:

- open doorways,
- burn-through, and
- leapfrogging;

and building-to-building modes are:

- flame impingement,
- radiation, and
- branding.

The design and development of a computer program to record the process of each of the above modes, individually and in interaction with others, leads to a profound understanding of fire spread. However, not all of these factors have been considered in detail in available models; in most cases, the modes have been simplified or neglected by the models. A brief explanation of the models of Cousins, Iwami, Scawthorn, Himoto and Tanaka, and Lee follows:

Cousins, Heron, Mazzoni, Thomas & Lloydd's (2002) model one of the successful examples of recent fire-spread models in urban areas. It is based on thermal physics but is simplified to apply the laws of the fire-spread process. The fire-spread process only includes the ignition and the fully developed phase, and neglects the growth and decay phases (fire phases and a review of available methods to determine them will be presented in Section 3.5.1).

This model includes a simplified version of the three building-to-building modes (for the fire-spread process divided into the three modules and each module also subdivided into the modes, see figure 3.1), for example, the effect of flame impingement in the horizontal direction was neglected. Furthermore, this model did not use a computational approach to conduct the modes to simulate the process, but rather adopted previous models' results and past events. For example, to estimate the travel distance of branding in each direction, a table was presented (based on previous models' results) but no computation was done.

Iwami, Ohmiya, Hayashi, Kagiya, Takahashi & Naruse (2004) created a heat generation curve over time for each building as fire spreads among buildings (see section 3.5.1). With regard to the heat-generation curves, the state of the fire was determined and fire spread is based on elapsed time. The model categorised a building as either unburned (receiver) or in the burning phase (radiator). The temperature of each building (receiver) is estimated by the received heat flux from flame radiation. It was assumed that when the heat in a building exceeds a certain value or if a flame from the radiator(s) contacts the receiver, ignition occurs. The scale of analysis of this model is the building, which means it only evaluates fire for a building and not for each room separately. The model is able to track the heat transfer in the direction of the existing wind. However, modeling the process of fire spread in two dimensions (2D) reduced the result's accuracy of applying this model to urban areas because there are significant height differences between buildings.

In 1987 Scawthorn realised that thermal radiation was the dominant mode of fire spread in large urban areas (Scawthorn, Eidinger & Schiff, 2005). Radiation affects close neighbouring buildings by causing spontaneous ignition through flame contact, and radiation pilots ignitions through gas radiation for buildings with greater distance between them. However, the 2005 version of the model indicated that branding spreads fire with double the speed compared to Scawthorn's 1987 results. Therefore, branding is considered to be the dominant mode of fire spread in large urban areas (Scawthorn, Eidinger & Schiff, 2005).

In early 2008, Himoto and Tanaka developed a computational physics-based model. The model was developed to evaluate the risk of fire spread in densely built urban areas. This model adopted equations from previous models which had a physics-based understanding of fire behaviour (Himoto & Tanaka, 2008:477). Himoto's model describes the relationship between heat transfer modes in a clear manner and predicts the influence of radiated heat from buildings in fire's fully-developed phase on neighbouring buildings. He assumed ignition occurs in neighbouring buildings if:

- the neighbouring buildings which received heat flux reach a critical point;
- branding with a high enough energy state lands on a combustible area (the model employs a probabilistic method to conduct this mode); and
- by convection when the temperature of the exterior wall (wooden walls were assumed) exceeds a critical value (Himoto & Tanaka, 2008:477).

This model treats geometric configuration and building material in reasonable detail, makes relatively few assumptions and neglects some parts of fire-spread modes (i.e. roof flames were not considered; section 3.5.3.2 will explain this matter in more detail).

Lee (2009) developed a new model to simulate the possibility of fire ignition and spread after an earthquake in an urban area. The new model implements a new state-of-the-art ignition model, which can be run deterministically or probabilistically based on a specific earthquake ground motion. After the fire occurred, caused by an earthquake, the new model simulates fire spread among the buildings based on physical laws and empirical data. While, according to Lee (2006), the vast majority of GIS-based fire-simulator models have been developed to simulate wildfire and only a few of them focused on urban fires, Lee (2009) presented a model which has two GIS algorithms: one specifically to divide the area of buildings into rooms and the second one to define the orientation parameters of buildings. The new model was applied in a district of a Los Angeles city that includes approximately 4000 buildings.

By a careful review of the sensitivity analysis of models from the past up to recent versions, changing scales sizes and more consideration of factors can be seen (see table 2.2). Initial models used a neighbourhood or a city block as unit for a model's scale, but in recent studies, scales have become smaller to include each floor of a building and all rooms to simulate fire in urban areas. For example, empirically based models such as Horiuchi (1974), Scawthorn (1986) and JASFE (1984, 1985) only simulate building-to-building fire spread, and use average building size and distance between buildings in their calculations. But more recent physics-based models, such as Iwami (2004), Himoto and Tanaka (2008) and Mohammad Zadh, (2011) adopt actual foot printing of buildings to analyse configurating factors in the fire-simulation process.

Since recent fire-spread models require more input data and computational work to simulate the process, the following challenges to physics-based models can be identified:

- Input data preparation
- Rapid increase in the amount of computation to simulate the fire-spread process
- Lack of sufficient technical methods to conduct fire-spread modes (section 3.5 reviews available methods for each task/mode).

Currently, these challenges are addressed by:

- taking advantage of available data of studied cases or using building codes data to deal with detailed data preparation (i.e. adopting fire load value and heat resistance of walls and floors from building codes);
- intensive computation is addressed by computer programming; and
- making assumptions and simplifying some processes to deal with shortcomings of the technical methods.

To compare empirically based and physics-based models, the following points are notable. While there are not many well-detailed fire experimental data available, and experimentally based models are developed by analysing the limited data of previous fire events that are recorded from a certain environment (mostly Japan, United States etc.), the same level of accuracy cannot be achieved by using empirically based models (Himoto & Tanaka, 2008:477; Wu & Chen, 2012:21; Zhao, 2010:83). In contrast, physics laws and principles are universal; therefore, a physics-based model is applicable to different case studies in the world. In addition, because physics-based models have the ability of involving a variety of factors to simulate fire (See table 2.3), the fire-spread simulation process can be better grounded on theory and more accurate results are achieved.

Table 2-2: Comparison of basis of fire-simulation models (Lee, Davidson, Ohnishi & Scawthorn, 2008:933)

Model	Based type	Modelling technique	Unit of analysis (Scale)	Output quantity	Time step	Reference
Hamada (1951,1975)	Empirical	Elliptical shaped fire	Equal blocks of equally spaced structures	Burned area	1 min	(Himoto & Tanaka, 2008:477),FEMA(2006)
Horiuchi (1974)	Empirical	Same as Hamada				JAFSE (1984, 1985)
Scawthorn et al. (1981)	Empirical	Same as Hamada				Scawthorn et al. (1986); Scawthorn et al.(1981,1986,2005)
Murosaki (n/a)	Empirical	Same as Hamada				JASFE (1984, 1985)
Omori et al.(1990)	Empirical	Same as Hamada				Matsuoko et al. (1997); JAFSE (1985, 1984)
System Earthquake Risk Assessment (SERA) (1995-2003)	Empirical	Simulation	N.A	Probability fire will spread	1 min	(Scawthorn, Eidinger & Schiff, 2005)
TOSHO (1997)	Empirical	Real-time simulation	Building	Fire spread speed	N.A	TFD (1997, 2001)

Table 2.2: Comparison of basis of fire-simulation models (Lee, Davidson, Ohnishi & Scawthorn, 2008:933)

Model	Based type	Modelling technique	Unit of analysis (Scale)	Output quantity	Time step	Reference
HAZUS (1997)	Empirical	Simulation, GIS	N.A	No. serious ignitions,total burned area, population and bldg exposure	1 min.	FEMA (1999)
Himoto &Tanaka (2000-2006)	Physical	N.A	Building	Buildings not burning, burning or burned at each time step	N.A	(Himoto & Tanaka, 2005:18; Himoto & Tanaka,2008:477)
Cousins et al. (dynamic) (2002-2006)	Physical	Cellular automata, GIS	3m x 3m room	At each time step, (1) state of each cell; (2) num., area, and value of buildings burned	2.5 min	(Iwami, Ohmiya, Hayashi, Kagiya, Takahashi & Naruse, 2004:132)
Otake et al. (2003)	Physical	Computational fluid dynamics	Building	Temperature	N.A	(Cousins, Heron, Mazzoni, Thomas & Lloydd, 2002)

Table 2.2: Comparison of basis of fire-simulation models (Lee, Davidson, Ohnishi & Scawthorn, 2008:933)

Model	Based type	Modelling technique	Unit of analysis (Scale)	Output quantity	Time step	Reference
Iwami (2004)	Physical	Simulation based on simplified physical relationships	Building	State of each building at each time step	1 sec	(Otake, Huang, Ooka, Kato & Hayashi, 2003:2)
ResQ Firesimulator (2004)	Physical	Simulation , GIS	Building	For each building, (1) percentage of initial fuel burned, (2) temperature of each building (3) energy	N.A	(Nüssle, Kleiner & Brenner, 2005:474)
Ohgai (2004)	Physical	Cellular automata	3m x 3m rooms	Probability each cell is in each state	1 min	(Ohgai et al, 2005:193)
Ren/Xie(2004)	Physical	Huygens' principle, GIS	Building	Buildings that are burned	N.A	(Ren & Xie, 2004:421)
Mohammad Zadh (2009)	Physical	Simulation, GIS	User defined	Rooms that burned	1 min	(Mohamadzadeh. 2011:)
Lee (2010)	Physical	Simulation, GIS	3m x 3m; 5m x 5m; 7m x 7m room	Room that burned	1 min	(Lee & Davidson, 2010:688)

2.3.2 Factors considered

In addition to factors relating to buildings, such as materials and building layouts, there are other factors which can influence the fire-spread process. Landscaping of urban areas includes the amount of vegetation and the urban plans (configuration factors of buildings) and has a significant effect on the speed of fire-spread (Cheng & Hadjisophocleous, 2011:211). This section offers a well-detailed review of factors considered by previous models, and therefore factors are categorized in three main categories:

- **Building:**
  - Damage state
  - Contents (e.g. residential or commercial)
  - Size and shape
  - Openings, size and location (windows and doors)
- **Landscape:**
  - Distance between buildings/blocks
  - Fire breaks
  - Vegetation
- **Environmental:**
  - Wind (velocity and direction)
  - Ambient temperature
  - Ambient humidity
  - Topography of ground

With regard to above-mentioned categories, Table 2.3 compares and summarises different models in terms of influential fire-spread factors. The following letters indicate to which extent each factor is considered by each model.

D: Factor is considered in detail

N: Factor is not considered individually

S: Factor is considered in simplified manner

U: Factor is considered but a clear description of the factor is not presented in referenced documents

N.A: Information is not available

Table 2-3: Comparison of factors considered for input data of fire-spread models.

.

Model	Reference	Input factors											
		Buildings					Landscape			Environmental			
		Material	Damage state	Occupancy	Dimension	Openings	Distance	Fire breaks	Vegetation	Wind speed	Wind direction	Ambient temperature	Topography of land
Hamada (1951, 1975)	Himoto and Tanaka (2008), FEMA(2006)	Fire-resistant wood., non-fire- resistant wood	N	N	S	N	S	N	N	D	D	N	N
Horiuchi (1974)	JAFSE (1984, 1985)	Fire-resistant wood., non-fire- resistant wood	N	N	S	N	S	N	N	D	D	N	N
Scawthorn (1981)	Scawthorn et al.(1981,1986,2005)	Wood	N	N	S	N	D	N	N	D	D	N	N
Murosaki (n/a)	JASFE (1984, 1985)	Fire-resistant wood., non-fire- resistant wood	N	N	S	N	S	N	N	D	D	N	N
Omori et al.(1990)	Matsuoko et al. (1997); Omori et al. (1990); JAFSE (1985, 1984)	Wood	N	N	N	N	N	N	N	S	S	N	N

Table 2.3: Comparison of factors considered for input data of fire-spread models.

Model	Reference	Input factors											
		Buildings					landscape			Environmental			
		Material	Damage state	Contents	Occupancy	Dimension	Distance	Fire breaks	Vegetation	Wind speed	Wind direction	Ambient temperature	Topography of land
System Earthquake Risk Assessment (SERA) (1995-2003)	Ostrom(2003); Scawthorn et al.(2005)	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A
TOSHO (1997, 2001)	TFD (1997, 2001)	Detailed seismic vulnerability analysis of water-supply system	S	N	S	N	S	S	N	D	D	N	S
HAZUS (1997)	FEMA (1999)	Fire-resistant wood., non-fire-resistant wood	N	N	S	N	S	N	N	D	D	N	N
Himoto/Tanaka (2000-2006)	Himoto and Tanaka (2000,2002,2008)	Wood, mortar plastered wood, fire resistant.	N	D	D	D	D	D	N	D	D	D	N
URAMP (2002)	Scawthorn et al. (2005), Seligson et al. (2003)	Construction materials	N.A	N	U	N	N.A	N.A	U	U	U	N	N

Table 2.3: Comparison of factors considered for input data of fire-spread models.

Model	Reference	Input factors											
		Buildings					landscape			Environmental			
		Material	Damage state	Contents	Occupancy	Dimension	Distance	Fire breaks	Vegetation	Wind speed	Wind direction	Ambient temperature	Topography of land
Cousins et al. (dynamic) (2002-2006)	Cousins et al. (2002,2003);	Combustible wall cladding or not, combustible roof cladding or not	N	N	D	S	D	D	N	D	D	N	N
Iwami et al. (2004)	Iwami et al. (2004)	Fireproof, covered wood, uncovered wood	N	D	D	D	D	D	N	D	D	D	N
Otake et al. (2003)	Cousins et al. (2002,	N.A	N.A	N.A	N.A	N.A	Y	N.A	N.A	Y	Y	Y	N.A
ResQ Firesimulator (2004)	Nussle et al. (2004)	N.A	N	S	D	N	D	D	N	D	D	S	N

Table 2.3: Comparison of factors considered for input data of fire-spread models.

Model	Reference	Input factors											
		Buildings					landscape			Environmental			
		Building material	Damage state	Contents	Size and shape	Openings	Distance	Fire breaks	Vegetation	Wind speed	Wind direction	Ambient temperature	Topography of land
Ohgai et al. (2004)	Ohgai et al. (2004)	Wood, fire prev. wood, fireproof	N	N	D	N	D	D	N	S	S	N	N
Ren/Xie(2004)	Ren and Xie (2004)	Brick & wood; mixed structure; reinforced concrete; other material.	N	N	D	N	U	D	N	S	S	S	N
Mohammad Zadh (2009)	Mohammad Zadh (2009)	user defined	N	D	D	S	D	N	N	S	S	S	N
Lee (2010)	Lee (2010)	Construction materials	N	D	D	S	D	S	N	D	D	S	N

2.3.3 Model validation methods and application

Regardless of the scope of fire-simulator models (ignition, spreading, fire suppression or integrated models), there are three ways to validate a new model (Golmohamadi & Mohamadfam, 2014:57):

- **Hindcasting :** To validate fire-simulator models by comparing their estimates to observations from actual fire event.
- **Compare with available models:** To compare a new model's result with other existing models in a same case study.
- **Expert option:** To validate a new model by interviews with professional people who have experience in the field.

Since no model or any other methods are available which can simulate fire completely accurately, using the hindcasting method is the best way to validate a new model (Lee & Davidson, 2010). However, because of limitation of data, it is not always possible to hindcast new models. Table 2.4 compares the validation methods of a selected group of models. A brief explanation of the ways in which Scawthorn and Ohgai validate their models follows:

Scawthorn used two different methods to prove the validity of his model in 1987. First, he chose five fire cases in the United States and hindcast the amount of burnt area with them. He also applied Hamada's model to those five case and compared the results of Hamada's model to the results of his own model.

Ohgai et al.(2004) validated his model with the Hamada model, and also with the results of this model and Thomas' model, and hindcast with observed documented data of fires namely: Napier, New Zealand 1931; and Kobe, Japan 1995 (Ohgai et al. 2004).

Table 2-4: Comparison of validation methods and application of the models

Model (published year)	Reference	Validation	Used by	Applied in real-life case study/studies
Hamada (1951,1975)	Himoto and Tanaka (2008), FEMA(2006)	N.A	N.A	N.A
Horiuchi (1974)	JAFSE (1984, 1985)	N.A	N.A	N.A
Scawthorn et al. (1981)	Scawthorn et al.(1981,1986,2005)	**Hindcasting:** 32 N.American data pts	N.A	**United states:** Los Angeles, San Francisco, Seattle. **Canada:** Vancouver, **Japan:** Osaka
Murosaki (N.A)	JASFE (1984, 1985)	N.A	N.A	N.A
Omori et al.(1990)	Matsuoko et al. (1997); Omori et al. (1990); JAFSE (1985, 1984)	**N.A**	N.A	N.A
System Earthquake Risk Assessment (SERA) (1995-2003)	Ostrom(2003); Scawthorn et al.(2005)	**Hindcasting :** Loma Prita fire, Northern California 1989	EBMUD, San Diego Water Dept, BART Dist.	**United states:** Hayward city; Calaveras County; Concord; California
TOSHO (1997, 2001)	TFD (1997, 2001)	**Hindcasting :** Sakata city fire 1923 Kanto fire ; Kobe fire,Japan 1995	Tokyo, Kyoto and Kobe Fire Departments	N.A
HAZUS (1997)	FEMA (1999)	N.A	Federal Emergency Mgmt agency, United State	All cites in United state

Table 2.4: Comparison of validation methods and application of the models

Model (published year)	Reference	Validation	Used by	Applied in real-life case study/studies
Himoto/Tanaka (2000-2006)	Himoto and Tanaka (2000,2002,2008)	**Compared to Hamada** model in hypothetical urban area with 2,500 buildings **Hindcasting:** Sakata fire, Japan 1976	N.A	**Japan:** Sanmachi, Takayama, Japan (172 buildings); Higashiyama, Kyoto, Japan (7,909 buildings)
URAMP (2002)	Scawthorn et al. (2005), Seligson et al. (2003)	N.A	California Governor's Office of Emergency Response	N.A
Cousins et al. (dynamic) (2002-2006)	Cousins et al. (2002,2003); Thomas et al. (2003,2006), Heron et al. (2003),	**Hindcasting:** Hawke's Bay(Napier) fire, New Zealand,1931	N.A	**New Zealand:** 75,800 buildings in Wellington City; Napier/Hastings;
Iwami et al. (2004)	Iwami et al. (2004)	N.A	Building Research Institute	N.A

Table 2.4: Comparison of validation methods and application of the models

Model (published year)	Reference	Validation	Used by	Applied in real-life case study/studies
Otake et al. (2003)	Cousins et al. (2002, 2003); Thomas et al. (2003, 2006), Heron et al. (2003)	N.A	N.A	**Japan:** Shirahama,Wakayama Prefecture.
ResQ Firesimulator (2004)	Nussle et al. (2004)	N.A	N.A	**Japan:** Kobe (1,269 buildings)
Ohgai et al. (2004)	Ohgai et al. (2004)	**Compare to Hamada model. Hindcasting :** Kobe fire,Japan 1995	Local/ community workshops	**Japan:** Futagawa district, Toyohashi Aichi Prefecture
Ren/Xie(2004)	Ren and Xie (2004)	N.A	N.A	**China**: Shantou City, (245 sq. km., 30,000 buildings)
Lee (2010)	(Lee & Davidson, 2010)	**Compare to Hamada model.**		**United states:** Los Angeles.
Mohammad Zadh (2011)	Mohammad Zadh (2010)	N.A	University of Tehran Faculty of Environment	**Iran**: Enghlab district, Tehran,
1 **N.A** = Not Available				

2.4 Conclusion

This chapter first provided a scientific conceptualisation of fire, both in general and in the case of urban areas, to help the reader develop a better understanding of fire's elements and the fire-spread process. Subsequently, a selected group of fire-simulator models were reviewed and discussed in order to compare the group, basis and approach, factors, validation methods and application.

Two major bases were identified to develop a fire-simulator model, namely, empirically based and physics-based models. Both approaches developed equations to estimate the fire-spread process, which are functions of the building, landscape and environmental factors. While empiricallybased models developed the equations based on empirical data of fire events, physics-based models rely on thermal physics laws to simulate the fire-spread process.

In comparing the empirically based and physics-based models, the following points were noted. Empiricallybased fire-simulator models require less data of a case study and are also simple to understand and apply. In contrast, physics-based models require a greater number of factors and they also consider these factors in more detail. Physics-based models are complex and have high computational requirements compared to empirical models, but, on the other hand, the results of physics-based models are more accurate and provide greater insight into the fire-spread process.

Since 2000, fire-simulator models have been developed based on the laws of physics instead of empirical analysis, which has caused three challenges: the rapid increase in computational demand, preparation of more detailed data as input of a model and the need for more technical methods to conduct modules of the simulation. Taking advantage of computer programing and relying on simplification are two common ways to address these challenges.

This chapter provides a theoretical basis for the development of a new model by discussing and comparing different aspects of available fire-simulator models. Therefore, with regard to the development of the new model, the next chapter will determine a suitable base and define the scope of the necessary factors to achieve this study's aim and objective.

Chapter 3 Model description

3.1 Introduction

The main aim of this study is to *present and validate a model* to study the impact of different factors on the spread of fire in low-cost settlements (see section 1.3). Based on the review of the development of the literature on fire-spread processes and the need for more accurate simulations, the physics-based approach has been selected to simulate the process of fire spread. The fire-spread simulation consists of different modules (see figure 3.1) which are determined by methods that will be adopted from other studies. In fact, this study does not present any novel methods to the modules of the simulation. This chapter will select the most appropriate methods for each module based on the aim of the study, and will present the modules in the appropriate sequence.

In chapter 2, the amount of computational work has been recognised as a challenge in the development of a physics-based fire-spread model. This study addresses this challenge by selecting methods that require less computational work, while maintaining a sufficient level of detail for the purpose of the study, and by using computer programming. Furthermore, computer programming has been used to address this challenge in the most recent fire-simulator models (Iwami, et al, 2004; Himoto & Tanaka, 2008; Lee & Davidson, 2010). The chapter consists of the following five main sections:

- The first section (section 3.2) determines the scope of the new model
- The second section (section 3.3) determines the input and output data for this model
- The third section (section 3.4) provides an overview of the fire-spread simulation process. Firstly, this section breaks the process of fire spread into modules, and modules into modes (See figure 3.1). Secondly, it presents a flowchart of the model and explains the sequence of the modules and modes
- The fourth section (section 3.5) reviews the available methods for each module or mode. Then it provides motivations for the selected methods for each module or mode of this model. Finally, the selected method is explained in-depth
- The fifth section (section 3.6) summarises and concludes all discussed issues in this chapter

3.2 Scope of the study

Fire simulation is a vast area of study. It covers diverse fields such as wildfire, urban and industrial fire (Mohamadzadeh. 2011). Also, each field includes a variety of influential factors which, as a result of technical shortcomings and the complexity of the work, currently cannot be fitted into a single model (Lee & Davidson, 2010). Therefore, with regard to the developmental aims and limitations of a model, each model has a determined scope. The determination of this model's scope is introduced next.

As the previous chapter mentioned, the process of fire consists of three parts: ignition, spreading and suppression. Regarding these categories, only the spreading part is included in the scope of this study.

The newly presented model in this study only includes the simulation of the spread of fire in one-storey residential masonry houses. Normally, residential areas consist of a variety of buildings. However, South African low-cost housing, which is the main focus of this study, mostly consists of single-storey, single-family buildings (I Schnetler 2014, pers,comm., 5 September). Hence, having this scope is considered a reasonable limitation.

Section 2.3.2 presented and compared the considered influential factors used by previous models and summarised them in three categories: buildings, landscape and environmental factors. This model, based on its aim and limitations, selects a group of factors. Only the factors listed in table 3.1 are included in the scope of this study. Any other factors that could affect fire spread, whether mentioned in chapter 2 or not, are not considered by the new model. The following section will explain how and to what extent these factors can be imported into the new model.

Table 3-1: scope of the factors in the model

Environmental	Wind speed
	Wind direction
	Ambient temperature
Buildings	Building material
	Contents
	Size and shape
	Openings
	Building height
Landscape	Distance
	Orientation

3.3 **Inputs and outputs of the model**

3.3.1 Inputs

The fire-simulator model is designed to incorporate all factors which are in the research scope. Input factors are divided into three main categories: (a) building factors, (b) environmental factors and (c) landscape factors. The following section provides an in-depth description of these three categories. Compression of input and output of wildfire simulator models (forest fire) is presented in Appendix D.

3.3.1.1 Building factors

When applied to a case study, this model requires the following input data:

(a) Building shape (height, width and length)

(b) Occupancy type (residential, commercial, etc.)

(c) The type of fire resistance of the internal walls

(d) The size of windows and doors (width and height)

This model aims to study the factors (Section 2.3.2) influencing the spread of fire among buildings. Therefore, the case studies will consist of areas containing a number of buildings. It is a time-consuming process to import locations, dimensions and orientations of the case study's buildings into the model. Furthermore, the amount of data increases the chance of human error. Hence, to overcome this challenge, the model uses a three-dimensional (3D) map of the case study. From the 3D map the foot print (location and orientation) and height of the case study's buildings will be extracted for the model (chapter 5 will explain this process in detail).

Each building needs to be divided into rooms by interior walls. The user has the option to define the maximum length for interior walls. Once the parameters of the rooms have been determined, the GIS Algorithm applies these configurations to the buildings in the case study.

Fire load is defined as the quantity of combustible material per square meter (kg/m^2) of a building's floor. The user has the option to define the amount of the fire load in this model (chapter 5 will explain how this factor is determined for the case study of this research).

3.3.1.2 Landscape factors

There are two landscape factors included in the scope of this study, namely distance between the buildings and building orientation. As noted, location and orientation of the building and the distance between them are respectively extracted from the 3D map of the study area.

3.3.1.3 Environmental factors

As is confirmed in section 3.2, the speed and direction of the wind, as well as ambient temperature, are included in the scope of this model. Before the simulation starts, the user has the option to determine the amount of ambient temperature. These amounts will remain constant in all time steps and iteration of the fire simulation.

As proven in previous research, wind is the most important environmental factor affecting the spread of fire in both room-to-room and building-to-building modes (Himoto & Tanaka, 2008:477; Zhao, 2010:83). At the moment, no model is available that can simulate the wind through buildings during the fire-spread process with 100% accuracy (Wu & Chen, 2012:21).

The presented model in this study offers two methods to the user for importing the data of the wind speed and wind direction. The user has the option to choose one of these two methods based on the availability of data and the objective of the work. When using the first method, the model takes one value for wind speed (m/s) and one angle for wind direction, which is measured clockwise from a northern direction. These values will not change during the fire simulation and the model will use the same data for all time steps. In the second method of wind-data input, the user imports a series of data that includes time (minutes), wind speed and wind direction into the model. For example, Appendix E presents a series that includes such data from Stellenbosch on 11/10/2014 (a period of one hour). The model assumes that the first row of series is the starting time of the fire (i.e. first row of the table 3.2). For each subsequent time step, the respective data regarding the wind speed and angle is extracted from the following row of the series.

3.3.2 Outputs

This model simulates fire spread over time in great detail. Therefore, a large variety of output describing fire spread inside a building and among buildings can be extracted. Some notable possible outputs are as follows:

- A plot of total burnt area in the study area versus/over time
- A plot of the speed of the fire spread among buildings versus/over time
- A time series of the map showing the evolution of the fire spread throughout the study area (Chapter 5 will present such a map series)
- To determine the percentage that different models of fire spread contribute to room to room fire spread (see figure 3.1 for the possible room to room fire-spread modes)
- To determine the percentage that different models of fire spread contribute to building-to-building fire spread (see figure 3.1 for the possible building-to-building fire-spread modes).

3.4 Overall simulation

The proposed fire-spread model includes different modules, and each module performs a particular task in modeling the spread of fire between rooms inside a building (room to room), or among the buildings (building to building). This section will break down the modeling process into steps and discuss their sequencing.

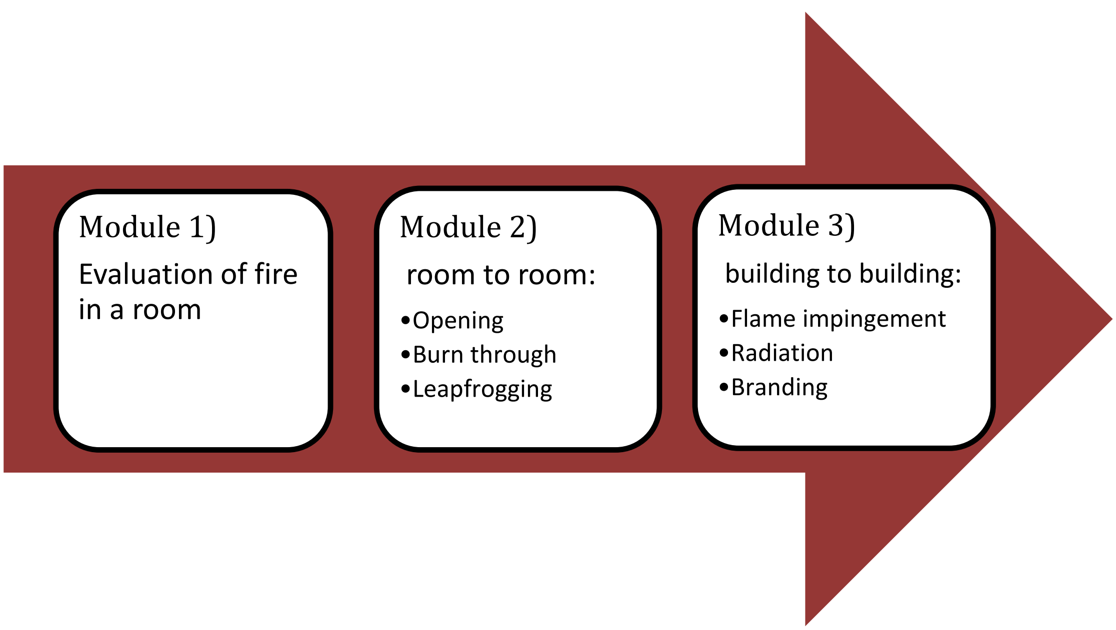


Figure 3-1: Modules and modes of fire-spread simulation (Lee & Davidson, 2008).

Figure 3.1 presents all fire-spread modules (each module can consist of different modes) including room-to-room and building-to-building. The following paragraphs provide a description of each module in figure 3.1:

Module 1: As soon as ignition takes place in a room (the fire point might be manually selected by the user or randomly determined by the model), the model starts to evaluate the fire in the room (see section 3.5.1).

Module 2: When the fire reaches the fully developed phase (see section 3.5.2), and the fire starts spreading from the burning room to neighbouring rooms through:

- *Openings* (windows or doorways)
- *Burn-through* to adjacent rooms from the separating wall or to the room above through the ceiling
- *Leapfrogging* of flames from the burning room window, to a window of the above room

Module 3: Fire spreads from a building to other buildings through (see section 3.5.3):

- *Flame impingement*, which occurs when a flame from the window of a building in a burning condition reaches the window of the neighbouring building
- *Radiation* of window flames, roof flame and gas
- *Branding* (embers)

Figure 3.2 presents the sequence of the modules of the model in a flowchart. To evaluate the fire in a room (module 1) at each time $step_t$, the model checks all rooms of the case study, and for all burning rooms, the fire phase is determined (growth, fully-developed or decay; see section 3.5.1). Here, after a room experienced a fully-developed phase of fire, it is called $room_b$. It is assumed that only in the fullydeveloped phase, fire can spread from a $room_b$ to other rooms inside the same building or to other buildings.

To simulate the fire spread inside a building for all $rooms_b$, the model determines that the fire spreads from a $room_b$ through: (1) an opening or (2) burning through walls (module 2). It is assumed that, if there is an open doorway between two rooms on the same floor of a building, then, as soon as the fire reaches the fully developed phase at any of those rooms, the other room will ignite immediately (closed doors are regarded as walls). The fire might burn through the shared wall of *room*$_b$ and a neighbouring room. With regard to size and location of windows, the fire might leapfrog from the windows of $room_b$ to the windows of the room upstairs. Considering the modes by which a fire spreads inside of a building (module 2), table 3.3 presents the possible heat sources and targets of module 2.

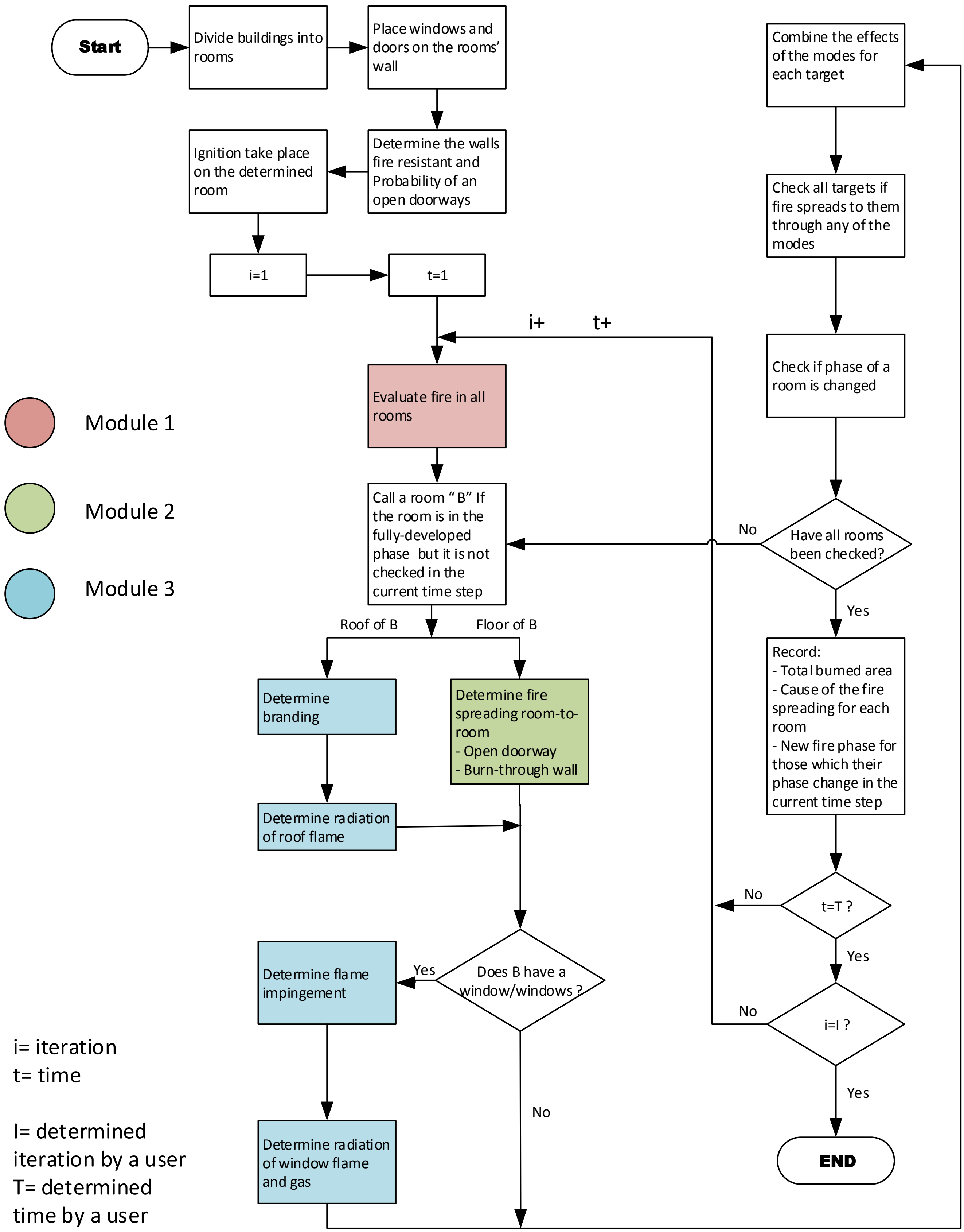


Figure 3-2: A comprehensive flowchart the new model's sequence.

Table 3-2: room to room, heat sources and targets

Mode of fire spreading inside of a building	**Source**	**Target**
Door way	All rooms in fully-developed phase	Neighbouring rooms
Burn-through	All rooms in fully-developed phase	Neighbouring rooms and roofs
Leapfrogging	Rooms with windows	Rooms in facing wall on the same floor

As module 3 in figure 3.1 (pg. 47) shows, there are three modes to spread the fire from building to building:

1) *Fire impingement:* It is assumed that if the length of an ejected flame through a window of $room_b$ is long enough to reach the window of a room of the neighbouring building, the associated room immediately ignites (see section 3.5.3.1).
2) *Radiation:* For each building that is not in a burning condition, based on the location of the building, the model calculates the total received heat, radiated from the window flame, windows gas and roof flame of all the burning neighbouring buildings.
3) *Branding (embers):* Plenty of embers are generated from a roof of $room_b$ and they are scattered by wind through other buildings. This model firstly determines the number and size of embers, and then determines possible places for embers to land on. Finally, if an ember lands on a building's roof, based on the size of the ember, the model defines the possibility of igniting the host roof. Finally, at the end of the time step, the model checks all rooms, and in cases where the condition changed during the time step, the new condition is recorded for the next time step. For example, if a condition of a room changed from the growth phase to the fully developed phase, the room will be counted as a radiator in the next step. Table 3.4 presents the possible heat sources and targets of module 3.

Table 3 3: Building-to-building fire spread, sources and targets.

Mode of fire spreading building to building	Source	Target
Flame impingement	Rooms with windows	Room in facing wall on the same floor
Window flame radiation	Rooms with windows	Room in facing wall on the same floor
Room gas radiation	Rooms with windows	Room in facing wall on the same floor
Roof flame radiation	Roofs	For all buildings in a specified radius in the direction of the wind 1) roofs and 2) windows in the nearest wall within flame height
Branding	Roofs	Roofs on neighbouring buildings

3.5 Reviewing and selecting technical methods for each module.

Whereas the previous section broke down the model into three modules, and each module into modes, this section aims to discuss each mode on a technical level. Firstly, a brief review of the available methods to conduct a mode will be provided. Secondly, for each mode a method is selected, plus the advantages and possible disadvantages of the selected method with regard to this study's aim and objectives. Finally, an explanation of the selected method and related equations will be presented.

3.5.1 Fire evaluation (Module 1)

Computational Fluid Dynamics (CFD), zoning and temperature-time curves are three main approaches to evaluate fire within a room (Lee & Davidson, 2010:688). To estimate the evaluation of fire, a CFD model firstly divides a room into several equally sized segments, and then performs the evaluation by solving fundamental equations of momentum, transfer of mass, and energy for each segment (Cheng & Hadjisophocleous, 2011:211). Zone models are easier to apply than CFD and are more commonly used by fire-simulator models. Zone models consider two layers inside each room: a hot layer on top and a cold layer at the bottom. Then these models solve equations of conservation mass, energy and momentum for both layers (Hua, Wang & Kumar, 2005:99). The temperature-time curve approach, unlike CFD and zoning, classifies a room only as one unit and estimates the temperature of the room over time.

For the purpose of this study, the temperature-time curve approach was selected to evaluate fire in rooms for the following reasons:

- Since the structural damage is not included in the scope of this research, the evaluation of fire in the different layers or segments of rooms is not relevant.
- To avoid unnecessary computational demands.
- The approach requires less detailed data compared to the other two approaches (Cheng & Hadjisophocleous, 2011:211).
- The temperature-time curve is the most common approach used to simulate the spread of fire on a large scale, such as urban areas (Walton & Thomas, 2002:171).

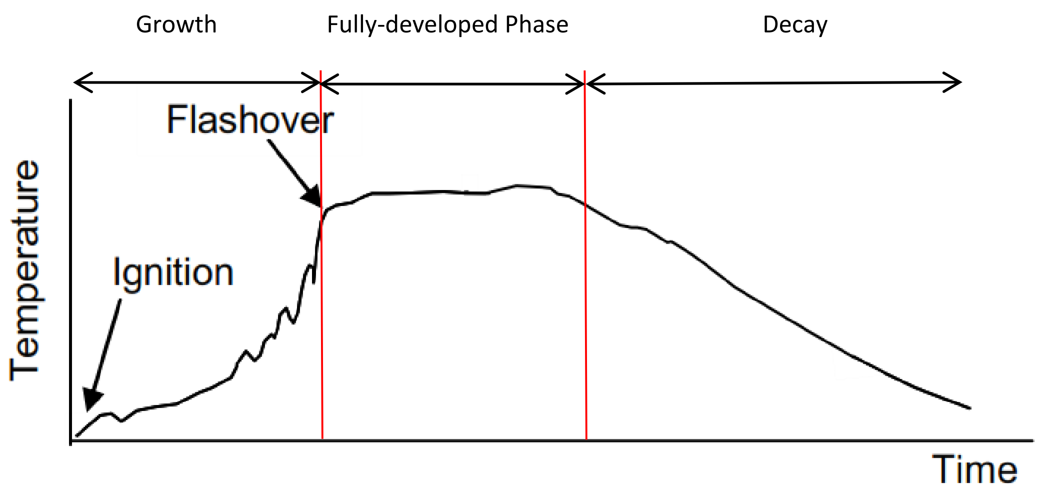


Figure 3-3: Fire phases, Temperature-time curve (Walton and Thomas, 2002)

Fire is commonly compartmentalized into three phases: the growth phase, the fully developed phase and decay phase (Walton & Thomas, 2002:171). Immediately after ignition, the growth phase starts, the fire grows and the temperature increases rapidly. Flashover is the transition point from the growth phase to the fully developed phase. At the point of flashover, the temperature reaches a level where, owing to the radiation of hot gas, all combustible material suddenly ignites (Walton & Thomas, 2002:171). There is not a precise definition of flashover that is commonly accepted (Himoto & Tanaka, 2008:477). Nevertheless, two ways of defining flashover are widely used (Walton & Thomas, 2002:171). Firstly, flashover occurs when a specified amount of fuel has burned, for example: (Corson, 1953:65) suggests 20% and Law 30% (1978:59). Secondly, flashover occurs when a specified temperature between 500^{0}C and 600^{0}C has been reached (Wu & Chen, 2012:21).

(Walton & Thomas, 2002:171) reviewed the history of predicting the temperature during the pre-flashover period and post-flashover period, and also the factors that influenced the temperature of the fully developed phase. During the fully developed phase, the temperature can reach, and at times exceed, 1 000 ^{0}C. Regardless of the type of combustible material (e.g.

wood, plastic etc.), three parameters influence the temperature during the fullydeveloped phase: (1) the quantity of the fire load, (2) the exposed surface area of combustible materials and (3) the availability of oxygen (ventilation-controlled). The amount of available oxygen is the most influential parameter (see figure 3.4).

The decay phase starts when a certain amount of the combustible material is consumed and the release of heat starts to decrease and this decay phase continues until the fire stops burning.

The fully developed phase has the highest temperature that is sufficient to spread fire inside of a building, or from a burning building to another building/other buildings. During this phase, the temperature reaches a state of equilibrium (see figure 3.3). Therefore, most fire-simulator models focus exclusively on this phase.

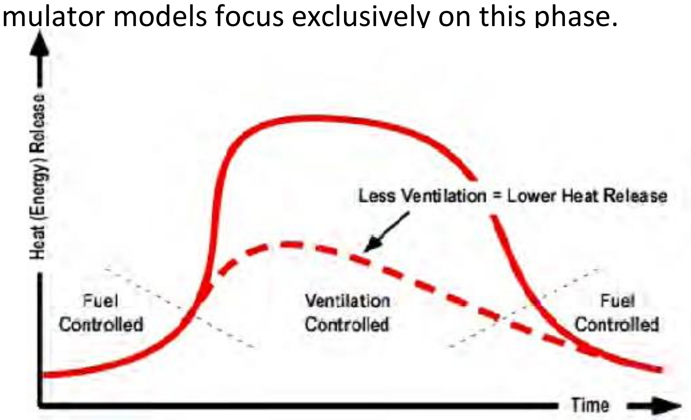


Figure 3-4: Effect of availability of oxygen on heat release (Carlsson, 1999)

The model presented in this dissertation uses Law & O'Brien, 1981 (Hereafter LOB). This method was selected for the following reasons: (1) the method has been verified with reasonable accuracy and it is widely used by fire simulator models (Mohamadzadeh. 2011), (2) it considers factors that this dissertation aims to study, such as room dimension, opening dimension and fire load, etc. and (3) this method also simulates flame geometry and emitted radiation of flame and gas (see section 3.5.3). The LOB method is described as follows:

After an ignition takes place in a room, the method firstly determines the ventilation condition of the room. The method divides the ventilation condition into two categories, namely through-draft condition and no through-draft condition. Secondly, based on the ventilation condition of the room, specific equations are applied to define the burning rate, fire phase and the average temperature of the room in fully developed phase. Figure 3.5 presents a flowchart of the LOB method divided into four steps. An explanation of each step and related equations are presented in Appendix F.

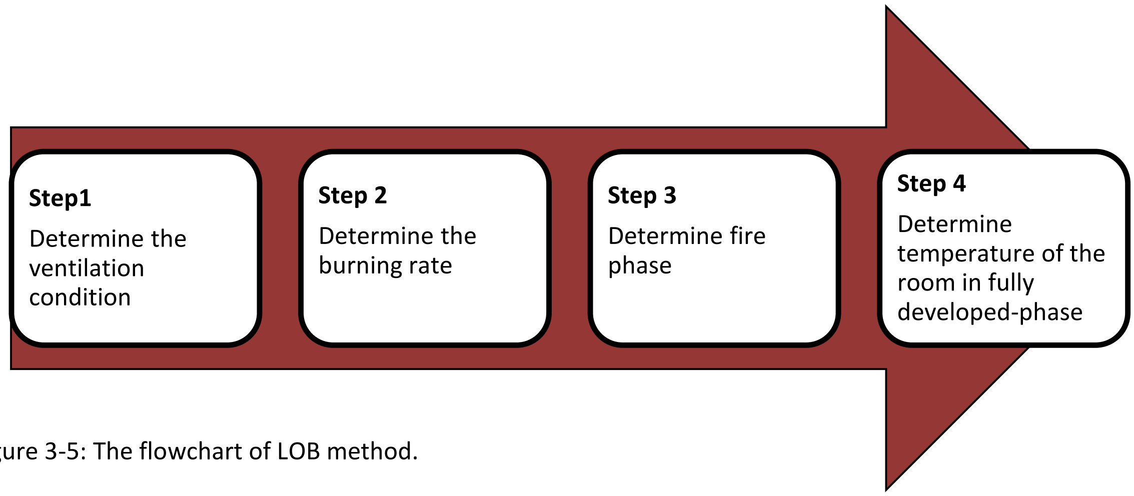


Figure 3-5: The flowchart of LOB method.

3.5.2 Room-to-room fire spread (Module 2)

Module 2 consists of three modes namely:

- openings (doors and windows);
- burn-through; and
- leapfrogging.

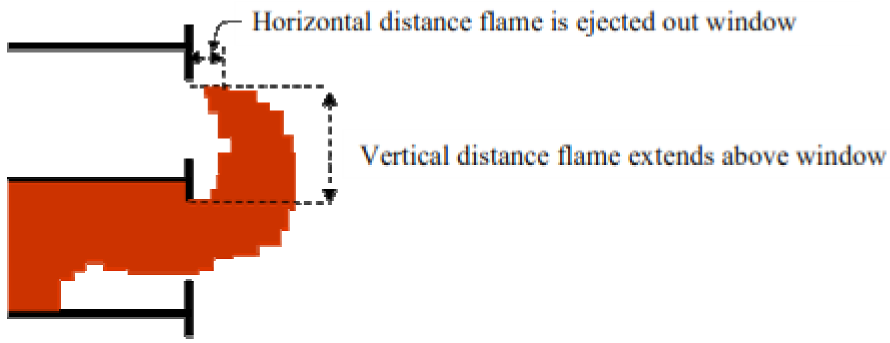
The fire might spread through any of these modes. Since it is impossible to predict whether doors are open or closed, this model assumes that each interior wall has an opening, and the user has the option to choose the probability that the opening is open. Furthermore, the selected possibility will be automatically applied to all openings in all buildings of the study area. It cannot be specified for each opening individually. It is also assumed that if an opening is open, the fire spreads immediately as soon as it reaches the fully-developed phase, and the neighbouring/adjacent room ignites. If the opening is closed, it is regarded as a wall and becomes subject to the burn-through mode.

Cheng & Hadjisophocleous,(2011:211) stated that "[t]he main reason for fire spread from the compartment of the fire origin to adjacent compartments is that the barriers between the compartments fail to contain the fire." The time it takes a fire to burn through a shared wall or ceiling of a room in a burning condition and the adjacent room is the key point of the burn-through mode of the simulation (Cheng & Hadjisophocleous, 2011:211). Regarding the fire resistance of different types of walls, there is an option for the user to assign the time it takes for burn-through to occur in an interior wall. In the case of multiple types of interior walls, the user can assign the probability of each resistance type and its corresponding burn-through time; then, based on the probability, the model assigns the resistance time for walls.

The most accurate way to measure the time it takes for burn-through to occur, is by conducting a test of some samples in the study area. Since conducting tests require funds and is a time consuming process, it may not be practical to adopt this approach when dealing with low cost housing areas. Alternatively, the associated fire resistance rating (the time delay) is available in accredited research publications and building codes. For example, there are different types of fire-resistant buildings as defined by the International Building Code (IBC). The IBC classified the fire-resistance rate of walls and ceilings according to the barrier and fire-resistant type (IBC, 2006:60478). Table 3.5 shows these rates.

Leapfrogging is the third mode and it only occurs in the case of multi-storey buildings. Through this mode, fire may spread from a lower to an upper floor, if the projected flame of a window reaches at least the bottom sill of the upper floor's window (see figure 3.6). Then, due to the assigned possibility for the window to be closed or not, an assumption of the time delay for igniting the upper-floor room will be made (e.g. Platt, Elms & Buchanan, (1994) assumed 3 minutes as the time delay for a new ignition). Since this study focuses exclusively on single-storey buildings, this mode is not applied and further explanation on leapfrogging will not be presented.

Table 3-3: Estimated time delay (IBC, 2006:60478)



-

Figure 3-6: Spreading fire through leapfrogging (Platt, Elms & Buchanan, 1994:367)

3.5.3 Building-to-building fire spread (Module 3)

The previous module explained all modes relating to the spread of fire inside a building (room-to-room). This module explains three modes that relate to the spread of fire between buildings, namely flame impingement, radiation (window flame, window gas and roof flame) and branding. These modes are discussed in the following sections.

3.5.3.1 Flame impingement

The mode of flame impingement only applies if the projected flame of a window of a room in a burning condition (radiator) is long enough to reach the facing wall, window or roof of a neighbouring building (receiver). It is assumed that the associated room of the neighbouring building ignites immediately. The assumption is made because, first, this model aims to simulate fire in low-cost housing areas and most often the structure of these buildings contains wood or other combustible materials (I Schnetler 2014, pers,comm., 5 September). Secondly, this is a widely used assumption in fire-simulation models, (Himoto & Tanaka, 2008; Mohamadzadeh. 2011; Lee & Davidson, 2010).

To define fire impingement and radiation, the flame geometry needs to be estimated. As noted, this model adopts the LOB method to evaluate fire, estimate fire temperature and determine fire phases. Therefore, the same method is used to estimate flame geometry and emitted radiation (see 3.5.3.1), which ensures consistency across modules. The following paragraphs provide a brief history of available methods to simulate the flame geometry, the advantages and shortcomings of the LOB method and possible effects of these on the accuracy of the results of this study's model.

Yokoi (1960) empirically investigated the key factors that influence flame geometry while Seigel (1969) developed equations to estimate flame geometry, based on the discovered factors. Thomas & Law (1972) re-examined previous experimental methods and modified equations (including those of Yokoi and Siegel). Law (1978:59), and later on LOB, presented a method of estimating flame geometry for the purpose of assessing fire safety for external elements of buildings (wall, roof, etc.), by using previous results and by conducting full-scale tests.

Certain studies focus on the effect of one specific factor on flame geometry, for example Bullen & Thomas (1979) investigated the relation of flame height to the amount of unburned fuel in a room. Sugawa & Takahashi (1995) examined the influence of the wind direction and wind speed on the geometry of external flames.

Klopovic & Turan (2001) investigated several experimental results of flame geometry and compared them with estimations of previous methods. The comparison concluded that the method by LOB created approximations consistent with experimental results (Klopovic & Turan, 2001:135). However, according to Drysdale (1998), the results of the method by LOB are less accurate when estimating flame geometry under the following conditions:

- If a projected flame loses a substantial amount of heat to a façade of a neighbouring building (it might happen because of rain or any other environmental condition that can affect the same)
- When there is a fire on the lower floor of a multi-storey building
- In the case of non-cellulosic fuel that requires a low amount of heat to produce volatiles or in the case of a room with a very large fuel bed (resulting in a higher burning rate and longer projected flame compared to LOB estimation)

Since the scope of this study's model includes only low-cost one-storey buildings, such buildings do not have very large rooms (fuel bed). The above-mentioned conditions cannot reduce the accuracy of this model's results. Appendix G describes the determination process of flame geometry based on the LOB method.

3.5.3.2 Radiation

From a room in a burning condition (radiator), heat might radiate through three modes: (1) window flame, (2) window gas and (3) roof flame. In this study, each of these three modes has a specific source and target (receiver) (see table 3.4). If the total amount of received heat flux by a receiver from multiple sources (R_{total}) reaches a critical value, then it corresponds to the period of time it takes for the receiver to ignite. With regard to defining the critical value, and the relation between the heat flux and the time delay to ignition, this model adopts the relation specified in the *Fundamentals of Fire Phenomena,* by James G. Quintiere (2006). According to Quintiere (2006), the critical heat flux is 12.5 kw/m^2 which correlates to a 30minute period before igniting the receiver (target). Any amount less than the critical flux cannot cause the target (receiver) to ignite, and if the received heat flux exceeds the critical flux, the time delay decreases (see figure 3.7). Lee (2009) divided Quintiere's (2006) correlation of flux and time-delay into five categories (see table 3.6). The two following subsections (window flame and gas radiation; roof flame radiation) will explain the methods of calculating the received heat flux by targets through window flame and gas, and roof flame.

Table 3-4: Classification of the relation between heat flux and ignition delay (Lee, 2009).

Radiation (kW/m^2)	Time delay until ignition (min)
12.5	30
15	25
17.5	10
20	7
30+	1

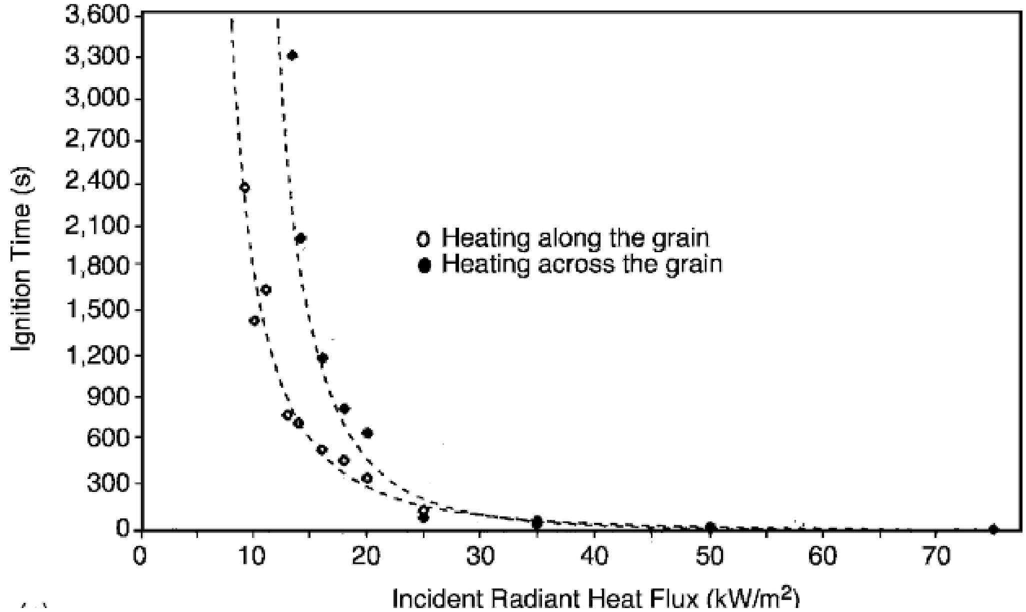


Figure 3-7: Critical heat flux over time (Quintiere, 2006:439).

Window flame and gas radiation

As noted, in this study the LOB method is adapted to estimate the received radiation (heat flux) by each receiver from window flame and gas. The following equations calculate the transferred radiation from hot gas and flame of a radiator's window to each receiver:

$$I_{window\ flame} = \sigma\varepsilon_f\ \emptyset\ (T_{flame}^4 - T_\infty^4) \quad (1)$$

$$I_{window\ gas} = \sigma\ \varepsilon_g \emptyset (T_{gas}^4 - T_\infty^4) \quad (2)$$

σ = The Stefan-Boltzman constant 5.6X10^{-12} W/m^{2}K^4

T_∞ = Ambient temperature

T_{flame} = Flame temperature

T_{gas} = Gas temperature

ε_g = Emissivity factor of gas, it is assumed to be 1.

Where ε_f is emissivity factor of flame and it is calculated by equation 3.

$$\varepsilon_f = 1 - e^{-0.3\tau} \quad (3)$$

τ is the window flame thickness. As is noted, it depends on the calculated ventilation condition:

Through-draft condition $\tau = \frac{2H}{3}$ and no through-draft condition $\tau = x$.

Configuration factor Ø represents: (1) the size of radiator's window, (2) distance between the radiator and the receiver, and (3) orientation. It is assumed that the radiator is a vertical surface with the same size and location of the window that the window flame and gas radiate from the surface to the receiver. In this study, because all windows are assumed to be rectangular (the user has the option to assign height and width), so radiators are also vertical rectangular. The receiver is a point either on the window or the cladding of the facing wall. In this study, because of? the type of exterior wall that was considered for low-cost housing (see section 3.2), igniting the receiver (room facing the radiator) through the window is easier than either ignition cladded combinable material of the wall or burn-through. Therefore, the receiver point (P') is assumed to be at the centroid the window of the receiver room.

The configuration factors Ø, with regard to the angle between the radiator and the receiver Θ, is calculated by the equations 4 & 5.

I. If (Θ = 0), refer to figure 3.8:

$$\emptyset = \frac{1}{2\pi}\left[\tan^{-1} a + ((\frac{(b\cos\theta - 1)}{(1+b^2-2b\cos\theta)^{0.5}}) * (\tan^{-1} a/(1+b^2-2b\cos\theta)^{0.5}\right] \tag{4}$$

II. If (0 < Θ<90), refer to figure 3.8:

$$\emptyset = \frac{1}{2\pi}\left[\tan^{-1} a + \frac{b\cos\theta - 1}{(1+b^2-2\cos\theta)^{0.5}} * \tan^{-1}\frac{a}{(1+b^2-2\cos\theta)^{0.5}} + \frac{a\cos\theta}{(a^2+\sin\theta^2)^{0.5}}(\tan^{-1}\frac{(b-\cos\theta)}{(a^2+\sin\theta)^{0.5}}\tan^{-1}\frac{\cos\theta}{(a^2+\sin\theta)^{0.5}})\right] \tag{5}$$

$$a = \frac{h'}{s'} \tag{6}$$

$$b = \frac{w'}{s'} \tag{7}$$

h'= height of the radiator's window; w'= width of the radiator's window and s' is the horizontal distance between the receiver and the radiator.

III. If Θ≥90, it means the receiver does not face the radiator, hence, no heat flux is received.

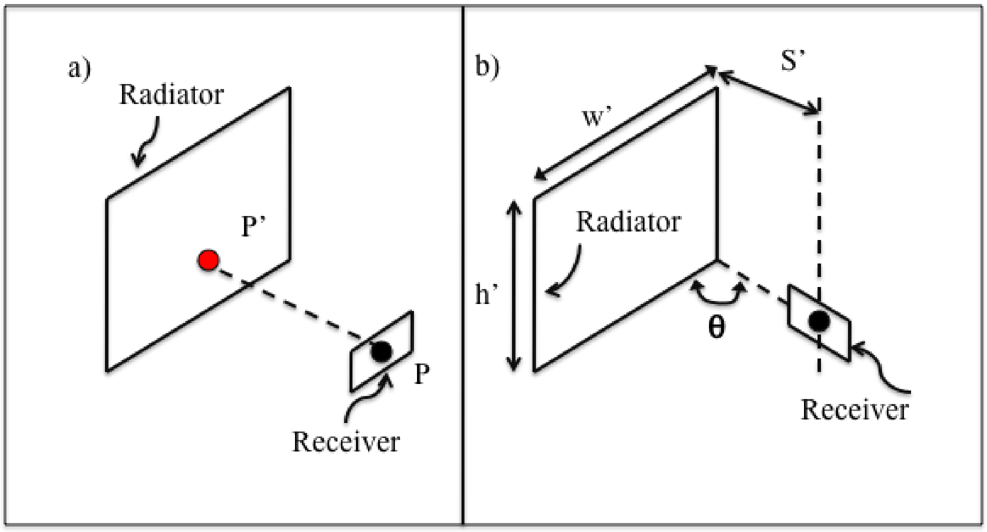


Figure 3-8: scenario when the radiator and receiver planes are a) parallel and b) non-parallel (Mohamadzadeh 2011).

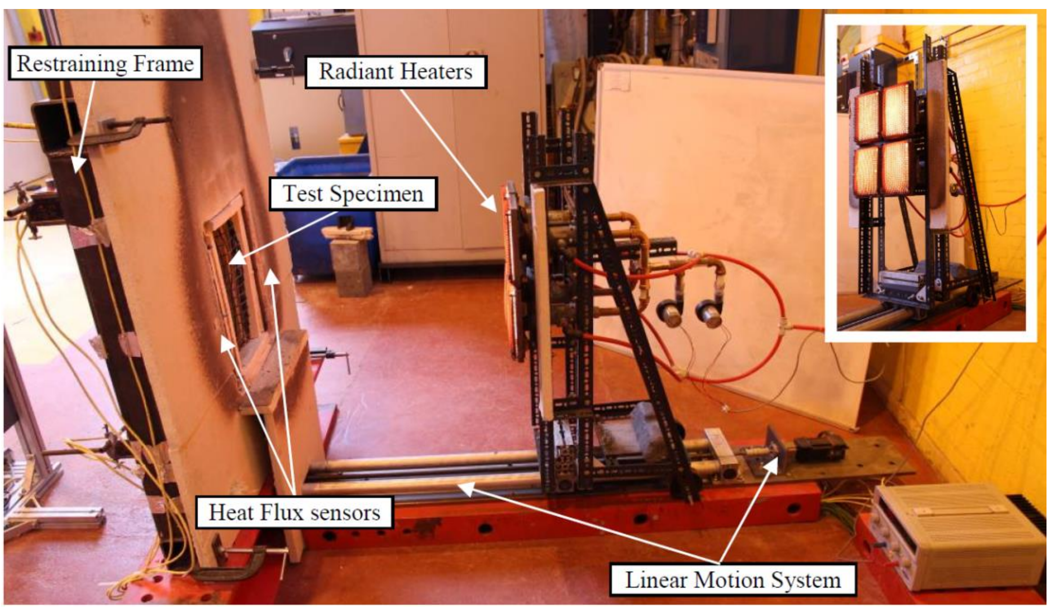


Figure 3-9: Heat-Transfer Rate measurement in different scenario of distance and orientation (Maluk & Bisby, 2012)

Roof-flame radiation

A roof flame radiates heat flux to targets around it and behaves differently when compared to a projected flame from a window (Beyler, 2002:268). In the case of multi-storey buildings, a roof flame can only occur if the fire takes place on the top floor of the building or when the fire reaches the top floor from lower floors. Therefore, some models that were originally developed for modern cities with plenty of multi-storey buildings, considered this mode ineffective, since its contribution was low in comparison to other modes. Thus, a very simplified version of the roof-flame radiation mode was used or even neglected completely, in order to avoid extra computational demand (Golmohammadi, 2010:456). For example, Himoto and Tanaka's model only used a very simplified method (point-method, explained later in this section) to address this mode (Himoto & Tanaka, 2008:477).

The presented model of this thesis regards the roof flame as an effective mode for two reasons. (1) This model focuses exclusively on one floor, low-cost buildings; hence, the roof flame would be the mode to transfer the heat flux for all buildings in the study area. (2) Combustible material (i.e. wood) is commonly used to construct or cover the roofs of these buildings (Mr Schnetler 2014, pers,comm., 5 September). Therefore, the roof flame is considered to be an important mode for the purpose of this study. Figure 3.10 shows a burned building after a fire in Kayamandi on 16 March 2013. It can clearly be seen that the roof is burned completely, which is evidence of the roof flame's effectiveness.

Figure 3-10: Inside view of a one-storey building after a fire in Kayamandi, an informal settlement (photographer, Author).

Because no method has been developed to estimate the roof flame in particular (Lee & Davidson, 2010:688), this study models the roof flame as an open-pool fire. In the case of open pool-fire, the fire is assumed to be freely exposed in the air and the flame tilts in the direction of wind (Beyler, 2002:268). Beyler (2002) reviews methods to simulate the roof flame geometry, the emitted heat from the roof flame and the amount of received heat by targets. With regards to flame geometry, it is typically assumed that the flame is cylindrical in shape, and the height of the cylinder is estimated as a function of the pool diameter and burning rate (Thomas, 1963;Heskestad, 1981; Moorhouse, 1982).

Beyler (2002) presents three types of methods to estimate the amount of received heat flux by targets (heat is emitted from the poolfire): (1) screen method, (2) point-method and (3) detailed method. Screen methods are only applicable when the pool-fire and target are at the same level, and heat flux is estimated as a function of distance from the pool-fire to the target and the pool-fire's diameter. Pointmethods are the easiest method to apply, because they assume both the flame and target as two points, and therefore the configuration factor is not required. However, pointmethods underestimate the heat flux over short distances (Drysdale, 1998) and in cases of high heat flux (greater than 5KW/m^2), the results are not accurate enough (Beyler, 2002:268). A detailed method requires more computational demand, but it can cover the limitations of the two above-mentioned methods, and also produces more accurate results. Beyler (2002) describes two detailed methods, namely those of Mudan (1984) and Shokri & Beyler (1989).

With regard to the purpose of this thesis, Mudan's method (1984) is selected for two reasons: (1) his method includes wind as one of the parameters while the effect of the wind is neglected in Shokri & Beyler method. (2) Muden's method (1984) is comprehensive and includes flame geometry, emitted heat flux from the flame and received heat flux by target. Shokri and Beyler's method does not estimate flame geometry. Furthermore, according to Beyler (2002), using a combination of methods to determine flame geometry and received heat flux by targets would cause unpredictable results, because of all of these methods have been developed empirically or semi-empirically. Appendix H presents an in-depth description of Muden's method.

3.5.3.3 Branding

Fire brands are diminutive pieces of fuel (can be in a burning or a glowing condition) that are scattered into the atmosphere by wind, and if they land on a fuel bed, it might result in a new ignition. In most cases, branding has been recognized as the dominant mode to spread fire among buildings. It is also regarded as the most complex mode to simulate (Golmohamadi & Mohamadfam, 2014:57; Himoto & Tanaka, 2008:477; Scawthorn, Eidinger & Schiff, 2005).

Manzello, Shields, Cleary, et al. (2008:258) divides the process of the branding into three parts:

- Brand generation
- Brand scattering and combustion
- The possibility of a new ignition on the host surface

Most research has focused on the transport phase, with some limited experimental work into generation and possible new fire ignition. Each phase is described in turn.

Firstly, each part of fire-brand simulation is explained and some of the available methods of each are reviewed. Finally, the process of branding in the new model will be described.

Brand generation

The goal of research into the generation phase is to determine *how many* brands will be released and *when*, and the *size and mass* distribution of the brands. Some experimental studies have been conducted in which a real-scale object is burnt, some or all of the resulting brands are collected in wet trays, and the brands are then dried and examined. Waterman (1969); Yoshioka, Hayashi, Masuda & Noguchi (2004:142), Manzello, Maranghides & Mell (2007); and Manzello, Maranghides, Shields, Mell, Hayashi & Nii, (2009) have conducted such studies for roof assemblies, a fire-preventive wood house, and trees, respectively.

While some lessons and models are transferable, there are important differences. The vegetation-generated brands in wildland fires tend to be spherical or cylindrical, coming from twigs, bark, leaves, cones and needles; whereas structure-generated brands more common in *urban fires* tend to be *disk-shaped*, resulting from thin, flat roof shingles and building contents. Disk-shaped brands are lofted more easily than spherical and cylindrical brands and have a much smaller terminal velocity leading to a greater potential for spot fire propagation (Woycheese, 2001:17).

Brand scatter

"The airborne firebrand receives the aerodynamic forces and moment from the surrounding fluid, which varies in time and space due to the change in its location and orientation" (Himoto & Tanaka, 2005:18). Many brand transport models have been developed, focusing on determining brand propagation distances, and sometimes the distributions of final brand size and burning status (glowing, flaming, neither) as functions of wind speed, heat release rate, air and brand properties (e.g., shape, density, size). These models include Tarifa, del Notario & Moreno (1965), Lee & Hellman (1970), Albini & Forest (1983), Stephen & Fernandez-Pello (1998), Woycheese, Pagni & Liepmann (1998), Woycheese, Pagni & Liepmann (1999), Himoto & Tanaka (2005); Huang, Ooka, Kato, Otake & Hayashi, (2004), Sardoy, Consalvi, Porterie & Fernandez-Pello (2007) and Anthenien, Stephen & Fernandez-Pello (2006). While they vary in detail and assumptions, the models typically combine three main sub-models that describe the (1) fluid motion, (2) brand motion, and in some cases, (3) temporal mass change of the brands.

The boundary layer of the atmosphere through which the brand is transported is a combination of the fire plume and wind speed fields, and has been modeled in 2D or 3D using plume and wind models (e.g., Woycheese et al. 1999) and computational fluid dynamics simulations (e.g., Huang, Ooka, Kato, Otake & Hayashi, 2004). Brand motion is typically determined using conservation of brand momentum equations, assuming two forces act on the brand, gravity and drag, which depend on the fluid motion. Some studies include a model of how the brand combusts and loses mass over time while being transported. This can affect the trajectory of the brand and the final mass when it lands, thus influencing its ability to ignite the fuel bed. In fact, a brand may completely combust in the air, posing no spotting risk. Brand combustion has been addressed using a burning spherical liquid fuel droplet model with the brand diameter following a regression rate (Woycheese, Pagni & Liepmann, 1999:32) and using a more complex model of pyrolysis (Sardoy, Consalvi, Porterie & Fernandez-Pello, 2007:151). (Woycheese, 2001:17) offers experimental data on the combustion of wood disk-shaped brands.

Possibility of a new ignition

Three primary mechanisms by which brands ignite structures have been identified (Manzello, Cleary, Shields & Yang, 2006:77):

(1) brands land on pine needles in gutters-

(2) brands get blown into attics where they ignite room contents-

(3) brands are trapped in small crevices in the structure (e.g., shingle overlap).

Experimental work in this area has been conducted by Waterman (1969), Dowling (1994), Ellis (2000) and Manzello et al. (2006) to investigate the effect of various parameters on the probability of ignition upon brand deposition. The parameters investigated include brand size, number of brands, brand status (glowing or flaming), air-flow velocity, moisture content of fuel bed, and fuel-bed type (pine needles, shredded paper, cedar shingle crevices for the case of structure ignition and mulch and cut grass for landscaped areas and vegetation around buildings).

Branding in this study

In the new model, with regard to Manzello, Shields, Cleary, et al., 2008:258), simulation of the branding is presented in three steps. Figure 3.11 shows these three steps and the explanation of each step follows:

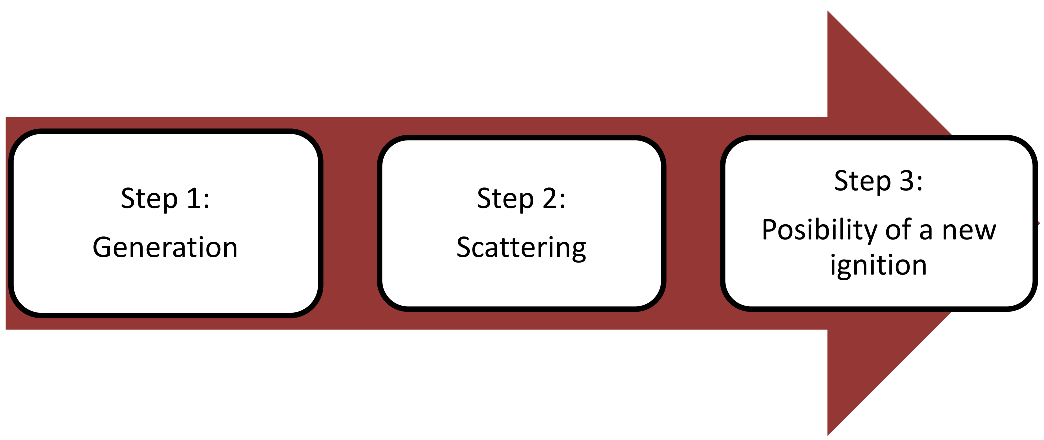


Figure 3-11: breaking the fire brand simulation process into three steps

Step 1

As noted, fire consists of three phases: the growth, fully developed and decay phase. But, following the Yoshioka (2004) suggestion, it is assumed that all brands are released during the fully developed phase, and the rate of generating fire brands are constant (Yoshioka, Hayashi, Masuda & Noguchi, 2004:142).

Waterman (1969) conducted several tests on buildings (8.5 m^2 area with a 45° roof slope, covered by 2.5 cm lumber sheathing and asphalt shingles). Different wind speeds were applied and the results were recorded. Based on the results of the test, he presented a relationship between wind speed and the number of released fire brands from a one square meter roof area.

To estimate the total number of generated fire brands, Waterman's (1969) method was selected. Reasons for the selection are as follows:

- This method exclusively focused on building-generated brands (as opposed to vegetation-generated brands).
- It has been widely used by fire-simulator models such as Mohamadzadeh (2011), Zhao (2010) and Lee & Davidson (2010).

Equation 8 presented by Waterman (1969) estimates the total released brands of one square meter of roof area N, which is a function of the wind speed U. The relation between wind speed and number of released brands is illustrated in figure 3.12. N is the total number of released brands per square meter of a roof in one second. Equation 8 calculates N. Regarding the area of the roof, N_i is the number of brands, released from the roof in a second, and the number of brands released in a time step $N_{t,}$ equation 9 & 10 are used (the duration of the fully-developed phase was determined in section 3.5.1).

$$N = 306.77e\ (0.1879 \times U) \quad (8)$$

Where e is Euler's number

$$N_i = N\ (\,roof\ area\,) \quad (9)$$

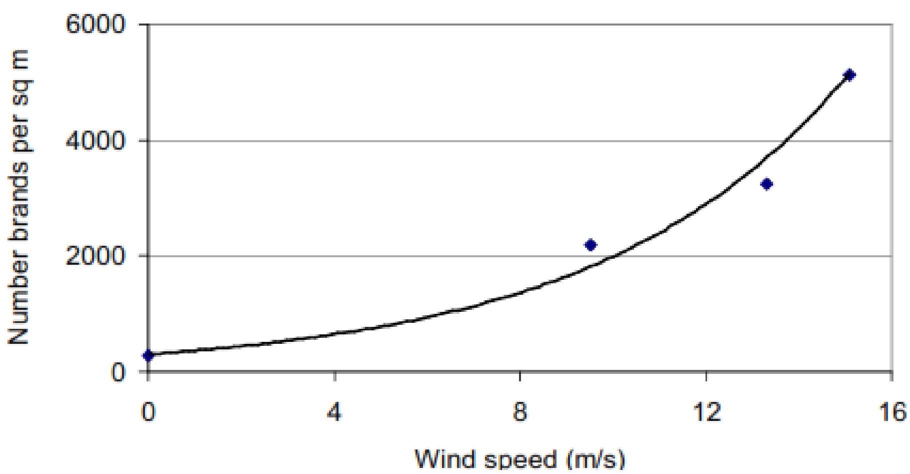


Figure 3-12: Number of brands versus wind speed (Waterman, 1969)

Based on Waterman (1969) and Ohmiya & Iwami (2000:27), Lee (2009) categorized fire brand into three sizes, namely, fine, medium and coarse. Lee also determined the frequency and probability of ignition of each size. Table 3.7 presents this categorization.

Table 3-5: Categorization of firebrand based on size and shape, and correlated percentage of generation and probability of a making new ignition.(Lee, 2009)

Size	Brand area[a] (cm^2)	Brand thickness[a] (cm) dp	Brand density (kg/m^3) ρ_p	Percentage of brands of this size	Probability of ignition of host material
Fine	0.13 to 1.29	0.25 to 0.76	50 to 200	71%	0
Medium	1.29 to 6.45	0.76 to 1.02	50 to 200	27%	0.005
Coarse	6.45 to 58.06	1.02 to 1.78	50 to 200	2%	0.020

Step 2

(Himoto & Tanaka, 2005:18) developed a numerical simulation of the scattering of disk-shaped brands in a 3D turbulent boundary layer. Unlike other studies, they then fit a probabilistic model to the numerical model results, assuming a lognormal distribution of brand propagation in the downwind direction and normal distribution in the crosswind direction (Figure 3.13). This probabilistic model was selected for the following reasons:

- This method exclusively models scattering disk-shaped brands, which is the type of generated brands in urban areas, not wildfire
- The ease of applying it is appropriate given the larger context of the research
- To avoid unnecessary computational demand, because this method ignored the effect of brand combustion

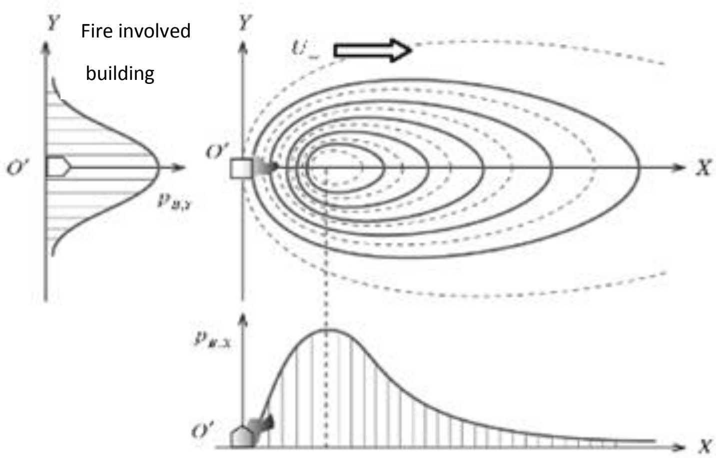


Figure 3-13: Probability of fire brand scattering released from a building in fully developed phase of fire (Himoto & Tanaka, 2005:18).

The location where a fire brand lands, is defined by X and Y, which are measured from the centroid of the burning building in the fully-developed phase. The X-axis represents downwind and Y-axis represents crosswind directions. Based on the selected method, the probability density functions, in the downwind (p_X) and upwind (p_Y), are calculated using equations 11 and 12.

$$P_x = \frac{1}{\sqrt{2\pi\sigma_{L,X}}X} exp\left\{-\frac{(LnX-\mu_{L,X})^2}{2\sigma_{L,X}^2}\right\} \qquad (0<X<\infty) \qquad (11)$$

and

$$P_Y = \frac{1}{\sqrt{2\pi\ \sigma_Y}} exp\left(-\frac{Y^2}{2\ \sigma_Y^2}\right) \qquad (-\infty<Y<\infty) \qquad (12)$$

$\mu_{L,X}$ and $\sigma_{L,X}$ are the mean and standard deviation of the logarithm natural to the transport distance lnX. In crosswind direction, Y, the mean deviation is set to zero, and only standard deviation σ_Y is considered.

$$\left.\begin{aligned} \frac{\mu_x}{D} &= 0.47\ B^{*2/3} \\ \frac{\sigma_X}{D} &= 0.88\ B^{*1/3} \end{aligned}\right\} \text{ And } \left.\begin{aligned} \frac{\mu_y}{D} &= 0 \\ \frac{\sigma_y}{D} &= 0.92 \end{aligned}\right\} \qquad (13)$$

Where D is a square root of the floor area, B^* is a dimensionless parameter, which is calculated by the following equation:

$$B^* = \frac{U_\infty}{(gD)^{\frac{1}{2}}} \left(\frac{\rho_P d_P}{\rho_\infty D}\right)^{-3/4} \left(\frac{Q}{\rho_\infty c_P T_\infty g^{-1/2} D^{5/2}}\right)^{1/2} \qquad (14)$$

Where Q is the fire's heat release rate (kW), it is calculated as follows :

$$Q = 1500\ A_{floor} \qquad (15)$$

A_{floor} = floor area;

U = the wind speed (m/s);

C_p = the heat capacity of gas (kJ/kgK);

g = the acceleration due to gravity (m/s^2);

ρ_∞ = density of air/ambient

T_∞ = temperature of air/ambient

d_P and ρ_P are brand thickness and density thatare based on the size category of the brand. These can be obtained from table 3.7.

Step 3:

Once the number and deposition location of released fire brands have been calculated in previous steps, the model can then check for each of them whether the brand lands on the footprint of a building or not. Without knowing the condition of the brand (burning, glowing or neither) and the properties of target combustible, it is not possible accurately to determine the probability of a new ignition. The probability of ignition is estimated based on the size category of a brand and whether a brand lands on a building (see table 3.7). Table 3.7 presented by Lee (2009) is based on the result of several tests conducted by Waterman & Tanaka (1969) and Ohmiya & Iwami (2000). As an example, Ohmiya and Iwami (2000) reported that in an area where fire brands greater than 1 cm (0.39 in) were flying, there was only one possibility of a new ignition due to the brand. Note that to avoid unnecessary computation demand, the deposition locations of fine brands are not calculated since the probability they will ignite a new fire is assumed to be zero.

3.6 **Conclusion**

In Chapter 2 a theoretical basis for the development of a new model was provided by reviewing the basis, influential factors and ways of validation of the selected group of fire-simulator models. A physics-based approach was selected to develop a new model to achieve this study's aim and objective. This chapter described the new model in four sections.

Firstly, based on the aim and objective of this study, the scope of the model was determined. Secondly, the sensitivity and import method of each factor was discussed. Subsequently, some of the possible outputs of the new model were presented.

Thirdly, an overview of the simulation process was presented. The process was broken down into three modules: (1) fire evaluation in a room, (2) room-to-room fire spread, and (3) building-to-building fire spread. Then the sequence of the simulation process was presented. Subsequently, the technical methods to conduct the tasks of each module were reviewed. Finally, the most appropriate method for each task was selected and reasons for the selection were discussed.

The new model was programmed in C#.net by an independent programmer, based on the selected methods and presented sequence in order to overcome the challenge of computational demand. Before this newly presented model can be used, it needs to be verified and validated, which is the focus of the next chapter.

Chapter 4 Verification and validation of the model

4.1 Introduction

In order to verify and validate the model, section 4.2 firstly verifies the model by determining whether the conceptual simulation model was correctly translated into the computer program. Secondly, the validity of the model is determined in section 4.3, by checking whether the model is an accurate representation of a real system for the particular aims of the study.

4.2 Verification

For the purpose of verification, a case study of two buildings is used, and the results from the software (see Figure 3.1) are compared with hand calculations. A case study with two buildings was chosen because of the minimum requirements of the simulation of fire-spread modules. Module1 (evaluation of a fire) and module 2 (room-to-room) can be conducted in one building, but module 3 (building-to-building) requires at least two buildings (see sections 3.4 and 3.5). Therefore, choosing a case study with more than two buildings is not necessary for the purpose of verification. In addition, a two-building case study is practical for hand calculations, in terms of computational demand.

The determination of the case study's input factors are as follows: The following input data forms the first scenario, and then second and third scenarios are formed by changing the value of the wind speed and the distance between buildings. Regarding building factors (see 3.3.1.1), as illustrated in Figure 4.1, the two buildings have the same dimensions (6m width, 12m length and 3m height) and each building of the case study has two rooms. Each external wall of a room has a window at the centre of the wall of 1 m height and 1.5 m width. The internal walls are non-bearing, unprotected (see table 3.5) and have an opening (it is assumed that in building number 1 the door between the rooms is open and in building number 2, it is closed). The amount of fire load is assumed to be 16 kg (wood)/m^2. The assumption is based on the suggested amount of fire load for a residential area by (Thomas, 1986:77), (appendix I presents fire load for different occupancies. The environmental factors (see 3.3.1.3) are as follows: the ambient temperature is 10^{o}C; regarding plan view, wind direction is 270^0 clockwise from north; wind speed is 10 m/s. Concerning the landscape factors (see subsection 3.3.1.2), the buildings are parallel orientated and the distance between the buildings is 3 m.

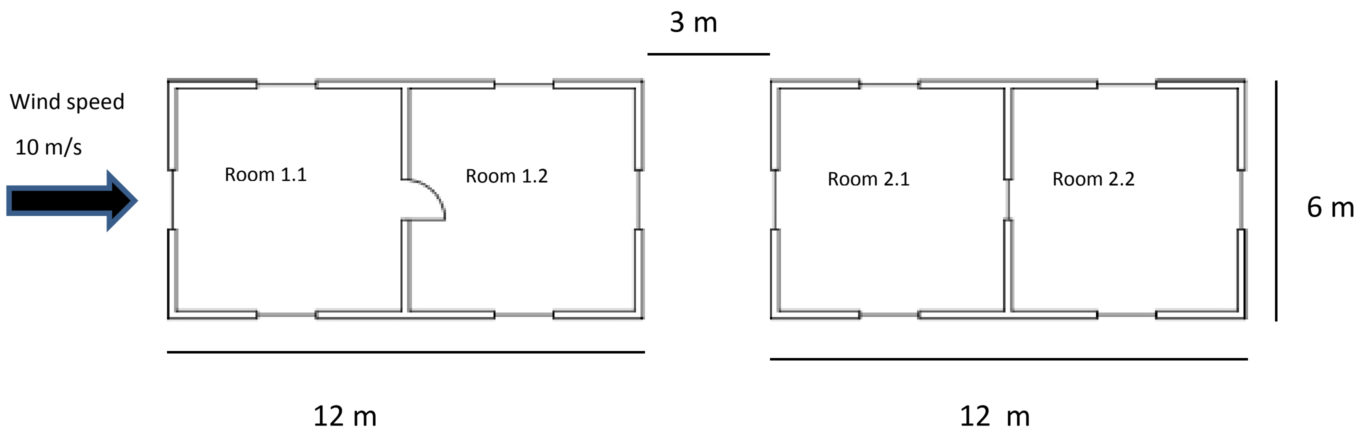


Figure 4-1: Illustration of the case study's buildings, dimensions and orientation.

First scenario:

The input data were imported into the model and were also used for hand calculations. Branding was the dominant mode of fire spread in both the software and hand calculations. Fire spreads between rooms at the same time steps and with the same modes in both the software and hand-calculation results. Only with regard to fire spread through the branding mode, fire spreads in slightly different time steps in the software and hand calculation's results, because a probabilistic method was used to determine the branding mode.

Second scenario:

Scawthorn, Eidinger & Schiff (2005) stated that in most cases branding is the dominant mode to spread fire between buildings, specifically under high wind-speed conditions. Therefore, the second scenario of no wind was assumed (the rest of the factors remained as determined above) which means that no brand can be generated (see section 3.5.3). In this scenario, both the model and hand calculation identified radiation as the dominant mode, and the fire spreads over the same time steps.

Third scenario:

As noted, flame impingement is the only mode that can cause immediate fire spread among buildings, but it only happens over short distances (as long as the length of the window flame). To verify this mode, the third scenario, in which the distance between the buildings was assumed to be 0.5m, as in the second scenario no wind condition was considered. In this scenario fire spread through flame impingement in the same time steps in the model as well as the hand calculation results.

Table 4.1 compares the software and hand-calculation results in the three mentioned scenarios by presenting the time of ignition in each room and the dominant mode of fire spread in the room.

Table 4-1: Comparison of the hand-calculation and the software results.

	Room	Time of ignition (min)		Reason of fire spreading
First scenario	1.1	Hand-calculation	0	Fire point
		Software	0	Fire point
	1.2	Hand-calculation	5	Open doorway
		Software	5	Open doorway
	2.1	Hand-calculation	8	Branding
		Software	7	Branding
	2.2	Hand-calculation	10	Branding
		Software	11	Branding
Second scenario	1.1	Hand-calculation	0	Fire point
		Software	0	Fire point
	1.2	Hand-calculation	7	Open doorway
		Software	7	Open doorway
	2.1	Hand-calculation	17	Radiation
		Software	17	Radiation
	2.2	Hand-calculation	32	Burn-through wall
		Software	32	Burn-through wall
Third scenario	1.1	Hand-calculation	0	Fire point
		Software	0	Fire point
	1.2	Hand-calculation	7	Open doorway
		Software	7	Open doorway
	2.1	Hand-calculation	7	Flame impingement
		Software	7	Flame impingement
	2.2	Hand-calculation	22	Burn-through wall
		Software	22	Burn-through wall

4.3 Validation

Chapter 2 identified that three ways have been used to validate fire-spread models (see 2.3.3). The method of comparing results with the other existing models is selected to validate the presented model of this thesis for the following reason:

Hindcasting is the most appropriate way to validate a model, but a suitable recorded fire could not be found. Since there are only a few well-recorded large urban fires and none of them can be fitted into the scope of this research; mainly because large existing urban areas normally include different types of buildings in terms of size, number of stories and occupancy type.

In order to validate this study's model, the method comparing a new model's result with available models' results is selected. The result of this study's model is compared to Hamada's as well as Lee's model in a hypothetical case study of 1024 buildings (figure 4.2 illustrates the area).

The Hamada model is the most well-known fire-spread simulator model for urban areas, and it has been used the most in practice (Lee & Davidson, 2010:688). This model has been validated using hind-casting in several cases. For example: The Hamada model was hind-casted with three fire events in Japan and five fire events in the United Stated of America (Lee & Davidson, 2010:688). Furthermore, this model has been used to validate many existing models such as Ohgai et al (2005:193) and Himoto & Tanaka, (2008:477). However, Hamada's model is an empirical model which can only estimate speed and direction of fire spread in a case study.

Lee's model is a successful recent physics-based model, which simulates fire spread in great detail, and therefore it was also selected for the purpose of validation. Lee's model will be used to compare both fire-spread rate and contribution of fire-spread modes with the new model (see figure 3.1). Section 4.3.1 describes the input data of the case study which will be used in the proposed model of this study as well as those of Hamada's and Lee's models, where after the results will be compared.

4.3.1 Input data

The hypothetical case study consists of 1 024 square-shape, one-storey and single-family buildings. Each building is 12 m wide12 m long and has a height of 3 m (144 m^2 areas). The area of each building is divided into rooms with the minimum length of 5 m for its interior walls. The interior walls are non-loading, unprotected (see table 3.5) and have an opening (possibility of being open is 50%). Each external wall of a room has a window at the centre of the wall (height 1 m, width 1.5 m). Regarding occupancy type, based on Thomas (1969), the fire load is assumed as a normal distribution with a mean of 16 kg of wood and a standard deviation of 4.4, N (16, 4.4). Table 4.1 shows the related fire load for each occupancy type:

Table 4-2: Related fire load for occupancy types (Thomas, 1986)

Occupancy type	Distribution of fire load
All residential rooms	N(16, 4.4)
Hospital (patient's room)	N(5.4, 1.65)
Govt. building, all rooms	N(27.75, 31.25)
Private office, all rooms	N(29, 26.75)
Department store	46.75
General warehouse	113.5
School (1 occupied room)	U(31.75, 177)

N: normal distribution U: uniform distribution

Ambient temperature is assumed to be 0^{0}C (273.15^{0}K) and wind speed is 7 m/s, blowing from the north direction. Concerning the landscape factors (see subsection 3.3.1.2), the buildings are parallel-orientated and the distance between the buildings is 6 m. Figure 4.2 illustrates the case study. The ignition point is showed by a red dot in figure 4.2.

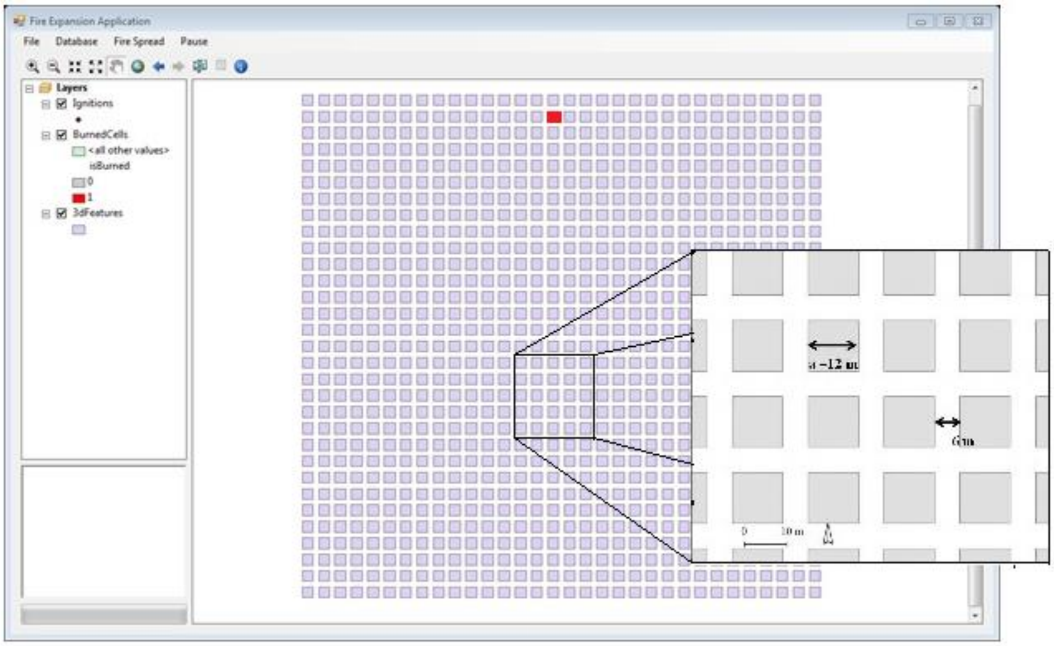


Figure 4-2: Study area developed for comparing results of the new model with the Hamada and Lee models.

4.3.2 Comparison results

First, the results of the new model 48 and 64 minutes after fire ignition will be compared with Hamada’s and Lee’s models. Then the percentage of contribution of fire spread modes, calculated by this study’s and Lee’s model, are compared.

Table 4.2 below presents the length of the fire spread in upwind and downwind directions from the fire starting point (the point is assumed to be the centre of the building in which the fire started indicated by a red dot in figure 4.2), the width of the fire flank-to-flank as well as the number of buildings in burning condition plus those that might already have burnt.

Table 4-3: Quantitative comparison between the new model's, Hamada's and Lee's models at 48 and 64 minutes after fire ignition.

	48 minutes			64 minutes		
	Hamada	Lee	Author	Hamada	Lee	Author
Length of fire upwind from ignition point (m)	41	0	0	94	0	0
Length of fire downwind from ignition point (m)	153	186	164	330	312	334
Width of fire from flank to flank (m)	45	174	196	103	246	268
Number of burned buildings by fire per fire outbreak	41	58	56	206	147	152
Total building area burned (sq.m)	5,910	8,496	8,203	29,686	20,160	21,888

From the new model as well as Lee's results, for both 48 and 64 minutes after fire ignition, the fire did not spread in an upwind direction, although, according to the new model's approach, it is possible for fire to spread in this direction. There are three reasons why the fire did not spread in an upwind direction:

- According to Himoto's method (2005) (see section 3.5.3.3), which is employed to simulate branding in the new model, brands can only be spread from a building in a fully developed condition in downwind and orthogonal directions, hence, branding cannot cause a new ignition in an upwind direction.
- With regards to fire spread through radiation, first the wind tilts the roof flames in a downwind direction and second because the closest distance of a building in fully-developed condition (radiator) from other possible targets is 6 meters, no target in an upwind direction received at least the critical amount of heat for a new ignition (the critical amount of heat was assumed 12.5 kw/m^2, see section 3.5.3).
- Flame impingement only occurs in short distances, because the window's or roof's flame must reach a neighbouring building. The 6m separation distance among the buildings, is too far for a flame to reach a neighbouring building. Hence, flame impingement did not occur in an upwind direction.

Unlike the upwind direction, fire spread in a downwind direction at approximately the same rate for the three models, although the new model's fire-spread rate shows great similarity to the result of Lee's model.

Figure 4.3 graphically presents a map series of fire spread among building and includes nine different time steps, from the ignition time to 128 minutes after. The ignition point is in the building, which is located at the intersection of the internal elliptical lines. Figures 4.4 a & b are based on the new model and Hamada's and Lee's models illustrated how fire spreads among? buildings in the study area visually, in 48 minutes and 64 minutes after fire.

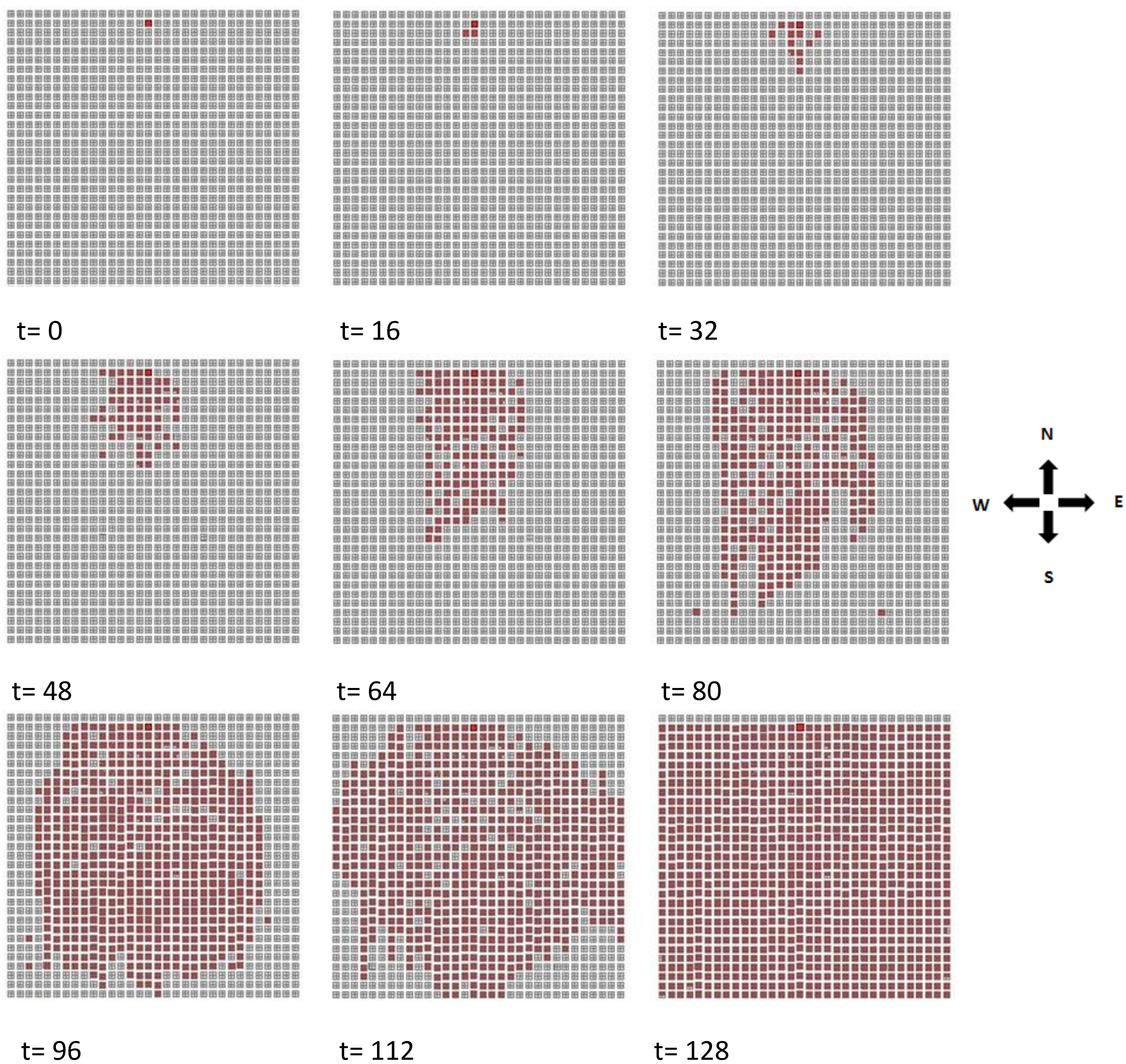


Figure 4-3: Progression of fire spread among buildings of the case study, map series of 9time steps, from the ignition time to 128 minutes after.

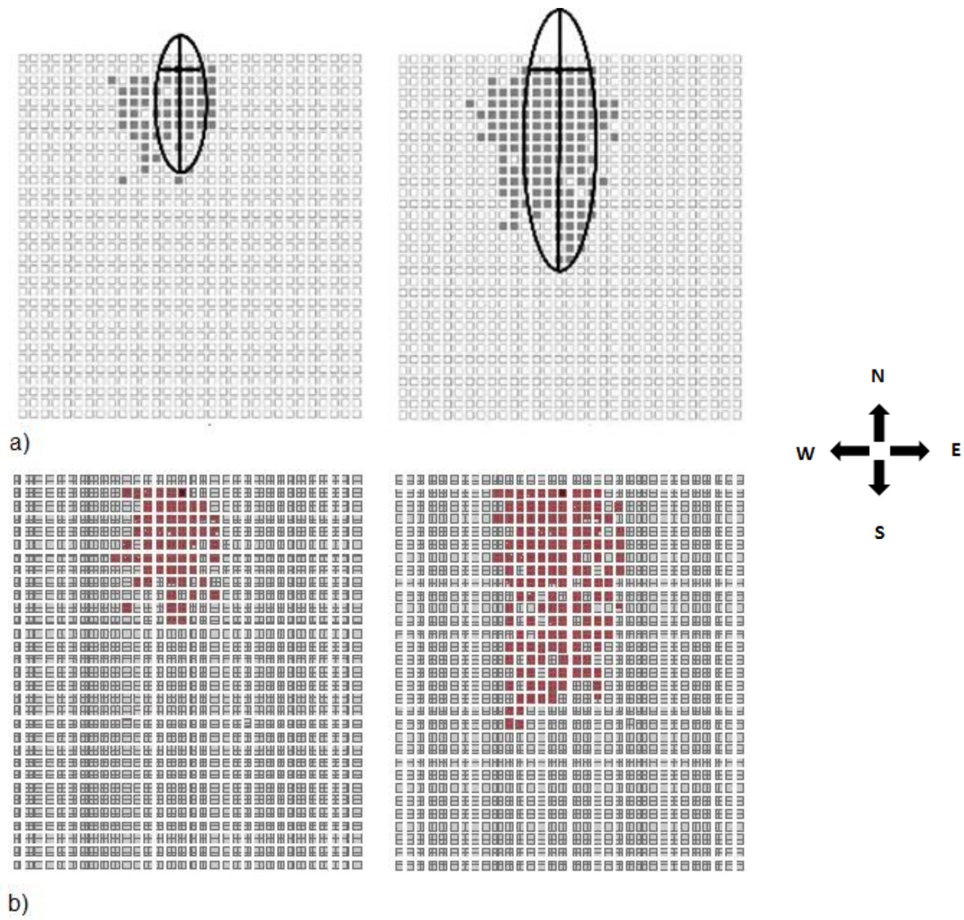


Figure 4-4: Illustration of fire progression of burnt buildings in the case study in 48 and 64 minutes after ignition, based on a) Hamada's and Lee's model b) the new model. The red arrow shows wind direction (Mohamadzadeh. 2011).

Since both Lee's model and the new model incorporate the different modes of fire spread and take into account fire spread by *open doorway*, *burn-through of internal walls*, *radiation*, *flame impingement* and *branding,* better comparison can be obtained from the results of the modes' contribution of Lee's model and the new model.

Both models resulted in the same dominant modes for fire spread in building-to-building and room-to-room. Branding is the dominant mode for building-to-building and open doorway for room-to-room fire spread. Although figures 4.5 & 4.6 show the modes' contribution of the two models in detail, they are slightly different. This slight discrepancy of the result is acceptable because:

- A probabilistic method was employed to conduct branding mode (see 3.5.3.3)
- No fire simulator exists that simulates fire spread with complete accuracy. Hence, the result of Lee's model simulation is not 100% accurate.

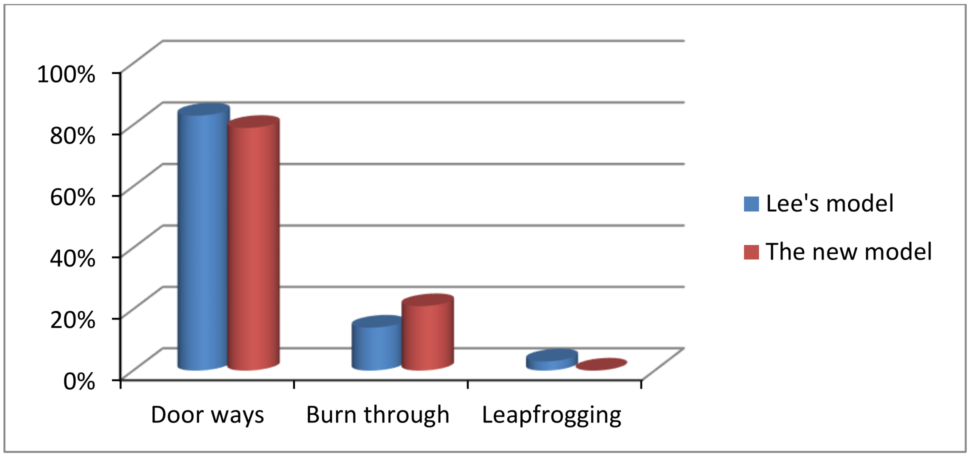


Figure 4-5: Compression of distributions of the modes of room-to-room fire spread, averaged over 50 simulations, between Lee's and the new model (Lee & Davidson, 2010:688).

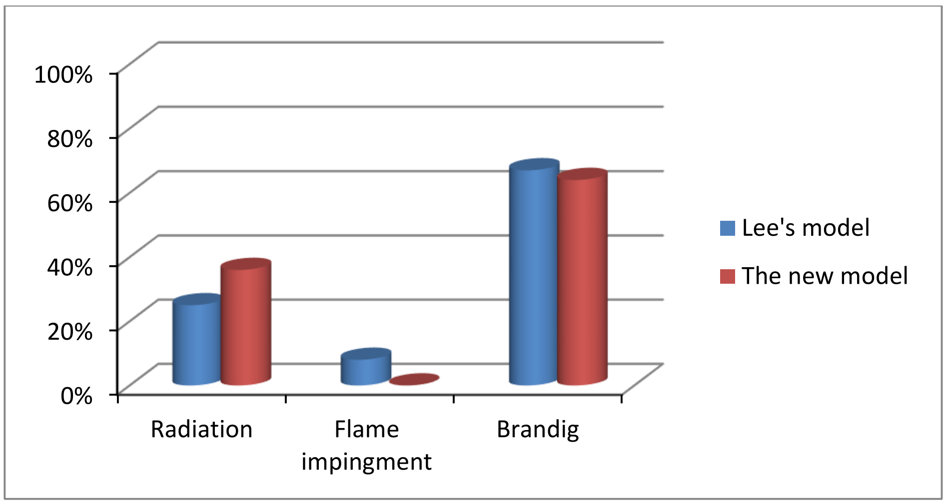


Figure 4-6: Compression of distributions of the modes of building to building to building fire spread, averaged over 50 simulations, between Lee's and the new model (Lee & Davidson, 2010:688)

4.4 Conclusion

Since the previous chapter described the development process of the new model, this chapter verified and validated the new model.

A case study of two buildings was used for the purpose of verification. The result of the new model was compared with a hand calculation. The comparison of the results proved that the conceptual simulation model was correctly translated into the computer program; hence, the new model was verified.

Three ways of validation were identified in the literature review of chapter 2. . Based on availability of data and the scope of this new model, the method of comparing the result of the new model with the result of existing models was selected. Furthermore, the reason for this validation method was described. To conduct the validation, Lee's and Hamada's models were selected. The reasons for selecting these two models are:

- Hamada's model has an empirical basis and is one of the oldest fire-simulator models that has been used most in practice
- It has been hind-casted several times, and the result was reasonably accurate
- Since the Hamada model is an old and empirical model and cannot incorporate the fire spread modes, Lee's model was also selected for use
- Lee's model is a recent model with a physics base
- It incorporates the different modes of fire spread and takes into account fire spread through open doorways, burn-through of internal walls, radiation, flame impingement and branding

An in-depth presentation of the three models' results follows: First in two time steps of 48 and 64 minutes after fire ignition, with the distance of fire from the ignition point in an upwind, downwind, orthogonal direction and number and area of burnt building's area, estimates by the three models were presented in table 4.2 and an explanation of the results followed. Second, the percentage of fire-spread modes, room-to-room and building-to-building, which resulted from Lee's model as well as the new model, were compared and discussed. From the comparison of the results, it was found that the new model estimated fire spread with an acceptable accuracy; therefore, the validity of the new model was determined.

Since this chapter verified and validated the new model, the next chapter will apply the model in a real-life case study.

Chapter 5 Case study

5.1 Introduction

It is estimated that between 26% to 33% of the population of urban areas in South Africa are living in low-income settlements (Pharoah, 2012). However, “it is likely that such figures substantially underestimate the number of people living in informal settlements” (Pharoah, 2012). Informal settlements are commonly known to be over-populated and under-serviced, and are therefore most vulnerable to disasters such as fire and flooding (Roth & Becker, 2011:443). As described in section 1.2, fire in particular has caused many financial losses and fatalities.

In order to contribute to the solution and mitigation of the fire risk in low-costsettlements, this study aims to develop and validate the first fire-spread simulator model specifically calibrated for low-cost settlements in South Africa. Chapter 3 and 4 covered the development and validation of the new model. This chapter applies the new model in a case study to illustrate the output results and demonstrate how the results can be used to identify and prioritise critical factors, which is the specific objective of this study.

This chapter comprises three sections. The first section (section 5.2) provides information about the low-cost settlement, Imizamo Yethu, its geography, population and history of fire risk in the area. The second section (section 5.3) determines the input-data preparation. The third section (section 5.4) includes a presentation, discussion and an analysis of the results.

5.2 **Case study: Imizamo Yethu**

Imizamo Yethu is one of 222 metropolitan low-cost settlements of the City of Cape Town, which is situated in the Hout Bay Valley on the Atlantic Ocean side of the Cape Peninsula. The settlement itself is located on the north facing slope of Skoorssteenberg. To the northwest it borders a narrow green belt which runs alongside the M63 (Hout Bay main road) coming in from Overkloof, to the south the settlement borders directly onto the ecologically sensitive Table Mountain National Park (Munnik. 2009: 92). Figure 5.1 shows the geographical location of Imizamo Yethu. Imizamo Yethu was established in 1991 (Smith, 2005:1333) for Black South Africans who mostly worked as domestic workers and in the fishing industry in the Hout Bay area (Harte, 2009). The settlement was originally designed to accommodate around 3 000 people, but in 2011 it was estimated that the population ranged from 16 000 – 36 000 inhabitants (Roth & Becker, 2011:443).

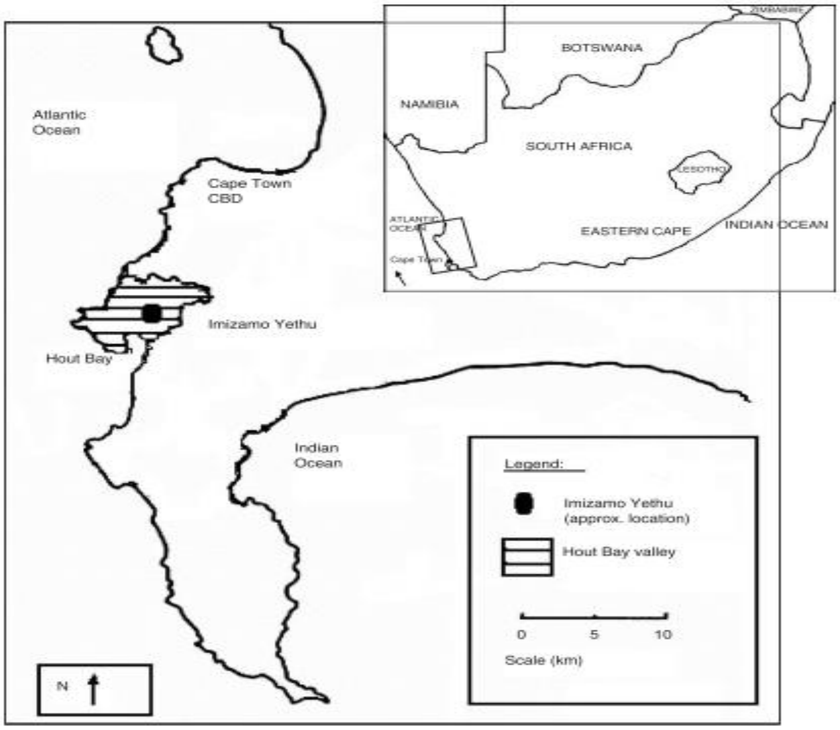


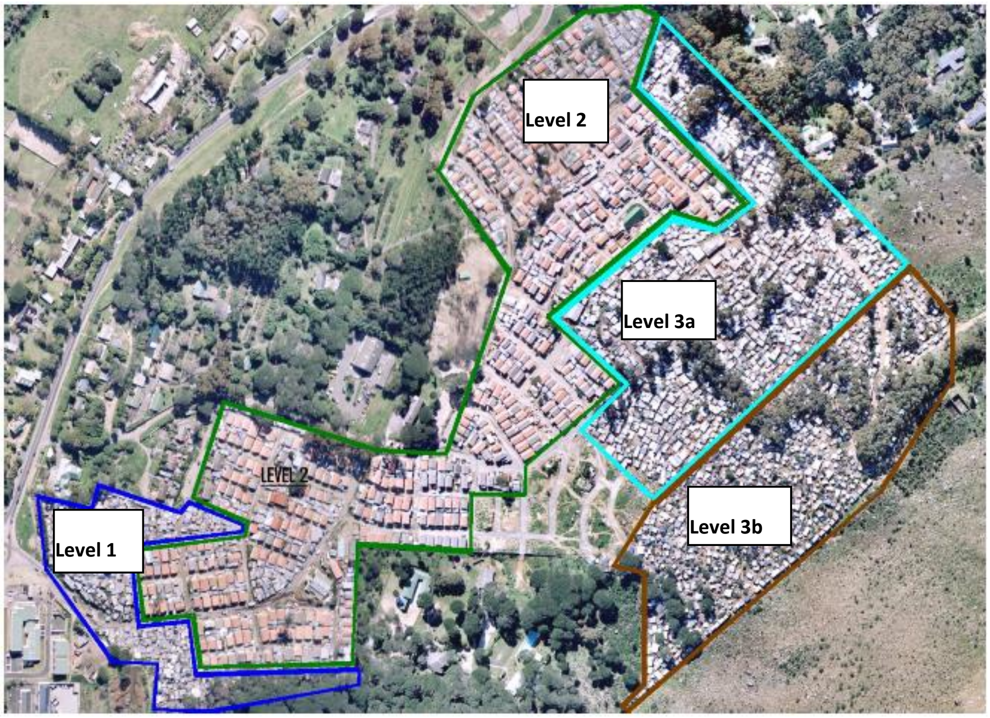
Figure 5-1: Imizamo Yethu settlement, Hout Bay, Cape Town (Harte, 2009).

There are many risks that have been identified in Imizamo Yethu, such as crime, flooding, falling branches, dangerous driving, alcoholism, poor service delivery, inadequate sanitation and fresh water infrastructure and HIV/AIDS, but "findings from the community risk assessment conducted in March 2008 indicates that the priority risks in Imizamo Yethu relate to fire and environmental health" (Munnik, 2009). Table 5.1 shows date of fires, number of burned houses and deaths and injuries and estimated homeless people.

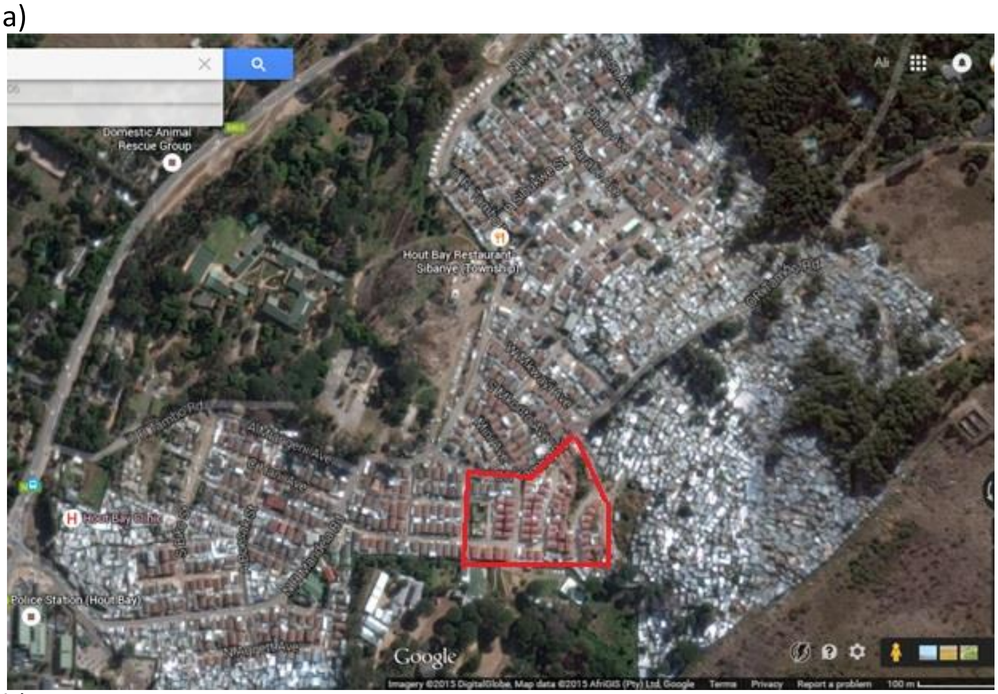
Table 5-1: Imizamo Yethu fire events (Harte, 2009).

	Date of fire (month/year)	Location	Houses destroyed	Deaths/ injuries	Estimated homeless
1	May 2007	Imizamo Yethu	30	1 dead	100
2	November 2006	Imizamo Yethu ('Shooting Range')	100	n/a	500
3	August 2006	Imizamo Yethu	4	n/a	15
4	June 2006	Imizamo Yethu	5	3 dead	25
5	February 2006	Imizamo Yethu	52	1 serious injury	'dozens'
6	February 2006	above Imizamo Yethu on mountain slope	n/a	n/a	n/a
7	April 2005	Imizamo Yethu	100	none	300
8	January 2005	Imizamo Yethu	3	n/a	n/a
9	February 2004	Imizamo Yethu	1200	n/a	5000
10	September 2003	Imizamo Yethu	82	none	'hundreds'
11	Christmas/New Year 2002/2003	Imizamo Yethu	53	n/a	300

(Munnik. 2009: 92) divided the area of Imizamo Yethu into the four levels; each level refers to a specific geographical area and is defined by the type of buildings. Table 5.2 defines the levels and figure 5.2 shows the locations of the levels.



a)



b)

Figure 5-2: a) Illustration of housing levels by (Munnik, 2009), b) 65 newly constructed core houses, circled with a red line.

Table 5-2: Description of housing levels (Oliver, 2009)

Housing Level	Dominant Housing Type	Households Interviewed	Avg. # of Residents per household	Range of Occupant s	Degree of Housing Regulation	Structural Density
Level 1	Serviced Freestanding Dwellings	3	5.3	3 to 7 people	Highly irregular	Extremely High
Level 2	Core Houses and Backyard dwellings	13	2.5	2 to 4 people	Relatively controlled to fringes of core houses	High
Level 3a	Serviced Freestanding Dwellings	5	3.2	2 to 8 people	Highly irregular	Extremely High
Level 3b	Un-serviced Freestanding Dwellings	5	3.6	2 to 7 people	Highly irregular	High

Four types of buildings were categorised: serviced freestanding dwellings, core houses, backyard dwellings and un-serviced freestanding. Among these buildings, only core houses were constructed by brick. As chapter 3, section 3.2 defined the scope of the new model; this model is designed to simulate spreading fire among one-floor brick houses. Therefore, only fire spread among core hoses of Imizamo Yethu can be simulated by the new model, appendix K presents some photos of core houses in Imizamo Yethu. The level 2 consists of 256 core houses, plus 65 new core houses that have been constructed in Imizamo Yethu after Munnik's research, that are selected as the case study. The newly constructed core houses are encircled in figure 5.2 b.

There are three reasons for selecting Imizamo Yethu as the case study for the new fire simulator model.

- fire is one of two top disasters of the area
- the area has been studied before by disaster risk management from a different view but a fire spread model has never been applied to the area
- the area was accessible for the researcher to conduct field measurements

5.3 Input data preparation

Section 3.3.1 determined the factors required to be used as input data for the new model. The input data were classified into three categories of environmental, building and landscape. With regard to the input data preparation, three methods have been conducted: (1) field measurement (2) using Google earth (to provide the landscape map of the area); and (3) determining parameters based on the environment of the area and fire codes. The following paragraphs, based on the three methods, will define the required data for each category.

The case study includes 321 single- family, one-storey masonry buildings. However, the buildings vary in terms of size and shape, as well as distance between buildings. In this regard, Google earth was used to draw a 3D map, which includes size, shape, distance between and orientation of the buildings. Although, as mentioned in section 3.2, the topography of land is not in the scope of the new model; therefore, all buildings are assumed to be on the same level. Figure 5.3 shows the map of the case study and the assumed fire starting point indicated by the red spot.

Figure 5-3: Case study area, includes 321 brick houses Fire point is indicated by red on the map,

With regard to the occupancy of different buildings, fire load has been studied and variety of estimations is presented (Appendix I presents some of the documents). No research has been found that exclusively studied the fire load in the case of formal low-cost settlements in South Africa.

Maree (2015) studied fire loads and burn characteristics of shacks in informal low-cost settlements. The research was conducted in Kayamandi, Stellenbosch on 25 randomly selected shacks. Figure 5.4 shows Maree's (2015) distributions of fire load densities of the selected shacks and table 5.3 compares the estimated shack's fire load to other occupancy types. Because Maree's document (2015) is the only available document of fire load of low-cost settlements in the case of South Africa, it was adopted for the purpose of application of the new model based on Imizamo Yethu. According to Thomas (1986), 1 kg wood can generate 20 MJ heat; thus, the converted fire load value found in Maree's document (2015) is 26.55 kg/m^2 wood.

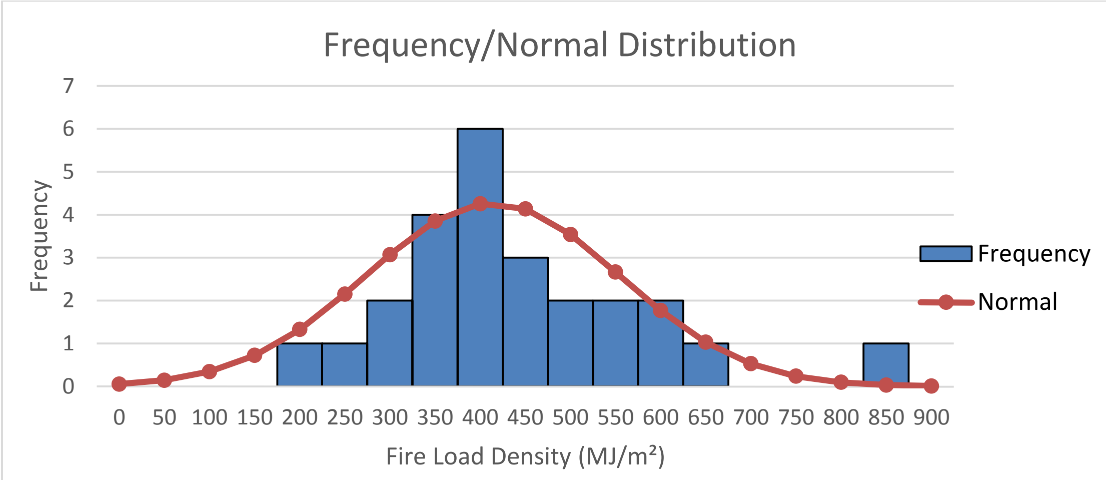


Figure 5-4: Distributions of fire load densities of 25 randomly selected shacks in Kayamandi, Stellenbosch (Maree, 2015).

Table 5-3: Comparison of fire load shack to fire load of some other occupancy (Maree, 2015).

Type of structure	Std. Dev	Average	80th Percentile
Hospital Room	69	230	280
School classroom	86	285	347
Hotel Room	93	310	377
Dorm Room	58	336	403
Office	126	420	511
SHACK	**139.9**	**413.9**	**531.4**
Dwelling	234	780	948
Library	450	1500	1824

A field measurement method was conducted to prepare data of windows' dimensions. Twenty buildings were randomly selected and the dimensions (height and width) of the windows were measured. Appendix J presents the dimensions of windows of the selected buildings. To simplify the simulation process, an average window dimension of 1.4 m height and 1m width (1.4:1) is assumed. Each exterior wall has a window with the assumed dimension at its center.

The model is able to divide buildings automatically into rooms and it only requires the maximum length of the interior wall. Due to the average size of the case study's buildings, the wall length is assumed to be 5 m. Since the fire resistance of the interior walls of the study area has not been studied, it is assumed that all walls are protected non-load based on the categories of IBC (see table 3.5). However, possible cracks in the walls and electricity channels, might reduce the fire resistance of the wall. On the other hand, extra cladding of the wall or painting the walls with heat-resistant colors can increase the fire resistance of the walls. Therefore, conducting the field measurement is the best way to estimate the burn-through time, but, because it is time and fund-consuming, this study used the mentioned assumption.

A northerly wind with speed of 10 m/s is assumed. According to McMichael, et al.(2008:1121) the annual average temperature of Cape town is 18.9^{0}C, although the average summer temperature is 24.3 ºC (City of Cape town, 2015). While in this application, the occurring fire in summer or winter time is not specifically targeted, the average annual temperature is used to simulate fire in the base case scenario.

5.4 Scenario creation and results analysis.

The required input data were determined for the case study and the determined data constitute the base case scenario. In this section, firstly, the results of the base scenario simulation are presented as (1) a map series of fire spread, (2) a contribution of the fire spread modes and (3) the area burned vs. time curve.

Secondly, for the purpose of prioritising the effect of the factors on fire-spread progression, nine parameters were selected from the three categories of influential fire-spread factors (environmental, buildings and landscape factors). These parameters are:

- wind speed
- ambient temperature
- heat resistance of interior walls
- wall length
- window size
- window dimensions
- probability of open doorway
- fire load
- distance between buildings

By changing the value of a parameter, different scenarios are derived from the base case. The results of each scenario are presented as (1) the area burnt vs. time and (2) the contribution of the fire spread modes. The scenarios considered in this section do not cover all possible scenarios that can be derived from the base case, for the current objective or any other possible objectives. In fact, this section only simulates the considered scenarios with the aim to:

- illustrate some of the possible outputs of the new model; and
- prioritise the influential factors by analyzing the results.

Finally, the results of the scenarios are discussed and presented in a tornado diagram to compare the effect of the varied influential factors on the total burnt area in the case study.

5.4.1 Base case scenario

With regard to the base case scenario, figure 5.5 presents total burnt area versus time curve. Figures 5.6 a & b show the contribution of building-to-building and room-to-room modes and figure 5.7 illustrates the fire-spread progression in a map series of the case study area.

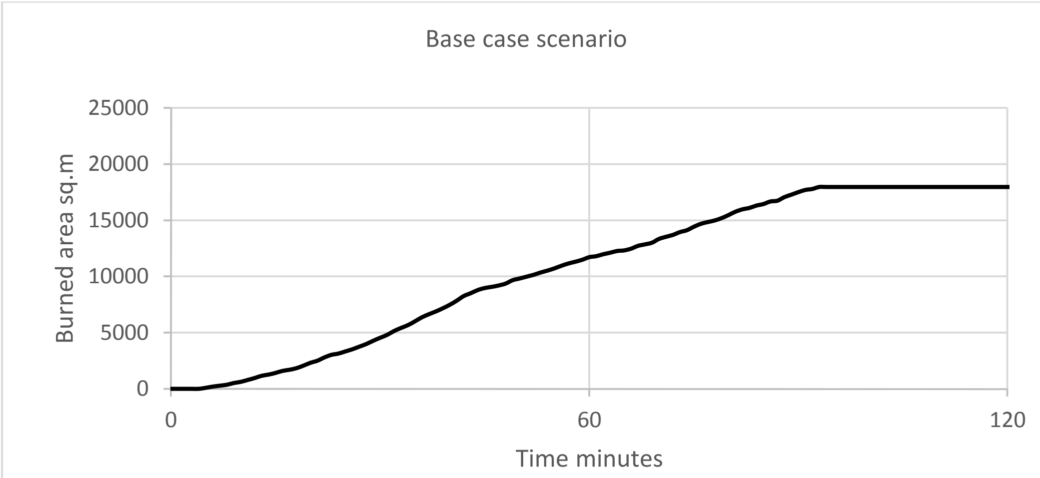


Figure 5-5: Total burned area verse time of the base case scenario.

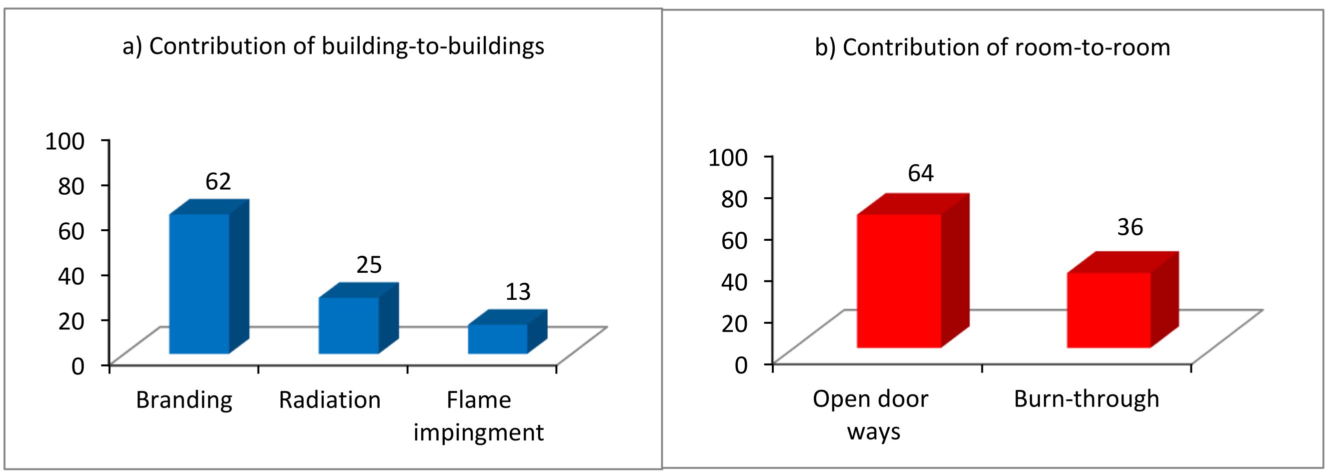


Figure 5-6: Contribution of a) buildings-to-building fire and b) room-to-room fire spread modes

The line graph in figure 5.5 shows that fire spreads gently for the first few minutes at the beginning but then the fire spreading rate grows sharply to 93 min. From 93 min. the fire does not spread further; therefore, the line continues constantly over time. The line graph grows in a near linear fashion, because of the fire starting point, wind direction and shape of the area. If any of the three mentioned items/parameters change, fire might spread differently in the area and the line grows non-linearly. It can be seen from the figure 5.6 a & b that branding and open doorways are the dominant modes to spread fire, building-to-building and room-to-room, by 62% and 64% contribution of fire spread. Furthermore, in the new model the branding characteristics was taken from the Waterman's (1969) experiment, but that this may not be representative of the actual conditions of Imizamo Yetho (the marital of the building's roof). Thus, conducting a test in the Imizamo Yetho's area to determine brand generation rate and possibility of a new ignition by brands will result in more accurate outputs.

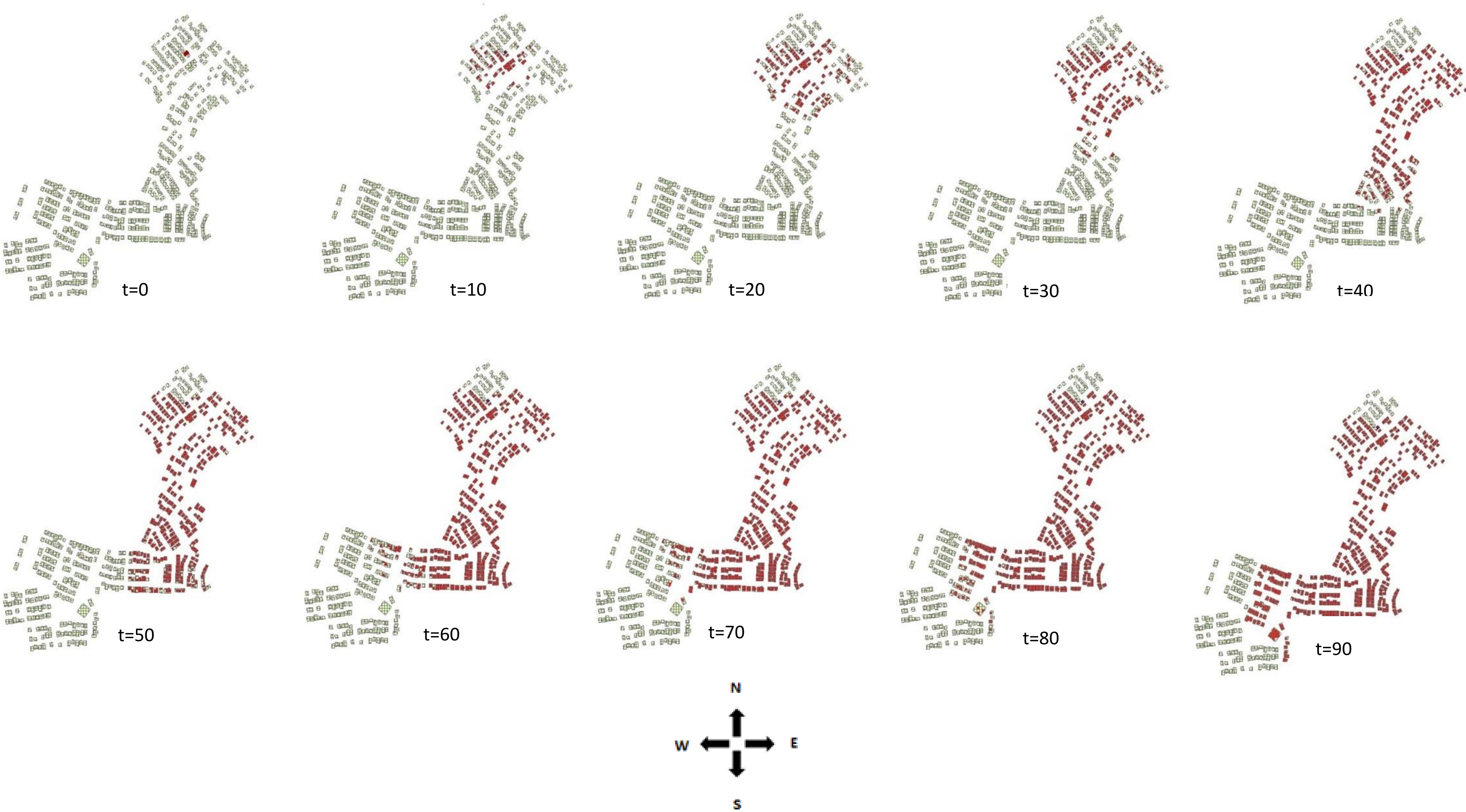


Figure 5-7: map series of the fire spreading progression in the case study area, based on the base scenario; includes 10 time steps, starts from the ignition time in time increment of 10 minutes.

5.4.2 Environmental factors

In this section the value of wind speed and ambient temperature are varied to alternatives. An in-depth explanation and the results of each factor are the following:

5.4.2.1 Wind speed

Wind is an environmental factor that has a strong effect on the spreading of fire among buildings. From the insight that chapter 3 provided on the fire spread simulated by the new model, the possible effect of changing wind speed on different fire-spread modes is explained in the following paragraphs.

Wind speed effects brand generation and brand scattering. In section 3.5.3.3, equation 8 showed that the increase of wind speed causes the increase of the number of generated brands rising from unit roof area. Considering the employed method by the new model to simulate the branding mode, increasing or decreasing wind speed changes how brands scatter in an area. As the wind speed increases, brands can travel for a longer distance from a burning roof and brands also scatter more in a downwind direction but less in an orthogonal direction (Himoto & Tanaka, 2005:18). This matter was also proved by other models and practical tests, which stated that "[a]t higher wind velocities, brands travel farther downwind but scatter less in the crosswind direction" (Huang et al. 2004).

Wind speed affects the ventilation condition of rooms; it might change the ventilation from a no through-draft to through-draft condition or vice versa (see section 3.5.1). Therefore, wind speed affects the burning rate, a burning room's temperature and the amount of radiated heat from a window flame.

The new model considered that the roof flame tilts on direction of the wind by an angle ɵ (it is in angle between the flame axial and the horizontal direction). Regarding equations 8.32 to 8.33 of Appendix H, this angle is a function of the wind speed. Thus, increasing or decreasing the wind speed causes downwind targets to receive more or less heat flux from the roof flame of radiators.

To quantify the effect of changes in wind speed on the fire-spread process, the new model simulates the fire spread for different values of wind speed. According to Kruger (2011), the average of annual maximum wind gust speeds of the City of Cape Town, from 1993 to 2008, is 27.7 m/s. Therefore, 30 m/s was assumed as the maximum wind speed for the case study, and wind speed varied from 0 m/s to 30 m/s, in increments of 10 m/s. Figure 5.8 compares the contribution of changing wind speed on the rate of the spreading fire and total burnt area. Figure 5.9 compares the contribution of the different fire modes during different wind speeds and table 5.4 shows the effects of the changes when compared to the base case.

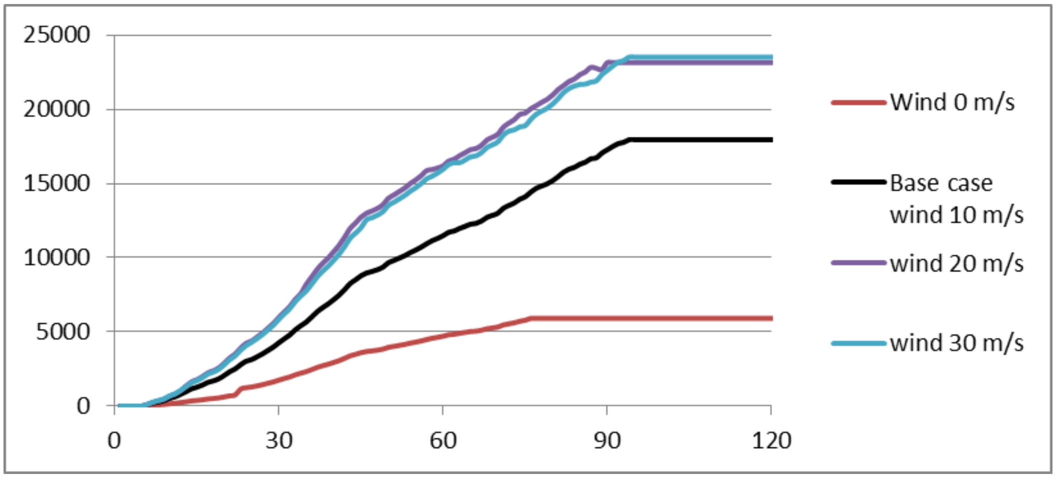


Figure 5-8: Total area burned verse? time for varying speeds.

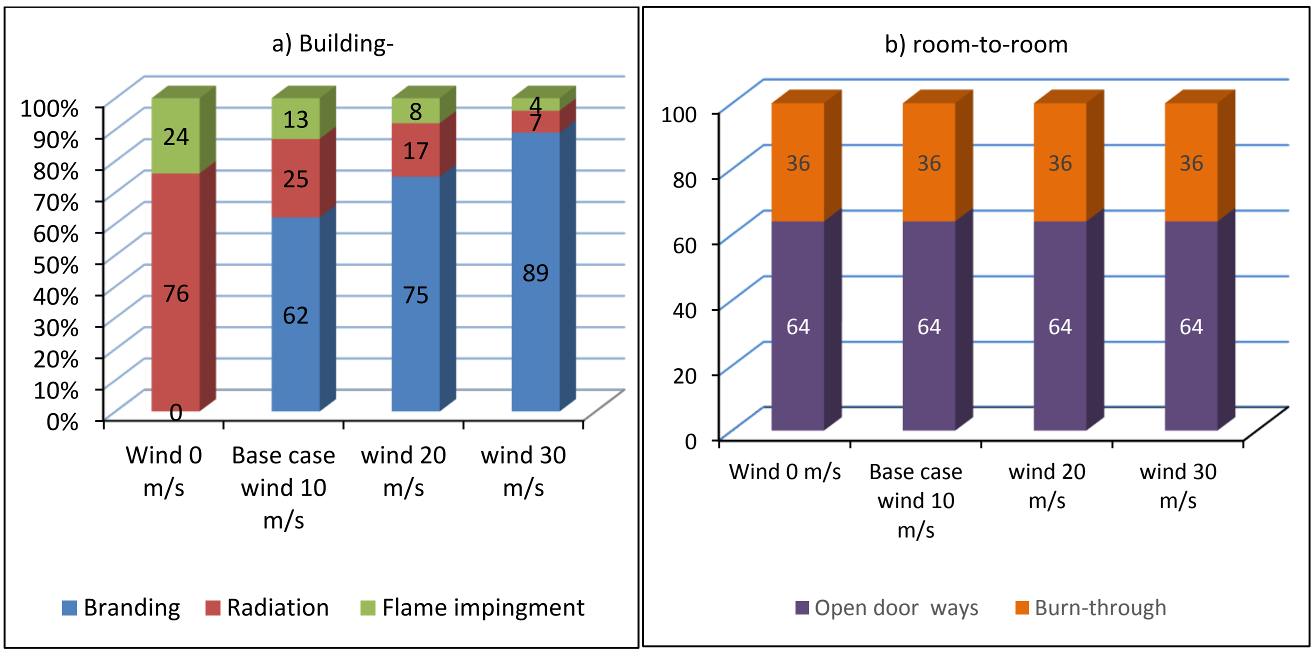


Figure 5-9: Comparison of a) building-to-building and b) room-to-room fire spread modes in different wind speed.

Table 5-4: Presenting the effects of changing the wind speed value to alternatives when compared to the base case.

Fire modes	Wind 0 m/s	wind 20 m/s	wind 30 m/s
Branding	-100%	20.9%	43.5%
Radiation	204%	-32%	-72%
Flame impingement	84.6%	-38.5%	-69.2%
Open doorway	0%	0%	0%
Burn through wall	0%	0%	0%

It can be seen from figure 5.8 that in a no-wind condition, fire spreads at a much slower rate and final total burnt area is much less compared to the base case. The total burnt area of the base case is 17952 m^2, but it is reduced to 5 908 m^2 in the no-wind condition. The main reason for this big difference is that in a no-wind condition, no brand can be generated (see figure 5.9a). While varying wind speed has no effect on the contribution of room-to-room fire spread modes, building-to-building modes are changed significantly. As the wind speed changed from 0 m/s to 10 m/s, the contribution of the branding mode suddenly grows from 0% to 62%, its contribution keeps growing in 20 m/s and 30 m/s conditions.

5.4.2.2 Ambient temperature

Regarding the climate of the case study's area, the ambient temperature is assumed to be 18.9^{0}C. Referring to Appendix F and equations 8.14 and 8.15, ambient temperature has an effect on window flame and room gas temperatures. Therefore, as the ambient temperature rises, more heat flux emits from the window flame and room gas. Hence, the incidents of spreading fire through radiation increases. To quantify the effect of ambient temperature on the fire spread in the case study area, the ambient temperature varied from 0^0 C to 24.3^{0}C (24.3^{0}C is the average summer temperature of the City of Cape Town).

Figure 5.10 compares the contribution of changing ambient temperature on the rate of the spreading fire and total burnt area. Figure 5.11 compares the effect of the three different ambient temperatures on the contribution of building-to-building and room-to-room fire spread modes, and table 5.5 shows the effects of the changes when compared to the base case.

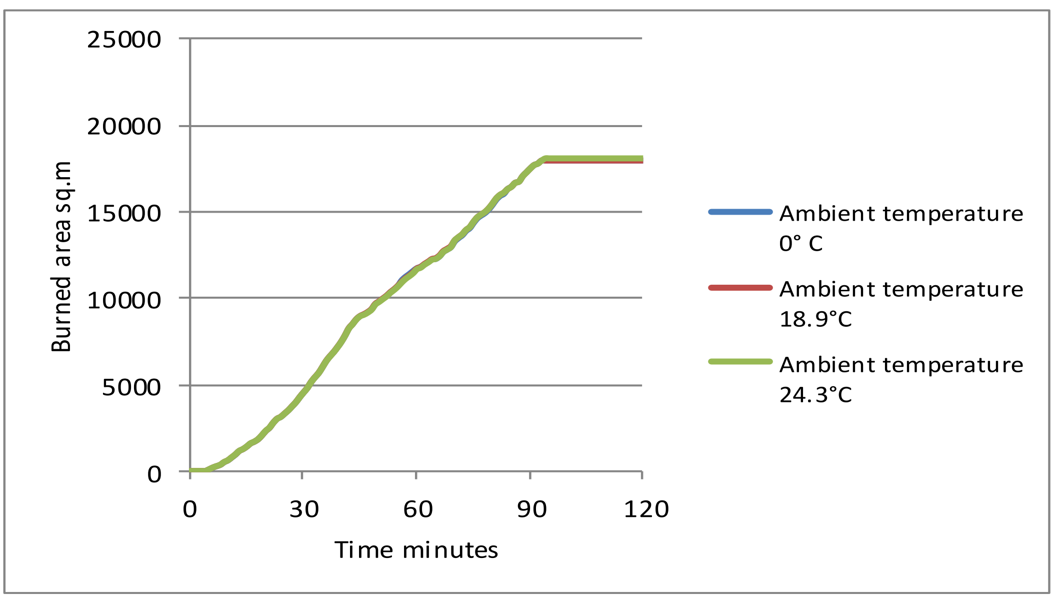


Figure 5-10: Total burnt area verse? time for three values of ambient temperatures.

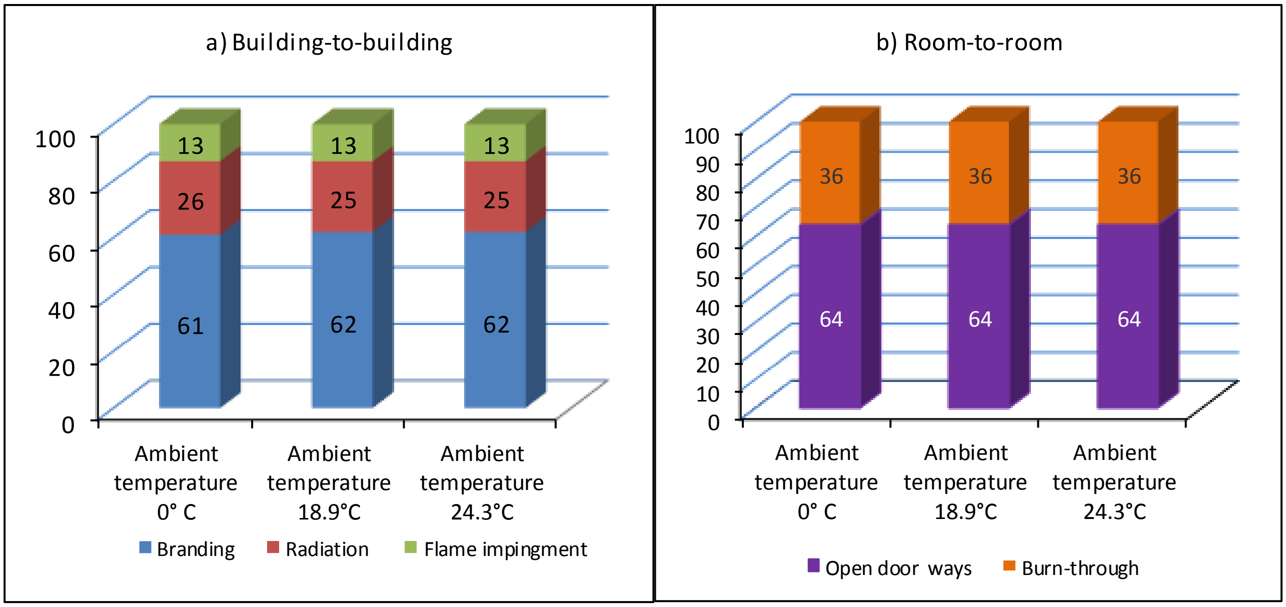


Figure 5-11: Comparison on the different ambient temperatures of a) building-to-building and b) room-to-room fire spread modes.

Table 5-5: Presenting the effects of changing the ambient temperature value to alternatives when compared to the base case.

Fire modes	Ambient temperature 0 C	Ambient temperature 18.9 C	Ambient temperature 24.3 C
Branding	-1.6%	62%	0%
Radiation	4%	25%	0%
Flame impingement	0%	13%	0%
Open doorway	0%	64%	0%
Burn through wall	0%	36%	0%

Figures 5.10, 5.11 and table 5.5 show that an increment or decrement in the ambient temperature does not have a significant effect, neither on the rate of fire spread and total burnt area, nor on the contribution of the fire-spread modes. In figure 5.10, the three lines are almost on top of each other, which means fire spreads almost/fairly in a same manner at an ambient temperature of 0^0C, 18.9^0C and 24^0C, respectively. Figures 5.11 a & b show that only the contribution of branding mode changed from 62% in base case to 61 % in 0^0C, which, according to table 5.5, is a -1.6% reduction. This small change in the contribution of branding mode is negligible, because of the probabilistic method that was employed to conduct it.

5.4.3 Building factors

In order to quantify the effect of changing the building factors, the value of each factor was decreased by 20% and then increased by 20%, except for window orientation. The in-depth presentation of the results follows:

5.4.3.1 Interior wall heat resistance

As noted, fire can spread on the inside of a building through two modes (referring to - section 3.5.2): open doorway and burn-through. In the open doorway mode fire spreads immediately from a burning room (in fully-developed phase) to an adjacent room. When there is no open doorway, fire can only spread by burn-through of the shared wall. Therefore, the wall fire resistance is the key point to stop or delay the room-to-room spread of fire.

In the new model, wall fire resistance is addressed by the minimum required time for a fire in the fully-developed phase to burnthrough the wall. Based on the IBC categories of fire resistance of a wall, all interior walls of the case study's buildings were assumed to be protected non-loading, which can resist a fire for up to 15 minutes. To quantify the effect of this parameter on the progress of fire spread, the resistance time was varied in an increment and a decrement of 20% from the assumed time of the base scenario.

Figure 5.12 compares the contribution of interior wall heat resistance on the rate of the spreading fire, total burnt area and time of fire spreading. Figure 5.13 compares the effect of varying interior wall heat resistance value on the fire-spread modes and table 5.6 shows the effects of the changes when compared to the base case.

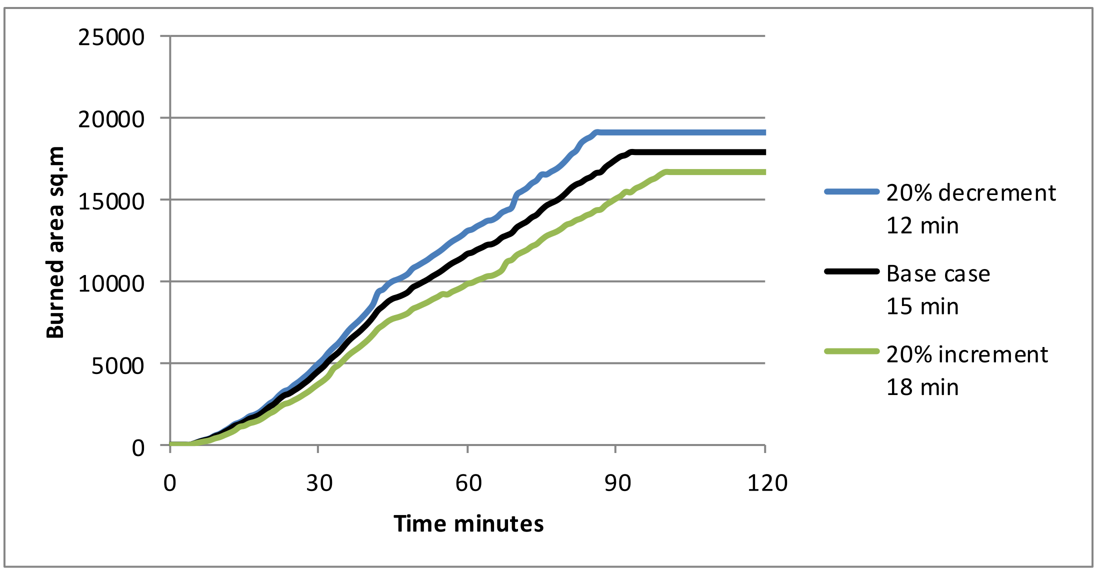
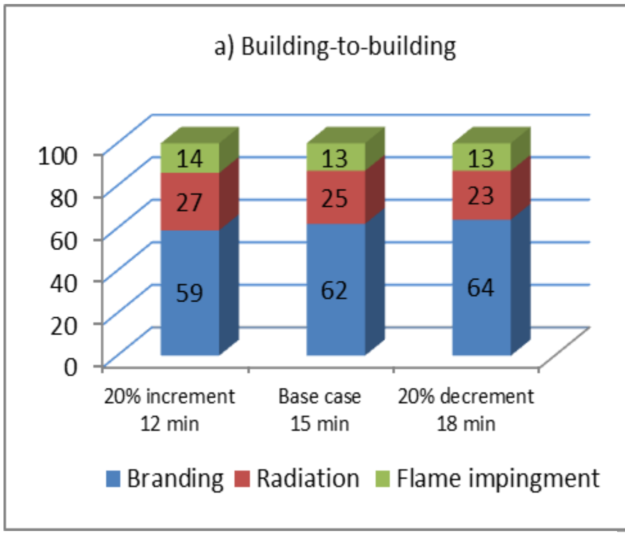


Figure 5-11: Total burnt area versus time for the three different assumed fire resistances of interior walls of buildings in the case study.



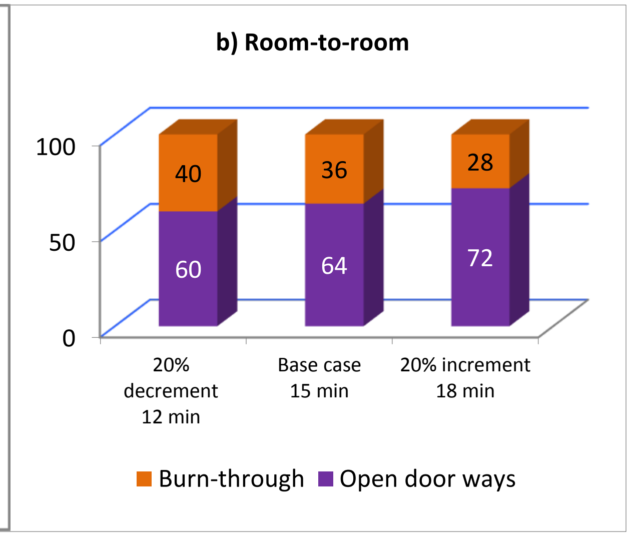


Figure 5-12: Comparison of the contribution of fire resistance values of interior walls on the (a) building-to-building and (b) room-to-room fire spread modes.

Table 5-6: Presenting the effects of changing interior wall heat resistance value to alternatives when compared to the base case.

Fire modes	20% decrement 12 min	20% increment 18 min
Branding	-4.8%	3.2%
Radiation	8%	-8%
Flame impingement	7.7%	0%
Open doorway	-6.25%	12.5%
Burn through wall	11.1%	-22.2%

It can be seen from figure 5.12 that increasing fire resistance of interior walls decreases total burnt area and fire spread rate, but increases the final time of fire spreading (the point where the line becomes horizontal). The total burnt area drops from 17952 m^2 to 16677 m^2 and the final time slightly grows by 7 minutes.

As figure 5.13 and table 5.6 show increment of the fire resistance results to increase the contributions of branding and open doorway. On the other hand, decrement of the fire resistance caused the contributions of radiation, flame impingement and burn-through to increase.

5.4.3.2 Room size

The new model divides a building into rooms based on the maximum length of the interior wall. The length of the interior wall can be determined by a user. Shorter wall lengths divide the building into smaller rooms. When a building is divided into smaller compartments, a fire has to burn through more walls to spread inside a building. Such division slows down the process of spreading fire inside a building, as well as the progress of fire spread among buildings.

To determine the effect of dividing a building into smaller rooms, the maximum length was varied by an increment and decrement of 20% from the assumed length in the base case scenario.

Figure 5.14 compares the contribution of room size/ interior walls' length with the rate of the fire spread, total burnt area and time of fire spread. Figure 5.15 compares the contribution of the different fire modes in different room sizes while table 5.7 shows the effects of the changes when compared to the base case.

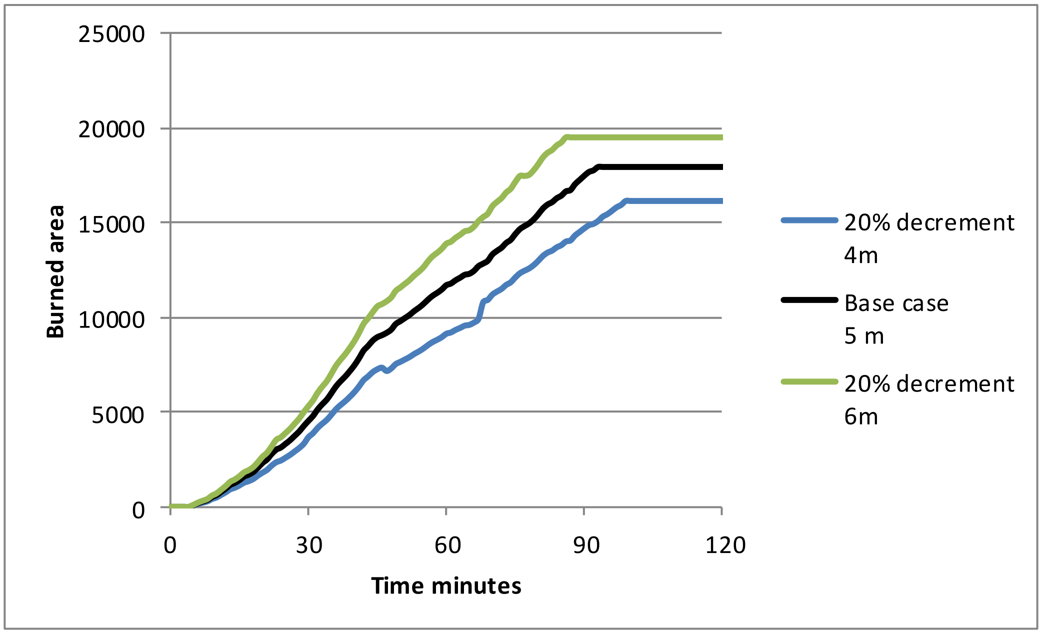


Figure 5-14: Total burnt area versus time, for three different maximum lengths of the interior walls.

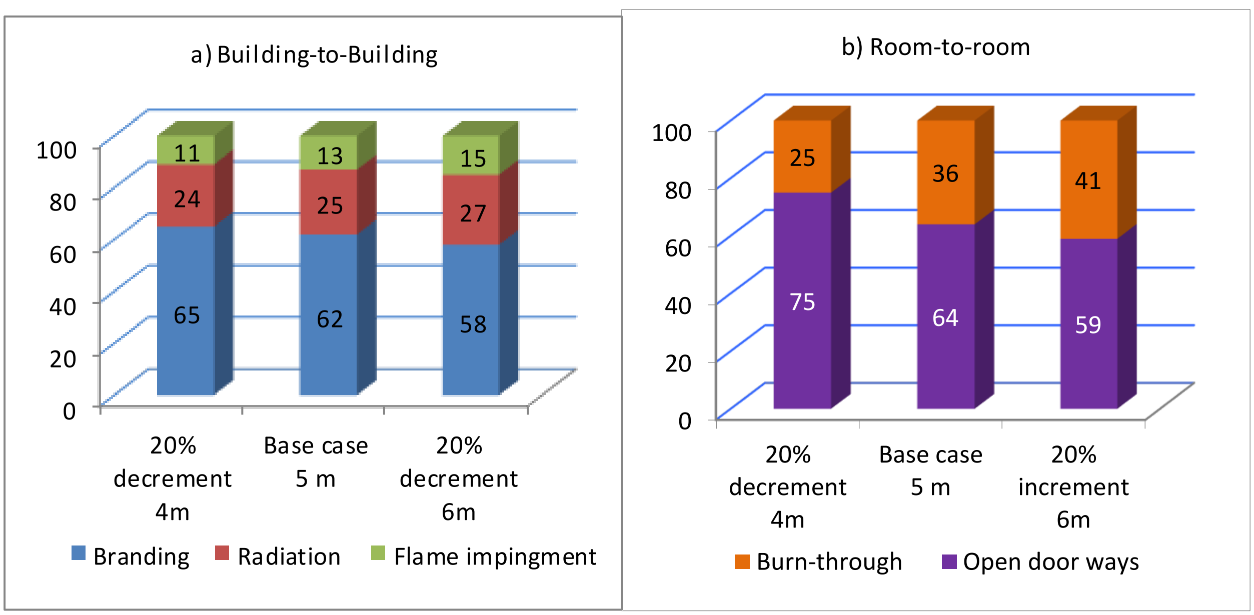


Figure 5-13: Comparison of contribution of (a) building-to-building and (b) fire-spread modes for the three assumed maximum lengths of interior walls.

Table 5-7: Presenting the effects of changing room size value to alternatives when compared to the base case.

Fire modes	20% decrement 4m	20% increment 6m
Branding	4.8%	-6.4%
Radiation	-4%	8%
Flame impingement	-15.5%	15.4%
Open doorway	17.2%	-7.8%
Burn through wall	-30.5%	13.9%

It can be seen from figure 5.14 that, as the length of the walls decreases, the rate of fire spread and the total burnt area decreases; however, the final time gently increases. Vice versa condition occurs for increasing of the length of walls.

Figure 5.15 and table 5.7 show that a decrement in the walls' length causes an increase of contribution of branding in building-to-building and burn-through room-to-room fire spread.

5.4.3.3 Probability of an open doorway

As mentioned, it was assumed that a closed doorway is regarded as a wall. Therefore, instead of a fire spreading immediately through an open doorway, based on the fire resistance type of the wall, a period of time is required to burn through the wall. Also, if the fully developed phase of the fire is shorter than the estimated time needed for fire to burn through the wall, the fire cannot spread from one room to another.

In the base case scenario, probability of open doorway was assumed to be 0.5. Here, the probability varies with increments and decrements of 20%. Figure 5.16 compares the contribution of the probabilities of open doorway on the rate of fire spread, total burnt area and time of fire spread. Figure 5.17 again compares the contribution of the different fire modes in different probabilities of open doorway and table 5.8 shows the effects of the changes when compared to the base case.

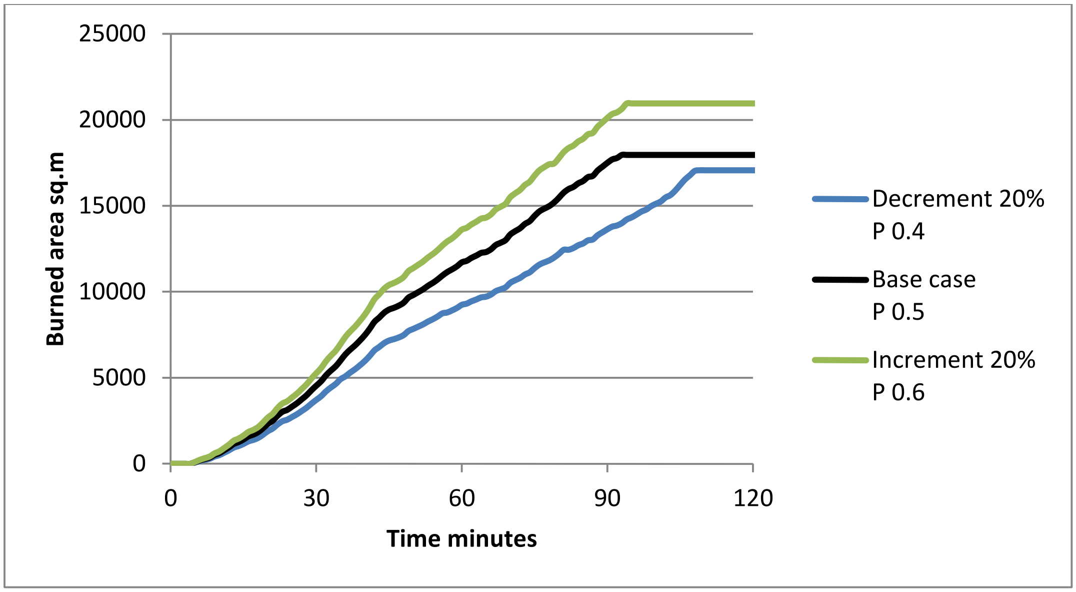


Figure 5-14: Total area burnt verse time for the three assumed probabilities of open doorway.

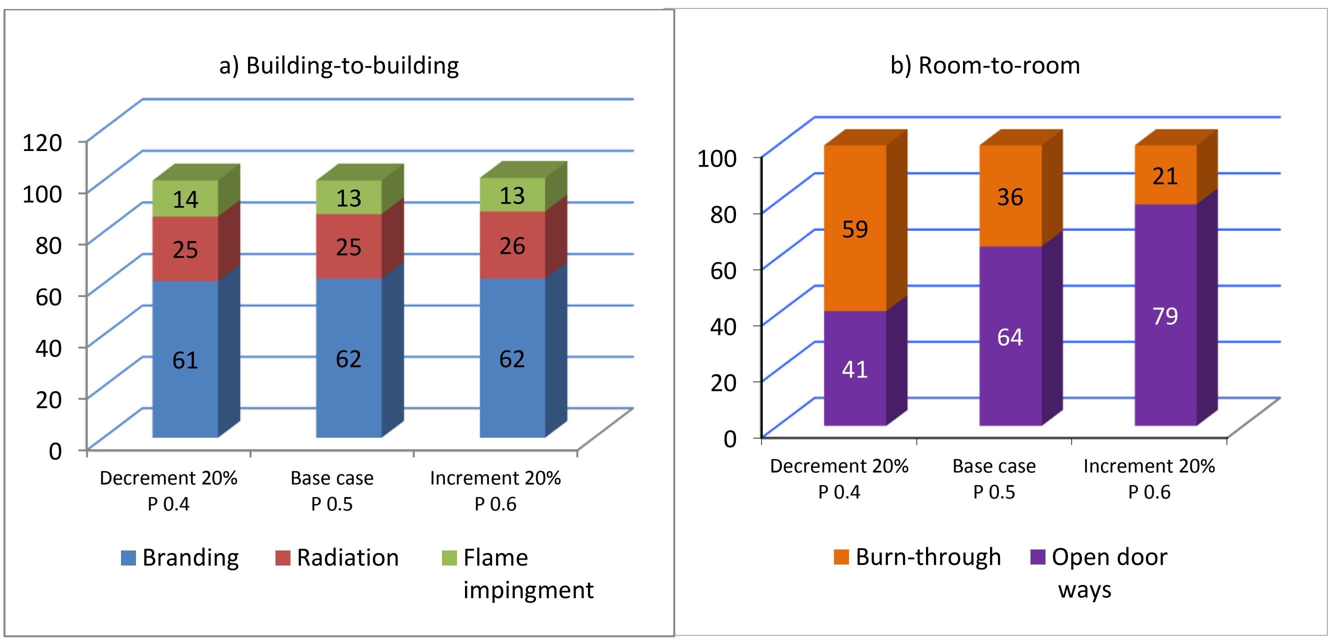


Figure 5-17: Comparison of the contribution of the three assumed probabilities of open doorway on the a) building-to-building and b) room-to-room fire spread modes.

Table 5-8: Presenting the effects of changing probability of an open doorway value to alternatives when compared to the base case.

Fire modes	Decrement 20% P 0.4	Increment 20% P 0.6
Branding	-1.6%	0%
Radiation	0%	4%
Flame impingement	7.7%	0%
Open doorway	-35.9%	23.4%
Burn through wall	63.9%	-41.7%

From Figure 5.16 a significant effect of changing probability of the open doorway can be seen. The 20% decrement of the probability decreases the rate of fire spread and slope of the trend when compared with the base case. The total burnt area also drops from 17953 m^2 to 17305 m^2, but the final time of fire spread is increased by 16 min.

The 20% increment in the probability increases the total burnt area by an extra 3 005 m^2, fire-spread rate increases respectively, but the final time of the fire spread is not changed significantly.

Figure 5.17 a & b and table 5.8 shows that changing the probability of open doorway has a considerable effect of room-to-room fire-spread modes but not on the building-to-building fire-spread modes.

5.4.3.4 Window size

Based on the conducted field measurement of 20 randomly selected buildings of the case study, it was assumed that each exterior wall of a room has a window at its center of 1.4 m height and 1m width. If the window area increases:

- the amount of radiated heat from the window flame and gas increases (see section 3.5.3.2 and Appendix F)
- the amount of radiated heat from the roof flame increases (see section 3.5.3.2 and Appendix H)

To quantify the effect of changes in the window size in the case study, the height and width of the windows were varied in an increment and decrement of 20%. Figure 5.18 compares the contribution of window size to the rate of the fire spread, total burnt area and time of fire spread. Figure 5.19 compares the contribution of the fire modes in the different window sizes and table 5.9 shows the effects of the changes when compared to the base case.

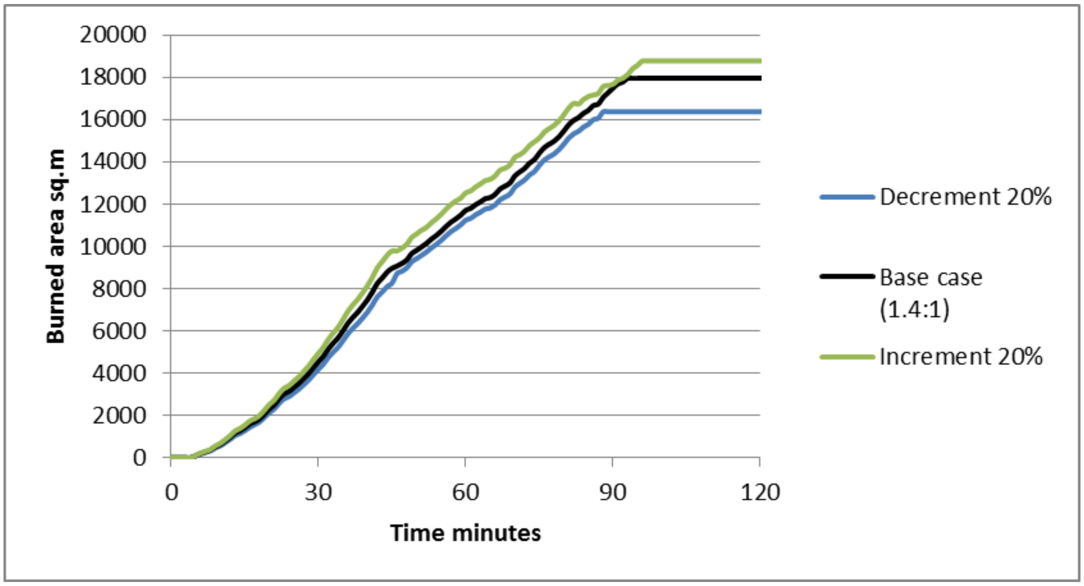


Figure 5-15: Total burnt area verse time for the three assumed window sizes; (0.9:0.5), (1.4:1) and (1.9:1.5).

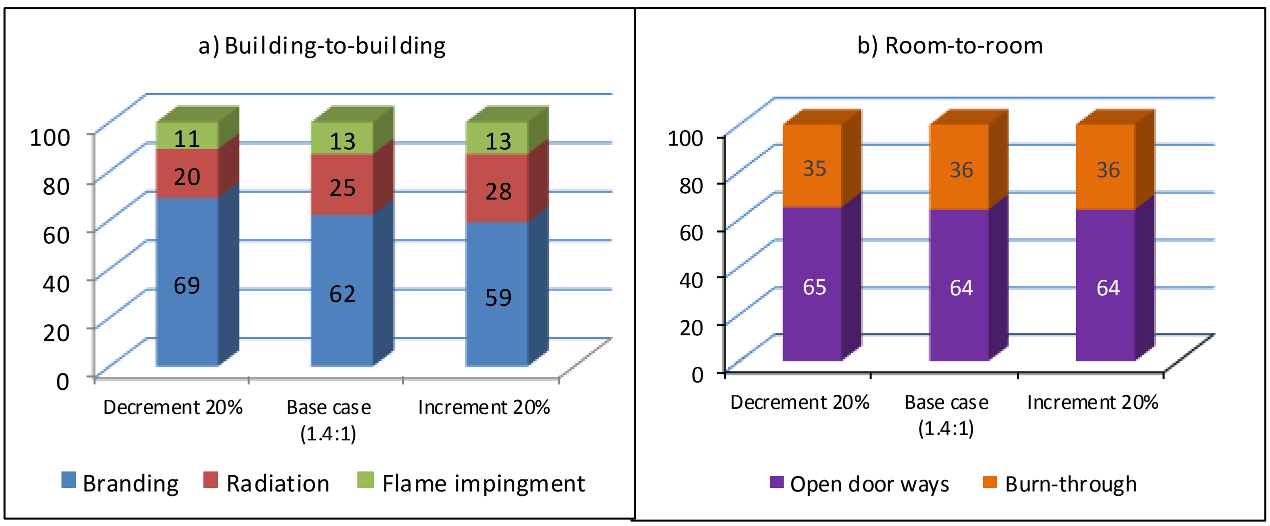


Figure 5-19: Comparison of contribution of a) building-to-building and b) fire spread modes for the three assumed window sizes.

Table 5-9: Presenting the effects of changed window size to alternatives when compared to the base case.

Fire modes	Decrement 20%	Increment 20%
Branding	11.3%	-4.8%
Radiation	-20%	12%
Flame impingement	-15.4%	0%
Open doorway	21.9%	-7.8%
Burn through wall	-38.9%	13.9%

It can be seen from figure 5.18 that the increment in window size slightly increases the total burnt area, fire-spread rate and the final time of fire spread. Similarly, a decrement in window size gently decreases the total burnt area, fire-spread rate and the final time of fire spread.

As figure 5.19 and table 5.9 show, changes in window size greatly affect the contribution of building-to-building modes Its effect is negligible on contribution of room-to-room modes.

5.4.3.5 Window orientation

The relationship between the width and the height of the window affects the window flame geometry. If the height of a window is greater than 1.25 times the window's width, then the vertical length of the window flame is longer (see Appendix G). In fact, this relationship of the width and height of the window can increase the incidents of flame impingement and radiation.

The assumed dimension of the base scenario is 1.4 m height and 1m width, in which the height is greater than 1.25 times the window's width. The orientation of the window was changed in order to quantify the effects. Figure 5.20 compares the contribution of window orientation on the rate of the fire spread, total burnt area and time of fire spread. Figure 5.21 compares the contribution of the fire modes in the different window orientations size and table 5.10 shows the effects of the changes when compared to the base case.

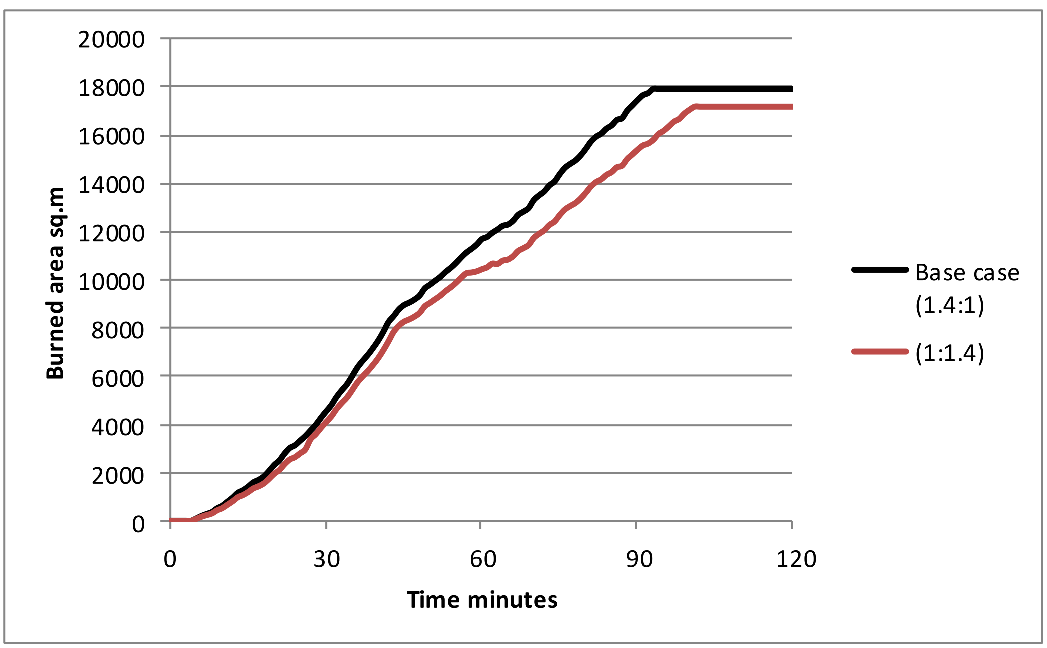


Figure 5-16: Total area burned verse time for the two assumed window dimension, (1.4:1) and (1:1.4).

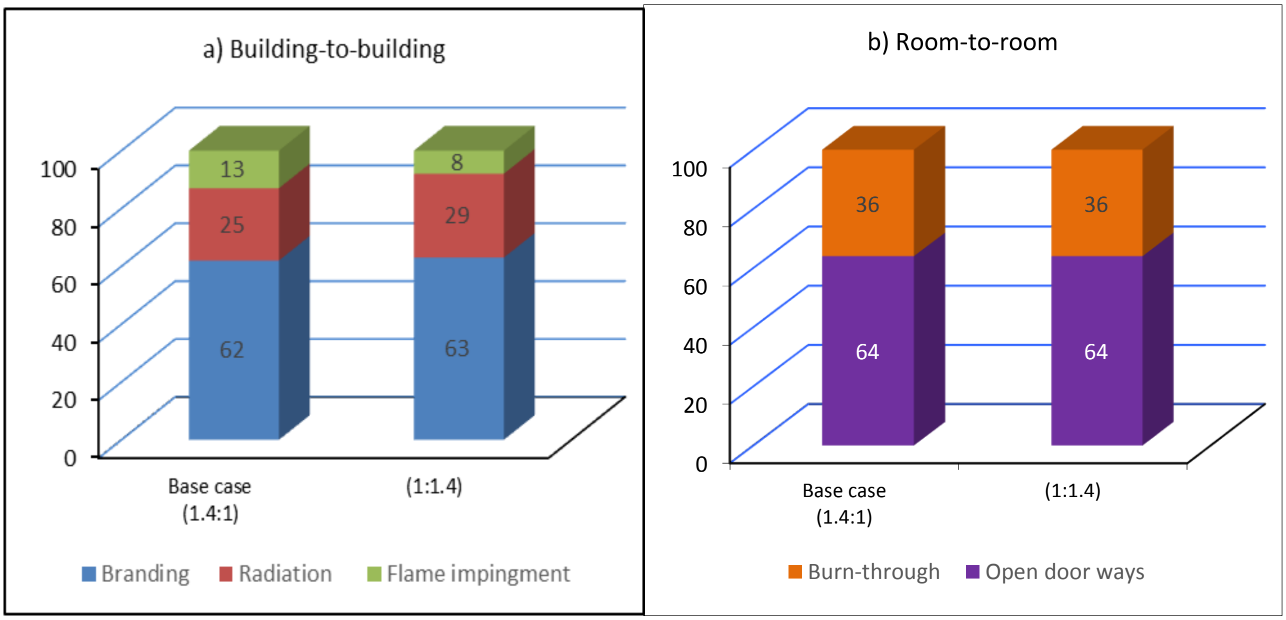


Figure 5-17: Comparison of contribution of a) building-to-building, and b) room-to-room fire spread modes for the two assumed window dimensions, (1.4:1) and (1:1.4).

Table 5-10: Presenting the effects of changed window orientation to alternatives when compared to the base case.

Fire modes	(1:1.4)
Branding	1.6%
Radiation	16%
Flame impingement	-38.5%
Open doorway	0%
Burn through wall	0%

Figure 5.20 shows that, while the size and location of the windows stayed the same, a change in the orientation of the windows led to a reduction of the total burnt area by 926 m^2. An increase in the fire-spread rate can also be seen.

As figure 5.21 and table 5.10 show, changing the windows' orientation only has an effect on building-to-building fire-spread modes and it does not affect room-to-room fire-spread modes. The contribution of radiation and flame impingement modes is changed significantly. However, contribution of branding modes only increases by 1 % and compared to the base case its contribution increased by 1.6%.

5.4.3.6 Fire load

This section discusses and quantifies the effect of fire load on the fire-spread process and on the contribution of the fire mode (see section 3.5.1). The effect of changing the fire load depends on the ventilation condition of a room. Therefore, the effect of changing the fire load affects rooms differently depending on the draft conditions. The following paragraphs firstly explain the effects of fire load changing on through-draft and on no through-draft conditions. The summary of the effects is presented in table 5.11. Finally, the fire load is varied to quantify its effects on the fire spread.

In the case of the no through-draft condition, as fire load density increases, the total fire load and duration of the fully developed phase increase. However, the burning rate, ejected flame height, and room temperature do not change. The longer, fully developed phase provides more opportunity to combine radiation from multiple sources; therefore, the absorbed heat by a target might exceed the critical heat value. Emitted room radiation heat flux, which depends on room temperature, is not affected in either draft condition.

In the case of a through draft, as fire load density increases, rate of burning and ejected flame height increase too. However, the duration of the fully developed phase and room temperature stays constant. The taller flame affects flame impingement and radiation owing to window flame; thus, the instances of flame impingement and radiation increase.

Table 5-11: Comparison of the effects of increment and decrement of fire load based on fire spread; based on the ventilation condition of a room, through-draft and no through-draft condition.

		duration of the fully-developed phase	Burning rate	Ejected flame height	Room temperature	Flame impairment incidents	Radiation Mode incidents
No trough-draft Condition	Increase of fire load	I	C	C	C	C	I
	Decrease of fire load	D	C	C	C	C	D
Trough-draft Condition	Increase of fire load	C	I	I	C	I	I
	Decrease of fire load	C	D	D	C	D	D

I = Increase , D = Decrease , C = Constant

To quantify the effect, the fire load was varied by an increment and decrement of 10 kg/m^2 wood. Figure 5.22 compares the contribution of fire load on the rate of the fire spread, total burnt area and time of fire spread. Figure 5.23 compares the contribution of the fire modes in the different fire load sizes and table 5.12 shows the effects of the changes when compared to the base case.

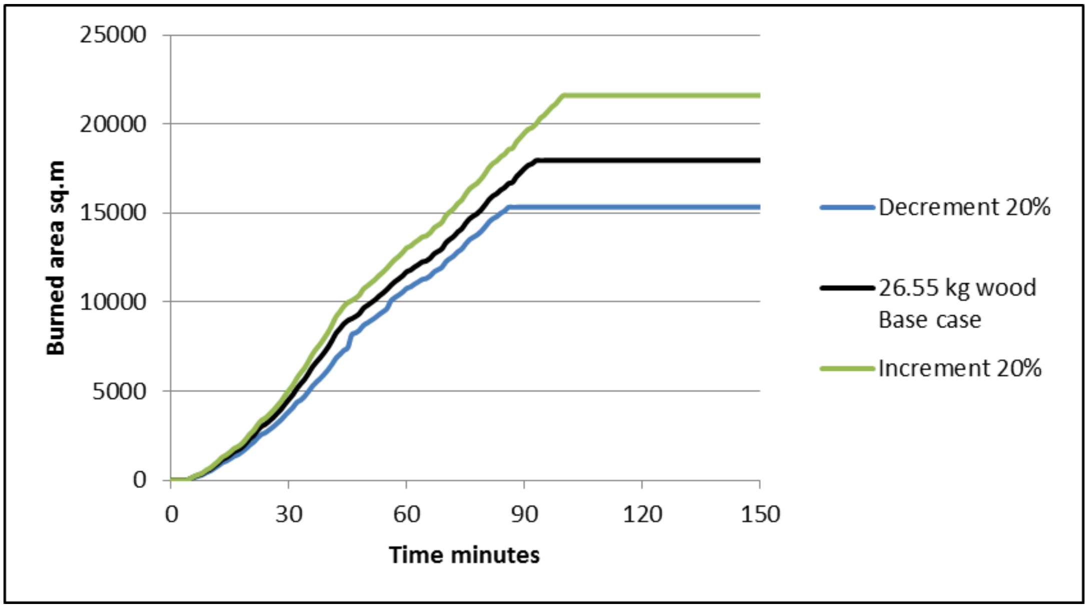


Figure 5-18: Total area burned verse time for three different values of fire load.

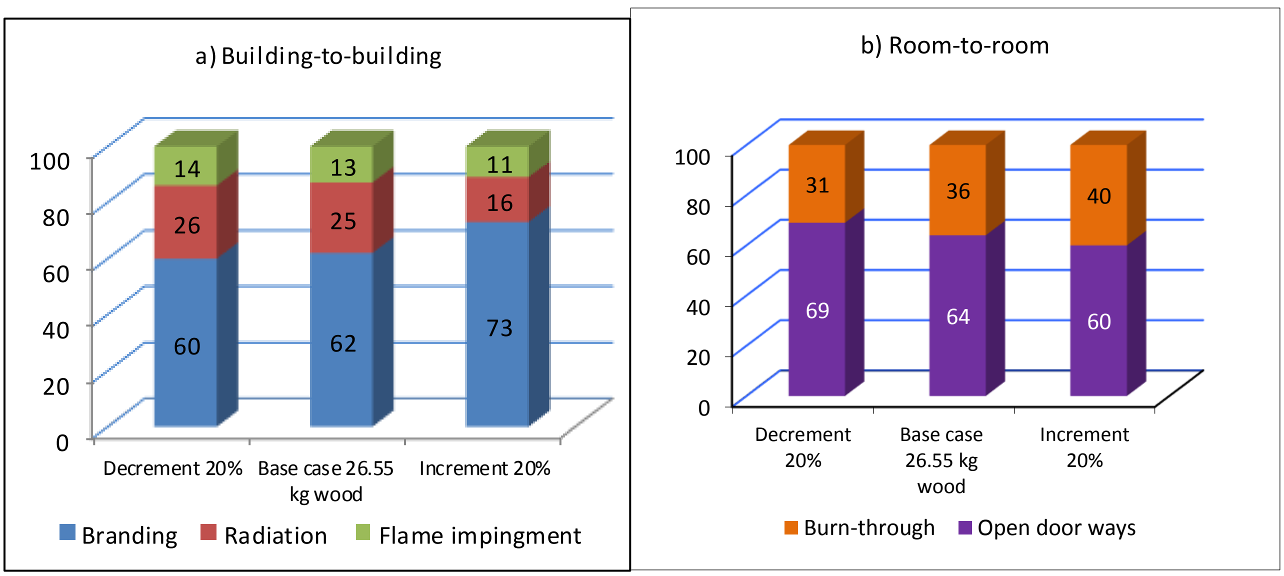


Figure 5-19: Comparison of contribution of a) building-to-building and b) fire spread modes for three different values of fire load.

Table 5-12: Presenting the effects of changing fire load to alternatives when compared to the base case.

Fire modes	Decrement 20%	Increment 20%
Branding	-3.2%	17.7%
Radiation	4%	-36%
Flame impingement	7.6%	-15.4%
Open doorway	7.8%	-6.25%
Burn through wall	-13.9%	11.1%

It can be seen from Figure 5.22 that the decrement and increment of fire load sharply affects the total burnt area and rate of fire spread as well as final time fire spread. As the fire load is increased by 20%, total burnt area increases by 3 657 m^2. When it is decreased by 20%, the total burnt area is decreased by 2 622 m^2.

Figure 5.23 and table 5.12 show that varying fire load has a strong effect on both the building-to-buildings and room-to-room fire spread modes. In the case of building-to-building fire spread, increment in fire load increases the contribution of the branding mode, but decreases the contribution of radiation and flame impingement. In the case of room-to-room fire-spread modes, increments in fire load increases the contribution of burn-through wall mode. There is vice versa condition to decrease fire load for both building-to-building and room-to-room.

5.4.4 Landscape factors

5.4.4.1 Distance between buildings

The distance between buildings is a landscape influential factor, which can have an effect on: 1) flame impingement, 2) the possibility of receiving more brands and 3) the amount of received heat by a target.

Flame impingement is the only mode to spread fire immediately, but it only occurs over short distances, thus, decreasing and increasing the distance has a significant effect on occurrence this mode.

According to Himoto (2005) brands are scattered more over shorter distances in a downwind direction. Therefore, as the distance between a radiator and a target becomes shorter, the target receives more brands and the possibility of ignition increases.

Although the distance between buildings, radiator and targets cannot influence the amount of radiated heat, the distance does affect the received heat by the targets. Thus, increasing the distance between buildings reduce the possibility of building-to-building fire spread through the radiation mode.

To quantify the effect of this factor, the distance between buildings was varied with an increment and decrement of 20%. A curve of total burned area over time for the varied above-mentioned distances is presented in figure 5.24. Figure 5.25 compares the contribution of fire spread modes size and table 5.13 shows the effects of the changes when compared to the base case.

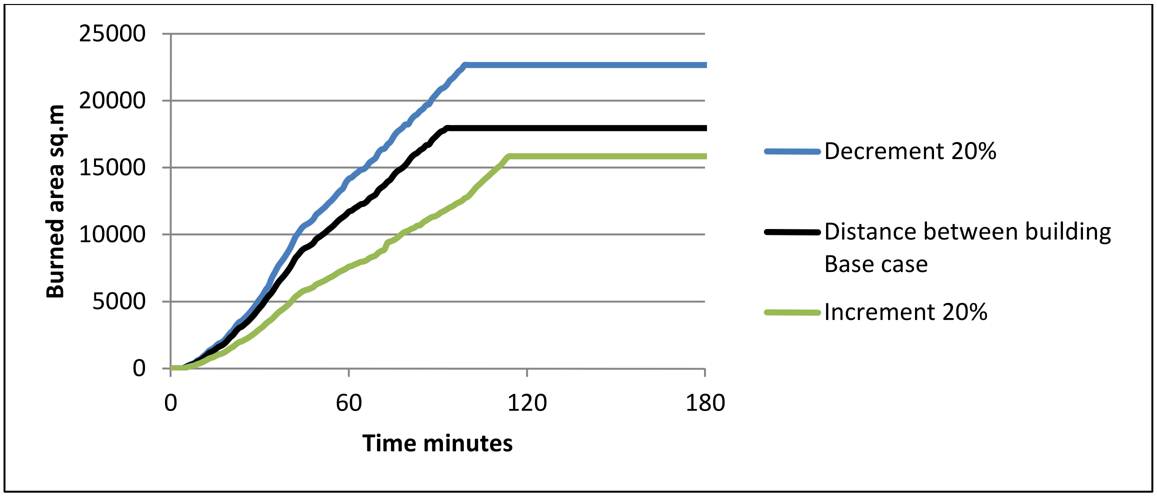


Figure 5-20: Total burned area verse time for 20 % increase and 20% decrease the distance between buildings.

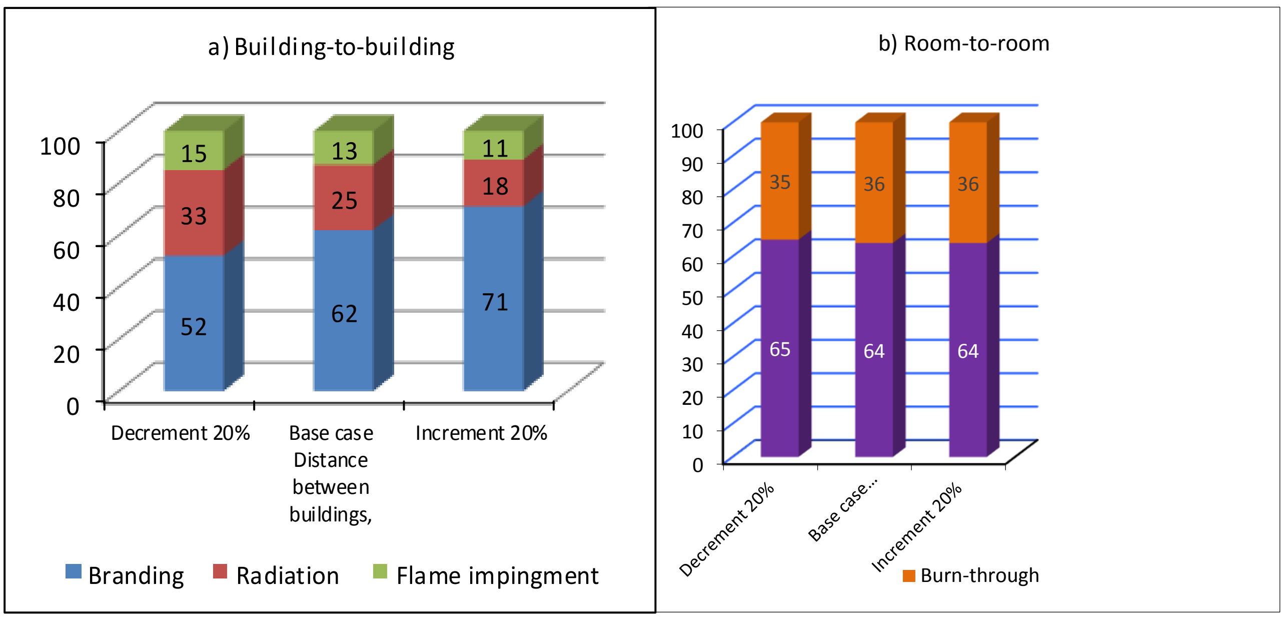


Figure 5-25: Comparison of contribution of a) building-to-building and b) fire spread modes over different distances between buildings, 20% increment and 20% decrement.

Table 5-13: The effects of changing distance between buildings to alternatives when compared to the base case.

Fire modes	Decrement 20%	Increment 20%
Branding	-16%	14.5%
Radiation	32%	-28%
Flame impingement	15%	-15%
Open doorway	1.6%	0%
Burn through wall	-2.8%	0%

It can be seen from figure 5.24 that decreasing and increasing distance between buildings significantly affects the total burnt area and fire-spread rate, as well as the final fire spread time.

The 20% decrement in the distance causes an additional 4 244 m^2 burnt area, whereas with the 20% increment, the distance reduces the total burnt area by 2 090 m^2.

Figure 5.25 and table 5.13 show that changing the distance between buildings has sharp effects on building-to-building fire spread modes, but not on the room-to-room modes. As the distance decreased, the contribution of radiation and flame impingement increased by 32% and 15% compared to the base case.

5.4.5 Data analysis

The values of nine different factors were varied and table 5.14 presents a list of the factors and a summary of the alternative values. Changing these factors' value created relatively large changes in at least one of the following items:

- Final total burnt area in the case study
- Speed/rate of fire spread in the case study
- Contribution of fire spread modes, building-to-building or room-to-room

Table 5-14: List of selected factors for the sensitivity studies, and the alternative values.

		Alternative values		
		Decrements	Base case	Increments
Environmental factors	Wind speed	0 m/s	10 m/s	20 m/s , 30 m/s
	Ambient temperature	0 C	18.9 C	24.3 C
Building factors	Heat resistance of interior walls	20% decrease	15 min	20% increase
	Room size	20% decrease; 4 m	5m	20% increase
	Probability of open doorway	20% decrease	0.5	20% increase
	Windows size	20% decrease	(1.4:1)	
	Windows dimension	Base case (1.4:1) ; (1:1.4)		
	Fire load	20% decrease	26.55 kg wood Base case	20% increase
Landscape factors	Distance between buildings	20% decrease	Distance between building Base case	20% increase

In the base case scenario, 17952 m^2 burned in 93 minutes after the first ignition. Figure 5.26 presents a tornado graph that compares the effects of all the alternative values on the total burnt area. The green column represents the base case scenario; the blue bars represent the decrements and red bar increments of the total burnt area. Therefore, the endpoints of each bar represent the lowest or highest mean total area burnt for the particular factor.

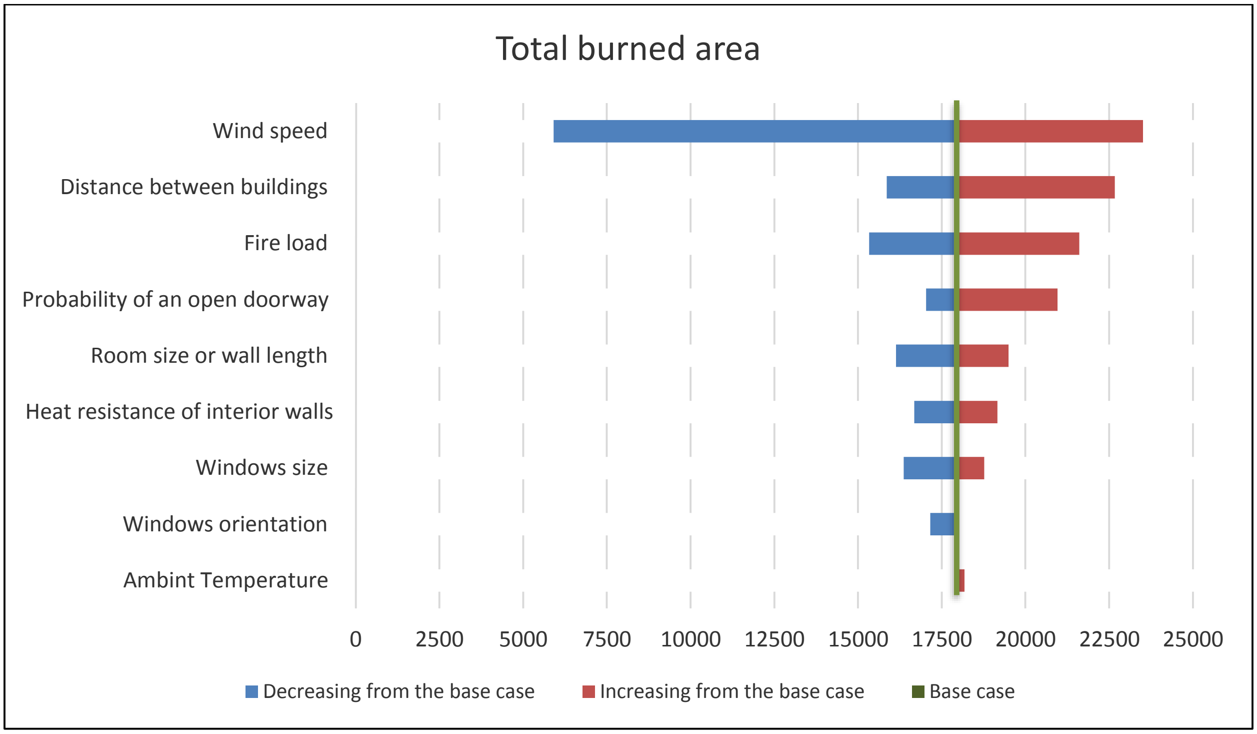


Figure 5-26: Comparison of the effect of factors on the total burned area by a tornado chart.

According to the graph, wind speed is the most influential factor. In a no-wind condition, only a 5 908.3 m^2 area was burnt and the speed of fire spread (see figure 5.8) was much lower than that of the other alternative values of wind speed. As the value of the alternative wind speeds increased, the total burnt area, speed of fire spread and the contribution of the branding mode increased rapidly. Furthermore, as it was mentioned that the presented/proposed model of this study used the Waterman's (1969) experiment to conduct the branding mode, this experiment may not be representative of the actual conditions of Imazio Yetho. Therefore, using an experiment that reflects the actual/exact conditions of the area (currently such experiment does not exist) might change the rate of wind speed's influence to spread fire by increasing or decreasing the contribution of the branding mode.

Ambient temperature had the smallest effect on the total burnt area and its effect on the speed of fire spread and the contribution of the modes is negligible. Therefore, both the greatest and the least influential factors were found in the category of environmental factors.

With regard to building factors, the values of six factors were varied with a decrement and increment of 20%. These factors are: heat resistance of interior walls, room size, windows size, windows orientation, probability of an open doorway and fire load. Among these six, the fire load had the greatest effect on the burned area and the window orientation the least.

As the amount of fire load increased from 26.55 kg to 31.86 kg wood, the total burnt area increased by 3656.881 m^2, from 17952 m^2 to 21609 m^2. Fire load also had a relatively high influence on the fire spread speed and the contribution of the fire-spread mode, specifically the burn-through mode (referring to figure 5.23 a).

Although changing the windows' orientation from (1.4:1) to (1:1.4) did not change the area of the windows (in both condition the windows' area is 1.4 m^2), it caused a shorter flame length; therefore, the contribution of the flame impingement mode decreased from 13% to 8%. Also, according to figure 5.21, the speed of the fire spread was slower, and the total burnt area became less than the base case scenario.

In the category of landscape factors, the distance between the buildings varied in a decrement and increment of 20%. The effect of these changes ranked as the second most important factor on the total burnt area among all nine selected parameters. By increasing the distance, the total burned area reduced to 15862 m^2. On the other hand, the 20% decrement in distance caused an extra 4716 m^2 burned, whilst the total burned area increased to 22668 m^2. As figures 5.24 and 5.25 showed, the shorter the distance between buildings, the faster the fire spread and the contribution of radiation and flame impingement grew rapidly. The opposite condition was experienced where a longer distance between buildings existed.

5.5 Conclusion

This chapter dealt with a suitable real-life case study and applied the model on the selected area, prioritising the influential factors on the fire spread process. Imizamo Yethu was selected as the case study because fire is one of two top risks of the area. The area has been studied before for disaster risk management from different perspectives, but a fire spread model has never been applied to the Imizamo Yethu settlement.

Imizamo Yethu, which is situated in the Hout Bay Valley, is one of the 222 Metropolitan Townships of the City of Cape Town. The exact geographical location, a list of different risks and in particular a short history of fire in the area were reviewed in depth.

Based on the scope of the new model (referring to section 3.2), 321 single family brick houses were selected as the study area. With regard to the selected buildings, to prepare the input data (see section 3.3.1) three methods were used, (1) field measurement, (2) Google earth (to provide the landscape map of the area) and (3) making relevant assumptions based on the environment of the area and fire codes. The input data formed the base case scenario.

To achieve the objective of prioritising the influential factors, nine factors of the input data were selected and each time the value of one factor was changed to an alternative. Therefore, nineteen scenarios were created. Based on the obtained results of the scenarios and on the insight into the fire-spread process provided by chapter 3, the effect of varying the factor's value on (1) the final total burnt area in the case study, (2) the rate of fire spread and (3) contribution of the fire spread modes were discussed and quantified.

Chapter 6 Conclusion and recommendations

Throughout history, fire has caused great losses and fatalities worldwide (Scawthorn, et el 2005). The hazard of fire becomes worse when it occurs in a densely built-up area. Currently, there are 2628 townships across South Africa (HAD, 2012). The townships are regarded as highly populated, poorly serviced and densely built urban areas. Under such circumstances, fire can spread faster, leading to greater losses and claiming more human lives. This study aimed to *develop*, *verify* and *validate* a computational fire-spread simulator model in order to contribute to finding solutions for fires. Fire hazard is a vast topic that can merge many sciences such as social sciences, engineering, etc. Thus, several objectives might be considered. This study's specific objective is to apply the new fire-spread model to a real-life case study, illustrate a number of outputs of the new model and to prioritise the fire-spread factors of the case-study area. Because of the fact that there is no existing application of a physics-based fire spread model in South Africa, this study presents the first application of such a model in South Africa.

Each chapter of the study researched a particular aspect and therefore each chapter offers a conclusion; however, all these conclusions are now drawn into a comprehensive conclusion as will be seen in section 6.1.

6.1 Conclusion

Chapter 2 provided a scientific conceptualisation of fire. Three aspects, namely the basis and approaches, the considered factors and the validation methods used for a selected group of fire-spread simulator models, were reviewed. These three aspects of the selected group of models were compared in order to find the most appropriate way to develop and validate the new model with regard to the aim and objective of the study. Two bases were examined in the development of the new model, namely empirical and physics. While empirically based models are easy to apply, they require less input data and computational work. On the other hand, physics-based models produce more accurate and detailed results. An important advantage of a physics-based approach is that it follows the laws of physics that makes such an approach applicable to all contexts.

Chapter 3 describes the development process of the new physics-based model. First, it determined a scope for the new model. Subsequently, based on the scope, data input of the new model and some of the possible outputs were defined and explained in depth.

In the second part of chapter 3, the process of fire-spread simulation was broken down into three modules and the modules were subdivided into modes (figure 3.1). Subsequently, an appropriate sequence of the fire-spread process was provided (see figure 3.2). As mentioned, reviewing the technical methods to conduct the modules was done in chapter 3. First, before assigning a method to conduct a task, some of the available methods were reviewed, and then the most suitable method was selected. Finally, the reasons for selecting the method were presented and an explanation of the method was provided. Since the suitable methods were selected and assigned to conduct the tasks and the sequence was defined, the entire process was programed in C#.net.

The new model was verified and validated in chapter 4. In order to verify the model, a case study of two buildings equal in size was selected and the results of the new model were compared to hand calculation. The comparison proved that the conceptual simulation model was correctly translated into the computer program. The validation of the new model was carried out with a hypothetical case study where 1 024 equally sized buildings were aligned at constant intervals. The obtained results of the new model were compared to two existing accredited models. The results were similar enough to validate the new model.

The new model was then applied in a selected case study. Chapter 5 includes a description of the case study, reasons for selecting the case study, input data preparation and the results. Imizamo Yethu was selected as a case study. Imizamo Yethu is a Metropolitan township of the City of Cape Town and fire is one of the two top-ranked risks in the area. Input data were prepared through the following three methods: (1) field measurement, (2) Google earth and (3) by determining parameters based on the environment of the area and fire codes. In order to prioritise the effects of influential fire-spread factors, in the case of Imizamo Yethu, the values of the parameters were varied and the results were presented and discussed.

6.2 Recommendations

In this section, recommendations are made to indicate possibilities of: (1) mitigating the fire-spread risk in low-cost settlements and particularly Imizamo Yethu, (2) future application of the new model and (3) model development.

6.2.1 Low-cost settlements

Regarding the results of the scenarios in this study, the following recommendations are made to mitigate the risk of fire spread in low-cost settlements.

Regarding fire spread inside buildings, as it was shown in chapter 5, open doorways have always been the dominant mode. As a result, changing the probability of an open door from 0.4 to 0.6 caused an extra 3 882 m^2 area to burn. It was observed by the author that the majority of buildings have either old wooden doors or only a curtain was used instead of a door. Therefore, providing the buildings with more appropriate doors that can resist fire are recommended. Applying this recommendation will lessen the total burned area and slow the spread of fire.

Although a field measurement to estimate the internal wall fire resistance was not conducted and the time required for a fire to burn-through a wall was adopted from IBC, the importance of this parameter was proved by varying its/the value. Therefore, maintaining the building wall in any possible form can increase the fire resistance and contribute to mitigating fire risk.

As proven in chapter 5, the branding mode was the predominant building-to-building mode in almost all considered scenarios. Therefore, any method that can reduce the number of generated brands or possibility of a new ignition if a brand lands on a target, can make a great impact on the reduction of the fire spread speed, as well as the total burned area. For example, providing roofs with a fire resistant material could decrease the probability of a new ignition through the branding mode.

As shown in figure 5.2, in some areas buildings are built extremely close to each other. Flame impingement contributed 13% and radiation 25% to building-to-buildings fire spread incidents in the base case scenario. Regarding the principles of flame impingement and radiation modes, the contribution of these modes will decrease if 1) the window size is reduced 2) the windows' orientation is modified to generate a shorter flame (see sections 3.5.3.1& 3.5.3.2).

In this study, nine parameters were selected and only a single parameter was varied at a time. Therefore, there is a possibility of creating more scenarios by 1) considering more parameters and 2) varying more than one parameter's value at a time and studying the interaction of the parameters.

6.2.2 Future application

Imizamo Yethu is one of the thousands low-cost settlements of South Africa. The new model was developed based on the laws of physics; therefore, it is applicable across different environments. Thus, other areas can be studied by applying the new model.

More research can be conducted on the preparation of input data. Despite the calculation accuracy of a model, the accuracy of the input data greatly influences the accuracy of the results. As mentioned in the current study, three methods were used to prepare the input data and an acceptable level of accuracy was achieved. However, it is recommended for future research work to measure the factor's value in with greater accuracy, for example conducting field measurement to estimate buildings' wall fire resistance.

6.2.3 Model development

This study exclusively focused on fire spreading and disregarded the ignition and suppression phases of a fire. The scope of this study also did not cover all fire spread influential factors (see section 3.2). Therefore, there are opportunities for considering ignition and suppression phases or by including more influential fire spread parameters. Some of these opportunities are as describes below.

As mentioned, fire can follow other disasters. There are a number of ignition-models that exclusively study ignition simulation, which can predict the fire starting points caused by earthquakes, flooding etc. To couple an ignition model with the presented model of this study a new comprehensive model can be created that can simulate fire spread following other disasters.

The suppression of fire is an important area for research that includes many activities such as the preparation of the fire department, accessibility of the area and the residents' response. Currently, this study's scope does not cover any aspects of fire suppression. Therefore, studying any suppression-related aspects and combining it with this study's model is a great opportunity for model development.

The topography of the land and vegetation are two of the important influential factors that are not in the scope of this study. This model assumed a flat empty land for the case study, which does not correspond to real life. Therefore, by including these two factors a more accurate result will be obtained.

Explosions are a highly complicated factor of fire spreading which is not included in this study or in any of the models that were reviewed. It could rapidly accelerate the fire spreading, and can increase financial losses and fatalities. Therefore, considering the effect of an explosion and involving this factor in the fire spread simulation, would be a step in advancing model development.

Better studies on the effect of shacks that are constructed among buildings (backyard dwelling) might effectively enhance the fire spreading model. Backyard dwellings are normally made from more flammable material than the? brick houses. Therefore, they can either cause a more rapid fire spread or can bridge the distance between the buildings that are otherwise too far apart to enable fire spread.

An estimation of the required amount of water is a critical factor in successfully extinguishing a fire. I Schnetler (2014, pers,comm., 5 September) saidthis estimation can enhance the fire department's performance. In fact, even if fire fighters arrive at the affected area promptly, little can be done without enough water. As this model can calculate the room's temperature as well as the total burning area in any time step; the amount of required water to cool down and stop the fire can be measured with some additional computer programing.

Owing to financial parameters being a critical factor, estimating the financial losses of a possible fire and comparing it with the different fire risk mitigation methods could contribute to the selection of the most effective and cost efficient mitigation method. Currently this model is able to calculate the total burned area under different circumstances and this metric plays the main role in determining the fire losses. Therefore, studying the other required items of fire financial losses and combining them with this model is an important possibility of future research.

Chapter 7 References and Bibliography

Ager, A.A., Vaillant, N.M. & Finney, M.A. 2010. A Comparison of Landscape Fuel Treatment Strategies to Mitigate Wildland Fire Risk in the Urban Interface and Preserve Old Forest Structure. *Forest Ecology and Management,* 259(8). :1556-1570.

Albini, F.A. & Forest, I. 1983. *Potential spotting distance from wind-driven surface fires.* US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station

Anthenien, R.A., Stephen, D.T. & Fernandez-Pello, A.C. 2006. On the Trajectories of Embers Initially Elevated Or Lofted by Small Scale Ground Fire Plumes in High Winds. *Fire Safety Journal,* 41(5). :349-363.

Arora, V.K. & Boer, G.J. 2005. Fire as an Interactive Component of Dynamic Vegetation Models. *Journal of Geophysical Research: Biogeosciences,* 110(G2). :- G02008.

Beyler, C.L. 2002. Fire Hazard Calculations for Large, Open Hydrocarbon Fires. *SFPE handbook of fire protection engineering,* 33:268-314.

Buchanan, A.H. 2001. *Structural design for fire safety.* Wiley New York

Bullen, M.L. & Thomas, P.H. 1979. Compartment Fires with Non-Cellulosic Fuels. *Symposium (International) on Combustion,* 17(1). :1139-1148.

Cheng, H. & Hadjisophocleous, G.V. 2011. Dynamic Modeling of Fire Spread in Building. *Fire Safety Journal,* 46(4). :211-224.

Chung, R., Madrzykowski, D., Stone, W.C., Lew, H.S., Taylor, A. & Hayes, J.R. 1996. *January 17, 1995 hyogoken-nanbu (kobe) earthquake: Performance of structures, lifelines, and fire protection systems, NIST SP 901 (ISCCS TR18).* Gaithersburg, MD: National Institute of Standards and Technology

City of Cape town. 2015. *Cape town offical tourist websit.* [Online]. Available: http://www.capetown.travel/content/page/weather

Corson, R. 1953. The Significance of Fire Loading. *Natl.Fire Protect.Assoc.Quart,* 47(1). :65-72.

Cousins, J., Heron, D., Mazzoni, S., Thomas, G. & Lloydd, D. 2002. *Estimating risks from fire following earthquake.* Institute of Geological & Nuclear Sciences Limited

Dawn, D. 2011. Autodesk Sustainability Workshop.

de Normalisation, C.E. 2002. Eurocode 1: Actions on Structures Part 1-2: General Actions– Actions on Structures Exposed to Fire.

DiNenno, P.J. 2008. *SFPE handbook of fire protection engineering.* SFPE

Dowling, V.P. 1994. Ignition of Timber Bridges in Bushfires. *Fire Safety Journal,* 22(2). :145-168.

Drysdale, D. 1998. *Introduction to fire dynamics.* Chichester: John Wiley and Sons

Ellis, P.F. 2000. *The aerodynamic and combustion characteristics of eucalypt bark: A firebrand study. Unpublished thesis.* Canberra: The Australian National University.Ph.D

Finney, M.A. 2004. FARSITE: Fire Area Simulator: Model Development and Evaluation.

FPASA. 2014. SA National Fire Statistice. *Fire Protection Association of Southern Africa,* 40 No2[Online], Available: The Devil in the detail June 2014:24.

Golmohamadi, R. & Mohamadfam, I. 2014. Planning an Automatic Fire Detection, Alarm, and Extinguishing System for Research Laboratories. *Journal of Occupational Hygiene Engineering,* 1(1). : 57-65.

Golmohammadi, R. 2010. *Fire engineering.* Tehran: Fanavaran

HDA, The Housing Development Agency. 2012. *South africa: Informal settlements status.* [Online]. Available: http://www.thehda.co.za/information/research/category/research

Heskestad, G. 1981. Peak Gas Velocities and Flame Heights of Buoyancy-Controlled Turbulent Diffusion Flames. Paper presented at Symposium (International) on Combustion.

Himoto, K. and Tanaka, T. 2005. Transport of Disk-Shaped Firebrands in a Turbulent Boundary Layer. Paper presented at the Eighth International Symposium on Fire Safety Science.

Himoto, K. & Tanaka, T. 2008. Development and Validation of a Physics-Based Urban Fire Spread Model. *Fire Safety Journal,* 43(7). : 477-494.

Holborn, P., Nolan, P. & Golt, J. 2004. An Analysis of Fire Sizes, Fire Growth Rates and Times between Events using Data from Fire Investigations. *Fire Safety Journal,* 39(6). : 481-524.

Horiuchi, S., Kobayashi, M. & Nakai, S. 1974. Study on the Emergency Escape in City Area. *Transactions of the Architectural Institute of Japan,* 223: 45-71.

Howell, J.R., Siegel, R. & Menguc, M.P. 2011. *Thermal radiation heat transfer.* CRC press

Hua, J., Wang, J. & Kumar, K. 2005. Development of a Hybrid Field and Zone Model for Fire Smoke Propagation Simulation in Buildings. *Fire Safety Journal,* 40(2). : 99-119.

Huang, H., Ooka, R., Kato, S., Otake, H. & Hayashi, Y. 2004. CFD Simulation of Thermal Plume and Firebrands Scattering in Urban Fire. *Fire Science and Technology,* 23(2). : 152-163.

IBC, I. 2006. International Building Code. *International Code Council, Inc.(formerly BOCA, ICBO and SBCCI),* 4051:60478-65795.

IFSTA. 2008. *Essentials of fire fighting.* Pearson

Iwami, T., Ohmiya, Y., Hayashi, Y., Kagiya, K., Takahashi, W. & Naruse, T. 2004. Simulation of City Fire. *Fire Science and Technology,* 23(2). :132-140.

Klopovic, S. & Turan, ÖF. 2001. A Comprehensive Study of Externally Venting Flames —: Part II: Plume Envelope and Centre-Line Temperature Comparisons, Secondary Fires, Wind Effects and Smoke Management System. *Fire Safety Journal,* 36(2). : 135-172.

Kruger, A.C. 2011. *Wind climatology of South Africa relevant to the design of the built environment,*

Law, M. 1978. Fire Safety of External Building Elements–the Design Approach. *Engineering Journal.American Institute of Steel Construction, 2n Quarter,*: 59-74.

Law, M. & O'Brien, T. 1981. *Fire safety of bare external structural steel.* Steel Construction Institute

Lee, S.W. 2009. *MODELING POST-EARTHQUAKE FIRE SPREAD. Unpublished thesis.* Cornell University.Ph.D

Lee, S.W. & Davidson, R.A. 2010. Application of a Physics-Based Simulation Model to Examine Post-Earthquake Fire Spread. *Journal of Earthquake Engineering,* 14(5). : 688-705.

Lee, S., Davidson, R., Ohnishi, N. & Scawthorn, C. 2008. Fire Following earthquake—Reviewing the State-of-the-Art of Modeling. *Earthquake Spectra,* 24(4). : 933-967.

Lee, S. & Hellman, J. 1970. Firebrand Trajectory Study using an Empirical Velocity-Dependent Burning Law. *Combustion and Flame,* 15(3). : 265-274.

Lee, S. and Davidson, R. 2008. Modeling Different Modes of Post-Earthquake Fire Spread. Paper presented at Proceedings of the 14th world conference on earthquake engineering.

Lopes, A.M.G., Cruz, M.G. & Viegas, D.X. 2002. FireStation — an Integrated Software System for the Numerical Simulation of Fire Spread on Complex Topography. *Environmental Modelling & Software,* 17(3). : 269-285.

Lynne, M.(ed.). 2005. *Fire detection and suppression systems.*

Ma, Tingguang,Larrañaga, Michael,. 2015. Theoretical Flammability Diagram for Analyzing Mine Gases. *Fire Technol Fire Technology,* 51(2).: 271-286.

Maluk, C. & Bisby, L. 2012. 120 Years of Structural Fire Testing: Moving Away from the Status Quo.

Manzello, S.L., Cleary, T.G., Shields, J.R. & Yang, J.C. 2006. On the Ignition of Fuel Beds by Firebrands. *Fire and Materials,* 30(1).: 77-87.

Manzello, S.L., Maranghides, A. & Mell, W.E. 2007. Firebrand Generation from Burning Vegetation. *International Journal of Wildland Fire,* 16(4).: 458-462.

Manzello, S.L., Maranghides, A., Shields, J.R., Mell, W.E., Hayashi, Y. & Nii, D. 2009. Mass and Size Distribution of Firebrands Generated from Burning Korean Pine (Pinus Koraiensis) Trees. *Fire and Materials,* 33(1).: 21-31.

Manzello, S.L. 2008. On the Development and Characterization of a Firebrand Generator. *Fire Safety Journal,* 43(4).: 258-268.

Maree, F. 2015. *Fire loads and burn characteristics of shacks in informal settlements. Unpublished thesis.* Stellenbosch University: Department of Civil Engineering.

McMichael, A.J. 2008. International Study of Temperature, Heat and Urban Mortality: The 'ISOTHURM' Project. *International journal of epidemiology,* 37(5). : 1121-1131.

Mohamadzadeh, B. 2011. *Fire following earthquake risk assessment and management in urban areas. Unpublished thesis.* Tehran: University of Tehran Faculty of Environment.

Moorhouse, J. 1982. Scaling Criteria for Pool Fires Derived from Large-Scale Experiments. Paper presented at The Assessment of Major Hazards, Symposium Series.

Mudan, K.S. 1984. Thermal Radiation Hazards from Hydrocarbon Pool Fires. *Progress in Energy and Combustion Science,* 10(1). : 59-80.

Munnik, O. 2009. *THE PROGRESSION OF VULNERABILTY TO INFORMAL FIRE RISK. Unpublished thesis.* University of Cape Town.

Nüssle, T.A., Kleiner, A. &Brenner, M. 2005. Approaching urban disaster reality: The resQ firesimulator, *RoboCup 2004: Robot soccer world cup VIII.* Springer.Pages 474-482 in

Ohgai, A., Gohnai, Y., Ikaruga, S., Murakami, M. &Watanabe, K. 2005. Cellular automata modeling for fire spreading as a tool to aid community-based planning for disaster mitigation, *Recent advances in design and decision support systems in architecture and urban planning.* Springer.Pages 193-209 in

Ohmiya, Y. & Iwami, T. 2000. An Investigation on the Distribution of Fire Brands and Spot Fires due to a Hotel Fire. *Fire Science and Technology,* 20(1). :27-35.

Otake, H., Huang, H., Ooka, Y., Kato, S. and Hayashi, Y. 2003. Simulation of Flames and Thermal Plume in Urban Fire Under Windy Condition. Paper presented at Proceedings, 17th Japan Society of Fluid Mechanics Symposium.

Pharoah, R. 2012. Fire Risk in Informal Settlements in Cape Town, South Africa. *Disaster Risk Reduction: Cases from Urban Africa,* 105

Platt, D.G., Elms, D.G. & Buchanan, A.H. 1994. A Probabilistic Model of Fire Spread with Time Effects. *Fire Safety Journal,* 22(4). : 367-398.

Quintiere, J.G. 2006. *Fundamentals of fire phenomena.* University of Maryland, USA: John Wiley & Sons

Ren, A. & Xie, X. 2004. The Simulation of Post-Earthquake Fire-Prone Area Based on GIS. *Journal of Fire Sciences,* 22(5). : 421-439.

Roth, A. & Becker, P. 2011. Challenges to Disaster Risk Reduction: A Study of Stakeholders' Perspectives in Imizamo Yethu, South Africa. *Jàmbá: Journal of Disaster Risk Studies,* 3(2).: 443-452.

Sardoy, N., Consalvi, J., Porterie, B. & Fernandez-Pello, A.C. 2007. Modeling Transport and Combustion of Firebrands from Burning Trees. *Combustion and Flame,* 150(3). : 151-169.

Scawthorn, C. 1987. Fire Following Earthquake—Estimates of the Conflagration Risk to Insured Property in Greater Los Angeles and San Francisco, Prepared for the all-Industry Research Advisory Council. *Oak Park, IL,*

Scawthorn, C. 1986. Simulation Modeling of Fire Following Earthquake. Paper presented at Proceedings of the Third US National Conference on Earthquake Engineering.

Scawthorn, C., Eidinger, J.M. & Schiff, A. 2005. *Fire following earthquake.* ASCE Publications

Schadschneider, A., Klingsch, W., Klüpfel, H., Kretz, T., Rogsch, C. &Seyfried, A. 2009. Evacuation dynamics: Empirical results, modeling and applications, *Encyclopedia of complexity and systems science.* Springer.Pages 3142-3176 in

Seigel, L. 1969. The Projection of Flames from Burning Buildings. *Fire technology,* 5(1). : 43-51.

Shokri, M. & Beyler, C. 1989. Radiation from Large Pool Fires. *Journal of Fire Protection Engineering,* 1(4). : 141-149.

Smith, H.M. 2005. The relationship between settlement density and informal settlement fires: Case study of imizamo yethu, hout bay and joe slovo, cape town metropolis, *Geo-information for disaster management.* Springer.Pages 1333-1355 in

Stephen, D.T. & Fernandez-Pello, A.C. 1998. On the Flight Paths of Metal Particles and Embers Generated by Power Lines in High Winds—a Potential Source of Wildland Fires. *Fire Safety Journal,* 30(4). : 333-356.

Sugawa, O. & Takahashi, W. 1995. Flow Behavior of Ejected Fire Plume from an Opening with and without External Wind. *Asia ame,* 95:15-16.

Tarifa, C.S., del Notario, P.P. and Moreno, F.G. 1965. On the Flight Paths and Lifetimes of Burning Particles of Wood. Paper presented at Symposium (International) on Combustion.

Thomas, P. 1986. Design Guide: Structure Fire Safety CIB W14 Workshop Report. *Fire Safety Journal,* 10(2).: 77-137.

Thomas, P. 1963. The Size of Flames from Natural Fires. Paper presented at Symposium (International) on Combustion.

Thomas, P. & Law, M. 1972. The Projection of Flames from Buildings on Fire. *Fire Prevention Science and Technology,* 10:19-26.

Walton, W. & Thomas, P. 2002. SFPE Handbook of Fire Protection Engineering, Chapter Estimating Temperatures in Compartment Fires. *National Fire Protection Association, Quincy, Massachusetts,* 3:171-188.

Waterman, T.E. 1969. *EXPERIMENTAL STUDY OF FIREBRAND GENERATION.,*

Woycheese, J.P., Pagni, P.J. & Liepmann, D. 1999. Brand Propagation from Large-Scale Fires. *Journal of Fire Protection Engineering,* 10(2). : 32-44.

Woycheese, J.P., Pagni, P.J. & Liepmann, D. 1998. *Brand lofting above large-scale fires.* Building and Fire Research Laboratory, National Institute of Standards and Technology

Woycheese, J. 2001. Wooden Disk Combustion for Spot Fire Spread. Paper presented at The Ninth International Fire Science and Engineering Conference (INTERFLAM).

Wu, C. & Chen, L. 2012. 3D Spatial Information for Fire-Fighting Search and Rescue Route Analysis within Buildings. *Fire Safety Journal,* 48(0). : 21-29.

Yokoi, S. 1960. *Study on the prevention of fire-spread caused by hot upward current.* Building Research Institute, Ministry of Construction

Yoshioka, H., Hayashi, Y., Masuda, H. & Noguchi, T. 2004. Real-Scale Fire Wind Tunnel Experiment on Generation of Firebrands from a House on Fire. *Fire Science and Technology,* 23(2). : 142-150.

Zhao, S. 2010. GisFFE—an Integrated Software System for the Dynamic Simulation of Fires Following an Earthquake Based on GIS. *Fire Safety Journal,* 45(2). : 83-97.

Appendixes

Appendix A: list of interviewed people in academia and industry

Table A1: Full name, organization, position and contact details of the interviewed people, in academia and industry.

Title	Full name	Organization	Position	Contact details
Dr	Ailsa Holloway	Stellenbosch University	Director, Research Alliance for Disaster and Risk Reduction (RADAR)	Tel: +27 21 808 9281/85 Email: ailsaholloway@sun.ac.za
Prof	Iguisi,Edwin	Centre for Disaster Management Ahamadu Bello University, Zaria,Nigeria	Director	Mobile: 0803 703 7516 Email: ediguisi@yahoo.com
Dr	Musa, Ibrahim	Department of Geography, Ahamadu Bello University, Zaria Nigeria	Head of Geography Department	Mobile: +234 803 968 2515 - 08054255454 Email: talktojaro@yahoo.com
Mr	Sawa, Bulus Ajiya	Centre for Disaster Management Ahamadu Bello University, Zaria,Nigeria	Senior Lecturer	Mobile: +234 803 705 1461 Email: sawaajiya@yahoo.com
Mr	Hendricks, Roland G	Gauteng Department Cooperative Government & Traditional Affires	Director	Telephone: +27 113 555 039
Mr	Rodney Eksteen	Provincial Government Western Cape - Fire Brigade Services	Disaster Risk Management Officer	Email: Rodney.Eksteen@westerncape.gov.za
Mr	Ian Schnetler	Fire Department City of Cape Town	Chief Fire Officer	Telephone: 021 590 1738 Fax: 086 201 2152 Mobile: 084 220 0214 Email: Ian.schnetler@capetown.gov.za
Mr	Mark Pluke	Disaster Risk Management Centre Area	Head of South/West Area	Telephone : 021 427 8013 Mobile: 084 711 7721 Email: Mark.Pluke@capetown.gov.za

Table A1: Full name, organization, position and contact details of the interviewed people, in

academia and industry.

Title	Full name	Organization	Position	Contact details
Mr	Lenders,Ricky	Disaster Risk Management City of Cape Town	Assistant Disaster Risk Management Officer	Mobile: 082 371 2580 Email: ricky.lenders@capetown.gov.za
Mr	Le Roux Deon	Disaster Risk Management City of Cape Town	Assistant Disaster Risk Management Officer	Mobile: 082 371 2580 Email: deon.leroux@capetown.gov.za
Ms	Myburgh, Marlene	Disaster Risk Management City of Cape Town	Assistant Disaster Risk Management Officer	Mobile: 083 835 174 71 Email:
Mr	Strydom,Morne	Disaster Risk Management City of Cape Town	Assistant Disaster Risk Management Officer	Mobile: 079 170 7828 Email: Sawaajiya@yahoo.com
Ms	Samuels, Nuraan	Disaster Risk Management City of Cape Town	Assistant Disaster Risk Management Officer	Mobile: 083 979 8123 Email: nuraan.samuels@capetown.gov.za
Ms	Michaels, Lenora	Cape Winelands District Municipality	Disaster Risk Management Officer	Mobile: 071 679 7555 Email: lenora@capewinelands.gov.za
Ms	Varachia,Amina	Disaster Risk Management City of Cape Town	Assistant Disaster Risk Management Officer	Mobile: 083 462 8045

Appendix B: a list of fire causes.

Table B1: Comparison of fire causes based on different occupancy in 2012, in the case of South Africa (FPASA, 2014:24)

DESCRIPTION	SMOKING	ELECTRICAL	OPEN FLAMES	COOKING	HEATING	WELDING	LIGHTING	ARSON	UNREST	UNDERBID	OTHER	TOTAL	DAMAGE (RAND)
Dwelling formal	99	934	744	408	298	22	39	219	3	1248	500	4514	556062426
Informal dwelling	88	506	1154	330	200	4	35	239	1	1685	219	4461	114556248
Flats	17	83	44	53	24	1	0	8	0	46	30	306	51584320
Hotels and boarding houses	4	27	11	2	3	0	1	1	0	12	10	71	22075400
Hospitals and nursing homes	1	22	8	4	2	0	1	1	0	8	14	61	82449620
Educational establishments	7	14	17	4	4	2	0	19	0	27	13	107	6496500
Churches and halls	3	13	6	6	2	0	0	8	0	8	2	48	7470000
Cinemas and theatres	0	2	1	0	1	0	0	2	0	1	0	7	48045000
Museums, libraries and art galleries	1	7	2	0	0	0	0	1	0	2	2	15	543000
Night clubs and dance halls	0	4	2	0	0	0	0	3	0	3	1	13	2273000
Restaurants and cafes	1	30	30	58	10	0	0	0	0	24	17	170	9831780
Offices	9	79	16	7	15	2	1	6	0	40	31	206	50027150
Department stores	2	19	3	37	5	1	0	1	0	6	6	80	36946100
Garages and workshops	6	36	18	5	3	7	0	10	0	26	7	118	24141200
Warehouses	2	11	11	3	1	2	0	3	0	14	12	59	83842100
Outside storage	2	18	63	1	4	4	1	11	0	54	10	168	42864000
Furniture	0	5	5	2	1	2	0	1	0	11	2	29	11395500
Plastics and rubber	0	4	36	0	8	1	0	4	0	17	7	77	80848000
Textile	0	7	7	0	4	1	0	2	0	8	6	35	2760200
Printing	1	4	0	0	1	0	0	0	0	1	1	8	1280000
Milling	0	6	3	0	5	1	0	1	0	10	7	33	9276000
Petroleum	0	5	5	0	4	2	0	2	0	5	4	27	1117500
Food and drink	1	10	8	1	10	1	0	0	0	5	2	38	2068500

Stellenbosch University https://scholar.sun.ac.za

Table B.1: Comparison of fire causes based on different occupancy in 2012, in the case of South Africa (FPASA, 2014:24)

DESCRIPTION	SMOKING	ELECTRICAL	OPEN FLAMES	COOKING	HEATING	WELDING	LIGHTING	ARSON	UNREST	UNDERBID	OTHER	TOTAL	DAMAGE (RAND)
Paper and packaging	4	6	6	7	2	0	0	2	0	12	11	50	41309640
Chemical	0	5	6	0	1	2	1	0	0	6	9	30	24596500
Metal	2	9	7	0	3	9	0	1	0	15	4	50	1280727000
Electronics	3	120	2	0	1	0	4	4	0	27	16	177	19286800
Mines (surface)	0	9	0	0	0	1	0	1	0	2	0	13	825000
Utilities	1	70	2	0	5	1	4	5	0	24	9	121	13604500
Cars and motorcycles	11	638	177	0	60	34	1	106	0	621	276	1924	78827641
Busses	0	51	17	1	10	6	0	17	0	18	16	136	14681800
Heavy good vehicles	5	87	45	0	77	7	1	28	0	136	73	459	113557500
Ships	0	3	1	0	0	3	0	0	0	3	1	11	3065500
Trains	0	14	4	0	1	1	0	11	0	18	4	53	54320200
Aircraft	2	1	46	0	0	0	0	2	0	32	25	108	2340000
Rubbish, grass and bush	1244	71	14345	0	71	81	45	401	4	5798	1727	23787	5982120
Plantations and forests	3	1	331	205	0	0	4	3	3	222	18	790	60520000
Agricultural	1	11	93	0	4	0	1	1	0	51	31	193	1924000
Miscellaneous fires	15	554	529	0	24	22	11	39	12	912	356	2474	44668478
Total	1544	3588	17840	19	882	229	152	1191	21	11251	3511	40228	3162240443
Total fire	4%	9%	43%	3%	2%	1%	0%	3%	0%	27%	9%		

Stellenbosch University https://scholar.sun.ac.za

Appendix C: description of the Hamada model

According to FEMA (2003), a brief description of Hamada model and the equations are presented in this appendix. Based on the Hamada model figure C1 illustrates the fire spread process.

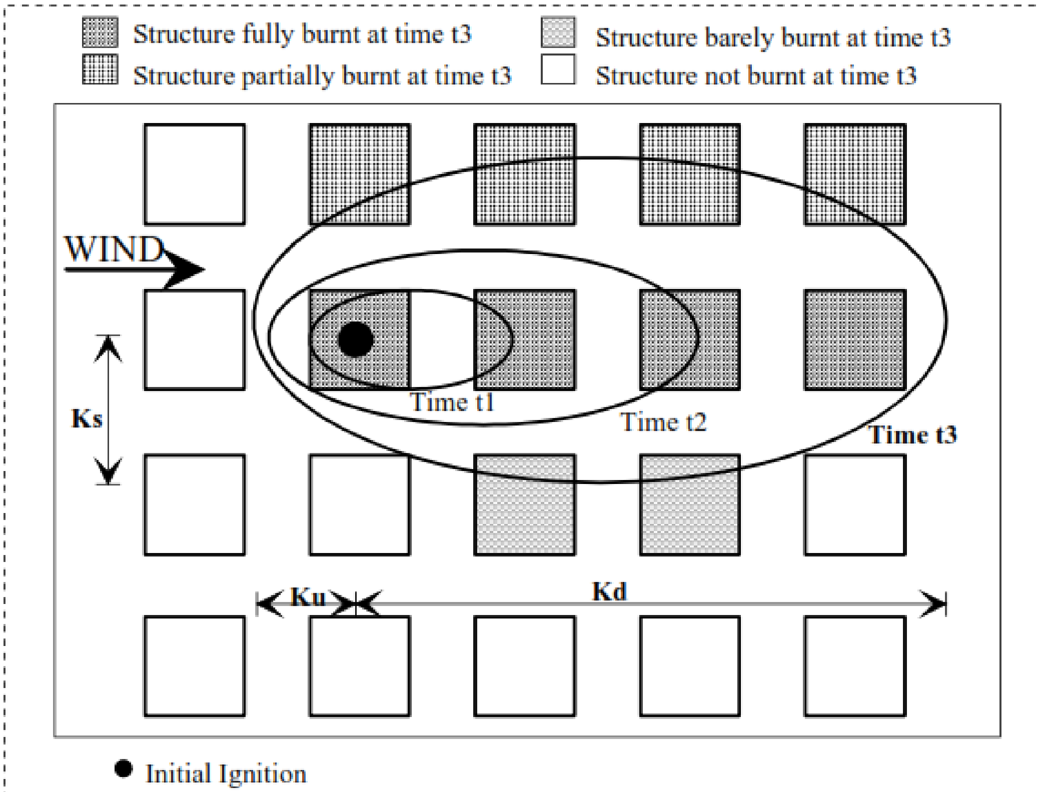


Figure C1: Illustration of Hamada's fire spread model.

The Hamada model assumes that the urban area consists of the equal size square blocks, which is the average of the real size buildings in the urban area. The block's dimension is denoted "a", hence, the area of each block is "a^2".

This model did not address the distance between buildings in detail. It only used the parameter 'd', which is average of side yards, backyards and front yards, but does not include streets and sidewalks. To address the effect of streets' and sidewalks' wide, the parameter of 'built-upness' or buildings density ratio is defined 'δ', it is determined by equation 8.2. If the value of δ is 0.1, it means the area is not very densely built, as the value of δ it means the density of the area also increase, 0.35 represent a very densely built area.

As it visually shows by figure 8.1, Hamada model assumes that fire spreads from the fire point amongst buildings in case of an ellipse. The ellipse grows over time and it is defined by three parameters; K_s , K_d and K_u . These parameters are functions of fire load, constant amount of wind speed, separation distance between buildings and density ratio of the area. The following equations will define the total number of burned buildings in each time step is defined by 'N_{tv} 'and above mentioned parameters.

$$N_{tV} = \frac{1.5\delta}{a^2} * K_s * (K_d + K_u) \tag{8.1}$$

N_{tv} = Number of structures fully burned

δ = "Built-upness" factor, dimensionless, described below

a = average structure plan dimension m

d = building density ratio m

K_s = half the width of fire from flank to flank m

K_d = length of fire in downwind direction, from the initial ignition location m

K_u = length of fire in upwind (rear) direction, from the initial ignition location m

$$\delta = \frac{\sum_{i=1}^{n} a_i^2}{\text{Tract Area}} \tag{8.2}$$

where:
a_i = plan dimension of building i
n = number of structures

$$K_d = \frac{(a+d)}{T_d} * t \tag{8.3}$$

$$K_s = \left(\frac{a}{2} + d\right) + \frac{(a+d)}{T_s}(t - T_s) \quad ; \quad K_s \geq 0 \tag{8.4}$$

$$K_u = \left(\frac{a}{2} + d\right) + \frac{(a+d)}{T_u}(t - T_u) \quad ; \quad K_u \geq 0 \tag{8.5}$$

$$T_d = \frac{1}{1.6(1 + 0.1V + 0.007V^2)}\left[(1 - f_b)\left(3 + 0.375a + \frac{8d}{25 + 2.5V}\right) + f_b\left(5 + 0.625a + \frac{16d}{25 + 2.5V}\right)\right] \tag{8.6}$$

$$T_s = \frac{1}{1 + 0.005V^2}\left[(1 - f_b)\left(3 + 0.375a + \frac{8d}{5 + 0.25V}\right) + f_b\left(5 + 0.625a + \frac{16d}{5 + 0.25V}\right)\right] \tag{8.7}$$

$$T_u = \frac{1}{1 + 0.002V^2}\left[(1 - f_b)\left(3 + 0.375a + \frac{8d}{5 + 0.2V}\right) + f_b\left(5 + 0.625a + \frac{16d}{5 + 0.2V}\right)\right] \tag{8.8}$$

where:

$$f_b = \frac{\text{Number of fire resistant buildings}}{\text{All buildings}} \tag{8.9}$$

Appendix D: input and output of wildland fire simulator models

Table D2: Compassion of input and output of wildland fire simulator models (Forest fire) (Lopes, Cruz & Viegas, 2002:269)

Fire simulation system	Components		intended use	Input		Output	Platform and software
	Prediction model	Simulation technique		GIS	Additional		
DYNAFIRE (KALABOKIDIS ET AL. 1991)	Physical-statistical (BEHAVE)	Cellular automation	To simulate the spread of low-to-moderate intensity surface fires	_Standard fuel types _Elevation _Slope _Aspect _Stream network	1- Temperature 2- Relative humidity 3- Fuel moisture 4- Wind speed 5-Wind direction	Map of: Fire perimeter Fire line intensity Average spread rate	_PC with MS-Dos and pMAP
EMBYR (Hargrove et al., 1995)	Probabilistic	Bond percolation	To simulate landscape-scale patterns	Aspect	1- Fuel moisture 2- Wind speed 3- Wind direction	Map of final burn pattern (50 m resolution)	_UNIX workstation _FORTRAN compiler
FARSITE (Finney, 1998)	Physical-statistical (BEHAVE)	Elliptical wave propagation	To simulate the spread and behaviour of wildland fire	Standard/custom fuel types Elevation Slope Aspect Canopy cover	1- Temperature 2- Relative humidity 3- Fuel moisture 4- Wind speed 5-Wind direction 6- Canopy characteristics	Maps of: Fire behaviour Fire perimeters (adjustable resolution)	_PC with windows Operating System

Table D2: Compassion of input and output of wildland fire simulator models (Forest fire) (Lopes, Cruz & Viegas, 2002:269)

Fire simulation system	Components		intended use	Input		Output	Platform and software
	Prediction model	Simulation technique		GIS	Additional		
FIREMAP (Ball and Gertin 1991)	Physical-statistical (BEHAVE)	Cellular automation	To simulate the spread of low-to-moderate intensity surface fires	_Standard fuel types _Elevation _Slope _Aspect	1- Temperature 2- Relative humidity 3- Fuel moisture 4- Wind speed 5-Wind direction	Maps of: Spread rate Fire line intensity Flame length Heat/unit area Reaction intensity Fire perimeter	_UNIX workstation -FORTRAN compiler
WILDFIRE (Wallace, 1993)	Physical-statistical (FBP system)	Elliptical wave propagation	To simulate the spread and behaviour of wildland fire	_Standard fuel types _Elevation	1- Wind speed 2- Wind direction	Maps of: Fire perimeters Fire intensity	PC with MS-Dos
Fire Station	Physical-statistical (BEHAVE)	Cellular automation	To simulate the spread and behaviour of wildland fire	_Standard/custom fuel types _Elevation	1- Temperature 2- Relative humidity 3- Fuel moisture 4- Wind speed 5-Wind reading by meteor station	Maps of: Wind speed Wind direction Spread rate Fire line intensity Flame length Heat/unit area Reaction intensity Fire perimeter FWI indices	_PC with Windows Operating System _Micro station software

Appendix E: a record of wind speed and direction.

Table E3: Records of wind speed and direction per minute (Meijers, 2015).

Date	Time	Record	Wind speed (m/s)	Wind direction	Time	Record	Wind speed (m/s)	Wind direction	Time	Record	Wind speed (m/s)	Wind direction
11/10/2014	00:00:00	45201	1.438	184.8	00:20:00	45221	2.8	164.1	00:40:00	45241	2.388	168.3
11/10/2014	00:01:00	45202	1.864	179.1	00:21:00	45222	2.363	218.2	00:41:00	45242	1.438	198.2
11/10/2014	00:02:00	45203	1.55	183.6	00:22:00	45223	1.525	195.8	00:42:00	45243	2.837	162.9
11/10/2014	00:03:00	45204	1.488	193.2	00:23:00	45224	1.888	183.7	00:43:00	45244	1.863	149.8
11/10/2014	00:04:00	45205	1.075	168.3	00:24:00	45225	2.55	203.1	00:44:00	45245	1.499	178.8
11/10/2014	00:05:00	45206	1.738	174.9	00:25:00	45226	1.143	194.2	00:45:00	45246	2.663	182.5
11/10/2014	00:06:00	45207	1.713	212.4	00:26:00	45227	1.263	183.8	00:46:00	45247	2.199	132.8
11/10/2014	00:07:00	45208	0.92	181.2	00:27:00	45228	1.725	182.8	00:47:00	45248	2.937	131.2
11/10/2014	00:08:00	45209	1.038	134.7	00:28:00	45229	1.706	208.1	00:48:00	45249	2.862	160.3
11/10/2014	00:09:00	45210	0.37	172.4	00:29:00	45230	0.68	175	00:49:00	45250	3.55	134.5
11/10/2014	00:10:00	45211	1.7	168	00:30:00	45231	1.306	154.9	00:50:00	45251	2.875	143.5
11/10/2014	00:11:00	45212	1.706	186.9	00:31:00	45232	2.013	167.8	00:51:00	45252	3.2	133.8
11/10/2014	00:12:00	45213	1.293	183.3	00:32:00	45233	2.575	172.3	00:52:00	45253	2.1	130.7
11/10/2014	00:13:00	45214	1.305	197.4	00:33:00	45234	3.737	149.4	00:53:00	45254	2.6	135
11/10/2014	00:14:00	45215	0.26	181.7	00:34:00	45235	3.425	143.5	00:54:00	45255	3.937	131.7
11/10/2014	00:15:00	45216	0.34	175.4	00:35:00	45236	3.1	163.4	00:55:00	45256	2.098	150.7
11/10/2014	00:16:00	45217	1.963	174.7	00:36:00	45237	2.887	168.5	00:56:00	45257	2.113	140.2
11/10/2014	00:17:00	45218	1.009	204.7	00:37:00	45238	2.488	177	00:57:00	45258	3.562	112.6
11/10/2014	00:18:00	45219	1.5	191	00:38:00	45239	2.775	177.8	00:58:00	45259	3.387	146.3
11/10/2014	00:19:00	45220	1.138	187.6	00:39:00	45240	2.638	158.4	00:59:00	45260	4.4	131.5
									01:00:00	45261	4.537	132.8

Appendix F: 4steps of the LOB

Step 1: ventilation condition

Ventilation of a room is assumed to be in a through-draft condition if:

- Wind speed is greater than threshold value; and
- the room has at least two openings (windows or doors) that are not located in the same wall and are open.

If a room does not satisfy the two mentioned conditions, no through-draft condition applies to the room. A closed opening is regarded as a part of the wall. However, if a room does not have any open openings, it is assumed that there is air leakage from closed openings in a room that keeps a fire burning in no through-draft conditions. There is a possibility of a room's ventilation condition shifting from a no through-draft to a though-draft condition. In a room with one open window or door, if the fire burns through a wall, that wall will be regarded as a wall with an open window from that time step until the end of the simulation. The same condition applies to a room without any open openings if a fire burns through at least two walls.

Drysdale,(1998) reviewed the research on threshold value, and concluded that 5 m/s is a reasonable estimation for the wind threshold value, because 5 m/s is estimated to be the avrooferage velocity of the gas outflow of a window (or door) of a room in burning condition. Hence, if speed value of the wind is greater than 5 m/s, it can overpower the outflow of the opening of the room.

Step 2: Burning rate

For the *through-draft conditions*, equations 1 and 2 apply to determine the burning rate (R):

$$R = \frac{L}{1200} \tag{8.10}$$

R = Burning rate (kg/s)

L = Total amount of fire load in the room (kg)

$$L = A_f\, Q \tag{8.11}$$

A_f = Area of the room (m^2)

Q = Fire load (kg/m^2)

For the *no through-draft condition* equations 3 and 4 apply:

$$R = 0.18(\,1 - e^{-0.036\eta})A_{window}(H_{opening}W_{wall})^{0.5}L_{room}{}^{-0.5} \quad (8.12)$$

$$\eta = \frac{A_T}{A_{window}H^{0.5}} \quad (8.13)$$

$H_{opening}$ = Height of the window or door;

W_{wall} = Width of the wall that the window or door located (m);

$L_{\,room}$ = Length of the room (m);

A_{room} = Area of the room (m^2);

A_{window} = Area of the window or door (m^2)

Step 3: Fire phase

LOB method defines the fire phases based on the percentage of the burned fire load of a room over a period of time t (L_t) (Law & O'Brien, 1981). This method assumes that flashover occurs when L_t is equal to 30% of the total fire load (L_t = 0.3 L). After flashover, the fully-developed phase starts and it ends when 80% of the fire load has burned (Lt = o.8 L). The decay phase only covers the last 20% of the fire load, therefore it starts from the moment that the fully-developed phase ends, and continues until the fire ceases(Law & O'Brien, 1981). Figure 3.6 illustrates the relation between the fire phases and percentage of burnt fire load.

Figure -F1: The relation between fire phases and Lt based on LOB method.

Step 4: Average Temperature of the room in fully-developed phase

If the *through-draft condition* applies:

$$T_f = T_a + 1200(1 - e^{-0.4\psi}) \quad (8.14)$$

If the *no through-draft* condition applies:

$$T_{f=}T_a + 6000(1 - e^{-0.1\eta})(1 - e^{-0.05\psi})\eta^{-0.5} \quad (8.15)$$

$$\psi = \frac{L}{\sqrt{A_T A_w}} \tag{8.16}$$

T_a = Ambient temperature

A_T = total area of interior and exterior walls, ceiling and floor minus total window area (m^2).

In this study, the estimation of the fully-developed phase temperature is the last task of the fire evaluation in a room, before the second module of the fire simulation (figure 3.1 broke down the fire spread into the three modules).

Appendix G: description of flame geometry based on the LOB method.

Typically, flame geometry is defined by four parameters (Drysdale, 1998):

- Window flame height (Z);
- the horizontal length of the centreline (axis) of the flame from the window (X);
- the width of the flame (W_{flame});
- the thickness of the flame (λ).

These parameters depend on the size and shapes of the associated windows, the ventilation condition (draft-through condition and no through-draft condition) of the room and, in the case of multi-story buildings, whether the fire is located on the top floor or any other lower floor. Parameters are defined as follows by LOB method (all dimensions are in meters) (Law & O'Brien, 1981)

:

No through-draft condition:

$$Z = 12.8\left(\frac{R}{W}\right)^{\frac{2}{3}} - H \quad (8.17)$$

As figure 8.3 shows, W_{flame} is estimated equal to a window's width (W_{indow}); and λ= 2H/3. Three conditions exist that determine the horizontal distance between the flame axis and the window (X):

If there is a wall above the window and

H<1.25 W_{window} $$X = \frac{H}{3} \quad (8.18)$$

Or

H ≥ 1.25 W_{window} $$X = 0.3H\left(\frac{H}{W}\right)^{0.54} \quad (8.19)$$

If there is not a wall above the window:

$$X = 0.6\left(\frac{Z}{H}\right)^{\frac{1}{3}} \quad (8.20)$$

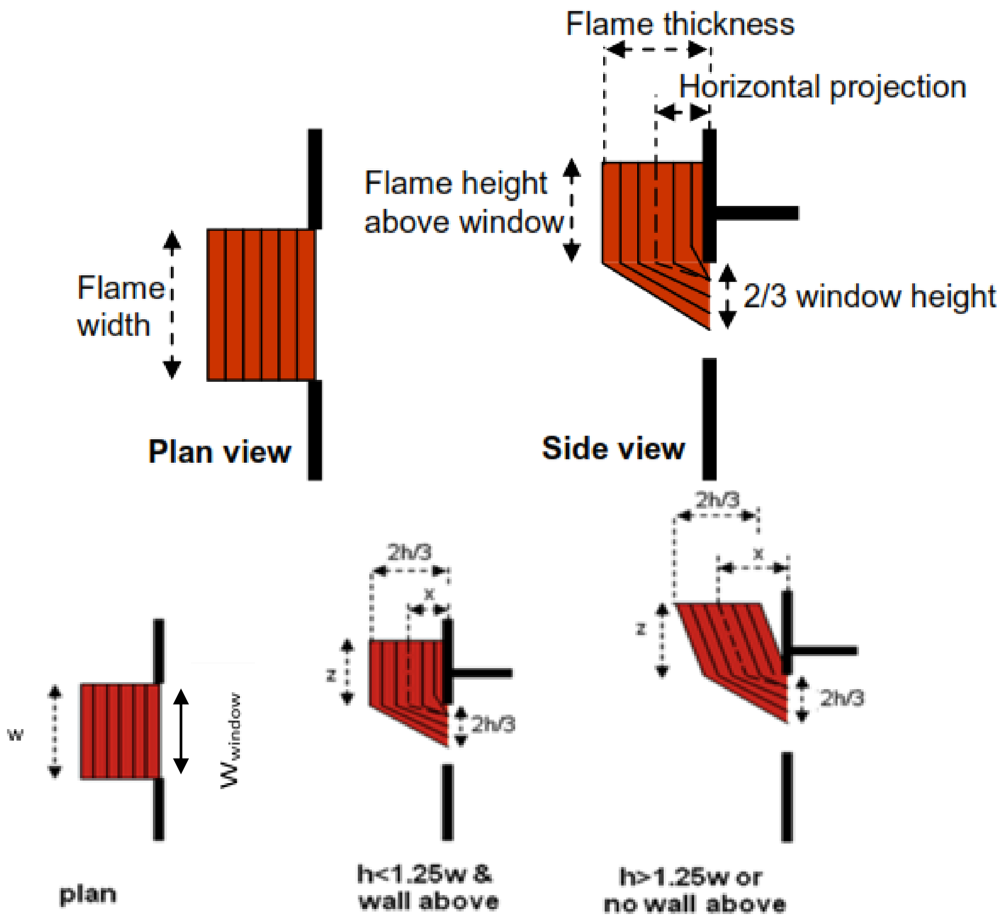


Figure G1: Estimated flame geometry, in no through-draft condition (Law, 1978:59).

Through-draft condition:

If a room has a window on the upwind side, it is assumed that wind blows in through the entire area of the window. Hence, no window flame can be projected or gas can be emitted from such a window and this model ignores the flame geometry and radiation in such cases. In contrast, when the window is located on a side of the building that is sheltered from wind or on the downwind side, the window flame and gas are considered. Under these conditions the flame geometry is calculated using the following equations and the assumed flame shape is illustrated in figure 8.4:

$$Z = 23.9\, u^{-0.43} R A_w{}^{-0.5} - H \tag{8.21}$$

Where

$u =$ Wind speed

λ = H

$$X = 0.605 \left(\frac{u^2}{H}\right)^{0.22} (Z + H) \tag{8.22}$$

$$W_{flame} = W + 0.4X \tag{8.23}$$

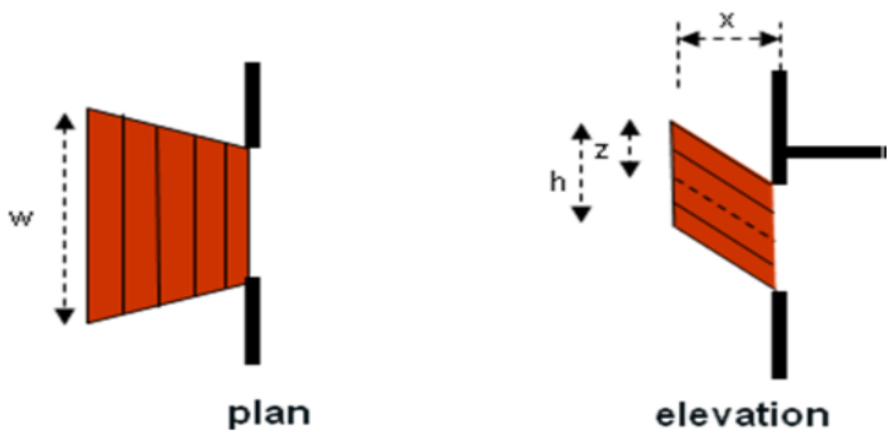


Figure G2: Estimated flame geometry, in draft condition (Law, 1978:59)

Appendix H: description of Roof flame, based on the Muden' method

Muden's method can be divided into three steps to make it easier to follow. Step 1 determines the burning rate and flame geometry, step 2 measures the amount of emitted radiation from the roof-flame, and finally, step 3 estimates the amount of received heat from the roof flame to targets.

Step 1:

Firstly, the burning rate and then the flame geometry are determined following the Muden's method. The roof flame was assumed as a room with the neutral plane at the height of the ceiling. The method assumes that air only inflows through window/windows and outflows through flows the roof (Lee, 2010). The inflow air speed is calculated as (Drysdale 1998, p.330):

$$v_0 = (2g\,y(\rho_F - \rho_0)/\,\rho_0)^{0.5} \tag{8.24}$$

then the mass inflow of air ($\mathfrak{m}_0$) as:

$$\mathfrak{m}_0 = (\frac{2}{3})C_d\rho_0 w(y_{bot})^{\frac{3}{2}}(\frac{2g(\rho_0-\rho_F)}{\rho_0})^{\frac{1}{2}} \tag{8.25}$$

where y is the height above or below the neutral plane,

ρ_F = is the gas density (it is assumed to be 0.27 kg/m^3);

$\rho_{0\,=}$ the ambient air density;

$C_{d=}$ discharge coefficient;

w = the width of the window (m);

y_{bot} is a horizontal height that is measured form bottom of window to the ceiling. In applying these equations, knowing that:

$$\rho_F/\rho_o=T_a/T_f, \tag{8.26}$$

T_f= the fully-developed temperature (It is assumed to be 1300^{0}K)

T_a= the ambient temperature

ρ_o=1.2 kg/m3.

The fuel burning rate is then

$$\mathfrak{m} = \mathfrak{m}_0/r \tag{8.27}$$

Where r is the stoichiometric air/fuel ratio, assumed to be 5.7 kg air/kg wood (Drysdale 1998: 331).

The roof flame geometry is determined by three parameters:

1) the flame base diameter (diameter of the cylinder) D_R ;

2) visible flame height H_R ; and

3) flame tilt angle θ_R.

Figure 8.5 illustrates these parameters and following equations determine them.

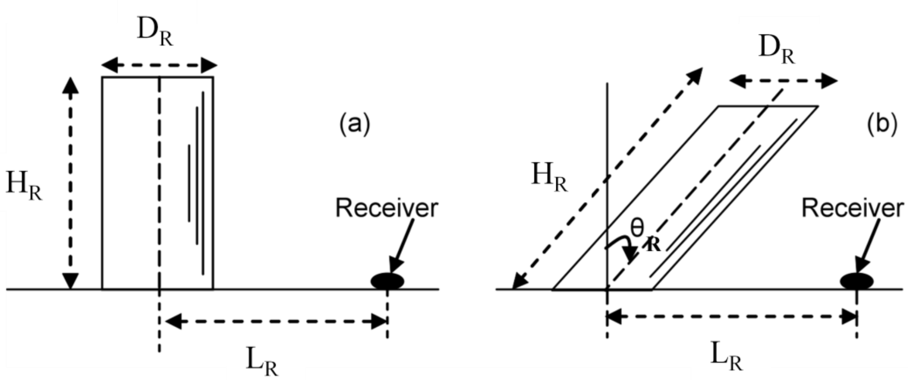


Figure H1: Illustration of roof flame (a) no wind, vertical cylinder (b) tilted flame because of wind (Muden, 1984).

$$D_R = \sqrt{4\,A_P/\pi} \tag{8.28}$$

Then if there is no wind:

$$H_R = 55D_R\left(\frac{\mathfrak{m}_\infty}{\rho_0\sqrt{gD_R}}\right)^{0.06}(u^*)^{-0.21} \tag{8.29}$$

A_P is the open pool area (m^2),

$\mathfrak{m}$ is the rate of mass burning per sq. meter of the open pool fire (kg/m^2s),

If there is wind:

$$H_R = 55D_R\left(\frac{\mathfrak{m}}{\rho_0\sqrt{gD_R}}\right)^{0.67}(u^*)^{-0.21} \tag{8.30}$$

Where

$$u^* = \frac{u}{\left(\frac{g m D_R}{\rho_F}\right)^{\frac{1}{3}}} \quad (8.31)$$

u = wind speed (m/s),

θ_R is the angle between vertical line and the flame axis:

For $u^*<1$

$$\theta_R = \cos^{-1} 1 \quad (8.32)$$

For $u^* \geq 1$

$$\theta_R = \cos^{-1} \frac{1}{\sqrt{u^*}} \quad (8.33)$$

Step 2:

This step determines the average amount received of emissive power (kW/m_2) by a target from the roof flame, based on Mudan's (1984) method

$$E = E_{max}e^{-sD_R} + E_s[1 - e^{-sD_R}] \quad (8.34)$$

E_{max} = the equivalent blackbody emissive power, 140 kW/m^2;

s = the extinction coefficient, 0.12 m^{-1};

E_s = the emissive power of smoke, 20 kW/m^2.

Step 3:

This step estimates received radiation of the roof flame by a specified target. All buildings that are within a threshold distance of the burning roof (roof $_b$) and are within a threshold angle of the direction the wind is blowing in (assumed to be 100 meters and 90^0, respectively), are considered target buildings. Based on attribute differences of the roof$_b$ and targets, three conditions are considered.

- If both roof$_b$ and a building in the threshold distance are in the same height, the roof/roofs of the neighbour building/buildings is the target.
- If the roof$_b$ is shorter than a building in the threshold distance, two targets are considered. First, the roof of the target building and second if the target buildings has a window in the same height of/with the roof$_b$ on the nearest wall to the roof$_b$.

- If $roof_b$ is taller than a building in the threshold distance, then there is no target is considered on the building.

There are two configuration factors are considered for targets, F_V when a target is vertically and F_H when a target is horizontally oriented. Following equations calculate F_V and F_H :

$$F_V = \frac{1}{\pi}\frac{a\cos\theta_R{}^2}{b-a\sin\theta_R}\frac{a^2+(b+1)^2-(1+a\sin\theta_R)}{\sqrt{AB}}\tan^{-1}\sqrt{\frac{A}{B}}(\frac{b-1}{b+1})^{1/2} + \frac{\cos\theta_R}{\sqrt{C}}\left[\tan^{-1}\frac{ab-(b^2-1)\sin\theta_R}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\frac{(b^2-1)\sin\theta_R}{\sqrt{(b\text{^}2-1)}\sqrt{C}}\right] \quad (8.35)$$

$$F_H = \frac{1}{\pi}\tan^{-1}\sqrt{\frac{b-1}{b+1}} - \frac{a^2+(b+1)^2-(1+a\sin\theta_R)}{\sqrt{AB}}\tan^{-1}\sqrt{\frac{A}{B}}(\frac{b-1}{b+1})^{1/2} + \frac{\sin\theta_R}{\sqrt{C}}\left[\tan^{-1}\frac{ab-(b^2-1)\sin\theta_R}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\frac{(b^2-1)\sin\theta_R}{\sqrt{(b\text{^}2-1)}\sqrt{C}}\right] \quad (8.36)$$

$$a = \frac{H_R}{R_R} \quad (8.37)$$

$$b = \frac{L_R}{R_R} \quad (8.38)$$

$$A = a^2 + (b+1) - 2a(b+1)\sin\theta_R \quad (8.39)$$

$$B = a^2 + (b-1) - 2a(b-1)\sin\theta_R \quad (8.40)$$

$$C = 1 + (b^2-1)^2\cos^2\theta_R \quad (8.41)$$

LR =the distance between the target and the centre of the pool fire;

R_R =the pool fire radius.

Finally, the intensity of received radiation at the target element is calculated by

$$q^{"} = EF\tau \quad (8.42)$$

Where F is F_V or F_H, depending on whether the target is vertically- or horizontally- oriented. τ is the atmospheric transmissivity and like Beyler's (2002), it is assumed to be 1.

Appendix I: fire load

Table I1: Fire load densities $q_{f,k}$ [MJ/m2] for different occupancies (de Normalisation, 2002)

Occupancy	Average	80% Fractile
Dwelling	780	948
Hospital	230	280
Hotel	310	377
Library	1500	1824
Office	420	511
Classroom of a school	285	347
Shopping centre	600	730
Theatre (cinema)	300	365
Transport (public space)	100	122
NOTE: Gumbel distribution is assumed for 80% fractile		

Table I2: fire load densities by occupancy type (Thomas, 1986:77).

Occupancy type	Distribution of fire load
All residential rooms	N (16, 4.4)
Hospital (patient's room)	N (5.4, 1.65)
Govt building, all rooms	N (27.75, 31.25)
Private office, all rooms	N (29, 26.75)
Department store	46.75
General warehouse	113.5
School (1 occupied room)	U (31.75, 177)

"The following fire load values, presented in table 8.5, are extracted from the Design Guide- Structural Safety (CIB,1986). The table gives average fire load densities using data from Switzerland. The following for fire load densities (only variable fire load densities) are taken from bailage 1: Brandschutztechische Merkmale verschiedener Nutzungen und Lagerguter and are defined as density per unit floor area (MJ/m^2)." (Buchanan, 2001)

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001)

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Academy	300	800
Accumulator forwarding	800	
Accumulator mfg	400	
Acetylene cylinder storage	700	
Acid plant	80	
Adhesive mfg	1000	
Administration	800	
Adsorbent plant for combustible	1700	
Aircraft hangar	200	3300
Airplane factory	200	
Aluminium mfg.	40	
Aluminium processing	200	
Ammunition mfg.	Special	
Animal food preparing mfg.	2000	
Antique shop	700	
Apparatus forwarding	700	
Apparatus mfg.	400	
Apparatus repair	600	
Apparatus testing	200	
Arms mfg.	300	
Arms sales	300	
Artificial flower mfg.	300	200
Artificial leather mfg.	1000	1700
Artificial leather processing	300	
Artificial silk mgs	300	1100
Artificial silk processing	210	
Artificial stone mfg.	40	
Asylum	400	
Authority office	800	
Awning mfg.	300	1000

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Bag mfg. (jute, paper, plastic)	500	
Bakery	200	
Bakery, sales	300	
Ball bearing mfg.	200	
Bandage mfg.	400	
Bank, counters	300	
Bank, offices	800	
Barrel mfg., wood	1000	800
Basement, dwelling	900	
Basket ware mfg.	300	200
Bed sheeting production	500	1000
Bedding plant	600	
Bedding shop	500	
Beer mfg.	80	
Beverage mfg.	80	
Bicycle assembly	200	400
Biscuit factories	200	
Biscuit mfg.	200	
Bitumen preparation	800	3400
Bind mfg., venetian	800	300
Blueprinting	400	
Boarding school	300	
Boat mfg.	600	
Boiler house	200	
Bookbinding	1000	
Book store	1000	
Box mfg.	1000	600
Brick plant, burning	40	
Brick plant, clay preparation	40	
Brick plant, drying kiln with metal grates	40	
Brick plant, drying kiln with wooden grates	1000	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Brick plant, drying room with metal grates	40	
Brick plant, drying room with wooden grates	400	
Brick plant, pressing	200	
Briquette factories	1600	
Broom mfg.	700	400
Brush mfg.	700	800
Butter mfg.	700	4000
Cabinet making (without wood yard)	600	
cable mfg.	300	600
café	400	
Camera mfg.	300	
Candle mfg.	1300	22400
Candy mfg.	400	
Candy packing	800	
Candy shop	400	
Cane production mfg	400	
Canteen	300	
Car assessory sales	300	
Car assembly plant	300	
Car body repairing	300	
Car paint shop	500	
Car repair shop	300	
Car seat cover shop	700	
Cardboard box mfg.	800	
Cardboard box	300	2500
Cardboards products mfg.	800	4200
Carpenter shed	700	2500
Carpet dyeing	500	
Carpet mfg.	600	
Carpet store	800	
Cartwright's shop	500	
Cast iron foundry	400	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Celluloid mfg.	800	
Cement mfg.	40	
Cement plant	80	
Cement products mfg.	120	
Chasse factory	170	
Cheese mfg. (in box)	100	
Cheese store	100	
Chemical plants (rough average)	300	100
Chemist's shop	1000	
Children’s home	400	
China mfg.	200	
Chipboard finishing	800	
Chipboard pressing	100	
Chocolate factory, intermediate storage	6000	
Chocolate factory, tumbling treatment	500	
Chocolate factory, all other specialities	1000	
Church	200	
Cider mfg.	200	
Cigarette plant	3000	
Cinema	300	
Clay, preparing	50	
Cloakroom, wooden wardrobe	80	
Cloth mfg.	400	
Clothing store	600	
Coal bunker	2500	
Coal cellar	10500	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2)

(Buchanan, 2001)

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Church	200	
Cider mfg.	200	
Cigarette plant	3000	
Cinema	300	
Clay, preparing	50	
Cloakroom, wooden wardrobe	80	
Cloth mfg.	400	
Clothing store	600	
Coal bunker	2500	
Coal cellar	10500	
Coca processing	800	
Coffee extract mfg.	300	
Coffee roasting	400	
Cold storage	200	
Composing room	400	
concert products mfg.	100	
Condiment mfg.	50	
Congress hall	600	
Contractors	500	
Cooking stove mfg.	600	
Coopering	600	
Cordage plant	300	600
Cordage store	500	
Cork products	500	800
Cosmetic mfg.	300	500
cotton mills	1200	
Cotton wool mfg.	300	
Cover mfg.	500	
Cutlery mfg. (household)	200	
Cutting-up shop leather, artificial leather	300	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Cutting-up shop textiles	500	
Cutting-up shop, wood	700	
Dairy	200	
Data processing	400	
Decoration studio	1200	
Dental surgeon's laboratory	300	
Dentist office	200	
Department store	400	
Distilling plant, combustible materials	200	
Distilling plant, incombustible materials	50	
Doctor's office	200	
Door mfg., wood	800	
Dressing textiles	200	
Dressing paper	700	
Dressmaking shop	300	
dry-cell battery	400	
Dry cleaning	300	
Dyeing plant	500	
Edible fat forwarding	900	
Edible fat mfg.	1000	
Electric appliance mfg.	400	
Electric appliance repair	500	
Electric motor mfg.	300	
Electric repair shop	600	
Electric supply storage	1200	
Electro industry	600	
Electronic device mfg.	400	
Electronic device repair	500	
Embroidery	300	
Etching plant glass/metal	200	
Exhibition hall, cars including decoration	200	
Exhibition hall, Furniture including decoration	500	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Exhibition hall, machines including decoration	80	
Exhibition painting including decoration	200	
Exclusive industry	4000	
Fertiliser mfg.	200	
Filling plant /barrels incombustible liquid filled and / or barrels combustible:	<200	
Risk class 1	>3400	
Risk class 2	>3400	
Risk class 3	>3400	
Risk class 4	>3400	
Risk class 5	>3400	
Filling plant/small casks:	>3400	
liquid filled and casks incombustible	>1700	
liquid filled and/or casks combustible:	<200	
Risk 1	<500	
Risk2	<500	
Risk3	<500	
Risk4	<500	
Risk5	<500	
Finishing plant, paper	500	
Finishing plant, textile	300	
Fireworks mfg.	spez	
Flat	300	
Floor covering mfg.	500	
Floor covering store	1000	
Flooring plaster mfg.	600	
Flour products	800	
Flower sales	80	
Fluorescent tube mfg.	300	
Foamed plastics fabrication	3000	
Foamed plastics producing	600	
food forwarding	1000	
food store	700	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
forge	80	
forwarding, appliances partly made of plastic	700	
forwarding, beverage	300	
forwarding, cardboard goods	600	
forwarding, food	1000	
forwarding, furniture	600	
forwarding, glassware	700	
forwarding, plastic products	1000	
forwarding, printed matters	1700	
forwarding, textiles	600	
forwarding, tin ware	300	
forwarding, varnish polish	1300	
forwarding, wood ware(small)	600	
foundry (metal)	40	
Fur, sewing	400	
Fur store	200	
furniture exhibition	500	
furniture mfg. (wood)	600	
furniture polishing	500	
furniture store	400	
furrier	500	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2)

(Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Galvanic station	200	
Gambling place	150	
Glass blowing plant	200	
Glass factory	100	
Glass mfg.	100	
Glass painting	300	
Glass processing	200	
Glassware mfg.	200	
Glassware store	200	
Glazier's workshop	700	
Gold plating (of metals)	800	3400
Goldsmith's workshop	200	
Grain mill, Without storage	400	13000
Gravestone carving	50	
Graphic workshop	1000	
Greengrocer's shop	200	
Hairdressing shop	300	
Hardening plant	400	
Hardware mfg.	200	
Hardware store	300	
Hat mfg.	500	
Hat store	500	
Heating equipment room, wood or coal-firing	300	
Heat sealing of plastics	800	
High-rise office building	800	
Homes	500	
Homes for aged	400	
Hosiery mfg.	300	1000
Hospital	300	
Hotel	300	
Household appliances, sales	300	200
Ice cream plant (including packaging)	100	
Incandescent lamp plant	40	
Injection moulded parts mfg. (plastic)	80	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Injection building	500	
Ironing	500	
Jewellery mfg.	200	
Jewellery store	300	
Joinery	700	
Joiners (Machin room)	500	
Joiners (workbench)	700	
Jute, weaving	400	1300
Laboratory, bacteriological	200	
Laboratory, chemical	500	
Laboratory, electric, electronic	200	
Laboratory, metallurgical	200	
Laboratory, physics	200	
Lacquer forwarding	1000	
Lacquer mfg.	500	2500
Large metal constructions	80	
Lathe shop	600	
Laundry	200	
Leather good sales	700	
Leather product mfg.	500	
Leather , tanning, dressing, etc.	400	
Library	2000	2000
Linguine mfg.	400	
Liqueur mfg.	400	800
Liquor mfg.	500	800
Liquor store	700	
Loading ramp, including goods (rough average)	800	
Lumber room for miscellaneous goods)	500	
Machinery mfg.	200	
Match plant	300	800
Mattress mfg.	500	500
Meat shop	50	
Mechanical workshop	200	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2)

(Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Metal goods mfg.	200	
Metal grinding	80	
Metal working (general)	200	
Milk, condensed, evaporated mfg.	200	9000
Milk, powdered mfg.	200	10500
Milling work, metal	200	
Mirror mfg.	100	
Motion picture studio	300	
Motorcycle assembly	300	
Museum	300	
Musical instrument sales	281	
News stand	1300	
Nitrocellulose mfg.	Spez	1100
Nuclear research	2100	
Nursery school	300	
Office, business	800	
Office, engineering	600	
Office, furniture	700	
Office, machinery mfg.	300	
Office, machine sales	300	
Oilcloth mfg.	700	1300
Oilcloth processing	700	2100
Optical instrument mfg.	200	200
Packing, food	800	
Packing, incombustible goods	400	
Packing material, industry	1600	3000
Packing, printed matters	1700	
Packing, textiles	600	
Packing, all other combustible goods	600	
Paint and varnish, mfg.	4200	
Paint and varnish, mixing plant	2000	
Paint and varnish shop	1000	
Painter's workshop	500	
Pain shop (cars, machines, etc.)	200	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Paper mfg.	200	10000
Paper processing	800	1100
Parking building	200	
Parquetry mfg.	2000	1200
Perambulator mfg.	300	800
Perambulator shop	300	
Perfume sale	400	
Pharmaceutical mfg.	300	800
Pharmaceuticals, packing	300	800
Pharmacy (including storage)	800	
Photographic laboratory	100	
Photographic store	300	
Photographic studio	300	
Picture frame mfg.	300	
Plaster product mfg.	80	
Plastic floor tile mfg.	800	
Plastic processing	2000	5900
Plastic products fabrication	600	
Plumber's workshop	100	
Plywood mfg.	800	2900
Polish mfg.	1700	
Post office	400	
Potato, flaked, mfg.	200	
Pottery plant	200	
Power station	600	
Precious stone, cutting etc.	80	
Precision instrument mfg.	200	
Precision mechanics plant	100	
Pressing, metal	200	
Pressing, plastics, leather, etc.	100	
Preparation briquette production	400	
Printing, composing room	300	
Printing, ink mfg.	700	3000
Printing, machine hall	400	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Printing office	1000	
Radio and TV mfg.	400	
Radio and TV sales	500	
Radio studio	300	
Railway car mfg.	200	
Railway station	800	
Railway workshop	800	
Record player mfg.	300	
Record repository, documents see also storage	4200	200
Refrigerator mfg.	1000	300
Relay mfg.	400	
Repair shop, general	400	
Restaurant	300	
Retouching department	300	
Rubber goods mfg.	600	5000
Rubber goods store	800	
Rubber processing	600	5000
Saddlery mfg.	300	
Safe mfg.	80	
Salad oil forwarding	900	
Salad oil mfg.	1000	18900
Sawmill (without wood-yard)	400	
Scale mfg.	400	
School	300	
Scrap recovery	800	
Seed store	600	
Sewing machine mfg.	300	
Sewing machine store	300	
Sheet mfg.	100	
Shoe factory, forwarding	600	
Shoe factory mfg.	500	
Shoe polish mfg.	800	2100
Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Shoe repair with manufacture	200	
Shoe store	500	
Shutter mfg.	1000	
Silk spinning (natural silk)	300	
Silk weaving (natural silk)	300	
Silverwares	400	
Ski mfg.	400	1700
Slaughter house	40	
Soap mfg.	200	4200
Soda mfg.	40	
Soldering	300	
Solvent distillation	200	
Spinning mall, excluding granting	300	
Sporting goods store	800	
Spray painting, metal goods	300	
Spray painting, wood products	500	
Stationery store	700	
Steel furniture mfg.	300	
Stereotype plant mfg.	200	
Stone masonry	40	
Storeroom (workshop storerooms etc.)	1200	
Synthetic fibre mfg.	400	
Synthetic fibre processing	400	
Synthetic resin mfg.	3400	4200
Tar-coated paper mfg.	1700	
Tar productions	800	
Telephone apparatuses mfg.	80	
Telephone exchange mfg.	100	
Test room, machinery	200	
Test room, textiles	100	
Theatre	300	
Tin can mfg.	300	
Tinned goods mfg.	100	
Tin ware mfg.	40	
Tire mfg.	120	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001).

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Tobacco products mfg.	700	1800
Tobacco shop	200	2100
Tool mfg.	500	
Toy mfg. (combustible)	200	
Toy mfg. (incombustible)	100	
Toy store	500	
Tractor mfg.	300	
Transformer mfg.	300	
Transformer winding	600	
Travel agency	400	
Turnery (wood work)	500	
Turnery section	200	
TV studio	300	
Twisting shop	250	
Umbrellas mfg.	300	
Umbrellas store	300	400
Underground garage, private	>200	
Underground garage, public	<200	
Upholstering plant	500	
Vacation home	500	
Varnishing appliances	80	
Varnishing, paper	80	
Vegetable dehydrating	1000	400
Vehicle mfg., assembly	400	
Veneering	500	2900
Veneering mfg.	800	4200
Vinegar mfg.	80	100
Vulcanising plant (without storage)	1000	
Waffle mfg.	300	1700
Warping department	250	
Washing agent mfg.	300	200
Washing machine mfg.	300	40
Watch assembling	300	40
Watch mechanism mfg.	40	

Table I3: average fire load densities of different occupancy per unit floor area (MJ/m2) (Buchanan, 2001)

Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
Watch repair shop	300	
Watch sales	300	
Water closets	¬0	
Wax productions forwarding	2100	
Type of occupancy	Fabrication (MJ/m2)	Storage (MJ/m2/m)
wax productions mfg.	1300	2100
Weaving mill (whiteout carpets)	300	
welding shop (metal)	80	
winding shop (metal)	400	
Winding room	600	
Winding textile fibres	700	
Window glass mfg. (wood)	800	
Wine cellar	20	
Wine merchant's shop	200	
Wine drawing	80	
Wire factory	800	
Wood craving	700	
Wood drying plant	800	
Wood grading	200	
Wood pattern making shop	600	
Wood preserving plant	3000	
Youth hostel	300	

Appendix J: windows dimension

20 buildings were randomly selected and the height and width of the buildings were measured. With regard height and width size of windows. Table 8.4 determines that each buildings has how many of each window type. Table 8.5 shows the related height and width of the windows' type separately.

Table J1: Buildings and the number of related/corresponded window.

	Windows 1	Windows 2	Windows 3	Windows 4	Windows 5	Windows 6
Building 1	4	0	0	2	1	1
Building 2	4	0	0	2	1	1
Building 3	4	0	0	2	1	1
Building 4	4	0	0	2	1	1
Building 5	2	2	0	1	1	2
Building 6	2	2	0	1	1	2
Building 7	2	2	0	1	1	2
Building 8	2	2	0	1	1	2
Building 9	2	2	0	1	1	2
Building 10	2	2	0	1	1	2
Building 11	0	4	2	1	0	0
Building 12	0	4	2	1	0	0
Building 13	0	4	2	1	0	0
Building 14	2	0	4	2	1	0
Building 15	2	0	4	2	1	0
Building 16	2	0	4	2	1	0
Building 17	2	0	4	2	1	0
Building 18	0	3	0	1	0	4
Building 19	0	3	0	1	0	4
Building 20	0	3	0	1	0	4

Table J2: Height and width of the windows.

	Height m	Width m
Windows 1	1.2	1.5
Windows 2	1.5	1.5
Windows 3	1.1	1
Windows 4	0.5	0.5
Windows 5	2.2	0.6
Windows 6	1.7	1
Average	1.4	1

Appendix K:


N R Mandela Rd
Cape Town, Western Cape
Street View - Sep 2009
S Biko St
N R Mandela Rd
Back to Map
Google


N R Mandela Rd
Cape Town, Western Cape
Street View - Sep 2009
7331
Back to Map
Google
Image capture: Sep 2009 © 2016 Google Terms Privacy Report a problem


N R Mandela Rd
Cape Town, Western Cape
Street View - Sep 2009
Back to Map
Google


N R Mandela Rd
Cape Town, Western Cape
Street View - Sep 2009
7331
Back to Map
Google
Image capture: Sep 2009 © 2016 Google Terms Privacy Report a problem