Fire Investigations for Informal Settlements

by

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Declaration

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Abstract

Fires in informal settlements (IS) are a significant problem in developing countries. According to the South African national statistics, 5544 IS fire incidents were reported during 2019. Although informal settlement fires only account for 11.6% (on average) of all fires, they cause approximately 40% of the total number of fatalities. It is with this backdrop that this dissertation seeks to develop an understanding of real IS fires. We need to know: what is causing fires? How do fires spread? What stops fires from spreading? How are fires put out? How many people are affected in an incident? How do inhabitants respond during an incident? To start answering these this work considers (a) the development of a framework for fire investigations in informal settlements (FFIIS), (b) the analysis of a real IS fire incident, (c) the application of the FFIIS to large post-flashover IS fires, and (d) work to understand the fire causes in IS fires.

First, the FFIIS that applies well-known forensic fire investigation principles and guidelines is developed in order to (a) identify the fire origin and the fire cause, (b) obtain data on human behaviour in fire, (c) understand the fire spread sequence, and (d) evaluate the effectiveness of suppression and response efforts. Then, a real IS fire that was recorded by a transit CCTV camera is analysed. The analysis allows for the study of (a) the fire spread, (b) the human behaviour, and (c) firefighters' response and operations. After this, the FFIIS is applied to three real fire events. The application of the FFIIS allows one to develop hypotheses that more accurately define the area of fire origin and pattern formation sequence. Understanding the limitations and the quality of the information that can be obtained when applying the FFIIS is fundamental to improve the guidelines proposed.

The work carried out reveals the difficulty in obtaining information pertaining to the fire cause of IS fires. Hence, to gain a better understanding of this topic a different approach was taken, whereby the fire risk perception of IS inhabitants is analysed. The analysis suggests that (a) the survey's risk target had a strong influence on the risk perception, (b) the inhabitants' fire risk perception of their settlement is similar to that of firefighters in previous research, (c) the risk mitigation proposals are mainly focused on decreasing the consequences of the fire, (d) the national fire statistics are not capturing the causes of real fire incidents, and (e) improvement of the documentation process after a fire event could provide critical information to implement prevention measures.

A better understanding on IS fires, through the investigation of past fire events, can be used to facilitate the design of prevention plans that respond specifically to informal settlements requirements, develop or validate fire spread models, enhance firefighter response and training, plan for incidents, and develop community fire awareness. This work may be applicable to other low-income communities such as refugee camps, markets, IS in other countries with different conditions, and similar settlements.

Opsomming

Brande in informele nedersettings (IN) is 'n beduidende probleem in ontwikkelende lande. Die Suid-Afrikaanse Nasionale Statistiek het rapporteer in 2019 dat daar 5544 IN-brande aangemeld is. IN-brande gemiddeld net 11,6% van alle brande, maar is verantwoordelik vir tot 40% van alle brandverwante sterftes. Die navorsing ondersoek dus die begrip van IN-brande in werklikheid. Die volgende vrae is belangrik: wat is die oorsaak van die brande? Hoe versprei die brande? Hoe kan die verspreiding van die brand voorkom word? Hoe word die brande geblus? Hoeveel mense word deur hierdie brande geraak? Hoe reageer die inwoners tydens 'n voorval? Hierdie werk beantwoord die voorgenoemde vrae deur (a) die ontwikkeling van 'n raamwerk vir die brandondersoek in IN, (b) die ontleding van 'n werklike IN-brandvoorval, (c) die toepassing van die raamwerk wat ontwikkel is vir 'n "post-flashover" IN-brand en (d) om die oorsake van brande in IN-brande beter te verstaan.

Eerstens word die raamwerk, wat gebruik maak van welbekende forensiese brandondersoekbeginsels en -riglyne, ontwikkel om (a) die oorsprong en oorsaak van n vuur te identifiseer, (b) data verkry van die menslike gedrag tydens die brand, (c) om die brandverspreidingsvolgorde te verstaan en (d) om die doeltreffenheid van die brand onderdrukking en reaksiepogings te evalueer. Daarna word 'n IN-brand, vasgevang op kringtelevisie kamera, ontleed. Die analise bied n geleentheid aan om die volgende te bestudeer: (a) die brandverspreiding, (b) die menslike gedrag en (c) die brandbestryders se reaksie en bedrywighede. Hierna word die raamwerk toegepas op die brandgebeure. Die toepassing van die raamwerk verskaf die geleentheid om hipoteses te ontwikkel wat die oorsprong van die vuur akkuraat defineer asook die patroonvormingvolgorde. Dit is fundamenteel vir die verbetering van die voorgestelde riglyne om die beperkings en kwalitiet te verstaan.

Die studie beklemtoon die moeilikhede omtrent die verkry van inligting omtrent IN-brande. Dus was 'n alternatiewe benadering gebruik wat fokus op die brandrisiko persepsie van die inwoners. Die ontleding wys op die moontlikehede dat (a) die opname se risiko teikengehoor die groot invloed het op die risiko persepsie, (b) die inwoners se brandrisiko persepsie van hul nedersettting dieselfde is as die van die brandbestryders van vorige studies, (c) dat risiko vermindering voorstelle fokus op die vermindering van die gevolge van die brand, (d) dat die nasionale brand statistiek nie die oorsake van brande aan teken nie en (e) dat die verbetering van die dokumentasie verwerking na 'n brand kritiese informasie kan lewer wat kan help met brandvoorkomingsmaatreëls.

Deur vorige brandgebeure te ondersoek verkry navorsers 'n beter begrip van IS-brande wat kan gebruik word om die ontwerp van voorkomingsplanne te fasiliteer wat spesifiek op informele nedersettingsvereistes reageer, brandverspreidingsmodelle ontwikkel of bekragtig, brandbestrydersreaksie en opleiding verbeter, beplan vir voorvalle, en gemeenskapsbrandbewustheid te ontwikkel. Hierdie werk kan van toepassing wees op ander lae-inkomste gemeenskappe soos vlugtelingkampe, markte, IN in ander lande met verskillende toestande, en soortgelyke nedersettings.

List of publications by candidate

Published journal papers based on, or related to, work in this thesis:

N. Flores Quiroz, R. Walls, A. Cicione. Developing a Framework for Fire Investigations in Informal Settlements, Fire Saf. J. 120 (2021) 103046. doi:10.1016/j.firesaf.2020.103046. **[Included as Chapter 4 in this dissertation]**

N. Flores Quiroz, R. Walls, A. Cicione, M. Smith. Fire incident analysis of a large-scale informal settlement fire based on video imagery, Int. J. Disaster Risk Reduct. 55 (2021). doi:10.1016/j.ijdrr.2021.102107. **[Included as Chapter 5 in this dissertation]**

N. Flores Quiroz, R. Walls, A. Cicione, M. Smith, Application of the Framework for Fire Investigations in Informal Settlements to large-scale real fire events – Consideration of fire formation patterns, fire spread rates and home survivability, Fire Saf. J. 125 (2021). doi:10.1016/j.firesaf.2021.103435. **[Included as Chapter 6 in this dissertation]**

N. Flores Quiroz, R. Walls, A. Cicione. Towards Understanding Fire Causes in Informal Settlements Based on Inhabitant Risk Perception, Fire. 4 (2021). doi:https://doi.org/10.3390/fire4030039. **[Included as Chapter 7 in this dissertation]**

A. Cicione, R. Walls, Z. Sander, **N. Flores**, V. Narayanan, S. Stevens, D. Rush. The Effect of Separation Distance Between Informal Dwellings on Fire Spread Rates Based on Experimental Data and Analytical Equations, Springer US, 2021. doi:10.1007/s10694-020-01023-8. **[Abstract included in Appendix A of this dissertation]**

A. Cicione, R. Walls, S. Stevens, Z. Sander, **N. Flores**, V. Narayanan, D. Rush. An Experimental and Numerical Study on the Effects of Leakages and Ventilation Conditions on Informal Settlement Fire Dynamics. Fire Technol (2021). https://doi.org/10.1007/s10694-021-01136-8. **[Abstract included in Appendix A of this dissertation]**

A. Cicione, R. Walls, **N. Flores**, J. Pretorius J., Z. Sander, V. Narayanan, S. Stevens, L. Gibson, D. Rush. An experimental study of the fire dynamics of double storey informal settlement dwellings. Under review. **[Abstract included in Appendix A of this dissertation]**

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Acronyms

CoCT	City of Cape Town
CSIRO	Commonwealth Scientific and Industrial Research Organization
FFIIS	Framework for Fire Investigations in Informal Settlements
FPASA	Fire Protection Association of South Africa
FRS	Fire and Rescue Services
FRSIR	Fire & Rescue Service Incident Report
HRR	Heat Release Rate
IAAI	International Association of Arson Investigators
IS	Informal Settlement
ISDs	Informal settlements dwellings
IY	Imizamo Yethu
LEAA	Law Enforcement Assistance Administration
MANDISA	Monitoring, Mapping and Analysis of Disaster Incidents in Southern Africa
NBS	National Bureau of Standards
NGO	Non-governmental organization
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
OC	Occurrence Book
PECC	Public Emergency Communications Centre
RUI	Rural-Urban Interface
SAPS	South African Police Services
WUI	Wildland-Urban Interface

Chapter 1: Introduction

1.1 Introduction to the work

Informal settlements (IS), can be defined as “areas where groups of housing units have been constructed on land that the occupants have no legal claim to, or occupy illegally or; unplanned settlements and areas where housing is not in compliance with current planning and building regulations (unauthorized housing)” [1]. ISs are typically low-income communities existing on the periphery of cities, characterised by poverty, poor infrastructure, lack of tenure and high dwelling density [2]. ISs are seen all over the world and, depending on the country they are, may be known as shantytowns, favelas, ghettos, squatter camps or poblaciones, while individual dwellings may be referred to as shacks, hokkies or mediaguas. It should be noted that some of these terms are derogatory in nature. Around 12.5% of the world’s population reside in ISs [3]. In terms of the proportion of the urban population, the percentage of people living in IS varies depending on the region, where in Africa it is more than 60%, in Asia is 30%, and in Latin America and the Caribbean is roughly 24% [4]. Fig. 1-1 presents the proportion of urban population living in IS for different regions. Although the graph depicts a proportional decrease for most of the regions, since 1990 the absolute number of IS’s residents has increased by 213 million [4]. Hence, the total number of people living in areas urban areas has increased faster than that in IS. Taking Western Asia as an example, even though the proportion of population in IS remains relatively constant, the absolute numbers show that in 1990 there were 12.3 million people living in IS while in 2014 there were 37.5 million [5].

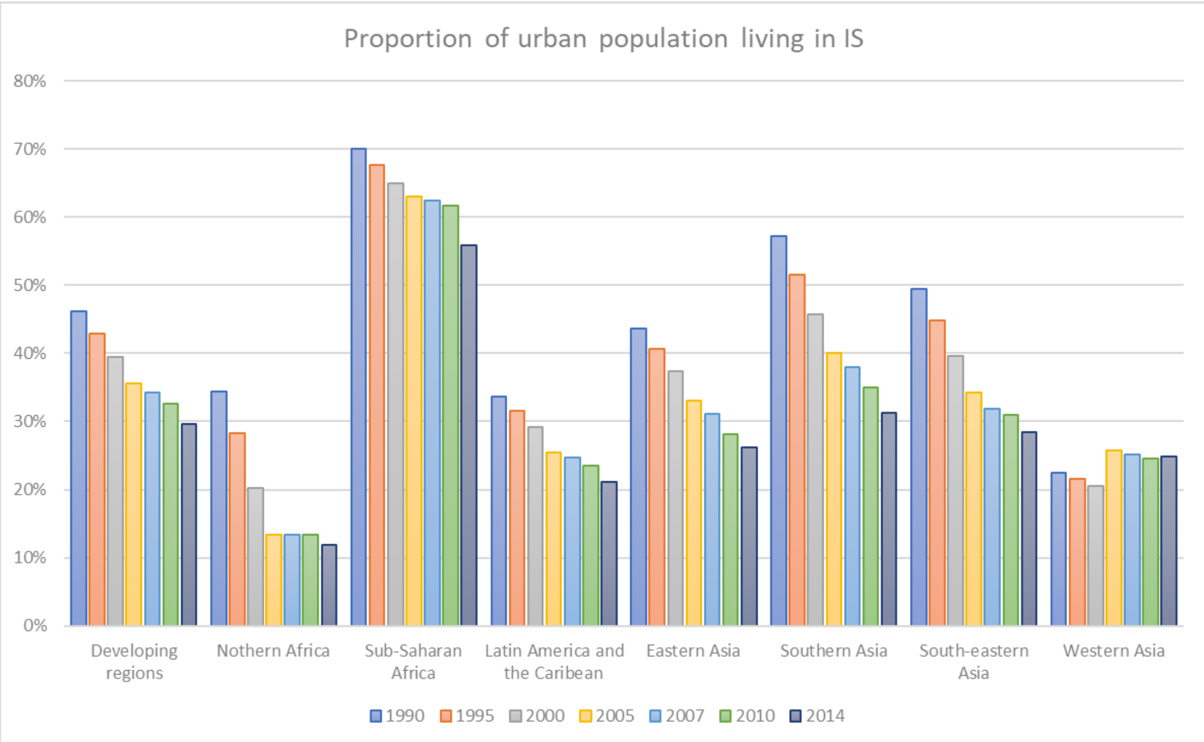

Fig. 1-1: Proportion of urban population living in IS [3].

IS are typically characterised by poverty, poor infrastructure and high dwelling density [1]. These factors create extremely vulnerable environments in which fires, flooding and other hazards are often seen [2,3]. Focussing on the fire problem, there are several conditions that enhance the occurrence of fires and their consequences. Hazardous sources of energy, informal electric supply, poor constructions methods and lack of water supply, all influence both the chance of ignition and rate of fire spread. Fires in IS are a significant problem in developing countries [6]. In South Africa, 5544 IS fire incidents were reported during 2019 [7]. On average, over the period 2003-2017 the number of IS fires increased yearly at 6% [8]. Furthermore, the number of fatalities increased at a yearly rate of 12.6% during the same period [8]. Although there is no information regarding the average number of dwellings that are affected, it is known that one very large single event can affect more than 2000 homes displacing roughly 10000 people [9]. Additionally, it has been acknowledged that often fires involving only one dwelling are extinguished by the residents and are not reported [10]. It is clear that fires in IS should be a significant concern and that efforts should be taken in order to understand them such that fire safety can be improved through an evidence-based approach.

1.2 Problem statement

Although in the recent years, there has been several research studies investigating fire dynamics and fire spread mechanisms in informal settlements [11–13], the research to date has tended to be theoretical or based on idealised experiments rather than in analysing real fire incidents. This is largely due to the difficulties associated with obtaining data from real incidents. Such incidents occur quickly, are very chaotic, have limited data collection being done after them, involve complex community interactions, and many variables affect the fire behaviour (e.g., settlement density, fuel loads, construction materials, firefighting activities, etc.). Currently, there is insufficient research available to understand what happens during IS fire incidents such that response efforts (e.g., active fire protection, passive protection, risk reduction, etc.) can be improved. We need to know: what is causing fires? How do fires spread? What stops fires from spreading? How are fires put out, either by residents or fire departments? How many people are affected in an incident? How do inhabitants respond during an incident?

There is negligible literature available on post-fire investigations for IS fires. As pointed out by Babrauskas [14] fire investigations can provide significant information to the fire safety engineering field. If possible, an investigation should cover a broad array of subjects such as fire origin and cause determination, fire spread, human behaviour in fire and firefighter’s performance. All of the aforementioned factors are important for fire brigades, municipalities, non-governmental organisation (NGOs) and engineers when developing fire safety interventions. By developing suitable fire investigations, the questions posed above can be answered, or at least the data we have can be significantly improved, such that IS fires can be addressed in the most effective manner.

1.3 Project goal and objectives

The main goal of this research is to understand fire incidents in IS through developing and applying a forensic investigation framework to address both ignition and fire spread. This research project seeks to address the following question:

What happens in IS fire incidents?

In order to answer this key question, the following additional questions must be addressed:

> ***How can a fire investigation in an IS be conducted?***
>
> Based on well-known forensic fire investigation principles a framework for fire investigations in informal settlements (FFIIS) will be developed.

Is it possible to determine the fire cause, fire origin and fire spread of an informal fire event by conducting a fire investigation?

By applying the FFIIS to real fire events hypotheses for the fire cause, point or area of fire origin and the pattern formation sequence will be proposed.

What are the causes of IS fires?

An important aspect to define is, to what extent can fire cause be determined based on evidence at a fire scene? Due to the lack of physical evidence in IS fires, as homes are typically destroyed and collapse, the application of the FFIIS does not provide information pertaining the fire cause. The use of existing investigation procedures (e.g., NFPA 921) also have limited applicability as investigators invariably will need to rely on eyewitness accounts for determining fire cause. Hence, to improve the understanding of fire causes in IS fires, the fire risk perception of IS's inhabitants will be analysed to provide a basis for inhabitant feedback and fire risk quantification.

1.4 Scope of the research

This work considers the investigation of real IS fires, focusing on (a) the determination of the fire cause, fire origin and fire spread, (b) the firefighters' operations, and (c) the IS's residents' behaviour during the fires. To this end, a framework to conduct fire investigations in IS will be developed and then applied to IS fire incidents. Although it is expected that the guidelines proposed in the framework can be applied to IS all over the world (but may require some modification), in this work the framework will only be applied to large fire incidents in Cape Town, South Africa.

1.5 Report synopsis

The structure of this dissertation to achieve the objectives listed in Section 1.3 is presented in this section. Note that this dissertation was done by publication and that Chapters 4-7 are exact copies of the journal papers. A visual representation of the transition between the different papers is shown in Fig. 1-2. The first paper, "Framework for Fire Investigations in IS" (Chapter 4), presents the considerations, challenges, and methodology to conduct a fire investigation in an IS which sets the basis for the other three publications. Chapter 5 presents the second paper "Fire incident analysis of a large-scale informal settlement fire based on video imagery", and this incident will be used to benchmark the findings of Chapter 6. Chapter 6 presents the third paper "Application of the Framework for Fire Investigations in Informal Settlements to large-scale real fire events – Consideration of fire formation patterns, fire spread rates and home survivability", where the Framework proposed in Chapter 4 is applied to three case studies. The last paper, Chapter 7 "Towards understanding fire causes in informal settlements based on inhabitant risk perception", analyses interviews conducted with IS's residents to gain the knowledge about fire causes that could not be obtained in the previous chapters.

I. Literature review: A literature review was conducted which covers aspects such as fire behaviour in IS, urban fires and wildland-urban interface fires, fire investigation methodology and techniques, and human behaviour in fire (Chapter 2). It is important to note that additionally, each journal paper contains a brief literature review.
II. Methodology (Chapter 3): Addresses how the scope was developed to suit COVID requirements and the ethical considerations, and also gives an overview of approaches used in the work.

III. "Developing a Framework for Fire Investigations in Informal Settlements" (Chapter 4 – published in the Fire Safety Journal):

   i. The literature review covers fire investigation techniques for enclosure and wildland fires.
   ii. Analysis of fire statistics in South Africa (Section 4.3). The analysis illustrates (a) the impact that IS fires have in the number of fatalities, (b) that there is a large number of fires for which fire cause is not determined, and (c) the need of investigating fires in IS.
   iii. The development of a Framework for Fire Investigations in Informal Settlements (FFIIS) is presented on Section 4.4. The FFIIS offers different approaches for the types of fires that can be seen in ISs (pre-flashover, post-flashover and large post-flashover fires).
   iv. The application of the FFIIS to the Imizamo Yethu fire (Section 4.5). This fire event was selected because it was analysed in depth by Kahanji et al. [15].
   v. It was found that for the particular case study the FFIIS allowed the identification of the fire origin area and the pattern formation sequence.

The FFIIS will be applied to more case studies in Chapter 6.

IV. "Fire incident analysis of a large-scale informal settlement fire based on video imagery" (Chapter 5 – published in the International Journal of Disaster Risk Reduction):

   i. The analysis of a real IS fire that was recorded by a CCTV camera.
   ii. The study includes:
      a) The fire spread analysis. The progress of the fire line and fire spread rates were estimated.
      b) The residents' actions during the different stages of the fire were identified.
      c) Firefighters' operations were observed and the problems they faced were identified.
   iii. It was found that (a) the wind was the main factor that affected the fire spread, (b) the residents' actions were similar to the actions observed in previous research in formal residential fires, and (c) the firefighters' operations were hindered by the lack of water supply.

This fire event will be used as the benchmark for one of the case studies in Chapter 6, when the FFIIS proposed in Chapter 4 is applied to three real IS fires.

V. "Application of the Framework for Fire Investigations in Informal Settlements to large-scale real fire events – Consideration of fire formation patterns, fire spread rates and home survivability" (Chapter 6 – accepted for publication in the Fire Safety Journal):

   i. The FFIIS developed in Chapter 4 is applied to three real large fire events. One of the fire events selected is the fire analysed in depth in Chapter 5, which was used to benchmark the FFIIS.
   ii. Hypotheses were proposed for the area of fire origin and for the pattern formation sequence.
   iii. It was found that (a) the FFIIS can accurately define the area of fire origin and for the pattern formation sequence, and (b) fire patterns for large post-flashover fires in IS can be treated as wildland fire patterns

VI. "Towards understanding fire causes in informal settlements based on inhabitant risk perception" (Chapter 7 – published in Fire):
   i. A survey consisting of data from 2178 IS households that were affected by a large-scale fire is presented. The survey considered questions related to the fire risk perception in the settlement.
   ii. It was found that (a) the survey's risk target had a strong influence on the risk perception, (b) the inhabitants' fire risk perception of their settlement is similar to that of firefighters in previous research, (c) the national fire statistics are not capturing the causes of real fire incidents, and (d) the improvement of the documentation process after a fire event could provide critical information for the implementation of prevention measures.

VII. Discussion and additional findings (Chapter 8): Provides additional information and discussions that were not included in the published papers of this dissertation but provide novel insight that will be beneficial in future work.

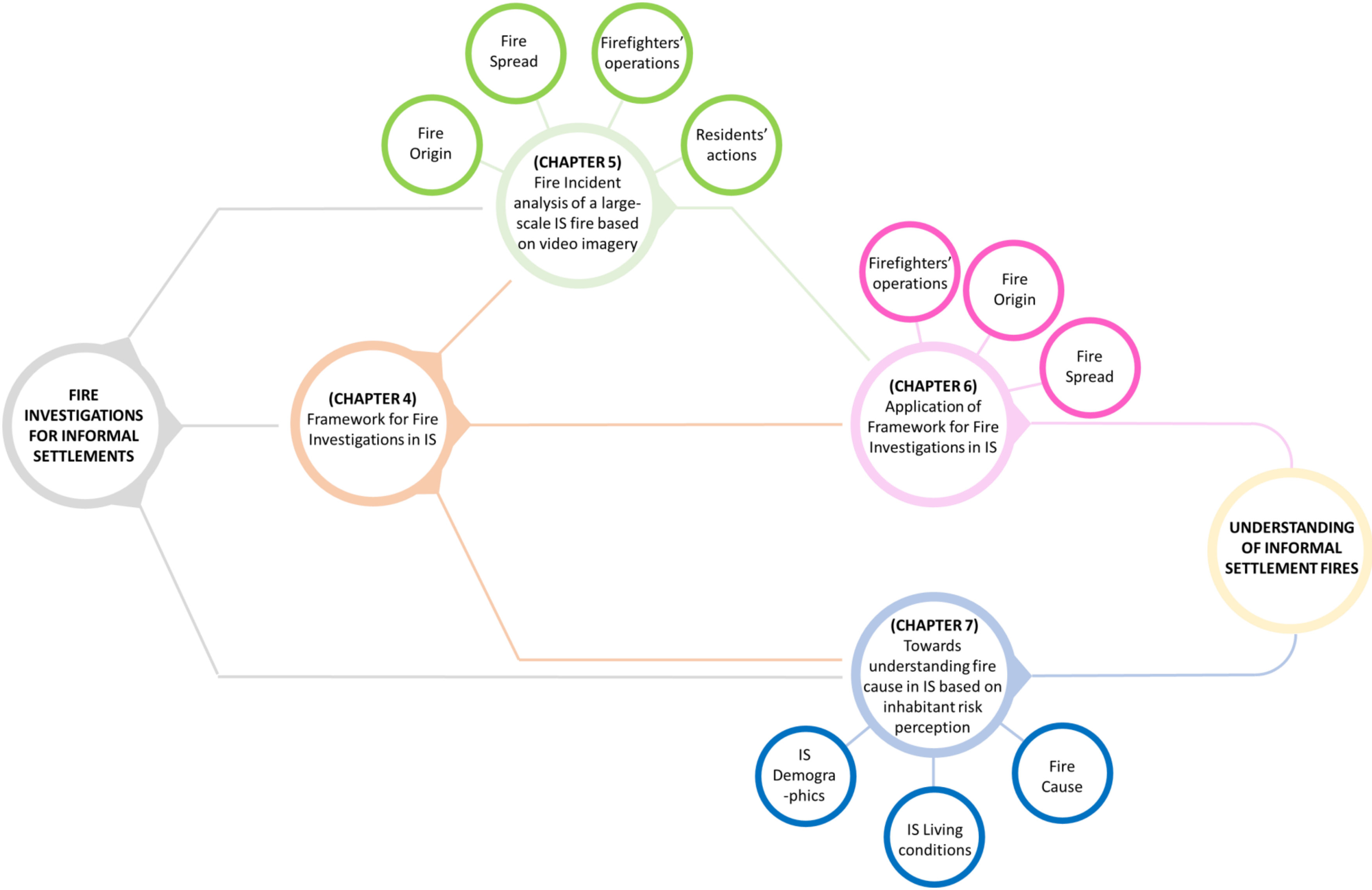

Fig. 1-2: Report structure. The dissertation topic 'Fire Investigations for Informal Settlements' was addressed through four papers.

1.6 Project exclusions and limitations

This work gives novel insight with regards to informal settlements fires by analysing and investigating past events. However, due to the difficulty associated with gathering information, only a limited number of fires were studied. This work can serve as basis for future research involving IS or other low-income community fires. The following are limitations or exclusions of the work done in this dissertation:

I. This work will only serve as basis to understand IS fires in a holistic way. Although it is expected that guidelines proposed in the FFIIS with respect to the fire cause, fire origin and fire spread determination can be applied to any IS or other low-income settlements, it should be noted that the fire development, people's behaviour, firefighting operations, and weather and wind conditions will change depending on the settlement.

II. This research project focusses on ISs located in Cape Town, South Africa. Furthermore, the fires that were studied correspond to large post-flashover fires (the dwelling of fire origin reached flashover allowing the fire to spread to a large number of homes). The findings of this work might not be representative of ISs located in other areas. The impact of geographical and cultural conditions should be studied in future work.

III. (a) Pre-flashover fires (the dwelling of fire origin did not reach flashover) and (b) post-flashover fires where spread to adjacent dwellings did not occur, or only spread to a small number of homes, were excluded from this work. This is due to the fact that usually those fires are extinguished by the residents, so they are typically not reported. Hence, negligible data is currently available for such incidents.

IV. This work is not sufficient to fully determine the effectiveness or the applicability of the FFIIS in general as there are a wide variety of conditions that influence fire spread in ISs. Further application of the FFIIS to different types of real fire incidents in ISs is required to identify possible changes or improvements that need to be done in order to obtain better results for each of the fire categories (i.e., pre-flashover fire, post-flashover fire, large post-flashover fire).

Chapter 2: Literature review

2.1 Introduction

This chapter discusses the basic concepts needed to understand the work done in the following chapters. Fire behaviour in ISs is described initially (Section 2.2). For that, a brief introduction to enclosure fires and wildland fires are presented, although the reader is referred to [16–19] for more detailed information. Then Section 0 presents urban and wildland-urban interface fires and their similarities and differences with IS fires. Section 2.4 introduces the basic concepts and techniques required to conduct fire forensic investigations in both enclosure and wildland fires. Finally, Section 2.5 reviews the topic of human factors and human behaviour in fire. It should be noted that Chapter 4, Chapter 5, Chapter 6 & Chapter 7 include a short literature review that presents (a) problems associated with investigating fires in IS, and statistical information pertaining IS fires in South Africa, (b) previous research on IS fires, and (c) fire risk and risk perception concepts.

2.2 Fire behaviour in informal settlements

ISs have characteristics that influence the fire behaviour in relation to formal homes (e.g., constructions materials and methods, close proximity between dwellings, the use of more dangerous sources of energy, etc). Depending on the fire development and scale, IS fires can present features of either enclosure and/or wildland fires. This section presents a brief description of enclosure and wildland fires and how IS fires combine both behaviours.

2.2.1 Enclosure fires

Fig. 2-1 depicts the different stages of an enclosure fire. After ignition, the fire can self-extinguish or grow. The fire can die out if the first ignited fuel completely burns without releasing enough heat for the fire to spread to adjacent fuels (curve 1 in Fig. 2-1). Another possibility is that as the fire is growing the oxygen levels decrease to the extent that the fire becomes ventilation controlled. Under this condition the HRR decreases entering the decay stage in which the fire could extinguish if the oxygen levels decrease to 10-15% (curve 2 in Fig. 2-1). If there is enough fuel and oxygen, the fire can spread and the HRR will increase. The fire will continue growing and the combustion products, such as smoke, start to rise. As the combustion continues a hot layer starts to develop. The temperature of the hot layer and its height continue increasing. The hot layer radiates downwards which enhance the rate of burning and the flame spread. Until this stage the fire is fuel controlled. How the fire behaves next will depend on the ventilation conditions. If there is enough oxygen available, the fire development follows curve 3 in Fig. 2-1. When the hot layer is hot enough (approximately 600°C) with heat flux at floor level of approximately 20 kW/m^2 the fire could reach flashover. Flashover can be defined as “the transition from a localized fire to the general conflagration within the compartment” [16]. After flashover, the fire becomes ventilation controlled and the fully developed stage comes. In this stage high heat release rates and temperatures (900-1100°C) are seen. The fully developed fire will last if there is fuel and oxygen available. Finally, the fire enters the decay phase, and usually the fire becomes fuel controlled. After flashover the structural components of the compartment are exposed to temperatures that affect their functionality. This could cause local failure or even collapse. If during the fire growth there is not enough oxygen available to reach flashover, the intensity of the fire will decrease as shown in curve 2 and 4 in Fig. 2-1. Even with the decrease of the HRR, the temperatures inside the enclosure are still high and pyrolysis could be taking place. If the oxygen deficiency continues the fire self-extinguishes as described previously. If additional air is provided (e.g., opening of a door or window) the fire can progress into a fully develop fire (curve 4 in Fig. 2-1). Due to the high temperatures and presence of unburnt combustibles gases in the compartment a rapid fire development (i.e., backdraft) could occur.

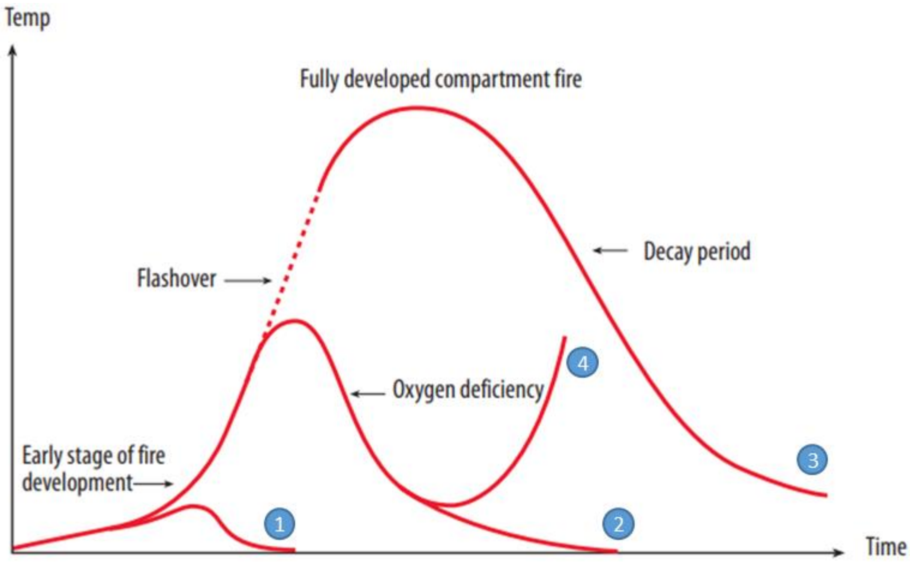

Fig. 2-1: Fire development.1) Self extinguishment due to fuel depletion or fire's availability to spread to adjacent fuel. 2) Self extinguishment due to oxygen depletion. 3) Well-ventilated fire. 4) Interrupted fire development due to oxygen deficiency [17].

2.2.2 Wildland fire behaviour

This section discusses the factors that determine the wildland behaviour. It is based on the Intermediate Wildland Fire Behaviour course from the National Wildfire Coordinating Group [20]. The fire forensic aspects for wildland fires are presented in section 0.

There are three main components that determine the behaviour of a wildland fire: weather, topography, and fuels. They are presented in more depth in Table 2-1. Weather refers to the short-term variations of the atmosphere. It is the most variable of the three, and includes temperature, relative humidity, wind conditions and atmospheric stability. Topography, on the other hand, is the most stable over time but changes over distance. Topography includes elevation, position on the slope, aspect, and steepness of the slope. The steepness of the slope directly affects the flame spread. Previous research [16] has shown that the higher the angle of inclination the higher the rate of flame spread (Fig. 2-2). Topographic features, such as narrow canyons or intersecting drainages, can also influence air flows.

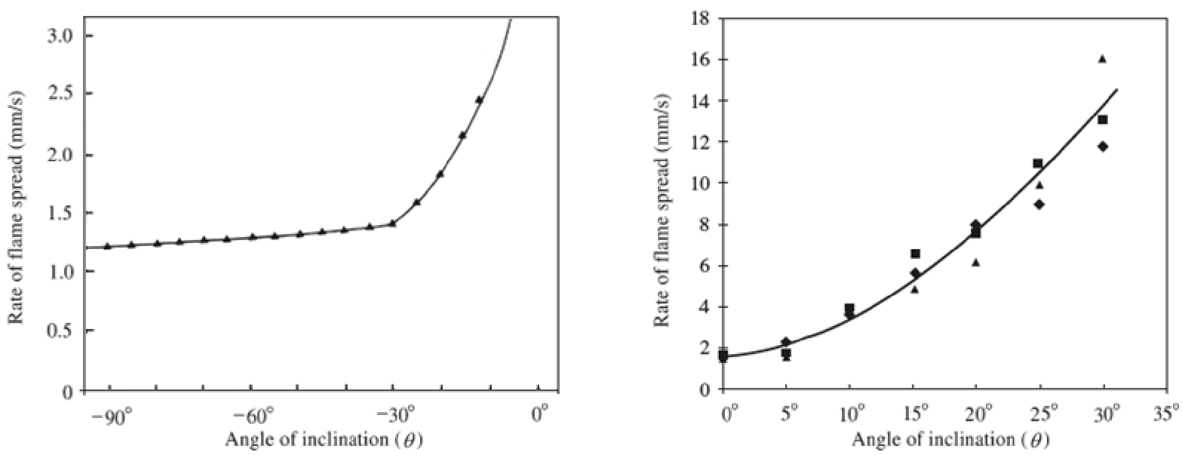

Fig. 2-2: Flame rate spread as function of angle of inclination [16].

Fuel includes living and dead plants. Fuel factors such as size, shape, compactness, continuity (horizontal and vertical), moisture content, and chemical content can change over time and over space. There are ground, surface, and aerial fuels. Ground fuels usually present slow smouldering or creeping fire spread. Surface fuels allow for fast spread rates. Additionally, most wildland fires ignite and spread on surface fuels. The fire spread in aerial fuels will depend on the canopy conditions (i.e., open or closed). Open canopies experience faster surface spread than closed canopies, and it is likely than torching[1] occurs. Closed canopies present better conditions for crown fires[2].

Table 2-1: Components that affect the wildland behaviour (I: Ignition, FI: Fire intensity, ROS: Rate of spread, S: Spotting, T: Torching, C: Crowning) [20]

	Component	Description	Affects
Weather	Temperature	Hot temperatures and direct sunlight can preheat fuels.	I - FI
	Relative Humidity	It affects the fuel moisture content. Relative humidity thresholds for extreme fire behaviour vary over time and space and are different for different fuel types.	I - FI
	Wind conditions	It is the most variable, difficult to predict, and critical factor affecting fire behaviour. It supplies oxygen for the combustion, it increases the fire spread by bringing the flames closer to unburnt fuels or by transporting embers creating secondary fires, its direction determines the fire spread.	FI - ROS - S
	Atmospheric stability	A stable atmosphere will resist vertical motion. However, they can produce foehn winds[3]. In an unstable atmosphere the vertical temperature change allowing air to move upward or downward. This promotes the formation of vertically developed clouds. Unstable atmospheric conditions are usually associated with extreme wildland fire behaviour.	FI-ROS
Topography	Elevation	Influences general climate affecting fuel availability.	
	Position on the slope	Influences temperature and humidity, affecting the types, load and moisture content of fuels. Fires that start at the base of a slope are more likely to become large fires.	
	Aspect	It is the cardinal direction that a slope faces and results in variations in direct sunshine, precipitation, and wind. Influences fire occurrence and burning conditions.	I - FI
	Steepness of the slope	Affects the fire spread influencing the preheating of upslope fuels, and the firebrands' transport.	FI - ROS

[1] The burning of the foliage of a single tree or a small group of trees, from the bottom up [175].
[2] A fire that advances from top to top of trees or shrubs more or less independent of a surface fire [175].
[3] A warm, dry and strong general wind that flows down into the valleys when stable, high pressure air is forced across and then down the lee slopes of a mountain range. The descending air is warmed and dried due to adiabatic compression producing critical fire weather conditions. Locally called by various names such as Santa Ana winds, Devil winds, North winds, Mono winds, etc [175].

Table 2-1: Components that affect the wildland behaviour (I: Ignition, FI: Fire intensity, ROS: Rate of spread, S: Spotting, T: Torching, C: Crowning) [20] *(Continued)*

Component		Description	Affects
Fuel	Loading	Amount of fuel available in terms of weight of fuel per unit area.	I -FI - ROS
	Size and shape	It is characterized by surface-area-to-volume ratio. High ratios burn more easily and are easier to lift. The size and shape are also important for spotting.	I -FI - ROS
	Compactness	It based on the space between fuel particles. Less compact fuels usually present higher ROS since they have more oxygen available for combustion. The fuel depth bed and orientation will have an impact.	I -FI - ROS
	Horizontal continuity	It is the horizontal distribution of fuels at different levels. In presence of barriers (fuel discontinuity) a strong wind will typically be necessary for the fire to continue spreading. Continuity in aerial fuels (closed canopy) reduces the wind speed and moisture evaporation.	ROS - C
	Vertical continuity	It is the vertical distribution of fuels. It can allow the fire to spread from surface into crowns of trees or shrubs.	T - C
	Moisture content	It determines how fast the fire will spread. The dead fuel component is critical because it heats the live fuels allowing the fire to spread.	I -FI – ROS - T - C
	Chemical content	A fuel's chemical composition can enhance or retard combustion. Volatile substances such as oils, wax, and resins can produce high ROS and high FI. Fuels with high mineral content can reduce ROS and FI.	I -FI - ROS

2.2.3 Fires in informal settlements

Fires in informal settlements has been studied in multiple projects in recent years. This section is based on the work presented in [21] that compiles the knowledge gathered in previous research.

Through experimental work, it was found in [9,13] that fires in within a single IS dwelling present similar behaviour to typical enclosure fires. After the ignition IS fires will have a growth stage and, if flashover occurs, a fully developed stage will follow, which finishes with a decay stage. A number of the conditions seen in ISs affect the fire behaviour. First, due to the reduced size of the dwellings, flashover can occur extremely fast (even one minute after ignition). Second, due to the poor construction materials and methods, the dwellings usually collapse, allowing for spread to adjacent dwellings. In [22] it was found that the fire spread between timber clad dwellings was much faster than for steel clad dwellings, with times of 4 to 8.5 minutes, respectively. Additionally, it was determined that the separation between dwellings should range between 3 and 5 m to limit the fire spread. When a fire spreads to multiple other dwellings the fire starts to resemble wildland fires and factors such as fuel continuity, weather and topography become critical. These aspects will be discussed in greater depth in later chapters.

2.3 Urban and Wildland-Urban Interface fires

Urban fires can be defined as fires that occur in an urban area where, due to the density and/or construction materials or methods, the fires spread to a large number of structures [23]. These fires have a big impact on people (many casualties are seen) and on property [23]. The zone in which urban structures are in, or near, wildland vegetation is referred to as Wildland-Urban Interface (WUI) [24]. WUI fires have received significant attention during the last decade. The rapid growth in the physical size of the WUI worldwide added to the effects of climate change have had a big influence in the number and magnitude of WUI fires [24,25]. The Large Outdoor Fires and the Built Environment (LOF&BE) group [26] has studied the large outdoor fire problem around the world, which includes urban fires, WUI fires, wildland fires and IS fires. In [27] Manzello et al conclude that urban, and specially WUI fires, are a concern in all regions.

2.3.1 Urban fires in Japan

Although large urban fires occur all over the world, urban fires in Japan are particularly relevant for this work. This is because the similarities that some Japanese cities have with ISs. Factors that make Japanese cities extremely vulnerable to urban fires, especially after an earthquake [28–31], are listed in [28]. These include narrow streets that allow a faster fire spread, blocked streets that hinder fire department access, old wooden dwellings, and the fact that some building sites do not comply with Building Laws. According to Himoto [28], thanks to new code regulations and the improvement of the fire brigade operations the damage due to “ordinary” fires (i.e., not a consequence of an earthquake) has considerably decreased in the last century. In 1951 Hamada developed the first model to predict urban fire spread rates, based on factors such as wind conditions, separation between dwellings, construction type, etc. [28]. It is interesting to note that these factors are also relevant in IS fires. Different equations were formulated for downwind, upwind and perpendicular to the wind fire spread [28]. Hamada’s work was the base for other fire spread models. Recently fire spread models have been developed that take into consideration factors such as thermal radiation and firebrands [29,30,32].

2.3.2 WUI fires

WUI fire research has been focussed on (a) the assessment of wildfire exposure to communities [33], (b) the economic, social and environmental impacts of WUI fires [34–36], (c) the transport and production of firebrands [37–41] and (d) the investigation of real incidents [42–47]. Focussing on the latter, institutions such as National Institute of Standards and Technology (NIST) in the USA, and the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia have conducted valuable research on real fire incidents, amongst others. NIST developed a methodology to collect and process data from WUI fires. This methodology has been applied to the Amarillo Fires [43,48], the Waldo Canyon Fire [42] and to the Camp Fire [49,50]. This work has allowed researchers to reconstruct fire timelines, identify the factors that influence fire losses, identify structure ignition vulnerabilities and structure ignition pathways, and to identify ways to improve the methodology developed. Australia is also known for being affected by WUI fires, also referred as bushfires. Iconic WUI fires have also been studied in order to understand them [51–54]. While this research has allowed for an understanding of fire spread mechanisms and factors that influence the fire spread it has also illustrated the impact that WUI fires have in life loss. In [54] Blanchi et al. analysed the civilian fatalities that occurred as a result of bushfires between 1901 and 2011 in Australia. One of the main findings was the fact that 78% of the fatalities occurred within 30 m of the forest edge. It was also found that between 1901 and 1964 around 82% of the fatalities are males, while between 1965 and 2011 it was only 56%. This can represent the change of gender role when responding to fires. The topic of human behaviour in fire will be discussed in Section 2.5.

2.3.3 Urban fires vs WUI fires vs Wildland fires

As mentioned in [27], fire propagation in urban fires and WUI fires is much more complex than in a building or wildland fire. It is important to identify similarities and differences among them to determine techniques, models, and/or approaches that can or cannot be used in the study of the different fires. In [55] Bryner presents some of the differences between urban fires, WUI fires and wildland fires focusing on the type of response, the extent of damage and their associated times. Table 2-2 presents these differences and also includes in the comparison the dominating fire spread mechanisms. It can be seen that firebrands are the dominating fire spread mechanism in large urban fires and WUI fires. It has been acknowledged that firebrands are the main concern in WUI fires as they contribute to fast fire spread [56], starting secondary fires sometimes even kilometres away from the fire front [45,57].

Table 2-2: Comparison between urban fires, WUI fires and Wildland fires

Type of fire	Response	Extent of damage	Times	Dominating fire spread mechanism
Urban fire	One or Multiple Fire Departments	Room of origin Floor of origin Building of origin Surrounding buildings Community*	Seconds /minutes Minutes / hours Hours	Flame impingement Radiation Firebrands*
WUI fire	Multiple Fire Departments and Jurisdictions	Interface boundary Neighbourhood Community Part of a City	Minutes Minutes / hours Hours / days	Flame impingement Firebrands
Wildland fire	Multiple Fire Departments and Jurisdictions	40 ha 400 ha 4000 ha 40000 ha	Hours Hours/ days Days	Firebrands

* For large urban fires

As a result of the research that has been conducted on large urban fires it has been noted that building design, town planning and peoples' behaviour have a big impact on the consequences of a fire [28,58]. However, it is very unlikely that the first two can be improved in ISs as they are inherently unplanned by formal agencies, although there can be significant planning within leadership structures in communities.

2.4 Fire Investigations

This chapter discusses the basics of fire scene investigation based on one of the National Protection Association (NFPA)[4] codes, the NFPA 921 "Guide for Fire and Explosion Investigations"[5] [59] and the "Guide to Wildland Fire Origin and Cause Determination" [60], the reader is referred to them for more details . The chapter starts with a historical review to show how the fire forensics field has developed. Then the methodology based on the scientific method is presented for the determination of fire origin, fire spread sequence and fire cause. This is followed by the process of data collection, data analysis and hypothesis development which are explained in depth. Since a sound procedure for carrying out investigations in IS does not exist it is important that the historical development of investigations be appreciated, such that a similar path can be followed in this work when improving post-fire data collection for settlements.

2.4.1 Historical Review

The NFPA 921 code "Guide for Fire and Explosion Investigations" is one of the most internationally utilised codes and sets the standards, requirements and procedures for fire investigations. According to NFPA 921 [59] "A fire or explosion investigation is a complex endeavour involving skill, technology, knowledge, and science". However, until 2001 the definition was "A fire or explosion investigation is a complex endeavour involving both art and science." This modification depicts the changes that fire investigation has gone through. Before NFPA 921 fire investigation was an empirical profession often without a significant scientific foundation. In 1977, the Law Enforcement Assistance Administration (LEAA[6]) published "Arson and Arson Investigation: Survey and Assessment" [61]. Chapter IV of the report presented the results of the methods used in arson investigation, some of them are presented in Table 2-3. It is mentioned that the chapter is not a manual of arson investigation and that there is not published material in the scientific literature to sustain their validity. However, in 1981, the National Bureau of Standards (NBS), now called National Institute of Standards and Technology (NIST), published the Fire Investigation Handbook [62], where some of the methods previously described by LEAA are presented without using cautionary language. Myths such as spalling (for concrete) or alligatoring (for timber), were presented as indicators to determine how fast the fire developed without having performed any scientific experiments to validate them, which allowed these myths to spread and gain credibility.

The first edition of NFPA 921 in 1992 represented a completely different approach for conducting a fire investigation discrediting the many myths that were being used and encouraging the use of the scientific method. The acceptance of NFPA 921 was not immediate, and in 1996 the International Association of Arson Investigators (IAAI) filed an amicus brief[7] [63], to support a fire investigator who

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[4] *"The National Fire Protection Association (NFPA)is a global self-funded non-profit organization, established in 1896, devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards."* [176]

[5] NFPA has recently published the 2021 version of NFPA 921: Guide for Fire and Explosion Investigations. However, the methodology proposed to conduct fire investigations, (which was used to develop the FFIISS), remains the same.

[6] *"The Law Enforcement Assistance Administration (LEAA) was a U.S. federal agency established pursuant to the Omnibus Crime Control and Safe Streets Act of 1968. It was a part of the U.S. Department of Justice. The LEAA was responsible for administering the federal funding to state and local law enforcement agencies. It administered the funding for educational programs, research, state planning agencies, and local crime initiatives. The LEAA was abolished in 1982".* [177]

[7] Amicus briefs are legal documents filed in appellate court cases by non-litigants with a strong interest in the subject matter.

was excluded from testifying because he failed to properly document his observations, requesting that "fire investigators should not be held to a strict reliability inquiry because fire investigation was less scientific." Only in 2000 the IAAI endorsed the adoption of the new edition of NFPA 921 [64].

Table 2-3: Methods to identify arson fires, according to the Law Enforcement Assistance Administration, showing many interpretations of effects that have subsequently be corrected [61]

Effect	Description	Interpretation
Alligatoring effect (Fig. 2-3(a))	Charred wood, giving it the appearance of alligator skin.	Large, rolling blisters indicate rapid, intense heat, while small, flat alligatoring indicates long, low heat.
Crazing of glass	Formation of irregular cracks in glass.	The crazing is due to rapid, intense heat, possible fire accelerant.
Depth of char	Depth of burning of wood.	The fire origin will be located near the deepest burn.
Spalling (Fig. 2-3(b))	Breaking off of pieces of the surface of concrete, cement, or brick due to intense heat.	Brown stains around the spall indicate the use of a fire accelerant.
Line of demarcation (Fig. 2-3(c))	Boundary between charred and uncharred material.	On floors or rugs, a puddle shaped line of demarcation is believed to indicate a liquid fire accelerant. In the cross section of wood, a sharp, distinct line of demarcation indicates a rapid, intense fire.
Sagged furniture springs	The loss of tensile strength and in the collapse of the springs.	Sagged springs are believed to be possible only in either a fire originating inside the cushions (as from a cigarette rolling between the cushions) or an external fire intensified by a fire accelerant.

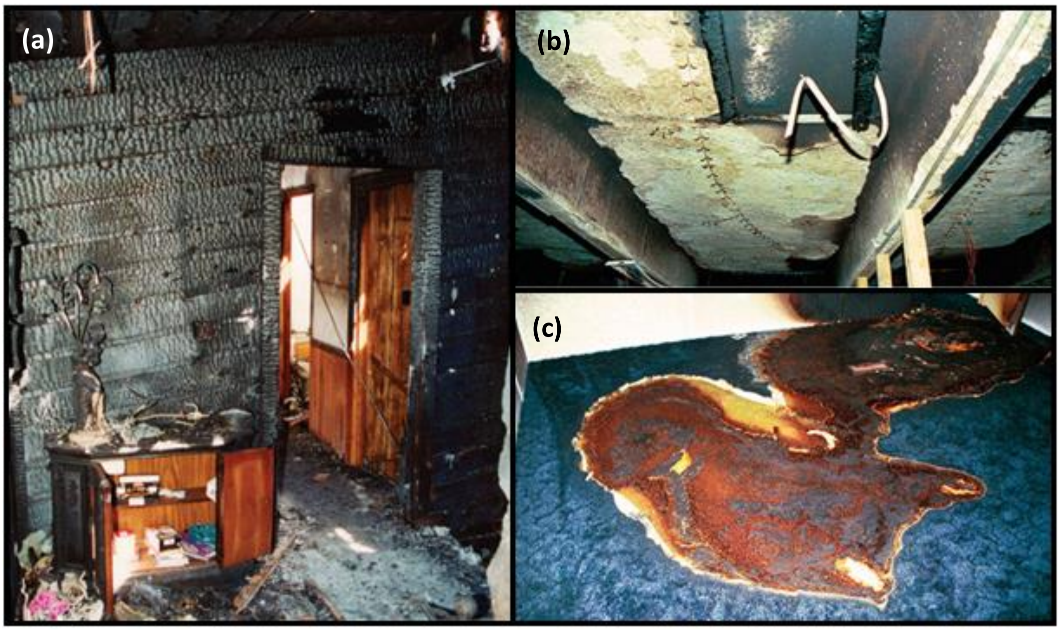

Fig. 2-3: (a) Different sized char blisters produced on the same wall product of the same fire [65]. *(b) Spalling on the ceiling* [66]. *(c) Lines of demarcation on a carpet* [65]

2.4.2 Methodology

The methodology that will be used to conduct fire investigations in ISs follows the scientific method proposed by the NFPA 921 [59]. "The basic methodology should rely on the use of a systematic approach and attention to all relevant details. With few exceptions, the proper methodology for a fire or explosion investigation is to first determine and establish the origin(s), then investigate the cause: circumstances, conditions, or agencies that brought the ignition source, fuel, and oxidant together". Fig. 2-4 presents the different stages for fire origin and fire cause determination. It can be seen that for both analyses the scientific method is used, and seven steps are defined. The steps are (a) recognize the need, (b) define the problem, (c) collect data, (d) analyse the data, (e) develop hypotheses, (f) test the hypotheses, and (g) select final hypothesis. However, the approaches to each step are different, and this is showed below. It is important to remember that in informal settlements fires, due to the rapid development of the fire [11] and the fast spread to adjacent dwellings the fire can behave as an enclosure fire or as a wildland fire. For this reason, the following sections, where the data collection, data analysis and hypothesis process are described, present techniques and concepts for both enclosure and wildland fires.

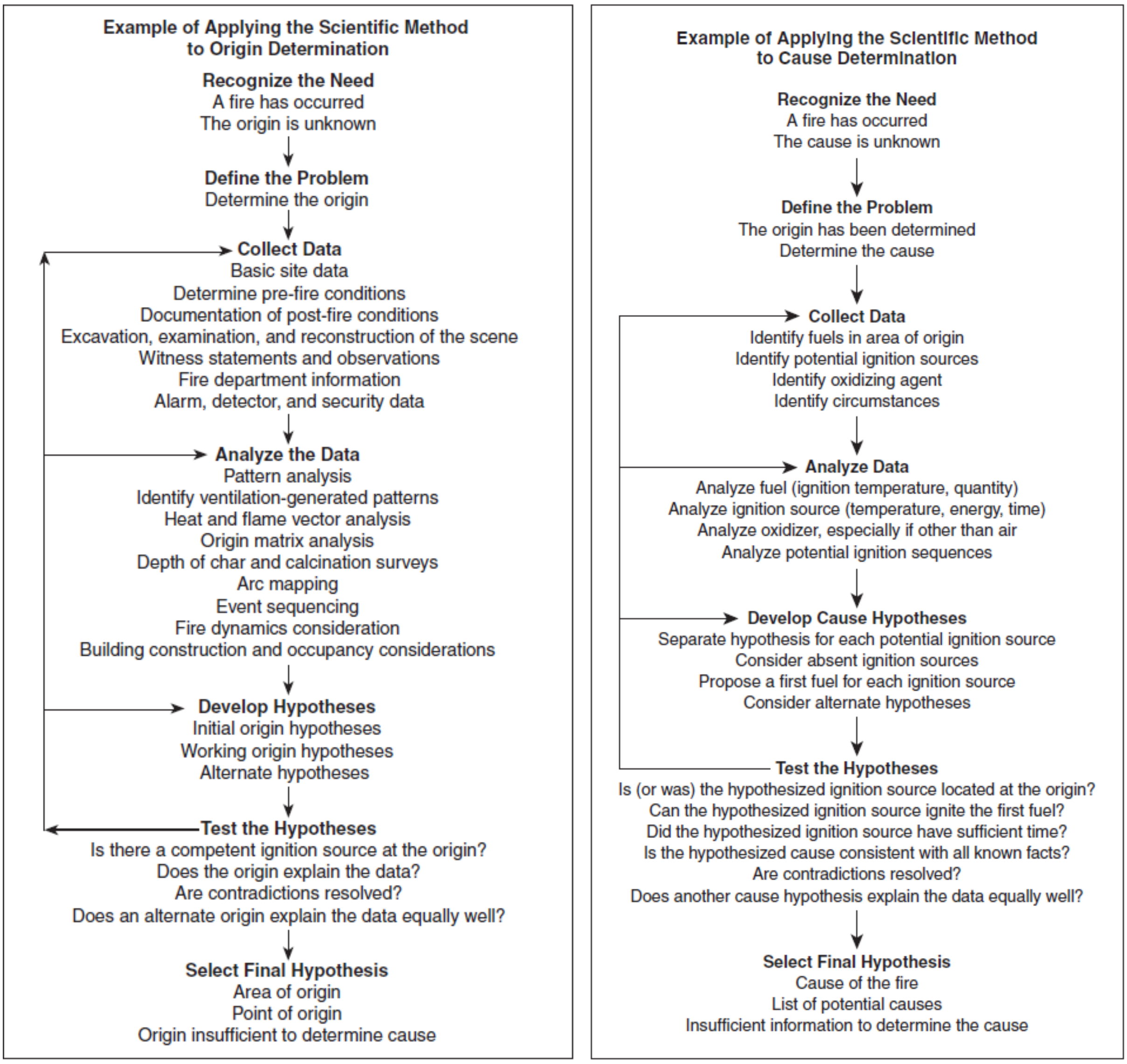

Fig. 2-4: Use of the Scientific Method in Fire Investigations [59]

2.4.3 Data Collection

In general, in any fire scene data can be found in the form of (a) physical evidence, such as fire patterns or artefacts, (b) witness statements, and/or (c) observations. Thus, physical evidence, witness statements and observations consequently are addressed below. In every fire, the investigator can find physical evidence, either inside the dwelling(s) or in the affected area. The physical evidence will help investigators understand the fire spread and, in the best scenario, the area of origin and the potential fire cause can be determined.

NFPA 921 [59] defines physical evidence as any physical or tangible item that tends to prove or disprove a particular fact. The main source of evidence within the fire scene are fire patterns and artefacts. The latter refers to any items related to the fire ignition, development, or spread. Evidence found must be documented through photographs, diagrams and/or field notes. NFPA 921 [59] define fire effects as the changes in or on a material as result of a fire, and fire patterns as the visible or measurable physical changes or identifiable shapes formed by a fire effect or group of fire effects.

2.4.3.1 *Physical Evidence for Fire Origin Determination*

Structural Fire Investigations

Table 2-4 and Table 2-5 address the fire effects and fire patterns present in enclosures, Fig. 2-5 to Fig. 2-7 illustrate the discussions of the aforementioned tables.

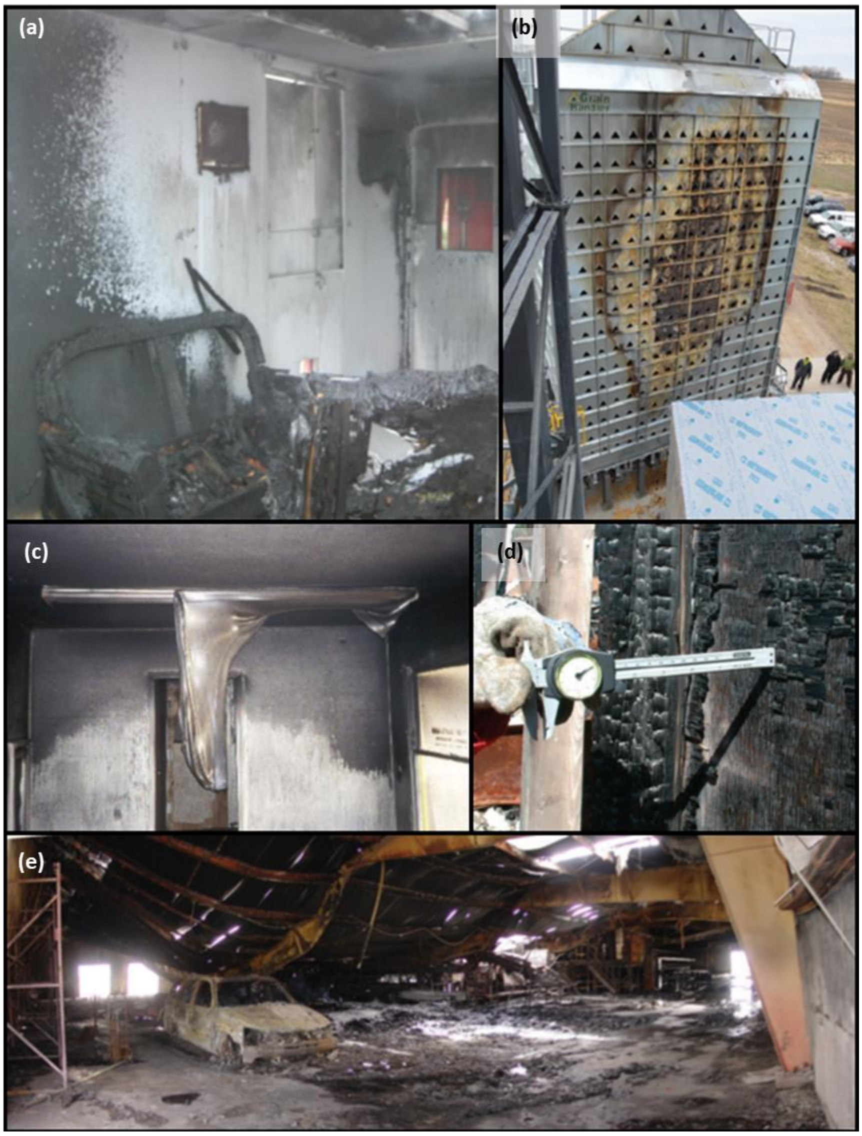

Fig. 2-5: Fire effects in enclosures [59]. *(a) Mass loss on a sofa and clean burn on wall surface. (b) Heat-Induced colour change to metal on a grain dryer. (c) Melted fluorescent light indicating heat travel from left to right. (d) Measuring depth of char with a dial calliper. (e) Steel beam deformed.*

Table 2-4: Fire effects in enclosures [59]

Effect	Description	Interpretation	Notes
Mass Loss of Material (Fig. 2-5(a))	Combustible and non-combustible materials may lose mass due to combustion, evaporation, calcination or sublimation.	May be used as an indication of the duration of the fire.	Generally, the rate of mass loss changes during the fire. The rate of mass loss depends on the heat flux, fire growth rate and HHR.
Clean Burn	Combustible layer(s) such as soot, paint, and paper have been burned away on the non-combustible surfaces. The effect may also appear where soot has failed to deposit because of high surface temperatures.	The lines of demarcation between the clean burned and darkened areas may be used by the investigator to determine direction of fire spread or differences in intensity or time of burning.	Clean burn areas by themselves do not necessarily indicate areas of origin.
Spalling (Fig. 2-3(b))	Breakdown in surface tensile strength of material caused by changes in temperature.	Can indicate steep temperature gradients (20°C-30°C/min) [67]	It is not an indicator of the presence or absence of liquid fuel accelerant.
Oxidation (Fig. 2-5(b))	Oxidation is the basic chemical process associated with combustion.	Oxidation of some non-combustible materials can produce fire patterns and lines of demarcation.	Surfaces may also be oxidized due to deposition of fire suppression agents such as dry or wet chemicals.
Melting of Materials (Fig. 2-5(c))	Physical change caused by exposure to heat.	Can give information on temperatures reached during the fire within the enclosure.	It is not an indication that accelerants or unusual high temperatures were present in the fire.
Depth of Char (Fig. 2-5(d))	Measure of the relative depth and extent of charring.	More reliable for evaluating fire spread, rather than for establishing specific burn times or intensity of heat from burning materials.	The rate of charring of wood depends on rate and duration of heating, ventilation effects, surface area to mass ratio, moisture content
Thermal Expansion/ Deformation of Materials (Fig. 2-5(e))	Temporarily or permanently change shape during fires.	Bending and buckling of steel beams and columns occurs when the steel temperature exceeds approximately 500°C	Deformation can result from a variety of causes, from thermal effects to chemical and mechanical effects.
Collapsed Furniture Springs	The loss of tensile strength and in the collapse of the springs.	May provide clues concerning the direction, duration, or intensity of the fire.	Comparative analysis of the springs can assist in developing hypotheses concerning the relative exposure to a particular heat source.

The production of lines and areas of demarcation on enclosures depend on a combination of variables: the material, the heat release rate, suppression efforts, temperature of the heat source, ventilation and amount of time of exposure. Table 2-5 presents a summary of the types of patterns that is possible to find on enclosures.

Table 2-5: Fire patterns in enclosures [61]

Type of pattern	Description	Interpretation
Plume-Generated (Fig. 2-6)	Demarcation lines of fire effects upon materials created by the three-dimensional shape of the plume.	At the beginning of the fire a fire pattern shape as an inverted cone may appear. The inverted cone may evolve to a more columnar appearance to then progress into conical shapes such as V, U or hourglass pattern.
Ventilation-Generated (Fig. 2-7(a))	Ventilation can affect the location, shape and magnitude of fire patterns	Areas of great damage are indicators of a high heat release rate, ventilation effects, or long exposure. Such areas, however, are not always the point of fire origin.
Full Room Involvement-Generated (Fig. 2-7(b))	Damage found at low levels in the room due to the effects of radiant flux and the convective heat from the descending hot gas layer and the contribution of an increasing number of burning fuel packages.	The degree of damage will increase with time. The extreme conditions of the full room involvement can produce major damage in a few minutes, depending on ventilation and fuels present.
Suppression-Generated (Fig. 2-7(c))	Agents used for fire suppression are capable of producing or altering patterns. Additionally, fire department ventilation operations can influence fire patterns.	The history of suppression-generated patterns can only be understood through communication with the responding fire suppression personnel.
Hot Gas Layer-Generated (Fig. 2-7(d))	The radiant flux from the hot gas layer can produce damage to the upper surfaces of contents and floor covering materials. This process commonly begins as the environment within the room approaches flashover conditions.	The degree of damage generally will be uniform except where there is drop down, where there is burning of isolated items that are easily ignited, or where there are protected areas.

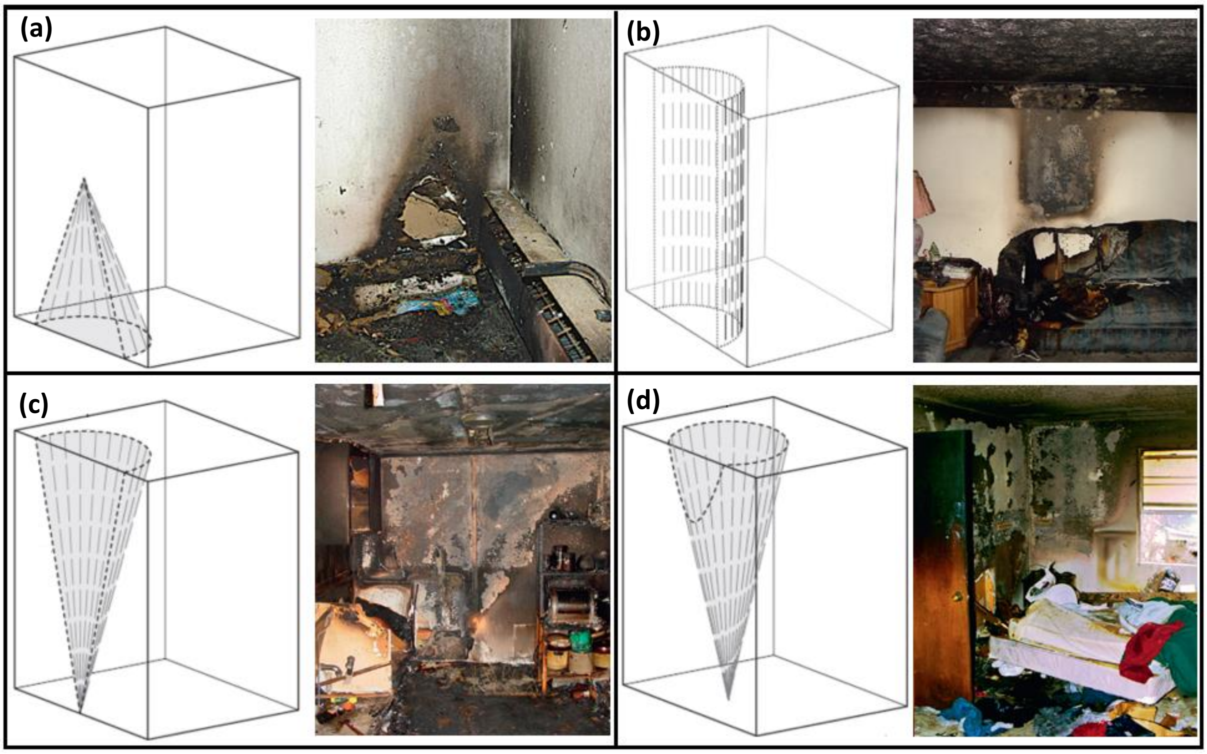

Fig. 2-6: Plume generated patterns [68]. *Left: Idealized pattern formation. Right: Real pattern. (a) Inverted cone. (b) Columnar. (c) V-Shaped (d) U-Shaped.*

Fig. 2-7: Fire Patterns [59]. *(a) Ventilation-Generated. (b) Full Room Involvement- Generated. (c) Suppression-Generated. (d) Hot Gas Layer-Generated.*

Wildland fire investigations

Table 2-6 present a brief description of some of the fire effects that can be found at the fire scene and how they should be interpreted. Fig. 2-8 to Fig. 2-9illustrate the discussions of the table.

In wildland fires, wind speed and direction have the greatest effect on pattern formation. Additionally, hot sparks and embers could be blown, and secondary fires could be ignited. Often readings from the nearest weather stations are not representative, because the measurements are taken at high levels above the ground, where the wind velocity profile is fully developed whilst the fire itself creates fire winds that will influence the fire spread rate [59,60]. For this reason, it is important to have wind readings as near to the origin area as possible. After wind, the slope of the affected area possesses the next greatest impact on the fire spread. Fires will burn faster uphill than downhill [59,60]. Previous research [2] has shown that large IS fires behave similarly to wildland fires, hence in this research wildland fire models and investigations are required.

Table 2-6: Fire effects in wildfires [59]

Effect	Description	Interpretation
Wild fire V-Shaped Pattern Fig. 2-9(b)	Horizontal ground surface burn pattern. V-shaped patterns are affected by wind and the slope of the terrain.	The origin of the heat source often is found at or near the narrowest point of the pattern.
Degree of Damage	Amount of fire-related destruction a combustible sustains.	It is an indicator of the fire's intensity, duration, and direction. Greater damage will be presented on the side from which the fire approached.
Spalling	Shallow, light-coloured craters or chips in the surface of rocks	Spalling is generally associated with advancing fire areas and will appear on the side of the rock exposed to the flames.
Angle of Char (Fig. 2-8)	Comparison between the angle of char and the slope of the terrain.	In an advancing fire the angle of char is steeper than the slope. In a backing fire the angle of char is equal than the slope.
Grass Stems Fig. 2-9(c)	The charred remains of the grass stems after the fire. High intensity fires and wind could affect the reliability.	In advancing fire areas the flames attack the stem from top to ground level, consuming everything but the base of the stem. Backing fire weakens the side exposed to the oncoming fire. The stem will fall in the direction the fire came from.
White Ash Deposit Fig. 2-9(d)	White ash is caused by exposure to heat and flames. It includes white ash by exposure and windblown.	It can be used to determine the direction of fire spread. More white ash will be created on the sides of objects exposed to greater amounts of heat and flames. When looking to (a) the direction the advancing fire spread, the burned area will appear lighter, and (b) the area the fire came from, the burned area will appear darker.
Cupping Fig. 2-9(e)	Concave or cup-shaped char pattern on grass stem ends, small stumps and terminal ends of brush and tree limbs.	In advancing areas of the fire, twigs and limbs on the unexposed side will show a sharply pointed or tapered end. Limbs on the exposed side of the brush or tree will usually be blunt or rounded off.

Table 2-5: Fire effects in wildfires [59] *(Continued)*

Effect	Description	Interpretation
Protected Fuels Fig. 2-9(f)	Protection of a fuel from heat damage by a non-combustible object or the fuel itself.	Surface fuels on the exposed side will exhibit a clean burn line, while the protected side will appear ragged and uneven.
Staining and Sooting	Staining is caused by hot gases, resins and oils condensing on the surface of objects. Carbon soot is caused by incomplete combustion and the natural fatty oil content in some vegetation.	Stains will appear on the side of the object exposed to the flames. Soot will be deposited on the side of fence wires facing toward the origin.
Depth of Char	Measure of the relative depth and extent of charring.	The side with the deepest charring will typically be on the side facing the oncoming fire.
Foliage Freeze	The heat of the fire causes green vegetation to soften while wind and/or gravity bend the foliage in the direction of the wind. Heat then removes moisture from the vegetation, drying and freezing it into a fixed position consistent with the wind direction at the time of fire passage	While this indicator is almost always an accurate reflection of wind direction at that precise point, it may not always coincide with fire direction.
Curling	Heat exposure causes leaves to dry out and shrink on the surface that is exposed to the heat. Shrinkage causes edges to curl in towards the source of the heat	They fold in the direction the fire is coming from. This usually occurs with slower moving, lighter burns associated with backing and lateral fire movement

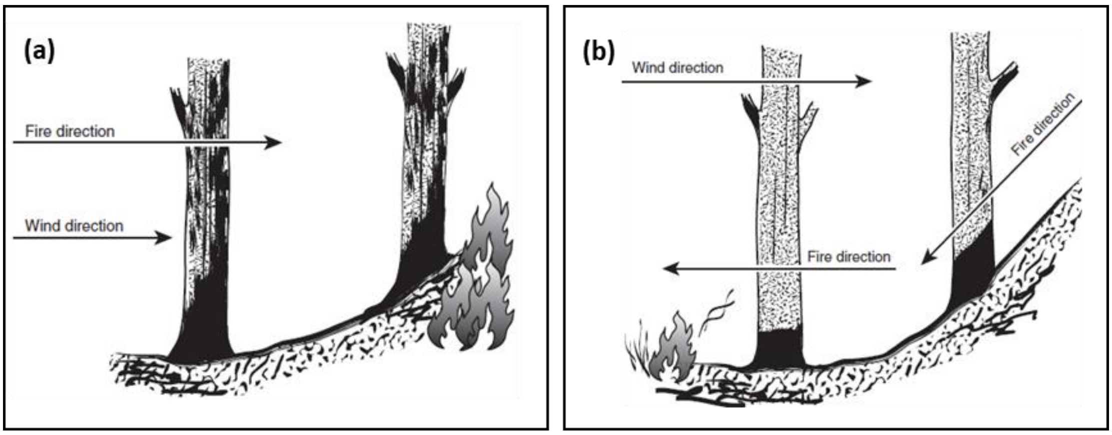

Fig. 2-8: Angle of char [59]*. (a) Fire burning uphill or with the wind. (b) Fire burning downslope or against the wind.*

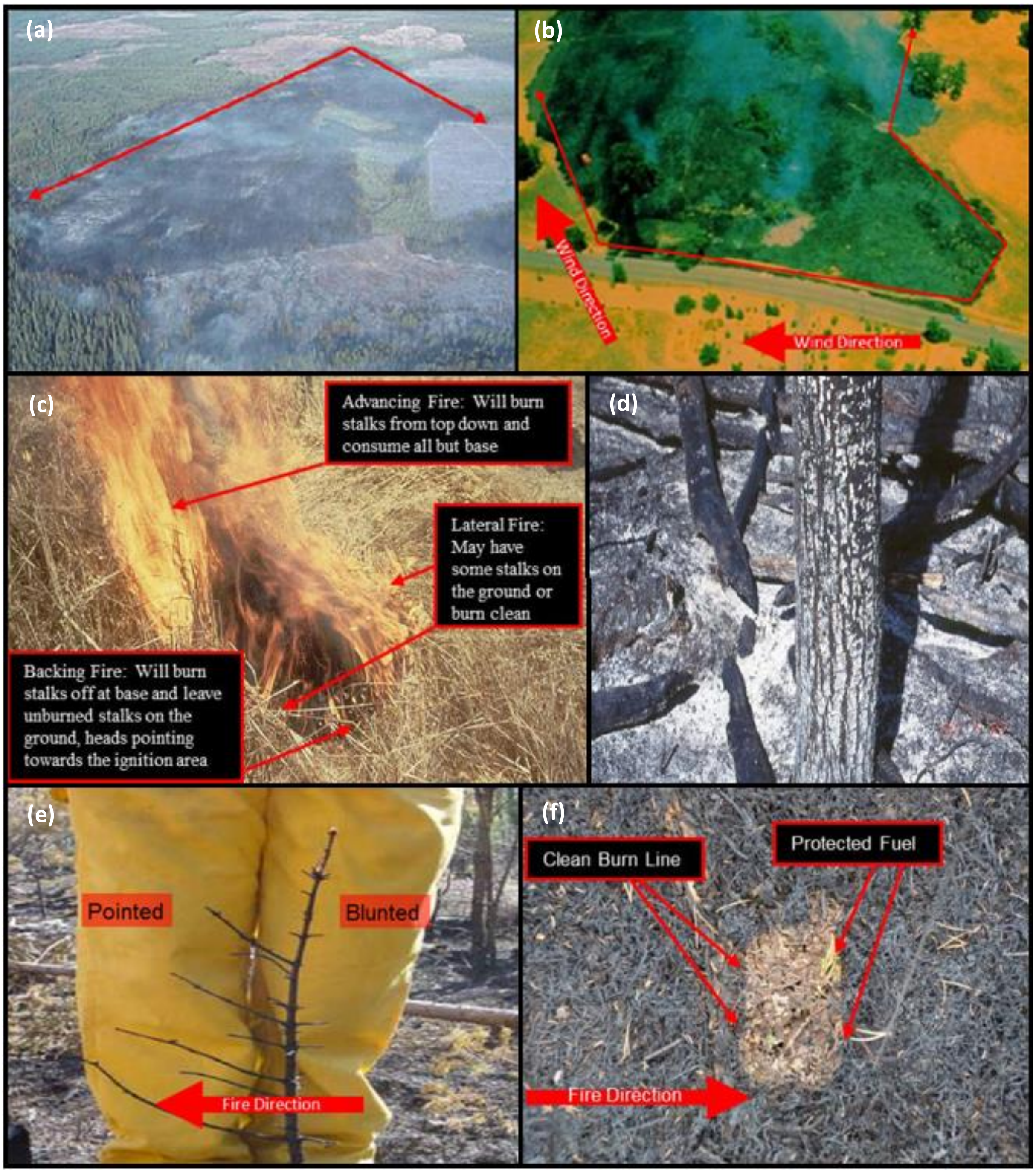

Fig. 2-9: Fire effects in wildfires [60] *(underlay used with permission of the National Wildfire Coordinating Group). (a) Irregular V shaped pattern. (b) Influence of wind and a road on the fire pattern. (c) Grass steam. (d) Advancing fire with white ash. (e) Cupping. Example of pointed and blunted twig ends. (f) Protected fuel.*

2.4.3.2 *Physical Evidence for Fire Cause Determination*

When investigating a fire, it is necessary to identify (a) fuel packages, (b) ignition sources, (c) oxidizers and (d) circumstances that brought them together. The identification of the initial fuel is essential to evaluate the capability of the ignition source. The focus should be on fuels that can easily be ignited and can allow the fire to spread to other items. The initial fuel could be part of a device that fails, or something located too close to the heat source. Heat producing items can include devices, appliances, open flames and hot surfaces. It is also important to notice the activities that were being carried out. Once all the elements have been identified it is necessary to develop the ignition sequence data to explain how the fire started. The number of artefacts left at the fire scene will depend on the fire development [67].

2.4.3.3 *Witnesses Statements*

Witnesses' statements can provide significant information about the fire origin, cause or/and on how the fire spread. The conditions before, during and after the fire event could be established with the testimonies given by first responders, firefighters and occupants. From these statements, not only information about the fire behaviour can be obtained, but also other important data such as human behaviour during the fire incident and firefighters' performance.

Firefighters can provide information about dispatch, arrival and fire control times. Also, they can indicate factors that influenced their performance, such as access conditions, water availability or/and resident interventions. Due to strained relationships with IS communities many instances have occurred with firefighters being stoned by communities when they arrive on the scene [77,78], as it will be discussed later in this work.

2.4.3.4 *Observations*

Observations involve field notes or diagrams. If possible, the fire investigator should take notes during the fire that record direction of spread, rate of spread, flame height and length. Weather and topography observations should be used to fully understand the fire's behaviour [60]. Once the fire is extinguished, the investigator can document evidence of fire spread and growth, scene conditions and other details through diagrams and sketches [59]. In particular, for IS fires, observations about wind and topography conditions, and factors that affect the firefighting actions are fundamental to understand the fire spread.

2.4.4 Data Analysis

The first stage is to understand the meaning of the data collected and determine if it is applicable for the specific case under consideration. NFPA 921 [59] indicates that this process requires knowledge, training, experience, and expertise of the individual.

2.4.4.1 *Fire Origin Determination*

Based on all the data collected, one or more potential fire origin should be identified. Physical evidence, witnesses' statements and observations must be analysed both individually and together.

The damage and burn patterns observed after a fire represent the entire history of the fire. It is acknowledged that the production of fire patterns both in enclosures and wildland fires depends on a combination of variables. For enclosure fires the main factors are the material itself, the rate of heat release of the fire, fire suppression activities, temperature of the heat source, ventilation, and the amount of time that the material is exposed to the heat. Determining which pattern was produced at the point of origin by the first material ignited usually becomes more difficult as the size and duration of the fire increases [79]. The following are some of the most commonly used methods to determine the point of origin on enclosure fires:

<u>Fire Pattern Analysis</u>: All observed patterns should be considered in the analysis, and these represent the total history of the fire. Determining the sequence of pattern formation is a hard task, especially when the fire has reached the fully developed stage. The place that presents the greatest level of damage cannot be assumed as the fire origin. Ventilation has a major impact on the heat release rate of the fire and the burn damage, especially in full room involvement conditions. The influence of other factors such as thermal exposure, firefighting efforts, etc. must be taken in consideration.

<u>Fire Vectoring</u>: Vectoring is applied by constructing a diagram of the scene. The diagram should include walls, doorways and doors, windows, and any pertinent furnishings or contents. Then, through the use of arrows, the direction of heat or flame spread are based upon the identifiable fire patterns

present. The size of the arrows should reflect the scaled magnitude of each pattern. The arrows can point in the direction of fire travel from the heat source, or point back toward the heat source, as long as the direction of the vectors is consistent throughout the diagram. The arrows can be labelled to show any one of several variable factors, such as temperature, duration of heating, heat flux, or intensity. Complimentary vectors can be considered together to show actual heat and flame spread directions. The diagram can also be used to identify any conflicting patterns that need to be explained.

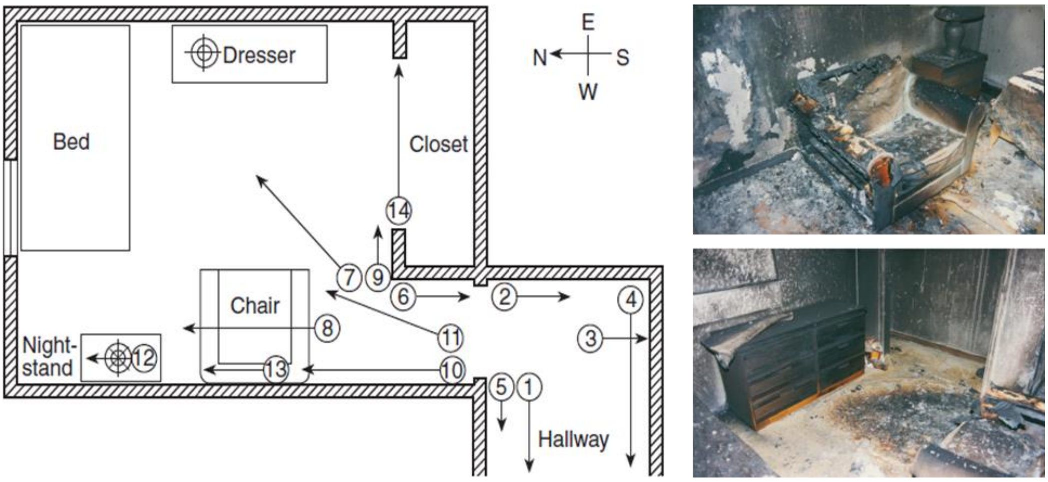

Fig. 2-10: Heat and flame vector analysis diagram (left). Photograph associated with vector #8 (right-top). Photograph associated with vector #7 (right-bottom). [59]

<u>Depth of Char Analysis</u>: By measuring the relative depth and extent of charring it may be possible to determine what portions of a material or construction were exposed the longest to a heat source. Each comparable depth of char measurement should be made with the same tool and same technique. By drawing lines connecting points of equal char depth (isochars) on the grid diagram, lines of demarcation may be identified. Suppression and/or overhaul efforts can modify or destroy char patterns. This method is more reliable for evaluating fire spread than for the establishment of specific burn times or heat fluxes.

<u>Lines or Areas of Demarcations</u>: The borders defining the differences in certain heat and smoke effects of the fire on various materials. They appear between the affected area and adjacent, less-affected areas.

<u>Arc-Fault Mapping</u>: Tracking the wiring from its power source and mapping the locations of all failures of the wire can provide a way to locate a possible area of origin of a fire. The locations of the arcing phenomena farthest downstream along a circuit from the power source are indicators of the point at which the fire first attacked the wiring [67]. The utility of arc mapping is primarily the analysis of the data to determine the sequence of events, but it should be noted that arc mapping can be useful in both formulating and testing hypotheses.

<u>Analysis of Sequential Events – Timelines</u>: This analysis allows one to show a relationship between events, identify gaps or inconsistencies in information and sources and assist in the analysis, reconstruction and investigation of the event. The timelines can involve information about heat release rates, fire spread, fire brigade times of alarm, dispatch, arrival and control, witness observations, etc.

<u>Fire Dynamics</u>: Fundamentals of fire dynamics can be used to analyse the data and identify potential fuels that may have been the first item to ignite, the sequence of subsequent fuel involvement, the recognition of other data that may need to be collected, the analysis of fire patterns, and the identification of potential competent ignition sources.

For wildland fires, the analysis is based on the V/U-shaped patterns. The V or U shape is developed in the first stages of a wildland fire. Usually, the ignition area can be identified by locating the narrowest point of the pattern [59,60]. The general origin area can be narrowed down based on indicators, witness statements and analysis of fire behaviour. The specific origin area is the area where the fire's direction of spread was first influenced by wind, fuel or slope. It is typically characterized by less intense burning. The point of origin is the place where the combustion started. It is possible to find physical evidence at or close to this point. The interpretation of the burn patterns should be based on the majority of the indicators and fire behaviour principles. Fire patterns are influenced by wind speed and direction, slope and obstacles, as discussed above.

2.4.4.2 *Fire Cause Determination*

According to [59], once the fire origin is determined, the analysis of the data related to the fire cause determination can be done. The analysis must determine, first, if the ignition source is capable of igniting the fuel. Then if the amount of fuel, (primary, secondary, etc.), was enough to explain the resulting fire. Finally, it must be found if there is a logical ignition sequence that allows the source of ignition, the fuel, and the oxidant to interact in the appropriate quantities and circumstance for combustion to result.

2.4.5 Hypothesis

Based on the data analysis, the investigator should produce one or more hypotheses to explain the origin, development and cause of the fire. Before selecting the final hypothesis, it is important to ask:

- Is there a competent ignition source at the hypothetical origin?
- Can a fire starting at the hypothetical origin result in the observed damage?
- Is the growth and development of a fire starting at the hypothetical origin consistent with available data at a specific point(s) in time?
- Is the hypothesized ignition source a competent ignition source for the first fuel ignited?
- Is the required time for ignition consistent with the timeline associated with the cause hypothesis and facts of the incident?
- What were the circumstances that brought the ignition source in contact with the first fuel ignited?
- What, if any, were the failure modes required for ignition to occur?
- Are there any other origin/cause hypotheses that are consistent with the data?

2.5 Human factors and human behaviour in fire

2.5.1 Historical review

Human behaviour in fire is a relatively new area of the fire safety field [80]. The First Edition of the *SFPE Handbook of Fire Protection Engineering*, published in 1988, contained four chapters that discussed human behaviour in fire. Only in 2003 a dedicated "consensus-based" document was published, the *SFPE Engineering Guide, Human Behaviour in Fire* [69]. In 1998 the First International Symposium on Human Behaviour took place. At this event Pauls presented his work [81], which exposed his perspective on the development in fire related human behaviour. He defined four phases (a) from 1956 to 1977 where the initial scientific research was conducted [71,82,83] including Fruin's work to understand pedestrian traffic relationships [84], evacuation drills were documented [75], and technical notes and reports were published [85,86], (b) the late 1970s to early 1980s where international seminars were held and books [87], papers and reports were published [75], (c) the late 1980s and the 1990s were major contributions were done by Sime [88,89], Proulx [73,74] and Fahy [90], and the firsts movement models were developed [83], and (d) the period that would come after the First International Symposium on Human Behaviour [75]. In [91] Bryan also reviews the development of the field, highlighting the importance of the research with regards to people with disabilities, evacuation models and how the study of real fire incidents are critical to their improvement.

2.5.2 Factors and considerations

According to Hall [92], when addressing human behaviour in fire, there are three main areas of concern (a) behaviours that impact the occurrence of a fire, (b) behaviours that impact the fire development, and (c) behaviours that impact harm from fires. The *SFPE Engineering Guide, Human Behaviour in Fire* [69] mainly focuses on behaviour associated with the third (e.g., evacuation, refuge-finding, relocation) and second aspects (e.g., firefighting, opening/closing doors categories, gathering belongings, etc.). Performance-based codes and international fire documents, including [69], indicate that there are six main topics that impact the analysis of the human behaviour in fire: building characteristics, evacuation strategies and procedures, occupant characteristics, occupant behaviour preceding the evacuation, occupant behaviour during movement and occupant exposure to the fire environment. Table 2-7 presents some of the factors and considerations to take into account.

*Table 2-7: Factors and Considerations in Human Behaviour Analysis (*list is representative but not all inclusive). Taken from* [69].

Building characteristics	**Evacuation strategies and procedures**
• Building type and use • Physical dimensions • Geometry of enclosures • Number and arrangement of Means of Egress • Architectural characteristics/complexity • Lighting and signage • Emergency information systems • Fire protection systems	• Total, zoned or staged evacuation • All or few occupants trained or drilled in procedures • Provisions for those with access and functional needs – infirm, disabled, incarcerated • Frequency of training or drills • Who is trained or drills • Defend-in-place • Relocation
Occupant characteristics	**Fire environment**
• Population and density • Individuals alone or groups • Familiarity with building • Distribution and activities • Alertness • Physical/cognitive abilities • Role/responsibilities • Location • Commitment to task • Gender/Age • Prior fire/evacuation experience	• Smoke and toxic gases • Temperature • Visibility • Transport, exposure, duration

As mentioned by Thompson [70], most literature on human behaviour in fires is focussed on fires occurring within public, commercial and industrial spaces. Although there is some research on human behaviour in residential occupancies [14,70–74], human behaviour in fires in informal settlements hasn't been studied yet. Hence, for this research interviews with the residents should include questions that investigate how people behave in a fire situation. Shields and Proulx [75,76] state that it is necessary to study how people became aware of the fire and what type of activities they are engaged with, and why, in order to develop effective fire safety plans.

2.5.3 Evacuation behaviour

In [93] Galea presented a framework to describe evacuation behaviour. As depicted in Fig. 2-11, the framework considers two main phases: the response phase and the evacuation movement phase. Understanding the factors that influence the duration of the response phase is critical to study different evacuations scenarios [94]. Significant amounts of research has been focused on the estimation of the evacuation movement time [73,95,96] and on the response time, also known as pre-evacuation time [73,74,97–99]. The notification phase starts with the first cues of the fire (e.g., smoke, flames) and ends when the occupants respond to the notifications and recognize that something unusual is happening. Other notification cues include alarms and staff intervention. The cognition stage starts with the occupants' interpretation of the notification cues. As shown in Fig. 2-12, there are three possible responses to the notification cues: seeking for additional information, undertake protective actions or reengage with their previous tasks. The activity stage starts when the occupant performs information (seeking, providing, or exchanging information with regards of the incident) or action tasks (e.g., gathering belongings, firefighting actions, notifying the fire brigade, etc.). As seen in Fig. 2-11, the occupant can return to the cognition stage, assess the situation, and conduct more activities. The activity stage ends when the occupant starts to evacuate.

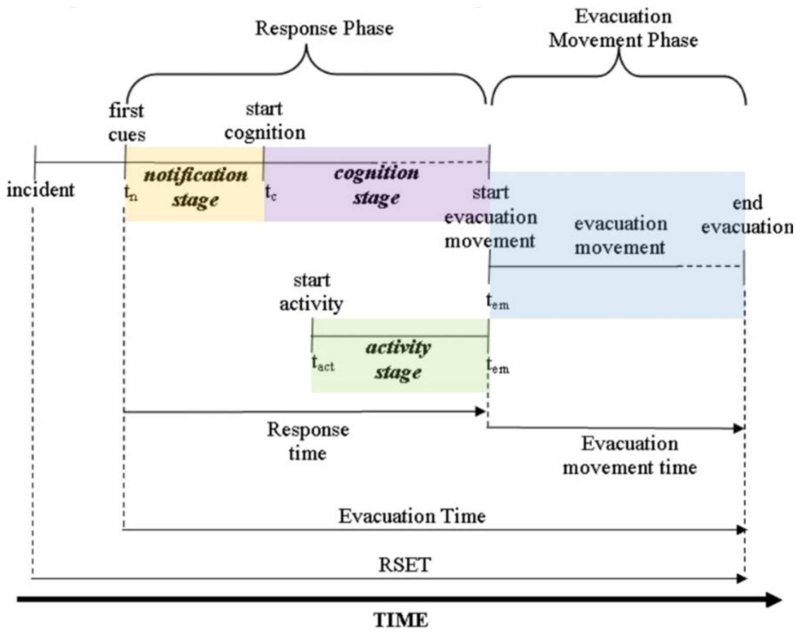

Fig. 2-11: Framework for describing evacuation behaviour [93]

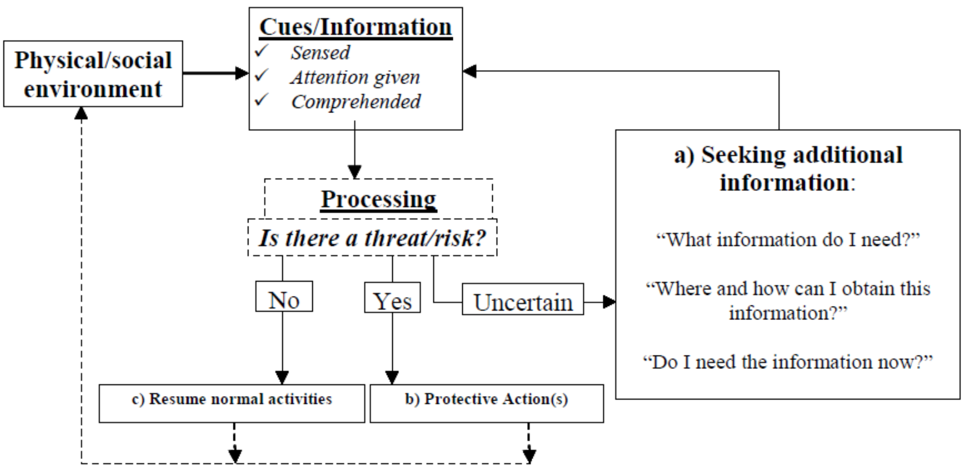

Fig. 2-12: The protective action decision model adapted to building fires (extracted from [69]*).*

2.5.4 Evacuation models

Evacuation calculations are necessary when conducting performance-based analyses to determine the level of safety provided in buildings [100]. Modern evacuation computers models provide a more realistic calculation compared to hand calculations and provide a good alternative to full-scale evacuation tests. Considering prescriptive-based analysis, they mainly consider the building configuration, focusing on travel distances, number of exits and exit width. Furthermore, prescriptive analysis fails to incorporate human behaviour and different fire scenarios [83]. According to [100], the different models can be categorized by (a) modelling method, (b) purpose, (c) grid/structure, (d) perspective of the model/occupant, (e) behaviour, (f) movement, (g) fire data, (h) visualization, and (i) validation. The needs of the user would determine the model that should be selected.

2.6 Summary

This section presented the basic concepts to understand (a) the fire behaviour in ISs (b) urban and WUI fires, (c) the different techniques available to conduct fire investigations, and (d) human behaviour in fire. These concepts will be used throughout the Chapters that follow.

Chapter 3: Methodology

3.1 Introduction

This brief chapter presents the methodology used in this work to understand fires in IS, indicating how the chapters that follow have been developed to address the overall aims. A general methodology is shown followed by the research design which presents a more detailed view of the techniques used in the data collection process. Finally, the ethical approval process for the work undertaken is provided. This chapter should be considered in relation to Fig. 1-2 which provides an overview of the structure of the thesis.

3.2 Methodology and implications of restrictions on the research

To fully understand a IS incident a significant amount of information is required such as: incident reports, witness and community accounts, firefighter interviews, photos of the fire site, location markers, fire lines during the incident and satellite images. An approach to obtaining such data is provided in Fig. 3-1 as the original plan for this work. The original data collection approach envisaged for this work represents a more suitable approach to that discussed below that could be implemented in the future, thus details regarding it have been included here. However, due to challenges discussed below the final methodology presented in this dissertation had to be modified to address the many components required to provide a holistic approach to fire investigations for IS, but has not been able to capture all aforementioned data fully.

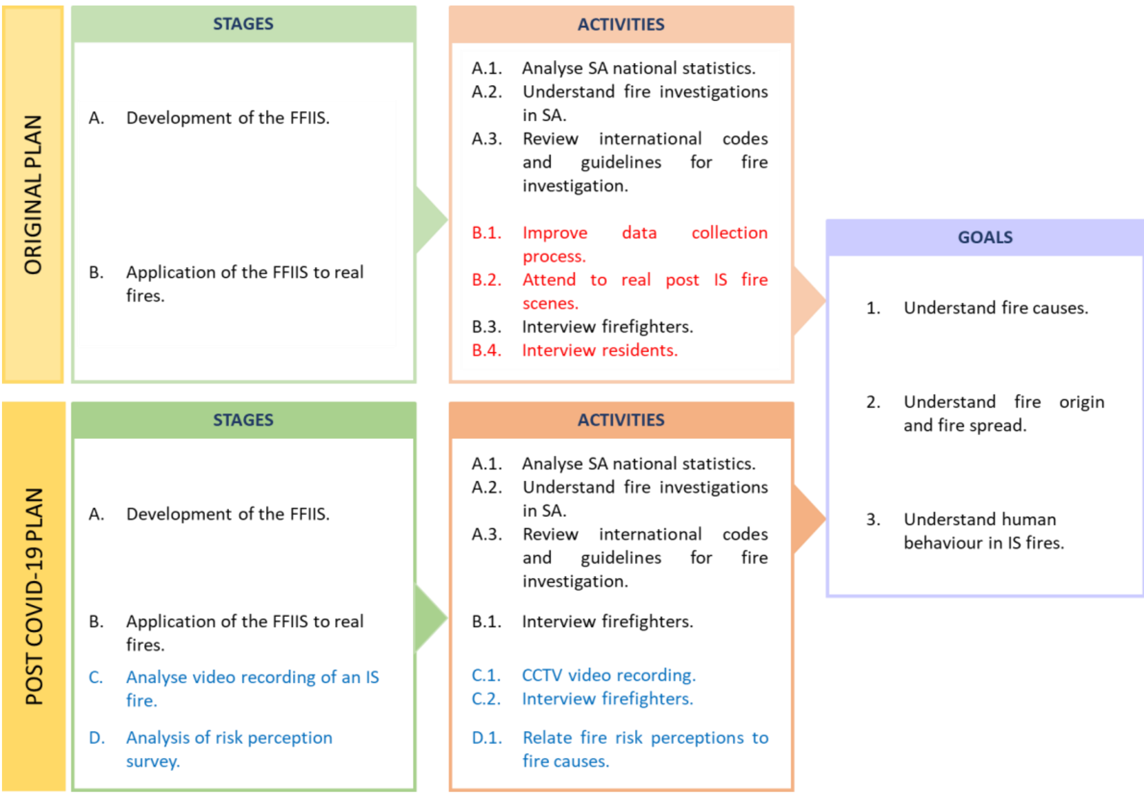

Fig. 3-1: Methodology of the research for this work showing the original and post-COVID approach to the work

Due to the COVID-19 pandemic, the initial research strategy could not be adopted. Hence, Fig. 3-1 also presents the modified approach used in this work. Due to COVID-19 restrictions in South Africa the activities shown in red could not be undertaken as they required face-to-face interaction between the author, data collection services, firefighters, and residents. Items in blue were added to the scope of the work to account for the lack of specific datasets. Items not included are discussed below.

(1) Not utilised in this dissertation, but provided in Appendix B, is a survey system that has been completed for post-fire investigations by firefighters which has been implemented with existing software. The system uses the (a) FireWeb Incident Management [101] platform, (b) includes the implementation of an additional fire report incident based on the NFIRS [60], (c) interviews carried out with residents, and (d) visual documentation (e.g., pictures, drawings.).
(2) In order to understand the firefighters' operations and the human behaviour during an IS fire researchers will need to attend to real fire incidents.
(3) Finally, to study the human behaviour in IS fires in depth, surveys with residents must be conducted. This activity would require working together with NGOs that are involved with IS communities in Cape Town, training the personnel, and interact with the IS inhabitants.

In lieu of the data above, the following information has been obtained to provide the scientific basis required in this work:

(1) The author consulted the City of Cape Town regarding CCTV footage of ISs fires. Thirteen videos were received, but only one had the quality necessary to be analysed which will be discussed in Chapter 5. This provides first hand data from a real incidents that provides novel findings on human behaviour, fire spread, firefighter response and other factors.
(2) To overcome the lack of information coming from IS residents, a previous survey conducted after the 2017 IY fire was used.

3.3 Research design

This research work considered different approaches to obtain the data required to gain understanding of IS fires. Fig. 3-2 depicts the research design. It can be seen that several research instruments were used in order to collect information about the fire development, inhabitants' behaviour, firefighters' operations and inhabitants' risk perception.

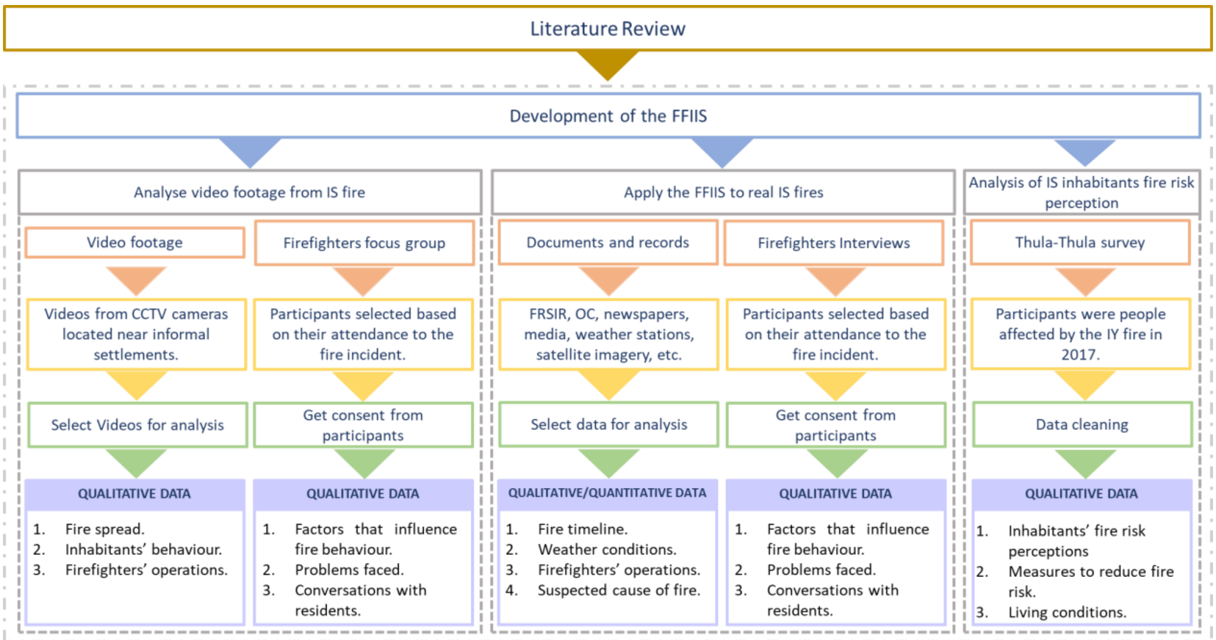

Fig. 3-2: Research design.

3.4 Quality of the data

The research design above employs multiple datasets, each with its own limitations. This section will discuss the factors related with the data used that could affect the findings of this work.

3.4.1 Firefighters' input

For the firefighters' input the original plan was to create a structured form (within the FireWeb Incident Management platform), where they could fill details of the fire in real time, and in that way similar data would be collected from several fires. Additional interviews would be conducted if necessary. Without the use of the FireWeb Incident Management system for regular data collection, only three fires could be analysed and the interview to the firefighters were done days or even weeks after the fire occurred. Although the interviews followed a structured component, on many occasions the firefighters could not provide specific information about certain topics. The open flow component, on the other hand, allowed for the firefighters to point out situations the author was not aware of.

3.4.2 Residents' input

While it was foreseen that having access to IS inhabitants would be difficult, not only due to the logistical challenges previously mentioned, but due to the fact that they would be asked to share traumatic experiences, with the pandemic this idea was dismissed. The author considered that even though Thula-Thula's dataset did not have all the desired information it still provide useful insights. It should also be acknowledged that it would have been very unlikely that under the initial conditions 2000 household could have been surveyed. This is one of the strengths of the survey considered in Chapter 7, that it is such an extensive set of surveys. Improvements suggested to the survey used are provided Section 8.3.2.

3.4.3 National statistics

Not all municipalities in South Africa submit fire incident data. This situation clearly affects the data provided by the Fire Protection Association of South Africa (FPASA) that was used in Chapter 4 and Chapter 7. Hence, the dataset can be considered complete but the extent to which the figures under-represent incidents in South Africa has not been quantified.

3.5 Ethical considerations

The work followed ethical considerations as required by Stellenbosch University. The research proposal for the analysis of the video footage and the application of the FFIIS was submitted to the ethics committee of Stellenbosch University in May 2020 under the project ID 15246. The application included (a) the application letter for institutional permission that was sent to the City of Cape Town Fire & Rescue Service, (b) participants consent form, and (c) the questionnaire that was going to be implemented. Copies of these documents are available Appendix B, Appendix D and Appendix E. The Research Ethics application process determined that the research was low risk, and the ethical approval was granted. For the use of the survey conducted by Thula-Thula after the Imizamo Yethu fire, the ethical approval to access the data was already granted under ING-2018-6450 as part of a larger study.

Chapter 4: Developing a Framework for Fire Investigations in Informal Settlements

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Declaration by the candidate:

The nature and scope of the candidate's contribution were as follows:

Nature of contribution	Extent of contribution
Writing the manuscript, establishing methodology, data analysis, and preparing figures and tables.	85%

The following co-authors have contributed to as follows:

Name and e-mails	Nature of contribution	Extent of contribution
Richard Walls rwalls@sun.ac.za	Supervised the work, advised on the work, and review the manuscript.	10%
Antonio Cicione acicione@sun.ac.za	Advised on the work and review the manuscript.	5%

Signature of candidate:
Date:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 4,
2. no other authors contributed to Chapter 4 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	04/08/2021
	Stellenbosch University	04/08/2021

This chapter is an exact copy of the journal paper referred to above

CHAPTER 4: DEVELOPING A FRAMEWORK FOR INVESTIGATIONS IN IS

Contribution of chapter to dissertation

In this chapter a framework for fire investigations in informal settlements is developed, which forms the foundation of this overall thesis. The findings of this work are applied in (a) Chapter 5, where a real IS fire incident is analysed in depth, (b) Chapter 6, in which the framework is applied to three case studies to gain more information about fire origin and fire spread, and (c) Chapter 7, which seeks to gain more knowledge about fire causes in ISs.

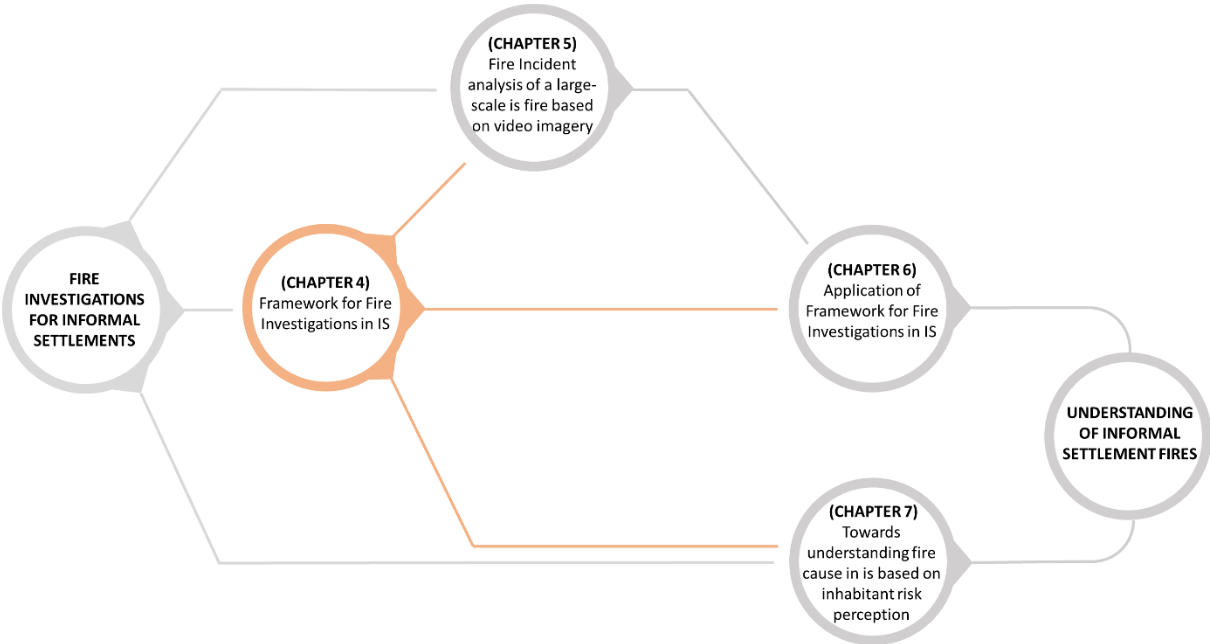

Fig. 4-1: Contribution of Chapter 4 to dissertation.

Note

The developed framework focusses on the investigation and determination of the fire origin, fire spread sequence and fire cause. However, there are other important topics that could be studied while conducting the fire investigation, such as the human factors that influenced the fire development and the human behaviour during a fire event. Considering that the framework already includes the residents as a source of information, specific questions that would provide the necessary information to analyse the residents' actions and behaviours could be asked. Appendix B propose a survey that can be implemented after a fire which includes several questions about their actions and the cues of the fire that triggered their response. The survey also includes questions about demographics, location with respect to the fire in order to contextualize the inhabitant's observations, and company at the time of the fire to evaluate the influence of family and friends in their behaviour. Furthermore, the human factors contributing to ignition presented in Table 7-11 can also be included.

CHAPTER 4: DEVELOPING A FRAMEWORK FOR INVESTIGATIONS IN IS

4.1 Abstract

Informal settlements regularly experience small and large fires. In South Africa, there were 5940 informal settlement fires during 2017, which is approximately 16 per day. Currently, post-fire investigations are often not being conducted, and close to 40% of all fire causes in informal settlements are labelled as "undetermined". Conducting post-fire investigations can provide important information to develop better evidence-based responses for improving fire safety in these communities. It is acknowledged that due to the inherent nature of informal settlements high levels of certainty in fire-cause determination are often not possible. After ignition, the onset of flashover occurs rapidly, thus most structures are destroyed within minutes, and often multiple dwellings are involved in a single incident. This paper seeks to apply well-known forensic fire investigation principles (primarily using NFPA 921), to informal settlements to develop a framework and guidelines, in order to (a) identify the fire origin and the fire cause, (b) obtain data on human behaviour in fire, (c) understand the fire spread sequence, and (d) evaluate the effectiveness of suppression and response efforts. The proposed methodology was used to analyse the Imizamo Yethu fire that occurred in 2017. Additionally, the work highlights the challenges associated with conducting such investigations.

4.2 Introduction

Fires in informal settlements (also known as slums, shantytowns, ghettos, etc.), are a substantial problem in developing countries [6]. In South Africa alone, 5940 informal settlements fire incidents were reported during 2017 [8]. Internationally, there have been several fires of great magnitude, with a recent incident on 16 August in Bangladesh, that destroyed more than 1200 dwellings [102], as shown in Fig. 4-3 (e). Informal settlements are typically low-income communities existing on the periphery of cities, characterised by poverty, poor infrastructure, high dwelling density and similar factors [2]. Informal settlements dwellings (ISDs) are constructed from any readily available material, meaning that they are typically highly flammable [103]. In recent years, there has been several research studies investigating fire dynamics and fire spread in informal settlements. Kahanji et al. [15] analysed the fire spread for the Imizamo Yethu informal settlement fire that occurred in 2017, where 2194 homes were destroyed. An experimental study on fire spread between multiple ISDs was conducted by Cicione et al. [9], where the experiments consisted of three full-scale mock ISDs, cladded with different materials, to study the effects of the cladding materials on fire spread. Cicione et al. [13] compared full-scale ISD fire experiments to numerical models and based on the numerical performance, determined the probability of fire spread for dwellings spaced at 3 m apart. Gibson et al. [104] showed that remote sensing can be used to track historical fires based on the albedo of ISD roofs before and after a fire incident. Beshir et al. [105] investigated the influence of horizontal openings on the heat fluxes, plume sizes emitted from dwelling openings.

World data from 2016 shows that even though only 20% of the world's population reside in countries with a low/ low-middle Socio-Demographic Index, nearly half of the fire related fatalities occurred in those countries [6]. Currently, there is insufficient research done to understand what happened during informal settlement fire events such that response efforts (e.g. active fire protection, passive protection, risk reduction, etc. [103]) can be improved. Additionally, there is negligible literature available on post-fire investigations for informal settlements fires. As pointed out by Babrauskas [14], fire investigations can provide significant information to the fire safety engineering field. Babrauskas [14] also stated that, if possible, the investigation should cover a broad array of subjects such as fire origin and cause determination, fire spread, human behaviour in fire and firefighter's performance. All of the aforementioned factors are important for fire brigades, municipalities and engineers when developing fire safety interventions.

It is with this backdrop that this paper seeks to develop a framework and guidelines for conducting forensic fire investigations in informal settlements. This is done by (a) understanding how fires are currently being reported and investigated in South Africa, and how informal settlement fire statistics are obtained, (b) determining the feasibility of using well-known forensic fire investigation principles for informal settlements fires, and (c) applying the methodology developed in this paper to a real informal settlement fire. This work has been developed based upon interviews, site visits, investigations and data collected in South Africa, specifically in Cape Town. However, it will typically be applicable to other low-income countries, but with consideration of variations due to local construction materials, cultural preferences, economic conditions, etc.

4.3 Fire Scene Investigation in Informal Settlements

One of the purposes of a fire investigation is to determine the fire cause to prevent similar incidents from re-occurring. In order to achieve this, it is necessary to first identify the area or point(s) of origin. Once the origin of the fire is known, the circumstances and factors that caused the start of the fire can be determined. According to NFPA 921 [59], fire investigation is a complex endeavour. In the context of fires in informal settlements, it is even more complex, with factors such as rapid enclosure fire development, rapid fire spread, and lack of evidence present at the scene. In order to best describe the current informal settlement post-fire investigation process and informal settlement fire history of South Africa, this section is divided into two subsections, namely: (a) What is currently being done in South Africa? and (b) Informal Settlement Fire Trends in South Africa.

4.3.1 What is currently being done in South Africa?

Currently, after attending to a fire incident, the fire department completes a Fire & Rescue Service Incident Report (FRSIR). Currently the FRSIR is a generic form that is used for all types of fires, and in terms of the fire origin and cause determination, does not require significant detail from the firefighters. Firefighters are typically only required to indicate what was burning, what the environmental conditions were at the time of the incident, and what the cause of the fire was, where the latter is the focus of this work. It is important to note that it is not possible to determine the cause of fire without knowing the fire origin, the first material that ignited and the source of ignition.

Anecdotal feedback from multiple firefighters indicates that in most cases detailed fire investigations are not conducted and that the inhabitants provide most of the information. When consulted about arson fires in informal settlements, the firefighters mentioned that on many occasions they allege that there are clear indications of the cause being arson, although in many cases this cannot be proved so recorded statistics are difficult to interpret. One of the most common examples of this is when they arrive at the scene where one dwelling is burning, but all the household content have already been removed from the dwelling. This could be due to inhabitants trying to obtain disaster relief support, which sometimes includes a small financial payment, or to obtain construction kits from municipalities.

When fire related fatalities occur, the South African Police Services (SAPS) conduct a separate investigation, but the findings are not disclosed to the brigades. A similar situation occurs when arson is suspected. Due to legal reasons, and potentially incriminating evidence, data from these investigations are not publicly available, such that they cannot be used to improve fire safety.

4.3.2 Informal Settlement Fire Trends in South Africa

A large-scale perspective on fire trends assists with understanding what may have occurred in single events. The Fire Protection Association of South Africa (FPASA) collects information from all the fire brigades in South Africa, and generates statistics regarding all types of fire incidents. Table *4-1* presents the number of fire incidents and fire fatalities reported between the years 2003 and 2017. On average more than 4200 informal settlements fire incidents are reported annually, while the total number of fires is around 39500 per year. It is interesting to note the impact informal settlement fires have on the total number of fatalities. The latter refers to all types of fire related fatalities listed in Table *4-1*, which include informal settlements. Although informal settlement fires only account for 10.3% (on average) of all fires, they cause approximately half of the total number of fatalities. Since 2014, the fire fatality rate has remained relatively constant, fluctuating between 4.02 and 4.63 fatalities per 100 fires, with an average of 4.3. It is interesting to note that during this period, the fire fatality rate in informal dwellings is more than double the fire fatality rate for formal dwellings, which is around 2.

Table 4-1. Fire incidents and fire fatalities in South Africa for 2003-2017 [8].

Year	All fires	Informal Dwelling fires	Number of fatalities		Number of fatalities per 100 fires	
			Total	Informal Dwellings	Total	Informal Dwellings[8]
2003	38,631	3,562	299	192	0.77	5.39
2004	36,591	3,566	258	105	0.71	2.94
2005	42,863	3,342	334	208	0.78	6.22
2006	26,475	3,105	240	141	0.91	4.54
2007	40,582	4,273	364	103	0.90	2.41
2008	35,432	3,279	No information			
2009	40,481	4,008	375	197	0.93	4.91
2010	26,574	2,590	228	106	0.86	4.09
2011	37,721	4,046	No information			
2012	41,481	4,516	No information			
2013	42,343	4,886	574	280	1.36	5.73
2014	46,187	5,191	855	238	1.85	4.58
2015	45,784	5,448	427	219	0.93	4.02
2016	41,873	5,283	529	221	1.26	4.18
2017	49,567	5,940	656	275	1.32	4.63

The causes of fires in informal settlements, according to FPASA [8], are presented in Fig. 4-2. The statistics imply that the leading cause of ignition is open flames, accounting for 27.1% of all ignition sources. Considering that open flames are used for cooking, heating or lighting purposes, the information presented does not provide enough detail to develop preventive measures and to make an accurate classification. Thus, it can be seen that the current data does not capture the required detail in order to developed evidence-based responses. This can be attributed to the generic FRSIR. For example, if the fire cause was open flames while cooking, it is not clear how the fire cause would be classified. According to NFPA 921 [59], the cause of the fire can be classified as accidental, natural, incendiary or undetermined. In this case, considering the data presented in Fig. 4-2, the six first categories correspond to accidental fires, accounting for a 50% of all fires, 6.4% are incendiary, and 37.4% are undetermined. It is not clear what the category 'Others' in Fig. 4-2 refers to. Accidental fires involve any unintentional human act due to careless or reckless behaviour, and to the failure of an equipment or heat source. Therefore, it is possible to infer that human factors are the leading cause of fire in settlements. There are several possible explanations for the large number of undetermined fire causes. Firstly, as mentioned above, fire investigations are not conducted after every informal settlement fire, and the information is mostly provided by witnesses. Secondly, due to the fast fire development and fire spread, there might not be enough evidence to determine the fire cause. Lastly, there is the possibility that there are no qualified staff to conduct the fire investigations. Whatever the reason, greater efforts are needed to ensure that every as many incidents as possible are investigated in detail, and that the fire cause be determined.

[8] The large data dispersion could be due to the quality of the data provided by the National Statistics as discussed in Section 3.4.3.

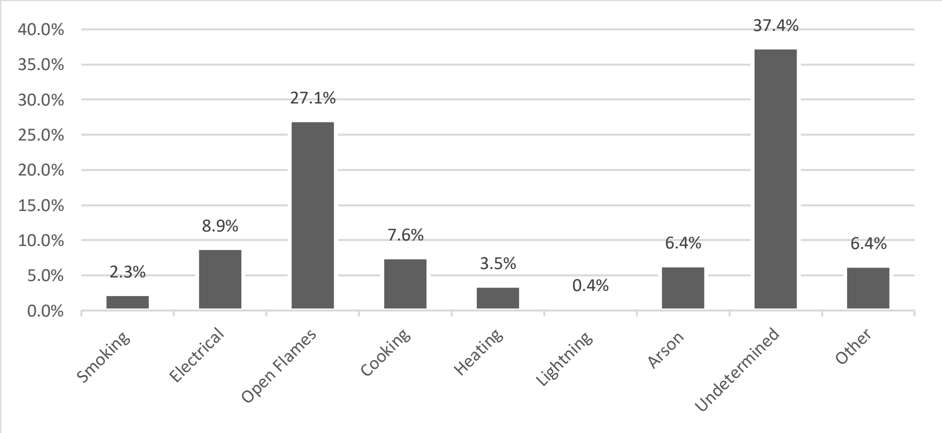

Fig. 4-2: Fire causes for informal settlements in South Africa for informal dwellings fires, average for 2003-2017 period [8].

Babrauskas [14] states that statistics obtained from fire investigations should be meaningful, such that the following critical questions can be answered: "(a) How did the fire start? (b) How were the occupants alerted? (c) How did the occupants cope? (d) How many people died, were seriously injured, or suffered minor injuries? and (e) How effective was the fire department?".

4.4 How to conduct a fire scene investigation in informal settlements?

Methodologies and methods to conduct a fire scene investigation in informal settlements are proposed below, with a summary presented in Table 4-2 which will be illustrated and explained in relation to Fig. 4-3. Guidelines and recommendations provided by NFPA 921 [59] for enclosures fires and wildland fires, with the inherent nature of informal settlements in mind, are considered.

Table 4-2. Summary of investigation considerations based on the size and type of the fire.

Classification	Techniques	Information	Notes
Pre-flashover fire	<u>Enclosure fire</u> Fire patterns in walls, floors and ceiling Furniture damage analysis Heat and flame vectors analysis Artefacts Witness statements	Point of fire origin Cause of fire Ignition sequence Fire spread sequence	Fire controlled by the residents. Usually, the fire would not be reported or investigated.
Post-flashover fire	<u>Wildland fire</u> Fire patterns in the affected area Witness statements	Dwelling of fire origin Fire spread sequence Limited data on fire cause. Most of the evidence is destroyed.	Witness statements are essential to identify the dwelling of fire origin and the potential fire cause.
Large Post-flashover fire	<u>Wildland fire</u> V or U shaped burn pattern in the affected area Witness statements	Area of fire origin Fire spread sequence Limited data on fire cause. Most of the evidence is destroyed.	

Fig. 4-3: Fire patterns of different fire sizes. Approximated number of dwellings affected: (a) yellow pattern: 15, orange pattern: 50 [106]*, (b) 260* [107]*, (c) 350* [108] *, (d) 600* [2] *and (e) 1200* [109]*.*

The size of the fire will determine the type of information that can be gathered and how it data can be used. The nature of information can broadly be classified as follows: (1) a pre-flashover dwelling fire, (2) a full burnout of the dwelling of origin has occurred, (3) large fires. Data obtainable for (1) to (3) ranges from detailed point of ignition and fire cause, to only considering global fire patterns. For a large fire behaviour becomes analogous to that of a wildland fire, with a continuous fire front progressively moving through fuel packages. Fig. 4-3 presents fires patterns from different fires sizes, ranging from small fires, consisting of approximately 15 and 50 dwellings, as shown in Fig. 4-3 (a), to large fires that affected more than 1200s dwellings as depicted in Fig. 4-3 (e).

Hence, depending on the number of dwellings affected by the fire and the degree of damage at the scene, the investigation should be conducted using a combination of techniques. To best conduct such a fire investigation the methodology presented will be divided in (a) considerations, (b) scene assessment, (c) data collection, (d) data analysis and (e) hypothesis development.

4.4.1 Considerations

4.4.1.1 *Construction methods, materials and configuration*

The investigator must be aware that ISDs are often built from a combination of materials that include timber, corrugated sheets, or any readily available product, as shown in Fig. 4-4. Usually, the dwelling is not completely sealed from the outside due to the poor construction methods used. The aisles that separate dwellings from each other are often extremely narrow [2,15], which may affect the fire spread and the physical evidence present at the scene after an incident.

Fig. 4-4: Informal settlement in Imizamo Yethu

4.4.1.2 *Fuel Loads*

In informal settlements, a broad range of fuel loads are observed [2,15]. As expected for residential occupancy, inside the dwellings it is possible to find mattresses, electrical appliances, furniture and clothing. Additionally, fuel loads with high calorific values such as paraffin stoves, candles and gas bottles can also be present. Furthermore, in the aisles, it is possible to find materials such as timber, tires or rubbish. The investigator should expect the presence of unusual fuel load configurations, which means that certain evidence that could be considered as an incendiary fire indicator in formal dwelling circumstances may not be so in these cases.

4.4.1.3 *Protection of the fire scene*

NFPA 921 [59] emphasises that the fire scene and physical evidence should be protected and preserved as intact and undisturbed as possible. For enclosures fires, the structure, content and fixtures should remain in their pre-fire locations, while for wildland fires, foot and vehicle movement through the area should be kept to a minimum. However, to accomplish this is one of the most complex issues in an informal settlement fire.

During the course of a fire, ISD inhabitants typically re-enter their dwelling multiple times in order to save their belongings (i.e. mattresses, furniture, appliances and other valuables) [2]. This added to the fact that there is usually structural collapse, means that alterations at the fire scene will be produced, and it is unlikely that the pre-fire conditions can be reconstructed. After the fire, the people residing in the affected dwelling(s) will quickly remove physical evidence and debris in order to start rebuilding their home. This is because the inhabitants need to have a shelter and they are concerned about losing the land in which their home was [2,15]. For these reasons, data collection for informal settlement fire investigations should be conducted as soon as possible after an incident occurred, as discussed further below. Pictures, diagrams and field notes should be taken. It is believed that firefighters or police officers are the most suitable for this job.

4.4.2 Scene Assessment

When arriving at the fire scene, the investigator needs to identify and evaluate the affected area. Depending on the magnitude of the event and its effect on the conditions of the structures involved in the fire the approach adopted will vary, as introduced in Table 4-2. The identification of the affected area will typically be done visually, but through the use of recent satellite imagery, and drone footage, the accuracy of the burn scar identified can be improved.

4.4.3 Data Collection

In general, data can be found in the form of (a) physical evidence, such as fire patterns or artefacts, (b) witness statements, and/or (c) observations. Thus, physical evidence, witness statements and observations consequently are addressed below. In every fire, the investigator can find physical evidence, either inside the dwelling(s) or in the affected area. The physical evidence will help to understand the fire spread and, in the best scenario, the area of origin and the potential fire cause can be determined. At the scene, it is almost always possible to find several witnesses that could provide valuable information for the investigation, due to the number of people in these areas.

4.4.3.1 *Physical Evidence*

NFPA 921 [59] defines physical evidence as any physical or tangible item that tends to prove or disprove a particular fact. The main source of evidence within the fire scene are fire patterns and artefacts. The latter refers to any items related to the fire ignition, development, or spread. Evidence found must be documented through photographs, diagrams and/or field notes.

4.4.3.1.1 Fire patterns

NFPA 921 [59] define fire patterns as the visible or measurable physical changes or identifiable shapes formed by a fire effect or group of fire effects. The analysis of fire patterns, heat and flame vectors, and damage patterns are used to determine the point or area of fire origin. For informal settlements, depending on the behaviour of fire that is being investigated, different fire patterns can be found, as shown in Fig. 4-5. When the fire in an ISD is controlled before structural collapse occurs, the investigator should look for fire patterns inside and outside the enclosure. As shown in Fig. 4-5 (a) and Fig. 4-5 (b), the fire effects and fire patterns in walls and ceiling can be identified, and the analysis and hypothesis can be developed. However, usually when this happens, it is because the residents controlled the fire by their own means. In this case, it is common that the fire would not be reported or investigated. If the enclosure fire is presented with the opportunity to reach flashover, a fully developed fire ensues, resulting in heat fluxes exceeding 150 kW/m^2 emitted from openings and ceiling temperatures of approximately 1000°C [9,13]. In this situation, it is likely for the ISD to suffer structural collapse approximately 8 minutes after flashover [11], although times vary significantly. This will have a direct impact on the fire spread and on the amount of evidence left at the scene. In post-flashover fires, fire typically spreads to the adjacent dwellings hence, the investigator should focus on the analysis of the V or U shaped burn pattern, as shown in Fig. 4-5 (c) and (d). The V or U shape is developed in the first stages of a wildland fire. Usually, the ignition area can be identified by locating the narrowest point of the pattern [59,60].

Fire patterns can significantly be affected by several factors. For enclosure patterns factors such as ventilation, radiation and suppression efforts should be considered. For wildland fire patterns wind speed and direction having the greatest effect. Additionally, hot sparks and embers could be blown, and secondary fires could be ignited. The investigator has to keep in mind that the urban canopy affects wind velocity and that the fire itself creates fire winds that will influence the fire spread rate [59,60]. Often readings from the nearest weather stations are not representative, because the measurements are taken at high levels above the ground, where the wind velocity profile is fully developed. For this reason, it is important to have wind readings as near to the origin area as possible. For this end, if possible, the firefighters should measure wind speed with portable anemometers. After the wind, the slope of the affected area possess the next greatest impact on the fire spread. Fires will burn faster uphill than downhill [59,60].

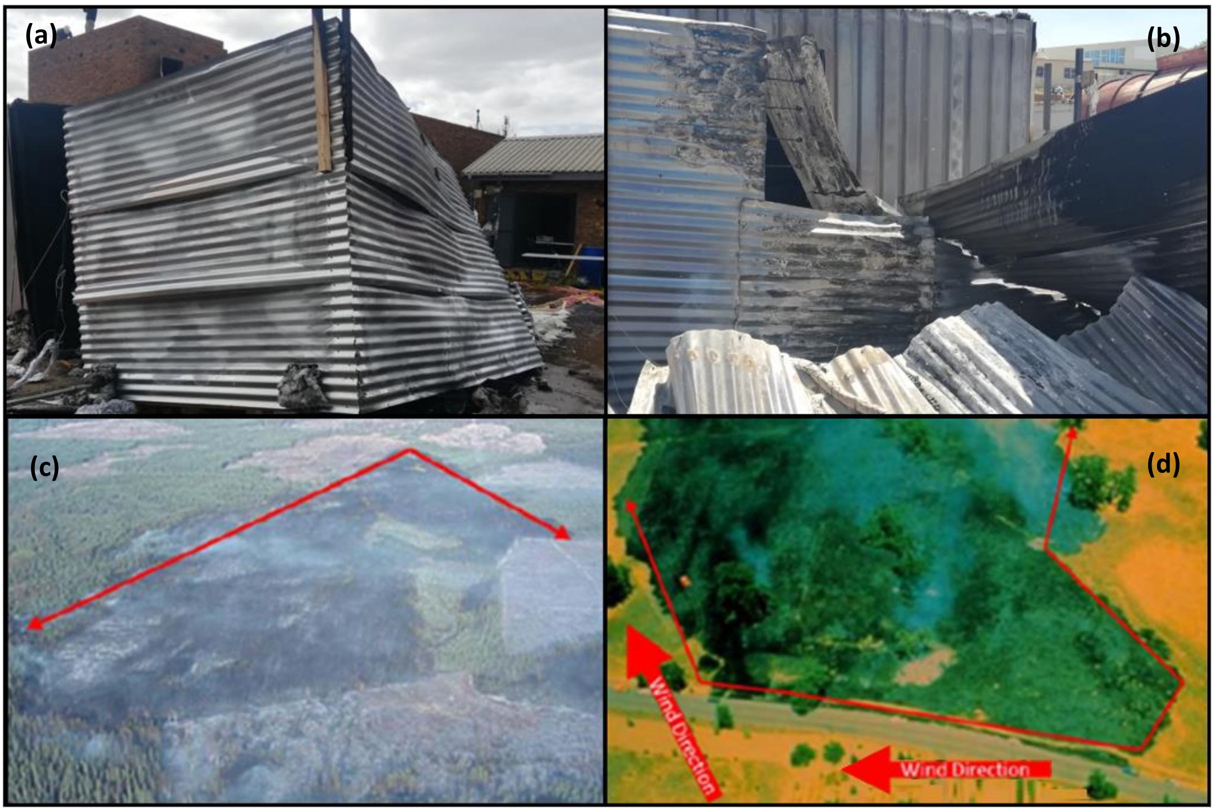

Fig. 4-5: Fire patterns. (a) Heat induce colour change in the dwelling. (b) Heat induce colour change and soot deposition in the dwelling. (c) Irregular V or U shaped [60]. *(d) Influence of wind and a road on the fire pattern* [60] *(underlay used with permission of the National Wildfire Coordinating Group).*

4.4.3.1.2 Artefacts

Once the potential point(s) of origin is/are located, the investigator should identify (a) the fuels present in the area, especially those that are easy to ignite, such as: furniture, bedding and curtains made of synthetic materials, paraffin stoves, repaired or altered gas bottles, etc, that later could allow the fire spread to other items, and (b) all possible ignition sources, such as illegal electrical connections, old reconditioned electrical appliances, open flames, etc. The number of artefacts left at the fire scene will depend on the fire development [67]. If the fire is extinguished during the pre-flashover stage of the initial dwelling, it is possible to find traces of the first material ignited or the ignition source. On the other hand, if the fire in the dwelling of origin becomes fully developed, all the combustible material present at the scene will typically be consumed, as shown in Fig. 4-3 and Fig. 4-6, thus leaving limited evidence, which makes the fire cause determination more complex.

4.4.3.2 *Witnesses Statements*

Witnesses' statements can provide significant information about the fire origin, cause or/and on how the fire spread. The conditions before, during and after the fire event could be established with the testimonies given by first responders, firefighters and occupants. From these statements, not only information about the fire behaviour can be obtained, but also other important data such as human behaviour during the fire incident and firefighters' performance.

Obtaining statements from informal settlements' residents can be difficult. There are several barriers that the investigator has to bear in mind. In many instances community members are unwilling to give their testimony. This is due to the fact that they may not trust the fire service. Alternatively, they could be scared of identifying the responsible person, or assuming the responsibility of the fire, because there could be reprisals against them. Additionally, even though many people may be at the scene, a large number of residents may not return permanently to the area until their homes have been reconstructed. In the case when community members are willing to give their statements, there are other issues to consider, such as language barriers (20 different languages can be spoken in one area), and even if the statement is given, the information could be inaccurate. The number of dwelling affected, people displaced, fire origin and/or the cause could be manipulated in order to get more disaster relief, or to not take the responsibility of the fire. Preferably, interviews should be conducted immediately after the fire, and if it is not possible at least critical witnesses should be identified such that their testimonies can be obtained afterwards. It is beneficial to have people that can speak the local language available. As a long-term consideration, it is important to improve the relationship between the fire brigade and the community to promote better investigations.

In terms of human behaviour during the fire event, people will engage in activities that (a) cause or prevent fires, (b) affect fires, (c) increase or reduce harm from fires [69]. Interviews with the residents should include questions that investigate how people behave in a fire situation. Shields and Proulx [75,76] state that it is necessary to study how people became aware of the fire and what type of activities they engaged and why in order to develop effective fire safety plans.

Firefighters can provide information about dispatch, arrival and fire control times. Also, they can indicate factors that influenced their performance, such as access conditions, water availability or/and resident interventions. Due to strained relationships with communities many instances have occurred with firefighters being stoned by communities when they arrive on the scene.

4.4.3.3 *Observations*

Observations involve field notes or diagrams. If possible, the fire investigator should take notes during the fire, direction of spread, rate of spread, flame height and length should be documented. Weather and topography observations should be used to fully understand the fire's behaviour [60]. Once the fire is extinguished, the investigator can document evidence of fire spread and growth, scene conditions and other details through diagrams and sketches [59].

4.4.4 Data Analysis

The investigator must understand the meaning of the data collected and determine if it is applicable for the specific case under consideration. NFPA 921 [59] indicates that this process requires knowledge, training, experience, and expertise of the individual. If the investigator cannot correctly attribute meaning to a piece of data, assistance should be required.

Based on all observed fire patterns, one or more potential fire origin should be identified. The investigator should keep in mind that the damage and burn patterns observed after a fire represent the entire history of the fire. Once this has been done, the potential first ignited fuel and the ignition source can potentially be identified. The analysis must determine, first, if the ignition source is capable of igniting the fuel. Then if the amount of fuel, (primary, secondary, etc.), was enough to explain the resulting fire. Finally, it must be found if there is a logical ignition sequence that allows the source of ignition, the fuel, and the oxidant to interact in the appropriate quantities and circumstance for combustion to result.

4.4.5 Hypothesis

Based on the data analysis, the investigator should produce one or more hypothesis to explain the origin, development and cause of the fire. Before selecting the final hypothesis, the investigator should ask, "Are there any other origin/cause hypotheses that are consistent with the data?" [59,60].

4.5 Case of Study: Imizamo Yethu fire

In this section, the methodology proposed above is applied to a real, large informal settlement fire. To this end, the Imizamo Yethu fire will be analysed from a fire forensic point of view. This event was chosen because it was previously studied in depth by Kahanji, et al. [15]. This analysis presents (a) a summary of the fire, (b) scene assessment, (c) the data collection from different sources, (d) the analysis of data to look for inconsistencies, (d) the development of hypotheses, and (e) a final discussion of the main findings of the fire investigation.

4.5.1 Imizamo Yethu fire

On March 10, 2017 at approximately 23:00 a fire started in Imizamo Yethu. The fire destroyed 2194 structures, leaving approximately 9700 people homeless. It is estimated that the fire started between 23:00 and 00:00 h. However, the Public Emergency Communications Centre (PECC) received the first message at 00:26 h. The Hout Bay fire department arrive at the scene a few minutes later. Nineteen other fire brigades also provided aid. During the first 7 hours, the fire was relatively under control, with 550 dwellings affected. However, in the next 5 hours, the number of affected dwellings approximately quadrupled. The fire was only extinguished by 13:00, leaving more than 2000 houses destroyed. Several factors contributed to the large-scale nature of the fire. These include the configuration and distribution of settlement, the construction methods and materials used in dwellings, people interfering with the extinguishment actions, blocked routes and especially the change in wind direction. Additional information is contained in the original paper.

4.5.2 Scene Assessment

Fig. 4-6 shows an image of Imizamo Yethu after the 2017 fire. The affected area was 76600 m^2. Due to the magnitude of the event, the focus is on analysing the wildland type fire patterns in the area. In order to understand the fire spread and determine the fire origin, the effects of the weather, the topography and the firefighting efforts are studied. As mentioned above, in these cases, most of the artefacts were completely burned out, which makes it difficult to determine the point of origin and the fire cause. Therefore, witnesses' testimony, such as residents of the dwelling where the fire started and first responders, are crucial to develop more specific hypotheses. As mentioned above, the fire scene suffered several alterations, as a result of the fire itself, the fire suppression actions and the occupants' interventions. Most residents did not leave the scene during or after the fire, but stayed to try reclaiming any unburnt possessions, and the land their homes were built upon.

Fig. 4-6: Aerial image of Imizamo Yethu after the 2017 fire (Image used courtesy of Bruce Sutherland, City of Cape Town)

4.5.3 Data collection

The data used below comes from statements from residents and firefighters, and from fire patterns. This will be analysed in the following section. Due to the magnitude of this event, the dwellings involved in the fire collapsed and all the combustible material burned out. Fig. 4-6 displays that what is left is mostly metal sheets. Thus, neither the investigation nor this work has focussed on looking for evidence of the first material ignited, or the ignition source.

4.5.3.1 *Witnesses Statements*

Kahanji, et al. [15] indicated that the information used to reconstruct the timeline of the events was based on interviews with the firefighters that were on the scene. In addition, images from media and municipal sources were used to validate the spread of the fire at different times. The witnesses' statements are divided into two subsections, namely residents and firefighters.

4.5.3.1.1 Residents

Community leaders indicated that the fire origin dwelling was the one where four fatalities were found. This cannot be proved, nor disproved, based on other evidence. There is no formal information about the activities undertaken by the occupants during the fire. However, Kahanji, et al. [15] indicate that inhabitants tried to save their belongings and engaged in firefighting actions based on firefighter feedback and media imagery.

4.5.3.1.2 Firefighters

Firefighters provided useful information with respect to the fire development and the problems they faced when trying to extinguish the fire. They indicated their locations at different times, which allowed for a better understanding of the fire spread behaviour. It was reported that only 10 minutes after the arrival to the scene the fire was starting to become under control. At this time, a resident cut one of the firefighter's hoses to redirect the water to their own dwelling, which resulted in them losing control of the fire, leading to faster fire spread. Between 02:00 and 07:00, the firefighters felt the fire was almost under control a number of times, but due to insufficient water pressure in the hydrants, the fire could not be extinguished.

4.5.3.2 *Fire Patterns*

Fire patterns were influenced by the firefighting efforts, wind speed and direction and the topography of the area. Each factor will be discussed independently in the sections that follow in order to be able to analyse the consistency between them later. Information presented by Kahanji, et al. [15] is used to analyse the fire spread.

4.5.3.2.1 Firefighting efforts

Fig. 4-7 was developed for the original investigation, based on the firefighters' testimonies and is recreated here. The figure shows the position of the fire brigades at different times. The first fire brigade got at the scene at around 00:30, and 7 hours later, the fire was contained to a quarter of the total affected area. However, the next 1.5 hours were the most destructive, consuming approximately 35% of the affected area. From 9:00 aerial support from helicopters was given, decreasing the rate of spread of the fire. At 13:00 the fire was extinguished. As mentioned above, the firefighting efforts were affected by the intervention of the residents and by the lack of water pressure in the hydrants.

4.5.3.2.2 Wind

According to the nearest weather station, during the fire the wind speed fluctuated between 28 to 46 km/h and the direction changed between South and South-southeast. On the other hand, firefighters' statements revealed that the initial wind direction was North West and that between 01:00 and 03:00 h the wind change direction to South East [15].

4.5.3.2.3 Topography

Fig. 4-7 shows the location and the elevation profile of the area affected by the Imizamo Yethu fire. The informal settlement is built on the slope of a mountain. The change of elevation is 64.5m over a distance of 333m, with an average slope of 19.3%.

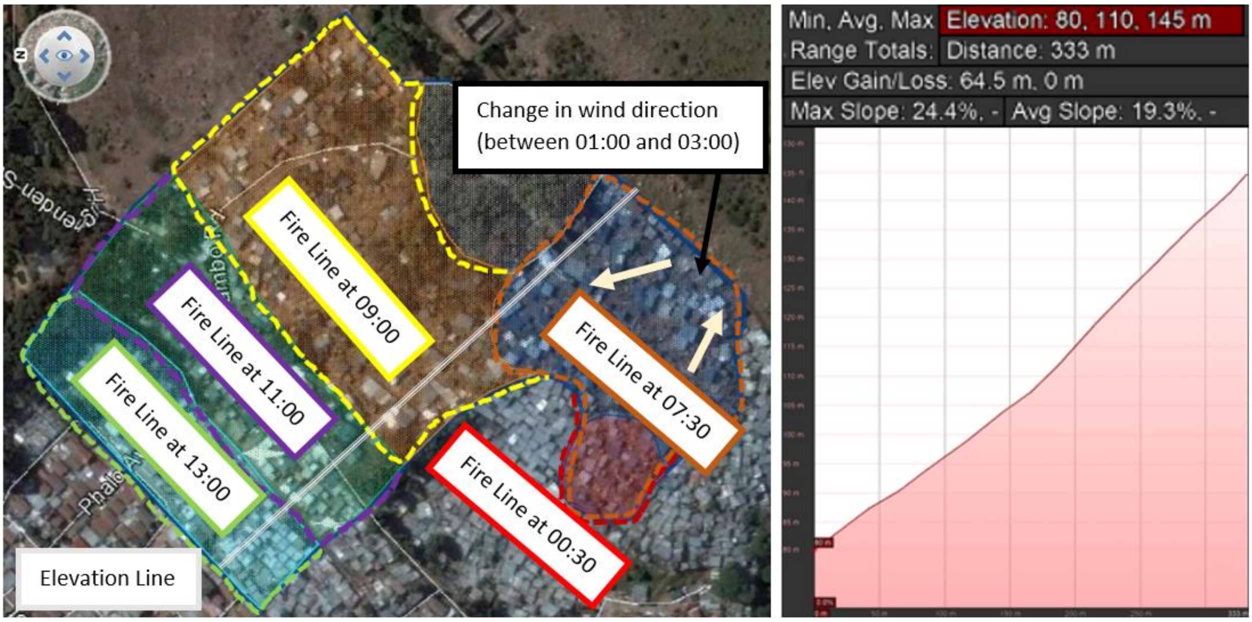

Fig. 4-7: Fire lines, wind direction and elevation profile [106] *in the Imizamo Yethu fire.*

4.5.4 Data Analysis

The data presented above is analysed below in order to determine if it is applicable to the specific fire. As indicated above, there is not enough information to determine the fire cause. For this reason, only the data related to the fire origin will be analysed. From the previous section it is possible to notice that there is an inconsistency between the wind readings from the nearest weather station and what was observed at the fire scene. This is not surprising as it was acknowledged above that the information from weather stations might not be representative of the particular area.

Fig. 4-8 depicts three possible V/U shape burn pattern of the scene that could be indicative of fire origin. Alternative (a) and considers an initial fire spreading uphill followed by a change of direction. Option (b) is similar, but the change of direction occurs at the end of the fire. Finally, (c) considers a downhill spread.

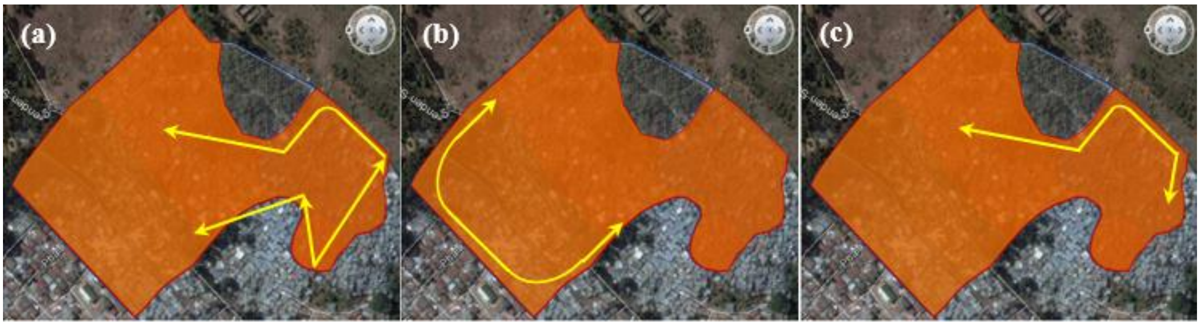

Fig. 4-8: Possible origin areas of the fire

By comparing the collected data with the potential fire origin areas presented in Fig. 4-8 it is possible to determine which one gives a closer representation of what actually happened. The slope of the area and the initial wind conditions suggests an uphill spread at the beginning of the fire, this situation will persist unless a change of wind direction will produce a downhill spread. That situation could describe (a) or (b), however, the U shaped pattern show in Fig. 4-8 (b) is usually found on flat ground or light wind conditions, so this option can be discarded, leaving (a) as the most probable solution. Pattern (a) is also consistent with the witnesses' statements.

4.5.5 Hypothesis

Burn pattern hypothesis: In this case, the only fire pattern formation sequence that is consistent with all the different data sources is presented in Fig. 4-9. The V shaped burn pattern associated with the beginning of the fire on a steep slope is located at zone A. This is consistent with the information given by the residents and firefighters. The fire starts to spread uphill to zone B, as expected considering the topography of the area and the wind conditions. However, due to the change in the wind direction, the fire starts spreading downhill from zones B to E. In this case, the wind had a major impact in the fire spread. It can be seen that in zones C, D and E the pattern does not widen, this can be attributed to the firefighting efforts in the Southwest side and to the lack of combustible material on the Northeast side of the settlement.

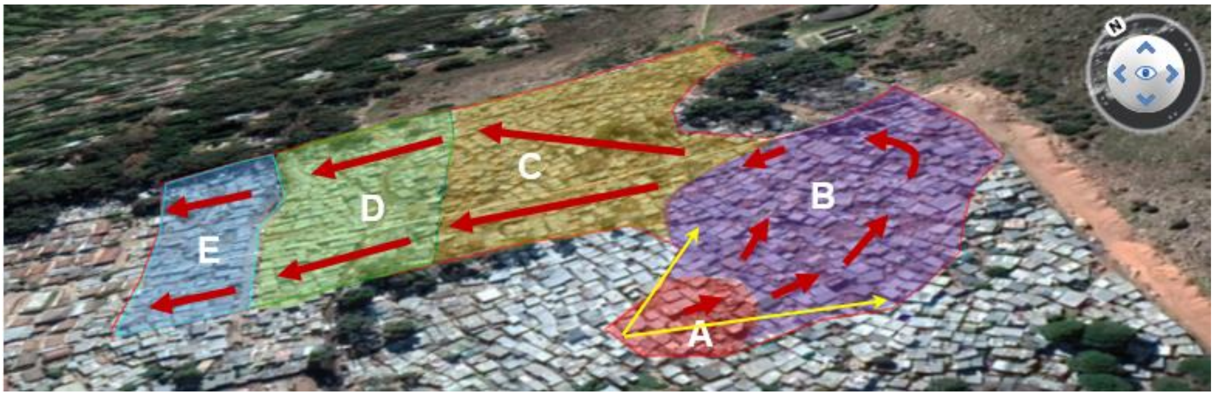

Fig. 4-9: Fire pattern analysis of the Imizamo Yethu fire [106]

Dwelling of origin hypothesis: There are two potential hypotheses that could be considered:

<u>Hypothesis 1: The dwelling where the fatalities were found is where the fire started.</u> Often, in residential fires, the fatalities are found in the room of fire origin [110,111] . It is even more likely to find the victims in the dwelling of origin [112,113]. People intimately related with the fire could be involved with the ignition or they might not be able to evacuate on time [114].

<u>Hypothesis 2: The dwelling where the fire started did not present casualties.</u> As pointed out by Kahanji, et al. [15], in fires in informal settlements it is unlikely that the person responsible assumes the responsibility. They fear the way their neighbours could react. Therefore, even if someone knew where the fire started and the fire cause, it is probably that the information would not be shared, and this hypothesis would need further information to be investigated.

4.5.6 Discussion

The analysis of the case study provided important insights about several topics important for fire safety engineering in informal settlements. First, it identified the factors that contributed to the fire behaviour and established the fire spread sequence. This knowledge is useful for firefighters, as it can contribute to a more efficient and effective use of the resources. Second, even if the fire cause cannot be determined, dangerous behaviours, processes and/or appliances can be identified. This information is critical to design prevention plans. Third, it highlighted the importance of human interventions in the fire development. The occupants of informal settlements have often witnessed more than one fire in their lives. This does not necessarily mean that they are well prepared for these events. Studying human behaviour in fires in informal settlements could lead to the implementation of plans to educate people on how to prevent fires for happening and how to act in a fire situation. Finally, it raises awareness of the problems that firefighters faced when trying to extinguish the fire. Further research is needed to address these topics.

4.6 Conclusion

This paper has presented a framework for conducting fire investigations in informal settlements. To address the nature of the fire behaviour in informal settlements, this work combines well-known fire investigation principles for in enclosures fires and in wildland fires. The size of the fire will determine what information can be gathered and how it can be used.

One of the most critical aspect when conducting a fire investigation in an informal settlement is to understand its characteristics and the limitations and problems that the fire investigator could face. These include, but are not limited to, lack of time and resources, not enough evidence on the scene and difficulties to collect witnesses' testimonies.

The Imizamo Yethu fire in 2017 was used as a case study. Testimonies of firefighters and residents test were supported by the analysis of the fire patterns present on the scene, which allowed the identification of the fire origin area. In addition, the case study provided important insights into the main factors that influenced the fire spread, the human behaviour during these events, and the problems the firefighters face.

Fire investigations in informal settlements will allow brigades and municipalities to, where possible: (a) identify the fire origin and fire cause, (b) understand fire spread sequence, (c) obtain data on human behaviour in fire, and (d) evaluate the effectiveness of suppression and response efforts. Learning from past fire events will facilitate designing prevention plans that respond specifically to informal settlements requirements, although this will never be an easy task.

4.7 Acknowledgements

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Chapter 5: Fire incident analysis of a large-scale informal settlement fire based on video imagery

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Declaration by the candidate:

The nature and scope of the candidate's contribution were as follows:

Nature of contribution	Extent of contribution
Writing the manuscript, establishing methodology, analysis of the video, conducting interviews, and preparing figures and tables.	83%

The following co-authors have contributed to as follows:

Name and e-mails	Nature of contribution	Extent of contribution
Richard Walls rwalls@sun.ac.za	Supervised the work, advised on the work, and review the manuscript.	8%
Antonio Cicione acicione@sun.ac.za	Advised on the work and review the manuscript.	5%
Mark Smith Mark.Smith@capetown.gov.za	Provide the video, coordinate interviews, and review the manuscript.	4%

Signature of candidate:
Date:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 5,
2. no other authors contributed to Chapter 5 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5 of this dissertation.

Signature	Institutional affiliation	Date
	Stellenbosch University	04/08/2021
	Stellenbosch University	04/08/2021
	Milnerton Fire Department	04/08/2021

This chapter is an exact copy of the journal paper referred to above

Contribution of chapter to dissertation

In this chapter a fire incident that occurred in an IS and that was recorded by a CCTV camera was analysed. The work analyses the fire spread, the residents' actions, and the firefighters' operations. This chapter is used in Chapter 6 to benchmark one of the case studies analysed.

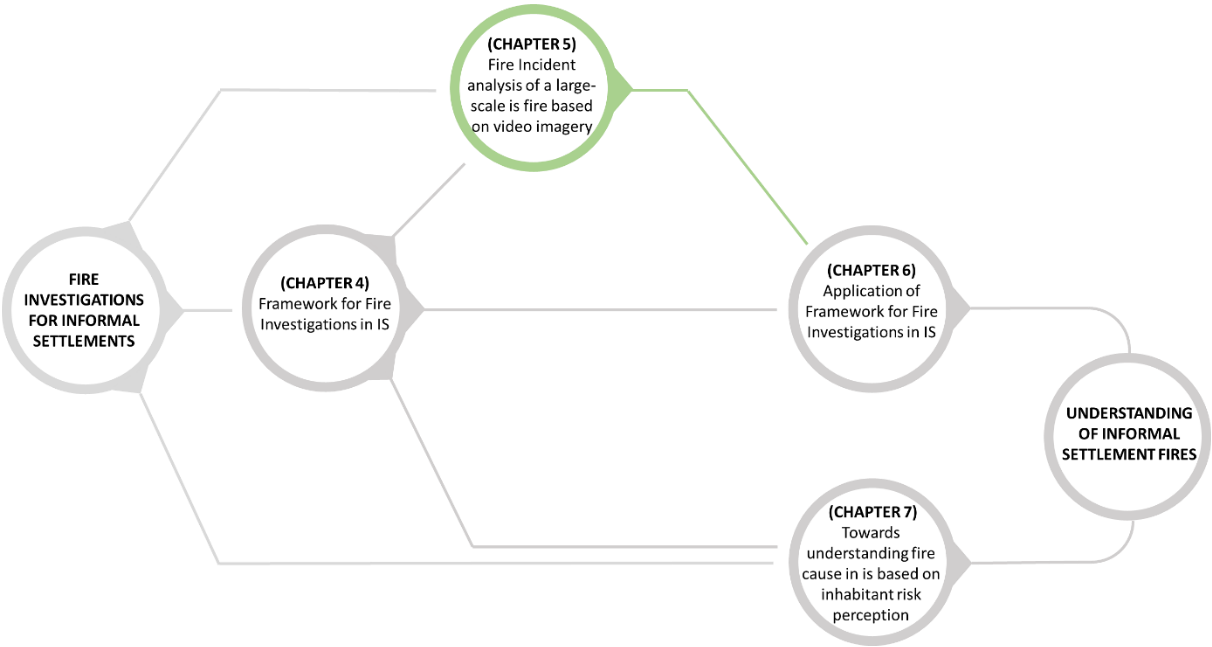

Fig. 5-1:Contribution of Chapter 5 to dissertation.

CHAPTER 5: FIRE INCIDENT ANALYSIS OF A LARGE-SCALE IS FIRE BASED ON VIDEO IMAGERY

5.1 Abstract

Informal settlements (IS) (also known as slums, shantytowns, ghettos, etc.) regularly experience fires. There has been an increasing interest in understanding fire dynamics in ISs. However, research has tended to focus on theories developed or based on idealized experiments rather than analysing real fire incidents, primarily because of the difficulty in obtaining data from real events. This work describes a recent fire incident that took place in an IS in South Africa. The analysis is based on the recording of a transit CCTV camera that captured the entire fire incident, the Fire & Rescue Service Incident Report and interviews conducted with the firefighters who responded to the incident. The footage provides high quality data allowing for novel analysis and understanding of such events never previously attainable. In a period of 33 minutes, an estimated 42 dwellings were affected at an average burning rate of 1.2 m/min and 15.45 m^2/min. This paper describes (a) the fire spread, (b) the human behaviour, and (c) firefighters' response and operations. The study of such incidents allows for a detailed understanding and development of policy for safety during urban environment large-scale fires. Additionally, improved interventions, firefighter strategies, community layouts, and response strategies can be developed for low-income communities.

Keywords: fire investigation; informal settlements; fire spread; human behaviour in fire, slums; disaster.

5.2 Introduction

Informal settlements (IS), also known as slums, shantytowns, ghettos, etc. (although these terms may be considered derogatory), regularly experience small and large fires, which is a substantial problem in developing countries [6]. In the recent years, there has been an increasing interest in understanding fires in IS. However, the research to date has tended to be theoretical or based on idealised experiments rather than in analysing real fire incidents. This is largely due to the difficulties associated with obtaining data from real incidents. Such incidents occur quickly, are very chaotic, have limited data collection being done after them, involve complex community interactions, and many variables affect the fire behaviour (e.g., settlement density, fuel loads, construction materials, firefighting activities, etc.). Experimental studies on fire spread mechanisms between IS dwellings have been conducted by Cicione et al. [9,13] to understand fire spread, and to ultimately develop fire spread models [13]. A full-scale fire spread experiment of a mock 20 dwelling settlement was conducted by de Koker et al. [12] with the purpose of understanding settlement-scale fire spread behaviour. The influence of horizontal openings on the heat fluxes, plume sizes emitted from dwelling openings has being investigated by Beshir et al. [105]. By using remote sensing Gibson et al. [104] proposed a method to track historical fires, based on the albedo of IS dwellings' roofs before and after a fire incident. In work somewhat similar to this paper, but on a much larger scale and without video footage available, Kahanji et al. [15] analysed the fire spread of the real informal settlement fire that occurred in Imizamo Yethu in 2017, where 2194 homes were destroyed. Rush et al. [115] discussed similarities and differences between IS fires in South Africa and those occurring in New Delhi, India, along with tented camps in Lebanon.

Although there has been a limited amount of researchers involved in studying IS fires, the fire behaviour is in some ways similar to large urban fires. Data from fires in urban areas with predominantly combustible structures may provide insight into a variety of topics for ISs fires. Yoshioka et al. [31] and Himoto [28] studied several large urban fires that have occurred in Japan. They identified that factors such as wind conditions, construction materials (mostly wooden structures) and the density of the area played an important role in the fire spread. Work done on wildland-urban interface fires [39–41] may provide insight into quantifying and understanding ignition due to firebrands. A recent review paper by Manzello et al. [27] reviews urban fires internationally and highlights that urban fires (a) are strongly influenced by the environmental and topographical conditions, (b) need forensic investigations to gain knowledge about factors that have an influence on them, (c) creates serious environmental and health impacts that should be studied, (d) require special emergency management strategies and (e) require more research on how the structures are ignited.

As stated by Babrauskas [14], fire investigations can provide significant information to the fire safety engineering field. He emphasizes that the efforts should be directed to collect meaningful data; such as how the fire started, how the occupants were alerted, what were their actions, the number of fatalities and injuries, the fire department effectiveness, etc. However, in the dedicated Framework for Fire Investigations in Informal Settlement developed by Flores Quiroz et al. [10], it has been acknowledged that fire investigation in an IS is a very complex endeavour, where factors such as rapid enclosure fire development, rapid fire spread, and lack of evidence present at the scene hinder the investigation.

This work describes a recent fire incident that took place in an IS in South Africa and can be used to better understand what happens in IS fires. The aim of this work is to answer the following questions: How did the fire spread? What was the impact of the residents and firefighters' actions on the fire's development? How did the residents behave during the fire? How did their actions change throughout the event? What were the firefighters' procedures? What problems did they face? Are there similarities with (a) IS fires, (b) IS experimental tests, and (c) other urban fires?

The fire that is analyzed in this study occurred on 30 September 2019, at around 10:30 in the morning. The dwelling of fire origin reached a fully developed fire stage within minutes after ignition, although specific details regarding the ignition and the first few minutes of development are not certain and subject to conjecture. After this, the fire spread rapidly (33 minutes) to approximately 40 other dwellings. Firefighter teams, from five different stations in the metropolitan area, attended to the scene, and they were able to control the fire around 25 minutes after the first unit arrived. The fire development, residents' behaviour and the firefighters' actions were recorded by a transit CCTV camera located near the settlement. Considering the minimal data regarding real incidents being available this footage presents novel information for understanding and improving the knowledge of IS fires. Additionally, the authors had access to the Fire & Rescue Service Incident Report (FRSIR) of the fire event and interviewed a number of the firefighters that attended to the incident.

This paper presents a summary and the findings of this real fire event. The work describes (a) the area where the event took place, (b) the methodology used, and (c) the results, in which the fire incident, the fire spread, the human behaviour and the fire fighters' response and operations are analysed.

For privacy reasons various details about the fire event have been intentionally excluded from the paper. These include (a) the exact location of the event, (b) people's faces and (c) specific details about the firefighters and fire stations involved.

5.3 The study area

The settlement's location is shown in Fig. 5-2; it is situated in an accessible zone, near highways and main roads. The topography of the area is characterized as a flat terrain, with variations in the elevation of less than one meter. The affected area is a small part of a much larger settlement, which is partially presented in Fig. 5-2(b), located on the south side of road A.

Fig. 5-2: Location of the affected area [106]. *(a) With respect of the CCTV camera. (b) With respect to the rest of the settlement.*

5.4 Methodology

This section describes the methodology used in the analysis of the fire incident. Fig. 5-3 provides a graphical representation of the methodology. Four different sources of information were considered: the video footage, Google Earth satellite imagery [106], ArcGIS satellite imagery and GIS data [116], and the fire brigade input. Data such as screenshots and satellite imagery were extracted and analysed to obtain information about the fire spread, human behaviour and firefighters' operations. The remainder of this section presents in detail (a) the sources of information used for this work and (b) the procedure applied to analyse the video recording.

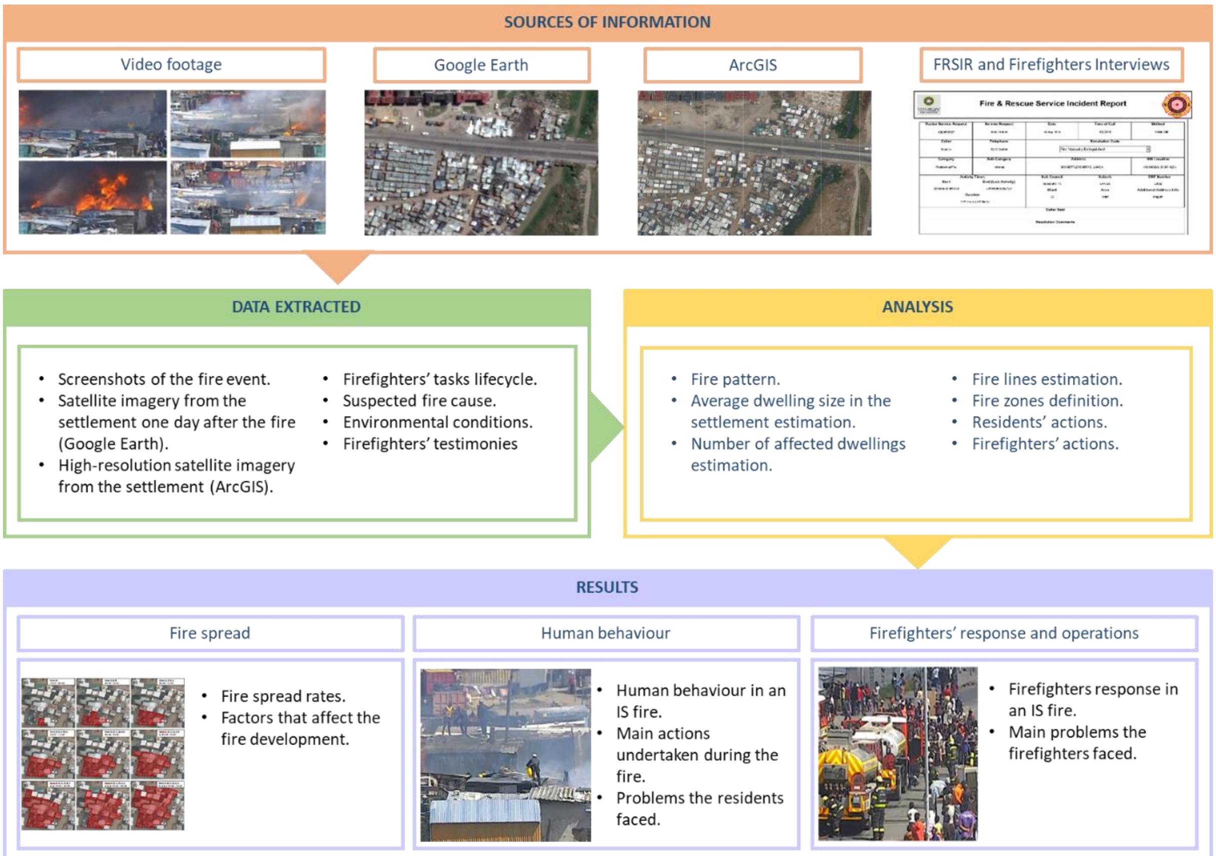

Fig. 5-3: Methodology

5.4.1 Sources of information

As mentioned above, the main source of information for this work was a CCTV recording. The CCTV camera that recorded the video is located approximately 120 meters away from the settlement, with the approximate location depicted in Fig. 5-2 (a). The video has a duration of 80 minutes and captured the fire incident from ignition in the dwelling of origin to the point of fire extinction. The video starts at 10:33:12 [hh:mm:ss] and ends at 11:52:43 [hh:mm:ss], which for the purpose of this paper will correspond to t=00:00 [mm:ss] to t=79:31 [mm:ss], respectively. The video provides information about the fire development, the residents' activities and the firefighters' actions during the event. To identify the affected area satellite imagery from Google Earth [106] taken one day after the fire was used. To estimate the fire spread rates the video was complemented with high-resolution satellite imagery from ArcGIS [116]. The latter did not have high-resolution images immediately after the fire so the former was used in that case. The FRSIR provided information about (a) time when the first call was received, (b) amount of fire stations that attended to the fire event and their response times, (c) environmental conditions (e.g., temperature and wind data) and (d) suspected fire cause.

5.4.2 Procedure

The video of the fire incident was analysed by capturing specific observations or findings as screenshots of the video and noting the time elapsed paired with each observation (i.e., each screenshot). Additionally, the fire spread was analysed by taking a screenshot every minute to see the progress of the fire. Fig. 5-4 depicts the form in which the progress of the fire line, the spread rates and the number of affected dwellings were estimated. The progress of the fire line was determined by using high-resolution satellite imagery from ArcGIS [116] and four dwellings, which are marked with the red circles in Fig. 5-4(a) and are seen in most parts of the video, as reference points. Based on the fire lines at different times, nine zones were defined, for each of them a specific colour and a letter from A to I were assigned. The red arrows in Fig. 5-4(a) depict the advancing fire front direction considered in each zone. The approximated linear and area spread rates were calculated considering the advancing fire front and the affected area divided by the time interval of each zone. The longitudinal and transversal progress was taken into consideration for zone B while for the remaining areas only the longitudinal spread was used.

To estimate the number of dwellings affected high-resolution satellite imagery [116] was used. The first step was to identify the number of roof/structures that were in the affected area. However, in some of the structures, there may be multiple units, or sections of a home, meaning that multiple households are present under one roof. As a commonly identified example: a single dwelling may be managed by an 'owner' who subdivides and rents the dwelling out to four unrelated people, meaning that the single structure could either be classed as either one household or four households. Such data is difficult to accurately obtain, even through community interviews, due to factors such as (a) illegal immigrants will be unwilling to acknowledge their presence, (b) inhabitants may report higher numbers of individuals affected to try obtain more relief support, (c) inhabitants are not present immediately after a fire to be enumerated. Hence, as a simplification, in this work all the structures with an area 50% larger than the average area will be considered as two dwellings. To estimate the average area of a dwelling in this location, a sample of 100 homes was analysed using satellite imagery [116]. It was found that the average structure roof size is around 12.4 m^2. This is 37% less that what was found by Kahanji et al. in [15], however the 'average' floor area will change significantly from province to province, city to city and from settlement to settlement. In this investigation, from the 38 roofs/structures identified four of them were recognized as above 'average', having an area superior to 18.6 m^2, meaning that the estimated number of dwellings affected is 42. Each of the dwellings are presented in Fig. 5-4(b), with a correlative number and with the colour associated to the zone to which they belong.

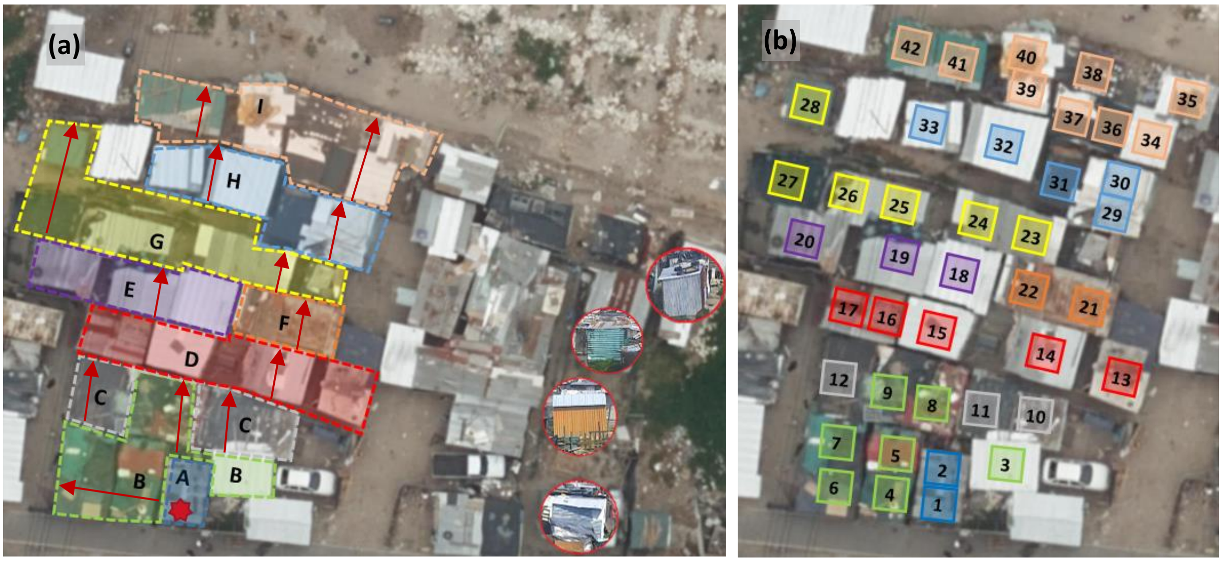

Fig. 5-4: Fire spread [116]. *(a) Estimated fire line progress. The red star represents the dwelling of fire origin. The different zones, A to I, are associated with the fire line at different times. (b) Estimation of number of dwelling affected by the fire. Each number is associated to the colour of the corresponding zone (A to I).*

5.5 Results

This section describes (a) the fire incident, (b) the fire spread, (c) the human behaviour and (d) the fire brigades' response and operations. The last three topics mentioned were analysed and presented separately even though they all are continuously interacting with each other.

5.5.1 The fire incident

As mentioned above, the fire occurred on Monday 30 September 2019, the last day of the third term school recess, at around 10:30 in the morning. According to the FRSIR, approximately 40 dwellings were affected and 90 people were displaced. This number of people affected may seem relatively low (e.g. for the Imizamo Yethu fire there were around four inhabitants per dwelling affected [15]). However, it has been acknowledged by the Housing Development Agency in [117] that the number of one-person households has increased in the last years, and possibly the community affected had a large number of single people. The FRSIR also stated that on the day of the fire, the sky was clear, there was a light south-east breeze, which is an important factor when considering the fire spread direction, and the ambient temperature was between 15°C and 20°C. Fig. 5-5(a) shows the affected area four days before the fire. In Fig. 5-5(b) it can be seen that the affected area is approximately 550 m^2. Fig. 5-5(c) presents the settlement 18 days after the fire, showing how fast ISs are rebuilt after this type of incident.

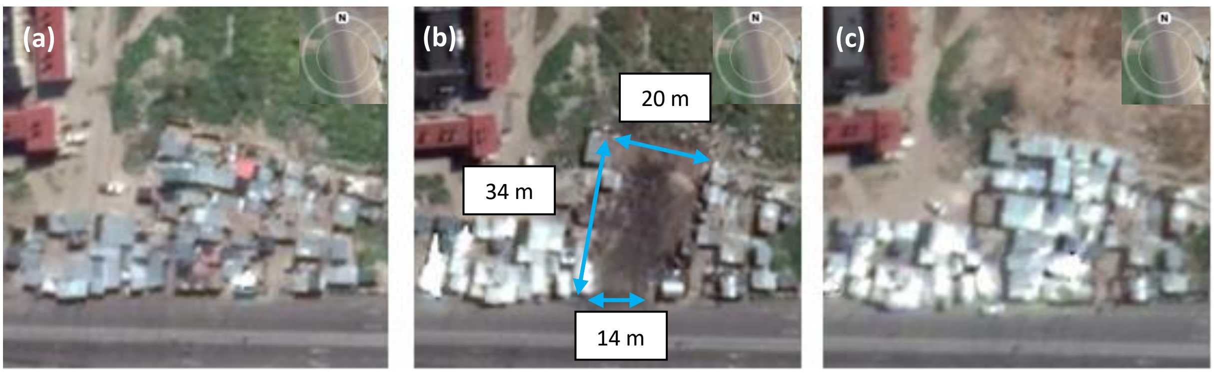

Fig. 5-5: Informal settlement affected by the fire. (a) 4 days before the fire. (b) 1 day after the fire. (c) 18 days after the fire. [106]

5.5.2 Fire spread

This section presents the fire development through a series of images, Fig. 5-6 to Fig. 5-10, that depict the fire spread. The images are complemented with Fig. 5-11 and Table 5-1 to indicate fire spread rates.

Fig. 5-6 presents the fire development during the first three minutes of the recording. At t=00:00, it is possible to see a small amount of white smoke coming out of the dwelling, which is an indication that the fire inside the dwelling just started to consume materials (Fig. 5-6(a)). Approximately one minute later, the dwelling reached a fully developed fire stage, which is identified by the flames ejecting from the dwelling openings (Fig. 5-6(b)). However, at t=02:50 only smoke is seen coming out from the dwelling of origin (Fig. 5-6(c)). It is possible that this was due to the buckets of water that the residents used to extinguish the fire (as discussed further below). The footage shows that in less than a minute, at least eight buckets of water, (approximated 20 L capacity per bucket), were thrown onto the burning dwelling. Despite the residents' efforts, at t=03:08 intermittent flames appear again (Fig. 5-6(d)).

The efficacy of the water of buckets application was studied by Löffel and Walls [118,119]. They observed that the temperature in the dwelling was strongly reduced, from 890°C to less than 200°C, after the application of eight 10 L buckets filled with 8 L of water. However, the findings of that work cannot be compared with this one. While in this case it is not possible to know how much water was actually used, regardless of knowing the capacity of the buckets; in their experiments, the possibility of re-ignition was not studied, and firefighters intervened after there was a flame reduction and the temperature significantly decreased.

Fig. 5-6: Fire development. (a) t=00:00. (b) t=01:17. (c) t=02:50. (d) t=03:08.

Fig. 5-7 depicts the fire development between t=05:00 and t=15:00. During this period, the fire spread beyond the dwelling of origin to an estimated 17 dwellings, at an average spread rate of 1.4 m/min and 17.5 m^2/min. The fire intensity gradually increases from t=05:00 to t=13:00, but in the last 2 minutes it can be seen that the fire intensity grew considerably, reaching a spread rate of 1.9 m/min and 36.5 m^2/min. This was due to an explosion that occurred at t=14:26, as depicted in Fig. 5-8. Discussions with firefighters have indicated that explosions occur often during fires in ISs in general. Previous research [2,15] has noted that the fire loads in IS include highly flammable materials, such as kerosene, gas bottles or paraffin, which could cause these explosions. In this instance, it is believed that a LP gas cylinder was the cause.

Fig. 5-7: Fire development from t=05:00 to t=15:00.

Fig. 5-8: Explosion at t=14:26, with images covering a period of approximately 2 seconds.

Fig. 5-9 presents the fire development from t=17:00 to t=37:00. During this period, the fire intensity fluctuated due to the firefighters' interventions. The fire spread to an estimated 42 dwellings, at an average spread rate of 1.2 m/min and 18.7 m^2/min. Even though the first unit arrived at t=11:00, it was only by t=17:00 when there were two fire stations' teams at the scene, that the firefighters' efforts started to have an effect. Between t=17:00 and t=21:00 the fire intensity started to diminish, and large amounts of steam can be seen, the spread rate reduced to approximately 0.9 m/min and 11.6 m^2/min. However, at t=25:00 the fire intensity had increased once more, between t=28:00 and t=30:00 the estimated spread rate reached 2.3 m/min and 33 m^2/min. By t=33:00 the fire had reached the back of the settlement and there were no more combustible material left to the north of the settlement.

Fig. 5-9: Fire development from t=17:00 to t=37:00. The fire intensity fluctuated due to the firefighters' interventions.

Fig. 5-10 depicts the fire behaviour in the last stage of the fire. From t=39:00 to t=79:00 it is possible to see the fire extinguishment due to the intervention of the firefighters. The firefighters' response and operations are discussed in detail in a section that follows.

Fig. 5-10: Fire development from t=39:00 to t=79:00. Fire extinguishment phase.

Fig. 5-11 presents the approximate progress of the fire line; the red star represents the dwelling of fire origin. Each of the figures depicts the progress from the beginning of the recording for each of the different zones, A to I, as depicted in Fig. 5-4(a). The details pertaining to the fire spread rates for each zone can be found in Table 5-1.

Table 5-1 presents each zone with its associated time, the approximated number of dwellings and area affected, and the burning rate. It can be seen that the linear and area fire spread rates increased gradually until t=13:00. In Zone D (t=13:00 to t=15:00), the fire reached a linear spread of 1.9 m/min while the area spread rate grew to 36.5 m^2/min, which is more than 2.5 times larger than the one calculated in Zone C (t=10:00 to t=13:00). This was due to the explosion that took place at t=14:26 (Fig. 5-8). When the fire line reached Zone E, (t=15:00 to t=18:00), the firefighters' actions reduced the fire intensity significantly. After that, the fire spread increases again reaching a spread rate of 2.3 m/min and 33 m^2/min in Zone H (t=28:00 to t=30:00). The fire was extinguished around t=48:00 after the remaining firefighter units arrived at the scene.

Fig. 5-11: Estimated fire line progress. The red star represents the dwelling of fire origin.

Table 5-1: Zones associated with the fire line at different times and corresponding numbers of dwellings and m² burnt.

Zone	Time [min:sec]	Approx. no. dwellings	Spread rate [dwelling/min]	Area affected [m²]	Area spread rate [m²/min]	Linear spread rate [m/min]
A	00:00 – 04:00	2	0.5	17	4.3	1.1
B	04:00 – 10:00	7	1.2	75	12.5	0.9 – 1.1
C	10:00 – 13:00	3	1.0	40	13.3	1.7
D	13:00 – 15:00	5	2.5	73	36.5	1.9
E	15:00 – 18:00	3	1.0	23	7.7	1.0
F	18:00 – 22:00	2	0.5	52	13.0	0.9
G	22:00 – 28:00	6	1.0	77	12.8	0.4-1.3
H	28:00 - 30:00	5	2.5	66	33.0	2-2.3
I	30:00 - 33:00	9	3.0	87	29	1.1-2.0
	TOTAL	**42**		**510**		

The calculated linear spread rates ranged from 0.4 to 2.3 m/min, which appear to be consistent with previous research in IS. In the Imizamo Yethu fire incident [15] the linear fire spread rates ranged between 0.5 m/min to 2.3 m/min, while in the experimental work by de Koker et al. [12] the average linear spread rate was 3.6 m/min. It has to be considered that the latter was a full-scale fire spread experiment of an idealized settlement in which there were no firefighting actions involved. When compared with other large urban fires the spread rates calculated in this work are closer to the lower values seen in urban fires in Japan [31]. Table 5-2 compares the values obtained for the aforementioned research with the ones calculated in this work. It is likely that the spread rate would have been significantly higher if (a) a much stronger wind been blowing (such as the strong "South-Easter" which often blows in Cape Town) and/or (b) if the settlement had been larger.

Table 5-2: Linear fire spread rates for IS fires and large urban fires

Fire event or experiment	**Spread rate m/min, (m/h)**	**Average spread rate m/min, (m/h)**
Case study	0.4 - 2.3 (24 - 138)	1.2 (72)
20 dwellings experiment [12]		3.6 (216)
Imizamo Yethu fire [15]	0.5 - 2.3 (30 - 138)	1.4 (84)
Urban fires in Japan (1940s-1960s) [31]	1.7 - 8.3 (100 - 500)	
Itoigawa Fire (2016) [31]		1.7 (100)
Sakata Fire (1976) [31]		1.7 (100)

5.5.3 Human behaviour

Human behaviour during fire incidents in informal settlements has received negligible attention in the literature. However, having a better understanding of people's behaviours and decisions during a fire situation is critical to develop fire safety measures [69]. As stated in [69], the anticipation of human behaviour and prediction of human responses during a fire event is one of the more complex areas of fire protection engineering. Through observation it was possible to identify some of the actions that residents of this IS undertook during the fire event. However, future work is required to (a) identify the occupants' characteristics; (b) identify cues that trigger their actions; and (b) to understand how people interpret the situations around them, which are critical to comprehend human behaviour in fire [120].

Some assumptions can be made with respect to the occupant's characteristics and the conditions in which they live that are important when analysing their behaviour in a fire event. First, considering that is a residential fire, (a) the residents are familiar with the layout of the area (settlement) [70] and b) there is social affiliation [70]. Second, for IS it is also expected (a) a highly dense population [103] and (b) that the occupants have been exposed to previous fire events [10]. In this particular case, since the fire occurred on a Monday at 10:30 am, it is expected that people were awake and alert. Throughout Fig. 5-12 to Fig. 5-19, the actions of the residents are shown in the different stages of the fire incident. As previous research indicated [70,71,73,91], residents' actions during a typical residential fire incident include: information seeking, firefighting attempts, valuables gathering and re-entry behaviour.

Residents became aware of the fire relatively fast. Fig. 5-12(b) shows that at t=01:06 there were eight people gathered outside the dwelling of fire origin, probably seeking more information to define their next actions. Once flames appear outside the dwelling, people start bringing buckets of water in an effort to extinguish the fire. As Fig. 5-13 depicts, in less than one minute (from t=01:30 to t=02:15), at least eight buckets of water were applied to the dwelling of origin. The response seems surprisingly fast, but as it was mentioned before, it is highly likely that the occupants had experienced previous fire incidents; hence, people knew how to react in this situation. Fig. 5-13 depicts the procedure for this task. Both men and women brought buckets with water to the dwelling, however, it appears only men carried out the water application.

Fig. 5-12: Residents' actions: (a) People have not noticed the fire (t=00:00). (b) People gather in front of the dwelling of fire origin seeking for information (t=01:06).

Fig. 5-13: Residents' actions during the early stages of the fire, with people bringing and throwing buckets of water into the dwelling of fire origin (from t=01:30 to t=02:00). Numbers shown indicate the buckets applied for suppression.

Between t=02:00 and t=03:10, the camera zooms out and it is not possible to observe in detail the situation. As the fire spread to the adjacent dwellings (t=03:00) and there is no more water immediately available in the vicinity of the fire origin, (between t=03:00 and t=04:00 only 3 buckets of water were applied), the residents' actions diversify. From the video, it is possible to identify three main actions during this stage (a) firefighting, (b) saving valuables and (c) the evacuation of the area. Further discussion regarding these actions are provided below.

Fig. 5-14(a) shows that at t=5:30 no more buckets are thrown onto the dwelling of origin, it appears that they are protecting the property from being looted. Possible explanations for the cease of the firefighting actions are that (a) this is a consequence of the lack of water near the fire origin, (b) people are protecting other residences or (c) occupants are undertaking other actions. It has been acknowledged that in informal settlements the lack of water supply is a major problem, especially in a fire event [2,15]. Usually, every dwelling will have a bucket of water for domestic use. However, the refilling process usually takes some time. Fig. 5-14(b) depicts a man refilling his buckets. The sequence shows the same man in four different locations, starting at (1) and ending at (4). The process, that lasts 75 seconds, is shown with yellow arrows. There is not clarity on where the people are refilling their buckets; however, the firefighting actions are seen during the whole incident.

Fig. 5-14: Residents' actions. (a) Protecting the property (presumably) at t=5:30. (b) Man re-filling buckets' secuence (t_1= 06:30, t_2= 06:35, t_3=07:22 and t_4= 07:45).

Fig. 5-15 presents the situation from t=10:15 to t=12:20. On the left side of Fig. 5-15, it is possible to see that the number of people watching the fire grows, becoming considerably large, and that people's belongings were placed in the street. As the fire grew, the residents' firefighting actions became even more dangerous; in the centre of Fig. 5-15 an example of this is presented. In the red dotted box, there is a man on the roof waiting for 'the right time' to pour water over a dwelling. He was on the roof for approximately 4 minutes, until t=12:58, before completing his task. This bold behaviour could have ended in the man being injured or even killed, especially considering that a minute and a half after he came down from the roof, the explosion shown in Fig. 5-8 took place. On the right side of Fig. 5-15, one can see residents moving their valuables to the open area.

Fig. 5-15: Residents' actions at t=10:15 and t=12:20. Left: People gathered watching the fire. Centre: Man pouring water over a dwelling. Right: Occupants saving their belongings.

Fig. 5-16 also shows the residents saving their valuables from their dwellings, by moving them to the open piece of land on the northern side of the settlement away from the fire. As the fire gets closer to the back of the settlement, the area used to place the valuables is no longer safe. Therefore, people continue moving their valuables, but this time they move the items to the northwest side of the settlement.

Fig. 5-16: Residents' actions from t=13:00 to t=36:00. People moving their belongings away from the fire to a safe area.

Fig. 5-17 depicts the situation at t=40:50 when the fire was under control. At this stage, most of the people have evacuated the affected area but remained in the vicinity. Many people congregated in the area, either to watch what was going on with the fire or to protect and look after their valuables.

Fig. 5-17: Panoramic view at t=40:50. Left: People gathered watching the scene. Right: People protecting and look after their valuables.

Fig. 5-18 presents a more detailed picture of the occupants' actions. Fig. 5-18(a) shows the residents, looking after their belongings, mostly furniture, mattresses, bags with what is believed to be clothing and bedding. There is a large number of children at the scene, presumably due to the fact that it was school holidays, and it is also possible to see a woman with a baby on her back. In Fig. 5-18(b), it can be seen that even when the fire is relatively under control, people continue to engage in firefighting and investigation activities. Three of the four men on the roof (Fig. 5-18(b)), seem to be looking at the situation, it appears as if they were giving information about the fire to the firefighters, while one of them was throwing buckets of water on a dwelling. They remained there until t=57:27.

Fig. 5-18: Residents' actions. (a)Looking after their belongings (t=41:17). (b) Throwing water on the dwelling (bottom) and observing the incident (top) (t=46:11).

The final minutes of the recording are shown in Fig. 5-19 (t=78:35 to t=79:25). The actions of the residents during this stage were: (a) leaving the surrounding area, for those people that were watching the situation, (b) cleaning of the debris and (c) bringing back belongings to the non-affected dwellings. In the centre of Fig. 5-19, demarcated with a red-segmented line, people are taking back their possessions (i.e., mattresses, furniture) to their dwellings. In the right side of Fig. 5-19 there are two men assessing the area and removing some of the debris. This situation clearly depicts the need of the residents to start rebuilding as soon as possible.

Fig. 5-19: Residents' actions during the last minutes of the recording. Left: People leaving the area. Centre: Residents taking back their valuables to their dwellings. Right: Occupants assessing the area and removing debris.

It was possible to see, throughout the whole recording, that several people are going in and out of the settlement repeatedly. It is postulated that they were inspecting the area looking for new information that could demand new occupants' responses. In the beginning, once they discovered the fire, the response of the resident was mainly focussed on firefighting actions. Then, when they realized that it is not possible to control the fire, the efforts changed to gathering their valuables, this action involves leaving and re-entering the dwelling. After the fire was extinguished, the main actions were looking after their valuables and cleaning the debris.

The firefighters mentioned that after an IS fire is extinguished, usually the leaders of the affected settlement go through the area interviewing residents to determine the number of dwelling burnt and people displaced, and to plan the rebuilding process. Residents will search the area looking for materials and possessions that could be recovered. These include metal sheeting, nails and other materials to rebuild their households, furniture, money, and copper electrical wires that can be resold.

5.5.4 Firefighters' response and operations

According to FRSIR, the first call was received at 10:38:48 (t=05:36). Once the call was received, the usual procedure was followed, meaning that three fire engines and two water tanks were assigned to attend to the scene. However, not all the fire stations in the area have water tanks, so often it is necessary to wait until one becomes available. After the arrival of the first fire engine, the scene was assessed and additional resources were requested. In total, five fire engines, one rescue vehicle and two water tanks arrived at scene. The first fire pump can be seen arriving at the scene 6.5 minutes after the call at t=12:05 and the first water application was half a minute later. The arrival of the remaining fire pumps was not captured by the video, arrive at t=16:17, t=30:28, t=31:48 and t=32:49 according to the FRSIR. The water tanks were seen arriving at t=43:31 and t=46:33, respectively.

The fire development around the time the firefighters arrived at the scene is presented in Fig. 5-9 and Fig. 5-10. As mentioned above the fire intensity fluctuated considerably from t=17:00 to t=37:00. By t=48:00 the firefighters were able to extinguish the fire.

Fig. 5-20 depicts various firefighter actions during the incident. At t=14:00 it is possible to see a black hose in the street and a large amount of steam, which implies the first water application. The video showed that during the 30 minutes that followed the first fire engine's arrival, the main problem that the firefighters faced was a lack of water. According to the firefighters' statements, there were no hydrants available in the settlement; this is because they were either non-operative or vandalized. The only water available was in the fire engine's water tank, which generally can provide water for approximately 15 minutes. At t=24:09 firefighters took back the hose that had been run into the settlement, probably because there was no more water in the engine. At t=30:53, on the left side of Fig. 5-20(c), several firefighters are seen waiting for the water tankers to arrive, and during this time more fire engines started running out of water. At t=37:49 four of the five fire engines that attended to the fire are visible. At t=46:31 the location of the water tankers can be seen. Finally, at t=58:35, Fig. 5-20(f) shows the firefighters in the last stages of the fire. Although the video only captured data until t=79:31, in the FRSIR it has been indicated that the firefighters stayed in the area for approximately another 50 minutes.

Other problems that the firefighters faced during the fire were the limited space between dwellings; obstacles, such as people's possessions in access paths; the fact that the electricity was not isolated during the incident; and the occurrence of the explosion depicted in Fig. 5-8. These problems are commonly seen in IS fires.

Finally, the FRSIR indicated that the suspected fire cause was a power surge due to a faulty plug socket. According to the firefighters' testimonies, this was determined by asking the residents.

Fig. 5-20: Firefighters actions. (a) First water application at t=10:47. (b) At=24:09, firefighters taking back the hose, presumably because there is no more water in the engine. (c) At t=30:53, firefighters waiting for the water tanks to arrive. (d) Fire engines' location at t=37:49. (e) Water tanks' location at t=46:31. (f) At t=58:35, firefighters in the last stages of the fire.

5.6 Discussion

The analysis of the real fire event by means of the video recording allowed for: (a) a detailed understanding of fire spread in informal settlements, (b) the identification of residents' actions during different stages of the fire, and (c) a study of the firefighters' response and operations.

The video provided valuable information that is extremely difficult to obtain from other sources, especially in these types of incidents. Usually, pictures or recordings are taken after the fire and all that is shown are the collapsed dwellings and people looking after their possessions or rebuilding their homes. On the other hand, using the video, it was possible to see how the different factors interact and affect each other. While the firefighting actions affect the fire development, the fire influences the residents' actions.

The fire spread was primarily influenced by (a) the wind, (b) the firefighting actions executed by the residents and the firefighters, (c) the availability of combustible material, and d) the close proximity between dwellings. The calculated spread rates ranged from: 0.4 to 2.3 m/min, 4.3 to 36.5 m^2/min and 0.5 to 3.0 dwelling/min, with averages of 1.2 m/min, 15.5 m^2/min and 1.3 dwelling/min. When comparing the linear spread rates with previous research they seem to be consistent. On the other hand, the linear spread rates calculated are closer to the lower values seen in urban fires in Japan.

In the video, it was possible to see the human behaviour dynamics in an IS fire event. It was interesting to see how the whole community worked together to try to minimise the damage produced by the fire. They clearly knew how to react and when to move from one action to the other depending on the situation. At the beginning, most of the occupants were focused on extinguishing the fire and it was possible to see the effectiveness of the bucket brigade. However, despite their efforts, the fire still spread to other dwellings. Nevertheless, this work presents the opportunity to analyse what was done and potentially look for ways to improve the residents' response (e.g., providing more buckets, encouraging residents to have buckets constantly filled in case of emergency, etc.). When the residents realise that the fire is spreading to the adjacent dwellings they proceed with other tasks. These actions include firefighting, saving valuables and the evacuation of the area. However, most of the residents are either moving their belongings or looking after them. The actions that the people undertook are very similar to what have been seen by other researchers in residential fires [70,71,73,91]. It was also observed that mostly men were in charge of performing the firefighting actions as mentioned in previous research [71].

The firefighters' response and operations are restricted by the problems they faced in these types of incidents. In this particular fire event, the main difficulty was the lack of water, both in the settlement and in their resources. Additionally, the limited space between the dwellings, which not only affects the fire spread, but also creates obstacles for the firefighters. It may be possible to develop community training/engagement systems to encourage inhabitants to support firefighters during operations, for instance by guiding them through settlements, by indicating where the fire is spreading to and by keeping access paths open. Furthermore, depending on the nature of the settlement affected, especially in terms of density, the standard operating procedures for each municipality should be reviewed to determine how many vehicles should be dispatched. However, this is often limited by the amount of resources available, especially considering that other fires can occur simultaneously.

This work demonstrated that the analysis of real fire events could provide valuable information. By understanding the factors that interact during a fire incident in an IS it may be possible to develop policy for safety during urban environment large-scale fires, develop or validate fire spread models, enhance firefighter response, better plan for incidents, develop community training mechanisms and to develop better fire safety interventions in general.

It is important to keep in mind that this work presents several limitations. With respect to the fire development, the limitations are: (a) there is no information about the first ignited fuel, the ignition source and the conditions that resulted into combustion, (b) the video only provides a side view of the incident hence, only the longitudinal fire spread can be estimated and (c) the uncertainties associated to the estimation of the number of dwellings affected. For the study of the human behaviour during the fire incident, the limitations are: (a) there is no evidence about what information or cue triggered a response from occupants, (b) the occupants' actions are seen but their motivations to undertake those actions remain unknown. Due to ethical research considerations and complexities, these factors could not be investigated further.

5.7 Conclusions

This paper presented a real fire event that took place in an informal settlement in South Africa. The primary source of information for this work was a video recorded by a transit CCTV camera located near the settlement under consideration. The footage provides high quality data allowing for novel analysis and understanding of such events never previously attainable. The recording was complemented with the Fire & Rescue Service Incident Report and with feedback from the firefighters who responded to the incident.

By analysing the information available, it was possible to gain a better understanding of the fire spread behaviour, the residents' actions and the firefighters' response and operations. The analysis allowed to (a) calculate spread rates that, ranged from 0.4 to 2.3 m/min, 4.3 to 36.5 m^2/min; (b) identify the actions undertaken by the residents; (c) understand the firefighters' response; and (d) identify the main problems faced by the firefighters. This information can be used to develop or validate fire spread models, enhance firefighter response, plan for incidents, develop community training mechanisms and to develop fire safety interventions in general.

The findings of this paper can be used for future research or for fire brigades and municipalities when developing fire safety interventions and procedures. Future research should include (a) the determination of the validity/representability of previous full-scale experiments, (b) feasibility of implementing and enhancing the Framework for Informal Settlement Fire Investigations and (c) continuing with the study of human behaviour in fire in informal settlements by interviewing the residents or by implementing questionnaires.

5.8 Acknowledgements

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Chapter 6: Application of the Framework for Fire Investigations in Informal Settlements to large-scale real fire events – Consideration of fire formation patterns, fire spread rates and home survivability

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Declaration by the candidate:

The nature and scope of the candidate's contribution were as follows:

Nature of contribution	**Extent of contribution**
Writing the manuscript, establishing methodology, collecting and analysing data, conducting interviews, and preparing figures and tables.	83%

The following co-authors have contributed to as follows:

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Signature of candidate:
Date:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 6,
2. no other authors contributed to Chapter 6 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 6 of this dissertation.

Signature	**Institutional affiliation**	**Date**
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	Stellenbosch University	
	Milnerton Fire Department	

This chapter is an exact copy of the journal paper referred to above

CHAPTER 6: APPLICATION OF THE FFIIS TO LARGE-SCALE REAL FIRE EVENTS

Contribution of chapter to dissertation

In this chapter three IS fire incidents are analysed. The framework developed in Chapter 4 is applied in the analysis. The study focusses on the fire origin and fire pattern formation sequence identification. The fire incident analysed in Chapter 5 is one of the study cases. Chapter 5 is used to benchmark the findings obtained through the application of the framework. The fire cause could not be investigated due to the lack of evidence.

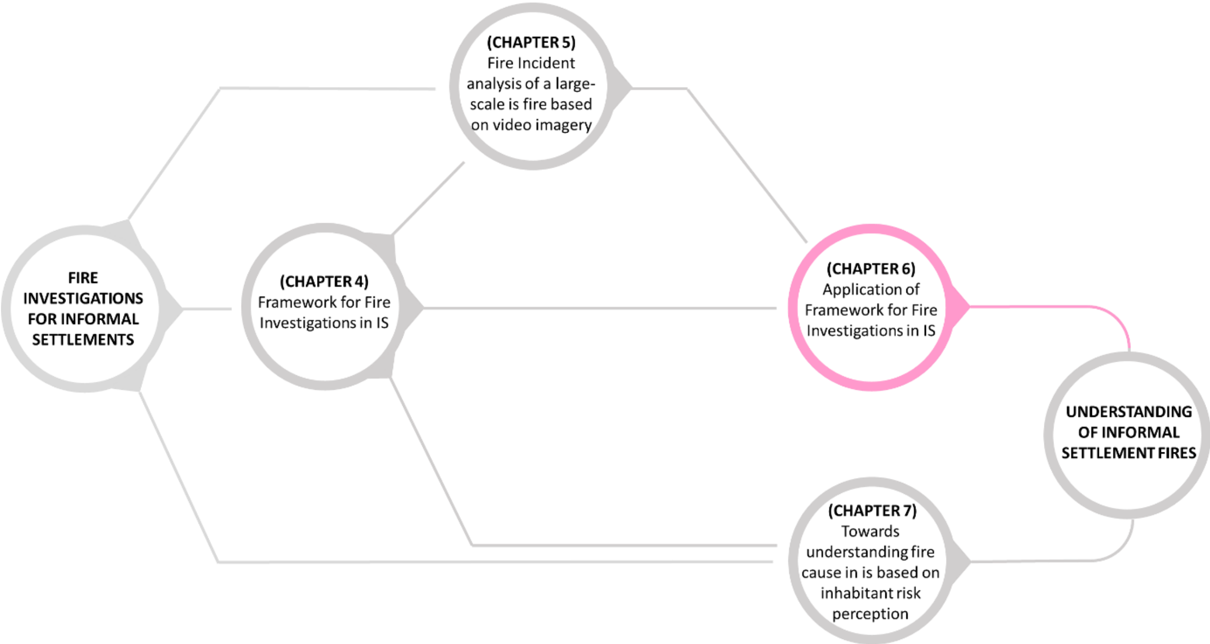

Fig. 6-1: Contribution of Chapter 6 to dissertation.

CHAPTER 6: APPLICATION OF THE FFIIS TO LARGE-SCALE REAL FIRE EVENTS

6.1 Abstract

In recent years, there has been a growing number of projects on informal settlement (IS) fire research, which has been primarily focused on understanding the fire dynamics in IS through full-scale experiments. However, much less is known about real IS fire incidents. Recently, a Framework for Fire Investigations in Informal Settlements (FFIIS) was developed. However, the FFIIS has not been applied to real IS fire incidents yet. This paper seeks to conduct fire investigations by applying the FFIIS to three real fire events. One of them was recorded by a CCTV camera and was analysed in depth in previous work. The video footage was used to benchmark the findings obtain using the FFIIS. The application of the FFIIS allows one to develop hypotheses that more accurately define the area of fire origin and pattern formation sequence. This implies that the fire pattern for large post-flashover fires in ISs can be treated as wildland fires pattern, as proposed by the FFIIS. Additionally, spread rates and the impact of dwellings' separation distances, in these incidents, are studied. Understanding the limitations and the quality of the information that can be obtained when applying the FFIIS is fundamental to improve the guidelines proposed.

Keywords: fire investigation; informal settlements; fire spread, home survivability.

6.2 Introduction

In recent years, there has been worldwide recognition of the problems associated with fires in informal settlements (IS), also known by more derogatory names such as slums, shantytowns, ghettos, etc. [6]. This has led to a growing number of informal settlement fire research projects, which have been primarily focused on understanding (a) fire risk and (b) fire dynamics of the phenomena through full-scale experiments. Rush et al. [115] studied the fire risks similarities and differences between ISs in New Delhi, Cape Town and in Lebanon. The fire risks in ISs in Cape Town have been studied in depth by [122] and [123]. The work has allowed researchers to develop a better understanding of the fire risk profile. Cicione et al. [9,13] have conducted experimental studies on IS dwellings to better understand the fire spread mechanism between dwellings. De Koker et al. [12] conducted a full-scale fire spread experiment of a mock 20 dwelling settlement to better understand settlement-scale fire spread behaviour. These are idealised experiments that do not take into consideration factors such as: settlement density, variability of fuel loads and construction materials, construction methods, community interventions, and firefighting activities, as typically seen in real IS fires [2,10,15,103,124]. Some of these factors (e.g., high density, constructions materials and methods), cause fire spread to occur more rapidly through settlements, such that conflagrations usually affect more than one dwelling and destroy most of the physical evidence required to accurately identify the fire cause. These problems are evident when considering the analysis of the fire incident that occurred in Imizamo Yethu (IY) [15], where 2194 homes were destroyed. With this in mind, Flores Quiroz et al. [10] developed a Framework for Fire Investigations in Informal Settlements (FFIIS), in which guidelines and recommendations to investigate real IS fire events have been proposed, with the aim of improving data collection after fire incidents. However, the proposed FFIIS has not yet been applied to a real fire event. The investigation of real fire events has proven to be beneficial to understand different aspects (e.g., fire cause, fire spread rates, fire spread mechanisms, etc) of all types of fires. In the last decade several WUI fire events have been studied, including the 2007 Southern California wildfires [46], the 2011 WUI Amarillo Fires [43], the 2017 Port Hill fires in New Zealand [44,125,126], and the 2017 Knysna fires [45,57,127]. Extensive fire investigation guidelines and techniques are provided in documents such as NFPA 921 [59].

In this work, the FFIIS is applied to three real IS fire events that occurred in South Africa. The first one (Case Study 1 – denoted as CS1) affected approximately 40 dwellings and was analysed in depth by the authors in previous work [124] based on a recording of a transit CCTV camera. The second (Case Study 2- denoted as CS2) and third (Case Study 3 – denoted as CS3) fires occurred in Cape Town and affected approximately 80 and 1100 dwellings, respectively. In both cases, the fires were documented in the conventional way, meaning that a Fire & Rescue Service Incident Report (FRSIR) and the Occurrence Book[9] (OC) were completed and thus provide information on these incidents.

This paper seeks to determine the applicability of the FFIIS to large-fire events. This is addressed by (a) applying the FFIIS to three real IS fires, (b) for CS1, drawing a comparison between the investigation findings and the real fire event documented in [124] (with the 'real' event being denoted as CS1*), and (c) identifying the limitations of the FFIIS. The remainder of this work presents (a) the methodology used, (b) the fire investigation, and (c) a discussion of the findings.

Further work is required to investigate the extent to which wildland fire and/or urban fire research and modelling can be applied to IS fires. In terms of fire spread mechanisms in IS fires, flame impingement and radiation are likely to be more dominant fire spread modes, whereas firebrands are likely to be less influential compared to wildland fires. However, in some larger IS fires, especially where vegetation was affected, firebrands do seem to influence spread rates, as seen in the IY fire [15]. Another factor that could affect the fire spread are the explosions of LPG cylinders or aerosol cans, as not only do they increase the fire intensity, but they could ignite secondary fires [124,128–130]. Firebrands (produced by wildland fuels or wooden structures), and hot metal fragments can be transported by the fire plumes or winds. If the particles land on a fuel bed (e.g., plastic sheets for rainproofing roofs) they could ignite it [38]. This will depend on the characteristics of (a) the fuel (i.e., type, moisture content, density, etc.), (b) the particle (size, temperature, state), (c) the landing of the particle on the fuel, and (d) the environmental conditions (temperature, wind velocity) [38]. On the other hand, significant research has been done to develop urban fire spread models, which could potentially be applied to IS fire spread in the future. In 1951, Hamada proposed an empirical model as a function of fuel load, wind speed, wind direction and others factors [30,32]. Szasdi Bardales et al. [32] compared Hamada's fire spread rate predictions with real fire events, where most of them were wildland urban interface (WUI) fires. They concluded that Hamada's model did not show good agreement with recent fires, as the conditions (e.g., wind speed, dry weather) seen in those fires were considerably different to the ones considered by Hamada. Physics based models (i.e., that apply physical laws and material properties) have also been proposed. In contrast to the macro approach used by Hamada, these models can represent different fire spread mechanisms [32], which may be suitable for the mechanisms observed in ISs. In [29], Li and Davidson study the performance of an urban fire simulation model, and the work used a case study to validate the model. The results showed good agreement with the fire event considered. However, wildland fires and urban fires have significant differences with IS fires. Therefore, further work is required to understand the extent to which the aforementioned studies, amongst others, could be applied to informal settlement environments.

6.3 Methodology

For the three case studies considered in this work, the fire investigation procedure applied is the same. The procedure follows the methodology proposed in the FFIIS [10]. Fig. 6-2 provides a graphical representation of the methodology. First, the affected area is identified and evaluated (i.e., the scene assessment). The scene assessment is an important step in the fire investigation, as it defines the approach that the fire investigation should follow (i.e., the approach proposed for pre-flashover, post-flashover or large post-flashover fires as discussed in detail in [10]). For pre-flashover fires, detailed fire scene assessments can possibly be carried out and fire cause determination is more feasible. For post-flashover fires much evidence is destroyed, although there is some potential for data collection. For large post-flashover fires, almost all evidence at the dwelling of origin is destroyed and only fire spread patterns and overall incident reconstruction are typically possible.

[9] The Occurrence Book contains entries about appliances, personnel, fire development, etc. of a fire incident [178], and is completed by the fire departments responding to incidents.

For the scene assessment in this work, satellite imagery [106] (for CS1 and CS2) and pictures from the media (for CS3), were used. While the images for CS1 and CS3 were taken one day after the fire, the information pertaining to the fire scar of CS2 was based on the albedo of IS dwellings' roofs before and after the incident, as proposed in [104]. Fig. 6-2 depicts the situation of the three case studies after the fire, where the dwellings affected have collapsed and most of the combustible materials were depleted. Thus, from Fig. 6-2, it is clear that there is negligible physical evidence after the fire to provide any information regarding the ignition source or the first-ignited material. Following the FFIIS classification and considering that these fire incidents involved multiple dwellings that were completely burnt down, the fire can be classified as a large post-flashover fire. This implies that the investigation should focus on obtaining information from the global burn pattern (V or U shaped burn pattern) of the affected area and from witnesses' statements. This information should allow the investigator to identify the area of fire origin and the fire spread sequence. The statements of the witnesses are critical to identify the dwelling of fire origin and the potential fire cause. Irrespective of fire size, witness statements are often the primary or only data upon which investigators may be able to rely for fire cause determination.

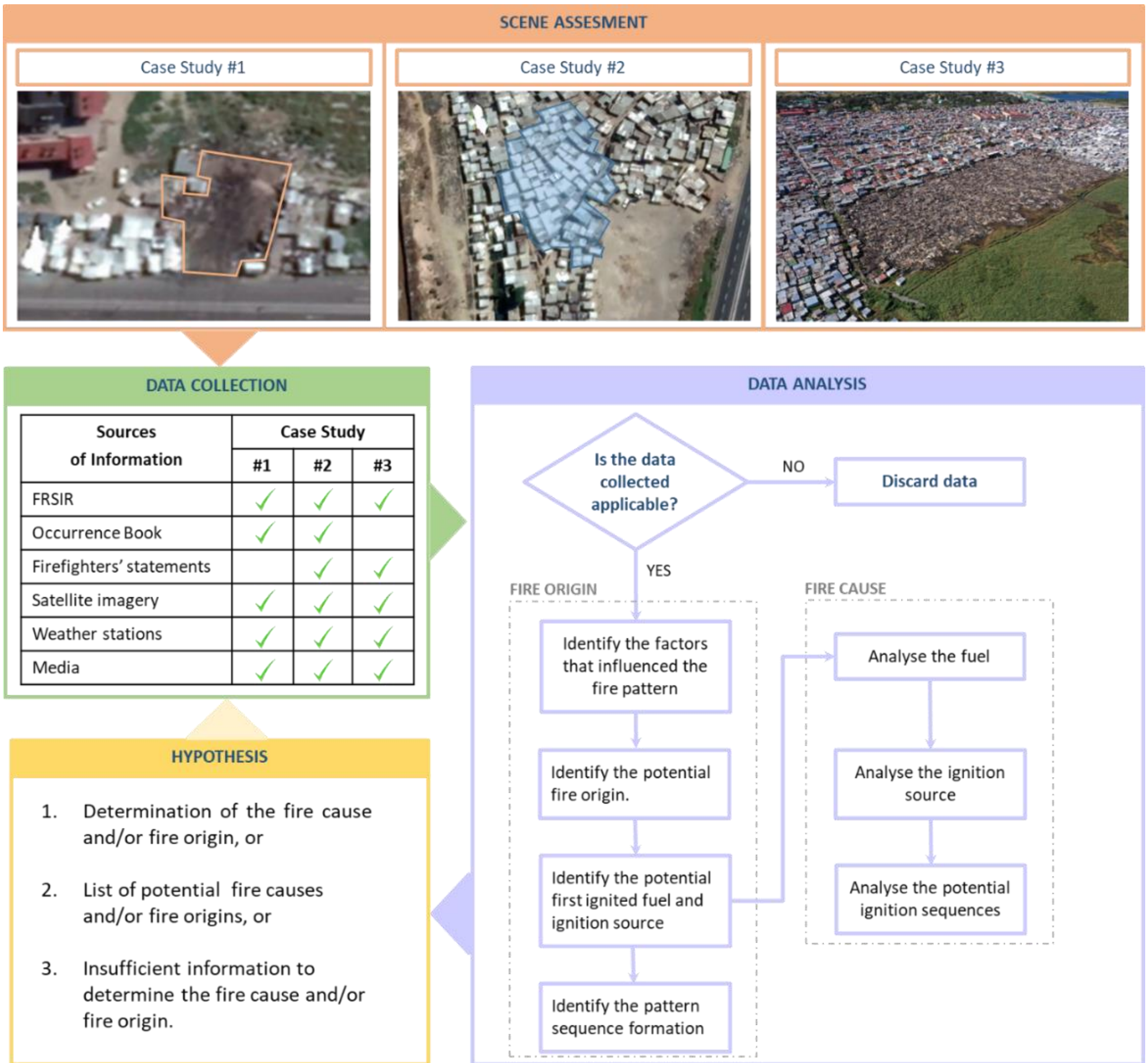

Fig. 6-2: Fire investigation methodology flow chart. (Images for CS1 and CS2 were obtain from Google Earth [106]*, image for CS3 used with permission of Bruce Sutherland, City of Cape Town.*

The data needed to conduct a fire investigation includes (a) the fire patterns, (b) ambient conditions, (c) topography of the area, (d) fire fighters' operations, and/or (e) conditions that led to the ignition. The data collection process considers several sources of information as seen in Fig. 6-2, including the FRSIR, OC, firefighters' statements, newspaper coverage, readings from weather stations, and satellite imagery [106,116]. These are sources of information that are typically available after an IS fire incident, especially large fires in metropolitan areas. In order to determine whether the FFIIS can be used to analyse IS fires, the video footage that was used in [124], to analyse CS1, is not used (since video footage is typically not available for IS fires). In the same way, the firefighters' testimonies are not used since they were obtained while watching the video and it is not possible to determine the impact of this on their statements. Rather, the video footage for CS1* (i.e., CS1 investigation including the video footage) can be used to benchmark the findings obtain using the FFIIS. For the analysis of the data, it is necessary to understand all the data collected and determine if it is applicable for the specific case under consideration. Based on the observed fire patterns and factors that may have influenced it, one or more potential fire origins should be identified. When possible, the first ignited fuel and the ignition source can potentially be identified. Finally, it would then be possible to produce one or more hypotheses with respect to the fire origin and/or the fire cause. In the case where the investigation did not provide enough information to determine the fire cause and/or fire origin, it is recommended to go back to the data collection process. If this is not possible, the fire cause and fire origin status will be documented as 'undetermined'.

6.4 Case Studies

This section presents the application of the FFIIS to three real fire events. For each case study the fire incident is presented, followed by the fire investigation. The fire investigation considers the data collection, the analysis of the collected data, and the hypothesis development. The application of the FFIIS only involve the identification of the fire origin location and pattern formation determination. Due to the lack of physical evidence, no hypotheses with regard to the fire cause could be developed. How the hypotheses compare to reality is discussed in the next section. Through the scene assessment presented above, the three fires were classified as a large post-flashover fire. No injuries or fatalities were reported in these fire events.

6.4.1 Case Study #1 – 40 dwellings

6.4.1.1 *The fire incident*

This fire incident occurred in September 2019, at around 10:30, in one of the informal settlements in South Africa (for privacy and ethical reasons, the exact location of the IS is not provided in this work). The fire incident was recorded by a transit CCTV camera located near the settlement, capturing the event from ignition of the dwelling of origin to the point of fire extinction. It was estimated by the firefighters that the fire affected approximately 40 dwellings. The reader is referred to [124] for a more detailed discussion of the event.

Fig. 6-3 depicts the timeline of what was observed in the video (events in blue), complemented with the information from the FRSIR (events in red). The video recording started at 10:33, and two minutes later it was seen that the residents tried to extinguish the fire by throwing buckets of water onto it. Unfortunately, this attempt was unsuccessful. At 10:38 a phone call was made to notify the fire brigade about the incident. Seven minutes later the first fire engine arrived at the scene. During the course of the fire there was an explosion (presumably from an LPG cylinder) that intensified the fire spread. After the second water tank arrived the fire was rapidly extinguished. Some of the fire units remained at the scene, conducting mopping operations and/or interviewing the residents. The inhabitants started to clean the debris and to move their belongings to a safe place. With the analysis of the video, it was also possible to analyse the fire spread and to estimate fire spread rates. The fire spread was primarily influenced by (a) the wind, (b) the firefighting actions executed by the residents and the firefighters, (c) the availability of combustible materials, and (d) the proximity of dwellings.

The average calculated spread rates over the period of the incident were 1.2 m/min [72 m/h], 15.5 m^2/min [930 m^2/h] and 1.3 dwelling/min [78 dwelling/h].

Fig. 6-3: Timeline of CS1 based on the information provided by the video recording* [124].

6.4.1.2 *Data collection for the FFIIS*

Table 6-1 presents a summary of the data collected for the application of the FFIIS. The settlement is on flat terrain, where over a distance of 31 m the change in elevation is less than 1 m. The fire affected approximately 40 structures and roughly 90 persons were displaced. The ambient conditions stated in the FRSIR present differences with respect to the readings of the nearest weather station [131]. The fire station received a phone call informing the brigade about the fire at 10:38. A total of six fire stations attended to the fire, with more detail pertaining to their arrival to the fire scene shown in Fig. 6-4. Furthermore, the FRSIR shows that at 11:59 the unit in charge of the operation indicated that no further assistance was needed. This notification is usually done when the fire is extinguished, or under control to the extent that only mopping up operations are occurring. On the other hand, in the media the Fire and Rescue Services (FRS) spokesperson mentioned that once the first unit arrived on the scene additional resources were requested and that the fire was extinguished "just after noon" [132], although this may refer to mopping up operations.

Table 6-1: Data collected for CS1.

Area affected	**FRSIR**	**Spokesperson** [133]	**Video Footage (CS1*)** [124]
Dwelling affected	40	31	42
People displaced	90	76	
Topography [106]	Slope: 1.43°		
Ambient conditions from 10:30 to 13:00	**FRSIR**	**Weather station** [131]	
Temperature [°C]		19	
Humidity [%]		49-56	
Wind speed [km/hr]	6-11	24-28	
Wind direction	South-east	South	
Firefighters' operations	**FRSIR**	**Spokesperson** [132]	**Video Footage (CS1*)** [124]
Fire engines dispatched	5		
Water tankers dispatched	2		
Phone call	10:38		
First unit at the scene	10:48		10:45
Fire extinguishment	11:59	just after noon	11:23
Fire cause	**FRSIR**	**Spokesperson** [133]	
Fire cause	Electrical Fault. Power surge due to a faulty plug socket	Unknown	

Due to the magnitude of the fire, information regarding the fire cause could only be obtained through witnesses' statements. While the FRSIR indicated that the suspected fire cause was a power surge due to a faulty plug socket, the FRS spokesperson mentioned that the fire cause was unknown [133].

6.4.1.3 *Data Analysis*

Based on the information provided by FRSIR and the spokesperson's testimony, it is possible to construct an estimated timeline of the fire incident, as depicted in Fig. 6-4. Ignition had to take place before 10:38, which was when the first phone call to the fire station was made. There is not enough information to determine the exact time or even to make an estimation of the exact time of ignition. According to the spokesperson's testimony and to the FRSIR, the fire was extinguished "just after noon". In the FRSIR it can be seen that there is a 'STOP' at 11:59, that means that no further assistance is needed, that could mean that the fire is under control or it is extinguished. Additionally, the time at which each fire unit has completed their task is known. These times are recorded when the units are back at the fire station. From conversations with firefighters, it is known that typically after a fire has been extinguished, the firefighters stay at the scene for an additional 45 or 60 minutes, performing other activities such as mopping up operations, interviewing people, etc.

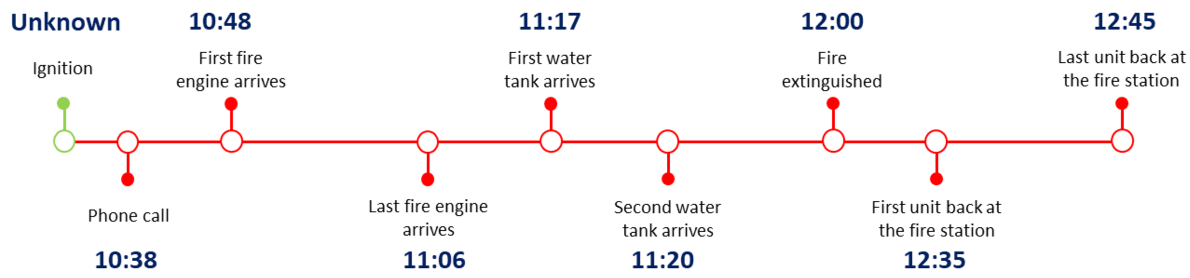

Fig. 6-4: Reconstructed timeline of CS1's IS fire, based on the data collected for the FFIIS.

Due to the flat terrain, it is expected that the wind would have had the biggest impact on the fire spread rate and direction. The two sources of information for the wind conditions presented some inconsistencies. It is important to remember that often the readings at the weather station are not representative of what happened at the fire scene. The measurements are taken at high levels above the ground and do not consider the effect of the urban canopy and the fire winds created by the fire itself [10]. On the other hand, the values indicated in the FRSIR are firefighters' estimations based on visual inspection and their experience. Even though these values might not be accurate, the wind conditions that were considered for the analysis are the ones indicated in the FRSIR. According to [60], based on the flat terrain of the area and the light south east breeze, the fire spread pattern should have had a U-shape. It has been acknowledged in the FFIIS that typically the ignition area can be identified by locating the narrowest point of the fire spread pattern. In addition, the fire spread direction should have been influenced by the wind direction, meaning that the point of fire origin should be located at the Southern side of the settlement.

With regards to the fire cause, even though the FRS spokesperson mentioned that it was undetermined, it is believed that it is likely that the final information with respect to the suspected fire cause may have been determined after the spokesperson gave her statement. It is assumed that the information presented in the FRSIR is official, therefore, the power surge due to a faulty plug socket will be considered as the suspected fire cause.

6.4.1.4 *Hypothesis*

In this section, the hypotheses for the area of fire origin and the pattern formation sequence are presented.

Burn pattern hypothesis: The fire pattern formation sequence that was consistent with all the different data sources is presented in Fig. 6-5(a It is postulated that the position of fire origin is located somewhere in zone A. From there the fire started spreading to the adjacent dwellings. The fact that the fire did not spread to some of the adjacent dwellings can be attributed to the effect of the wind and to the unusual spacings between the affected and the non-affected dwellings. At the back of the settlement (northern side) there were a few homes that did not get burned (denoted as B), this could also be attributed to the firefighting interventions. Fortunately, there was no combustible material at the back of the settlement (Zone C), it is believed that if this was not the situation there would have been many more houses affected. Fig. 6-5(b) presents a more detailed view of Zone C. The absence of combustible material was maintained until the end of October 2020. Fig. 6-5(c), taken at the beginning of December 2020, highlights how rapidly the settlement grew. The influence of the spacing between dwellings in home survivability is discussed in the Section 6.5.4.

Fig. 6-5: (a) Fire pattern analysis CS1. The fire scar is shown in orange. The dwelling of fire origin is identified as being in Zone A. The fire pattern formation sequence is represented by the red arrows. Zone B depicts the dwellings at the north of the settlement that did not get burned. Zone C is the area with no combustible material. (b) A more detailed image of Zone C (image taken on 26/10/2020). (c) Zone C. The area has now multiple dwellings (image taken on 3/12/2020), the image highlights how rapidly such settlements can grow.

Based on the video footage available, it can be confirmed that the fire spread hypothesis matches the actual behaviour. Due to the size of the fire, the wind direction, and burn scar, it is likely that the zone of fire origin would have been determined from the data, without witness statements. Due to the light wind conditions, it is expected to have some backing fire (i.e., fire spreading against the wind direction). This makes it more challenging to determine the dwelling of fire origin; nevertheless, it is possible to estimate the area of fire origin.

6.4.2 Case Study #2 – 80 dwellings

6.4.2.1.1 The fire incident

This fire incident took place on Monday, 2 November 2020, in the Dunoon IS, at around 21:00. This fire event was particularly dangerous because the settlement is located next to an industrial area. Fig. 6-6(a) shows that in the proximity of the affected area (less than 100 m away) there is a chemical factory. The main concern of the firefighters during the incident was that embers carried by the wind could cause secondary ignitions in or near the chemical factory.

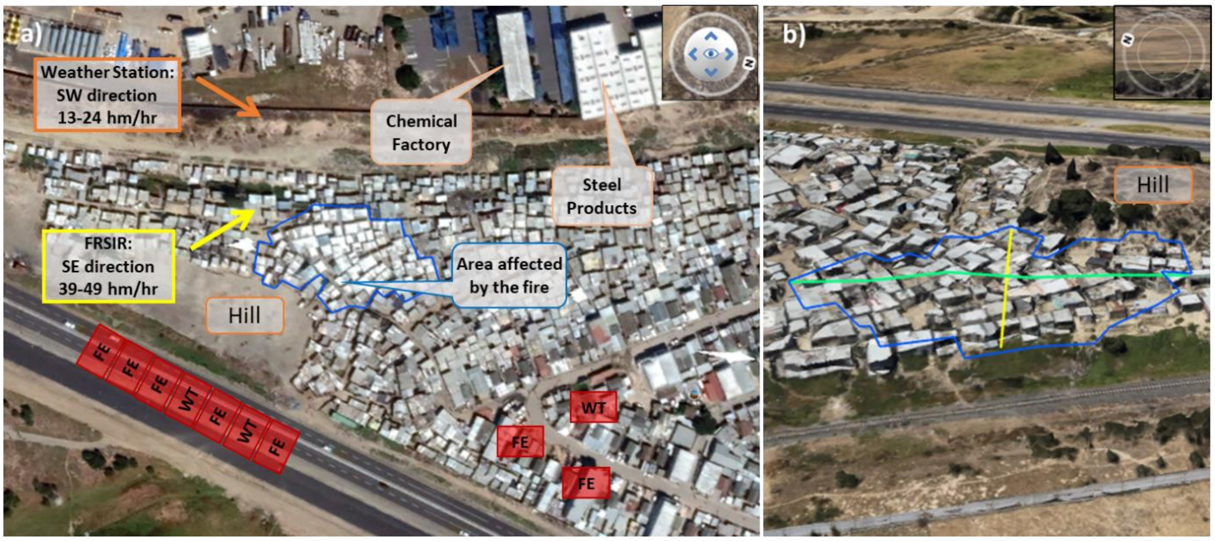

Fig. 6-6: Layout of the settlement. a) Firefighters unit's location and wind conditions (FE=Fire engine, WT=Water tank). b) Fire scar in blue, elevation lines in green and yellow.

6.4.2.2 *Data collection for the FFIIS*

Table 6-2 presents a summary of the data collected. The number of dwellings affected is not clear, because, while the FRSIR stated 80 dwellings, the City of Cape Town's Disaster Risk Management spokesperson stated that the fire destroyed 42 structures displacing almost 140 people [134]. Based on Google Earth [106], images from before and after the fire, it was possible to establish the fire scar and identify 82 roofs/structures in the area affected. Once again, the spokesman may have had to make these statements before the investigations had been completed, i.e., while the available information was incomplete. As shown in Fig. 6-6, the settlement is located on relatively flat terrain, next to a small hill and adjacent to an industrial area. The change in elevation over a distance of 48 m (yellow line in Fig. 6-6(b)) and 86 m (green line in Fig. 6-6(b)) is less than 2 m. The wind conditions stated in the FRSIR are very different from the readings of the nearest weather station [135]. Additionally, the FRSIR indicates that the visibility at the time of the fire was low because it was night, and the area did not have streetlights.

According to the FRSIR, the fire station received a phone call pertaining to the fire at 21:21. This phone call was transferred from the police department, which drastically affects the initial response time of the fire brigade. This situation is often seen in South Africa, where the police phone number is more commonly known that the fire brigade's number. A total of nine fire stations attended to the fire. It took 19 minutes for the first fire engine to arrive at the scene. According to the OC, the first fire unit arrived at Dunoon, under police escort, at 21:32. However, the low hanging electrical cables in the settlement hindered their arrival to the fire scene, which occurred at 21:40. Additionally, the FRSIR shows that at 23:13 the unit in charge of the firefighting operations indicated that no further assistance was needed and at 00:07 "the fire was out". The City of Cape Town's FRS spokesperson gave the same information for the fire extinguishment time.

One of the main difficulties of this fire event, was the lack of water supply in the vicinity. For this reason, the firefighters' strategy was to constantly send vehicles to collect more water. More details of the firefighters' operations are shown in Fig. 6-6 and Fig. 6-7. The official fire cause stated in the FRSIR was cooking, where a pot of food overturned and resulted in the ignition of the bed and bedding. Unofficial information, which cannot be verified, indicates that the resident of the dwelling, where the fire started, was under the influence of alcohol.

Table 6-2: Data collected for CS2.

Area affected	**FRSIR**	**Spokesperson** [134]
Dwelling affected	80	42
People displaced		140
Topography [106]	Slope (green line): 1.3° Slope (yellow line): 1.1°	
Ambient conditions from 21:00 to 00:00	**FRSIR**	**Weather station** [135]
Temperature [°C]		18-19
Humidity [%]		78-83
Wind speed [km/hr]	20-35	13-24
Wind direction	South-east	South- west
Firefighters' operations	**FRSIR**	**Spokesperson** [134]
Fire engines dispatched	7	
Water tankers dispatched	3	
Phone call	21:21	
First unit at the scene	21:40	
Fire extinguishment	00:07	00:07
Fire cause (FRSIR)	Cooking. A pot of food overturning and igniting the bed and bedding.	

6.4.2.3 *Data Analysis*

Based on the information provided by the FRSIR and the OC, it was possible to reconstruct an estimated timeline of the fire incident, as depicted in Fig. 6-7. The ignition had to take place before 21:21, which was when the phone call was transferred to the fire station by the police. Similar to the previous case, there is not enough information to estimate the exact time of ignition. However, according to the firefighters' testimony, fires that occur at night typically take longer to be discovered and hence, it takes longer to be reported. According to the spokesperson and to the OC, the fire was extinguished at 00:07, although it might have been under control much earlier, since at 23:13 it was indicated that no further assistance was needed. According to the firefighters' statements, by attacking the head of the fire and using a mixture of water and foam they were able to prevent the fire from spreading to the rest of the settlement.

Since the terrain is relatively flat, it is expected that the wind would have had the biggest impact on the fire spread direction. In this case, the two sources of information provide contrasting information pertaining to the wind speed and direction. Following the same reasoning as used in CS1, this analysis will assume the FRSIR as the correct source of information. According to [60], due to the strong south-east wind, the pattern should have a V-shape. However, the small hill located at the east of the affected area could have had an influence on it by causing a localised change in direction.

The only information regarding the fire cause is found in the FRSIR. The fire cause was classified as cooking, due to a pot of food overturning and igniting the bed and bedding.

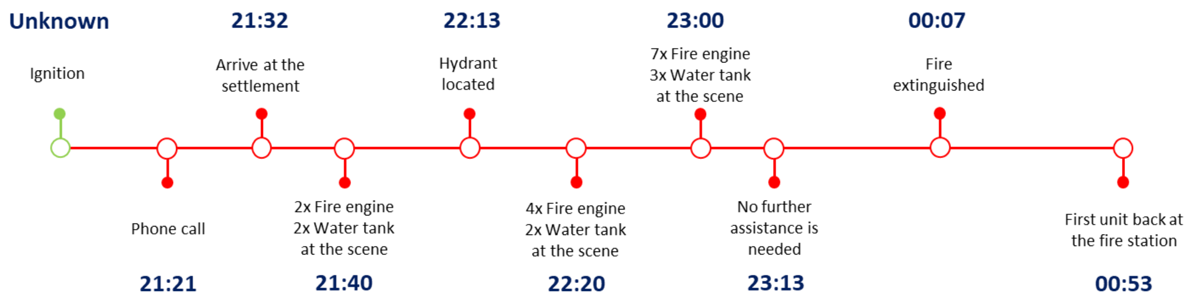

Fig. 6-7: Reconstructed timeline of CS2's IS fire, based on the data collected for the FFIIS.

6.4.2.4 *Hypothesis*

In this section, two hypotheses for the area of fire origin and the pattern formation sequence are presented.

Burn pattern hypothesis #1: The fire spread sequence is depicted in Fig. 6-8(a). The strong wind conditions allow the formation of a V-shape pattern. From there the fire started spreading to the adjacent dwellings. The firefighting efforts stopped the fire spreading to the rest of the settlement.

Burn pattern hypothesis #2: The fire spread sequence is depicted in Fig. 6-8(b). The influence of the small hill located at the south of the settlement on the wind direction and speed could have allowed the formation of a U-shape pattern. The small hill can produce a reverse flow region (i.e., localised change in direction), as seen in [136,137], in which the speed decreases and wind direction changes in the vicinity of the hill. This will also explain the spread to the heel/left flank of the fire. From there the fire started spreading to the adjacent dwellings. The firefighting efforts stop the fire spreading to the rest of the settlement.

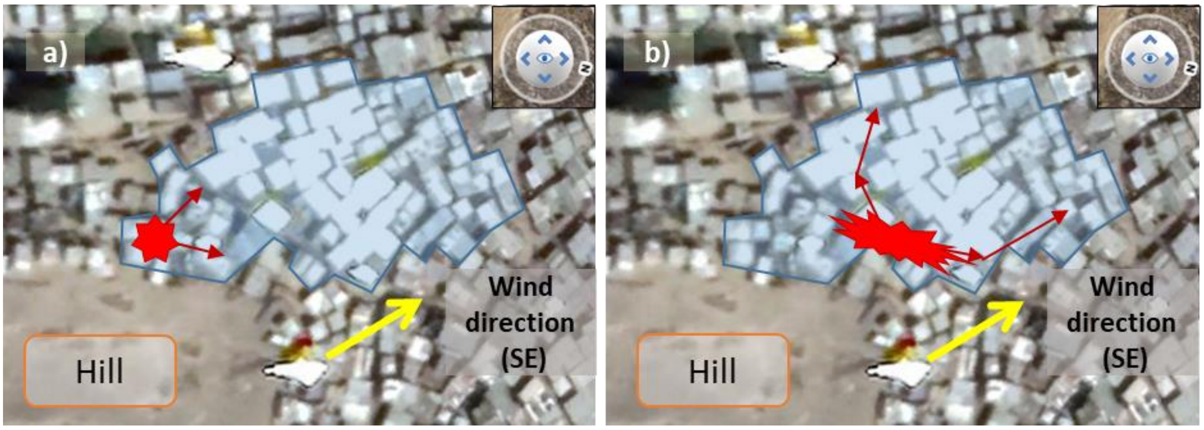

Fig. 6-8: Fire pattern analysis CS2 showing the burn scar and fire origin associated with two hypotheses developed.

The fact that it was not possible to obtain an image of the fire scar and the fact that it is difficult to quantify the effects of the hill on the fire spread make the incident's reconstruction process challenging. Under these conditions it is critical to have validation of events by the firefighters. They confirmed the estimated burn scar obtained by the analysis of the albedo of IS dwellings' roofs. This means that this is a potentially reliable method to estimate the fire scar of an IS fire. Additionally, they indicated that the fire spread was best represented by hypothesis #2.

6.4.3 Case Study #3 – 1000 dwellings

6.4.3.1 *The fire incident*

This fire took place on 17 December 2020, in the Masiphumelele IS complex, at around 15:00 hours. The fire affected an area of approximately 31000 m^2. According to the firefighters' testimony, the fast fire spread rate through this dense settlement is attributed to the wind conditions at the time of the fire. The incident was declared a local disaster by government due to the number of homes affected.

6.4.3.2 *Data collection for the FFIIS*

Table 6-3 presents a summary of the data collected. The official information indicates that more than a 1000 homes were affected during the fire. The settlement is on a relative flat terrain next to a wetland. The area presents minor changes in elevation, with only a 2 m change in elevation over 160 m. The wind conditions stated in the FRSIR are approximately similar to the readings of the nearest weather station [135].

According to a resident, the fire started at around 15:00 [138]; however the fire station only received a phone call informing them about the fire at 16:16. The caller indicated that thick black smoke was coming from Masiphumelele. A total of 15 fire stations attended to the fire. The units sent included fire engines, water tankers and one helicopter. At 01:01 it was indicated in the FRSIR that no further assistance was required, additionally the spoke person confirmed the fire was extinguished at this time. However, more units attended to the scene after that time to perform mopping up activities. The last unit went at 06:30 to make sure there were no hotspots left.

The official fire cause stated in the FRSIR was open flames. Although there are no details in the document, unofficial information indicates that hot coals from a barbecue were the ignition source.

Table 6-3: Data collected for CS3.

Area affected	**FRSIR**	**Media** [139]
Dwellings affected	>1000	>1000
People displaced		4000-5000
Topography [106]	Slope: less than 1°	
Ambient conditions from 21:00 to 00:00	**FRSIR**	**Weather station** [140]
Temperature [°C]	25-30	18-24
Humidity [%]		56-64
Wind speed [km/hr]	35-50	30-48
Wind direction	South-east	South
Firefighters' operations	**FRSIR**	**Spokesperson** [141]
Fire engines dispatched	15	
Water tankers dispatched	1	
Helicopters dispatched	1	
Phone call	16:16	16:13
First unit at the scene	16:22	
Fire extinguishment		01:00 (18/12/2020)
Fire cause (FRSIR)	Open flames	
Fire ignition [138]	15:00 according to a resident.	

6.4.3.3 *Data Analysis*

Based on the information shown above, it was possible to reconstruct an estimated timeline of the fire incident, as depicted in Fig. 6-9. According to a resident's statement (if it is accurate), the ignition had to have taken place before 15:00. The phone call was received more than one hour later. This makes sense considering that the caller's statement gives the impression that it was not someone from the settlement that contacted the firefighters (i.e., since it was noted that they saw smoke from a distance). The fire lasted around 10 hours, being extinguished at 01:00.

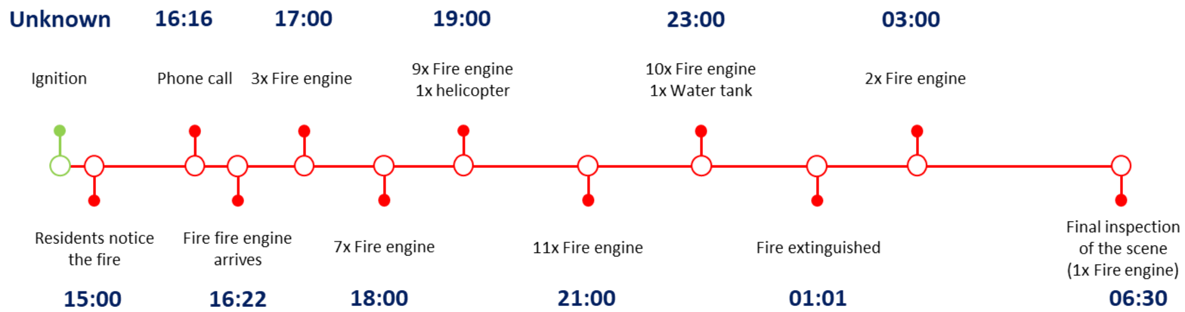

Fig. 6-9: Reconstructed timeline of CS3's IS fire, based on the data collected for the FFIIS.

Considering the topography of the area and the wind conditions stated in the FRSIR, the pattern should have a V-shape. With respect to the fire cause, the official information is that it was due to open flames.

6.4.3.4 *Hypothesis*

In this section, the hypotheses for the area of fire origin and the pattern formation sequence are presented.

Burn pattern hypothesis: The fire pattern formation sequence that was consistent with all the different data sources is presented in Fig. 6-10. It is possible to see that the affected area is completely framed between Road 1 (denoted as R_1) and Road 3 (denoted as R_3). It could be inferred that these roads prevented the fire from spreading to the other sections of the settlement. It is postulated that the position of fire origin (red star) is at the bottom-right corner of the burn scar. It is believed that Road 2 (denoted as R2), also prevented the spread to the adjacent section of the settlement (Fig. 6-10(a) to Fig. 6-10(d)). Perpendicular to R_1, R_2 and R_3, at the bottom of the settlement, there is the main road (denoted as MR). R_2 does not continue through to the MR as R_1 and R_3 do. Where R_2 is discontinuous, the fire started spreading to the adjacent section (Fig. 6-10(e) and Fig. 6-10(f)). It is expected that the fire spread shown in Fig. 6-10(c) and Fig. 6-10(d) is slower since the spreading occurs to the left flank of the fire. From Fig. 6-10(e) onwards the spread rates should have increased. The firefighter vehicles were located on the MR. The width of R_1 and R_3 are at some points less than 3 and 4 m, respectively. This, added to the fact that those roads were being used by the residents to evacuate and protect their belongings from the fire, prevented fire engines from getting closer to the head of the fire.

Fig. 6-10: Fire pattern analysis CS3 showing the burn scar (yellow), hypothesised progress of the fire (light red) and possible fire origin (red). Roads R_1-R_3 influenced fire spread, along with the wetland at the top and the formal homes at the bottom and the firefighters' units located in the main road (MR).

Of the three case studies, this incident is the most difficult in terms of accurately defining a location of fire origin. The hypothesised spread pattern presents a very plausible scenario that matches general information available. However, there are higher levels of uncertainty regarding whether firebrands may have influenced spread at any time, and whether a certain amount of fire spread may have occurred against the wind. The latter could cause the fire origin position to move further to the top left of the position shown on Fig. 6-10(a).

6.5 Discussion

This section discusses the main findings of this work. It presents the analysis of (a) the fire origin and the pattern formation sequence, (b) the fire cause, (c) fire spread rates, and (d) spacing between dwellings.

6.5.1 Fire origin and pattern formation sequence

In all three case studies the hypothesis developed for the area of fire origin and the global fire pattern formation sequence showed good agreement with the real event, (this was confirmed with the video recording for CS1 and with the firefighters' statements for CS2 and CS3). This implies that the fire pattern for large post-flashover fires in informal settlements can be treated as a wildland fire pattern, as suggested by the FFIIS. This implies that the topography of the area and the wind conditions have a significant impact on the fire spread direction and speed. Currently, the wind speed and direction at the fire scene are only being estimated through approximate observations. Additionally, it was seen in this work that readings from nearby weather stations are not always representative of what was observed at the scene. Due to the importance of the wind conditions for this analysis, it is recommended that the firefighters carry out periodic observations of the weather conditions during incidents in a more accurate fashion. Having real-time data collection and verified data that is based on measurements instead of estimations will benefit the fire investigation outcome. Furthermore, there is information related with the fire incident, such as real time fire dynamics or the effect of the suppression actions over the fire development, that could not be obtained in this work due to the limited amount of data available. To better obtain information for incidents in South Africa, it would be necessary to implement new data collection systems and procedures.

6.5.2 Fire cause

It was not possible to confirm or even to obtain information regarding the fire cause. In the FFIIS it is acknowledged that it would be extremely difficult to determine the fire cause by means other than witnesses' statements. It was seen that not even the video recording used in [124] could provide information regarding the fire cause.

6.5.3 Fire spread rates

In addition to the study of the fire cause, fire origin and pattern formation sequence, this work allows one to estimate average fire spread rates. Based on the reconstructed timelines (Fig. 6-4, Fig. 6-7, Fig. 6-9) areal and linear fire spread rates were calculated for CS1, CS2 and CS3. Table 6-4 presents the estimated fire spread rates and the observed wind conditions for the three case studies in this work, and the ones calculated in previous work (CS1* [124] and the IY fire [15]) for comparison purposes. The linear fire spread rates estimated through the application of the FFIIS are similar for all three case studies. However, they are lower than the ones presented in previous work [15,124], where the average fire spread rates were 1.2 m/min [72 m/h] and 1.5 m/min [90 m/h] (ranging from 0.5-2.3 m/min [30-138 m/h] and from 0.4-2.3 m/min [24-138 m/h]), respectively. A graphic representation of Table 6-4 is shown in Fig. 6-11, in this case the slope is included for all case studies.

Table 6-4: Fire spread rates estimated for the case studies and IY fire.

Case Study	Area affected [m^2]	Fire duration [1] [min]	Areal spread rate [m^2/min] / [m^2/h]	Average linear spread rate [m/min] / [m/h]	Wind conditions [km/hr]
CS1	550	80	6.9 / 414	0.4 /24	6-11
CS1* [124]	550	50	15.5 / 930	1.2 / 72	6-11
CS2 (H1)	2060	106	19.4 / 1164	0.55 / 33	20-35
CS2 (H2)	2060	106	19.4 / 1164	0.34 / 20.4	20-35
CS3	31000	600	51.7 / 3102	0.5 / 30	35-50
IY[2] [7]	7985	210	38 / 2286	1.2 / 72.9	32[4]
IY[3] [7]	68615	600	115 / 6900	1.5 / 90	28-48[4]

[1] Fire duration considers as initial time the time when the phone call was received or when the video recording started for CS1.*

[2] Uphill fire spread (19° slope).

[3] Downhill fire spread (19° slope).

[4] The wind speed corresponds to the information provided by the weather station.

Considering the results for CS1, it can be seen that the estimated rates through the application of the FFIIS were less than half of the average calculated for CS1* [124]. This is not surprising, through the comparison of the timelines (Fig. 6-3 and Fig. 6-4), it can be seen that the total approximated fire duration in this analysis is 60% longer than the actual fire duration [124].

The investigation of the real fire events reveals the problems when estimating fire spread rates. Firstly, it was not possible to estimate the time of ignition for any of the case studies. For CS1, as a result of the CCTV footage, it is known that the phone call was received during the initial stages of the fire. However, for CS2 and CS3 (where no CCTV camera footage was available) it is unknown at what stage of the fire the call was made. Furthermore, for CS3 the comment made by the caller about the thick black smoke was coming from Masiphumelele combined with the resident statement, implies that the phone call was received anything up to one hour after the fire started. Secondly, although the time of fire extinguishment is obtained, there is no information of the fire line at different times. As explained in the fire spread rate analysis of CS1, the time of fire extinguishment may not be representative of the time that it took to burn the affected dwellings. Having information about the fire line at different times could help to reduce the impact of these factors, improve the accuracy of estimates, and provide a better understanding of the fire spread rates in these types of incidents. Such data would be useful to developing and calibrating fire spread computational models.

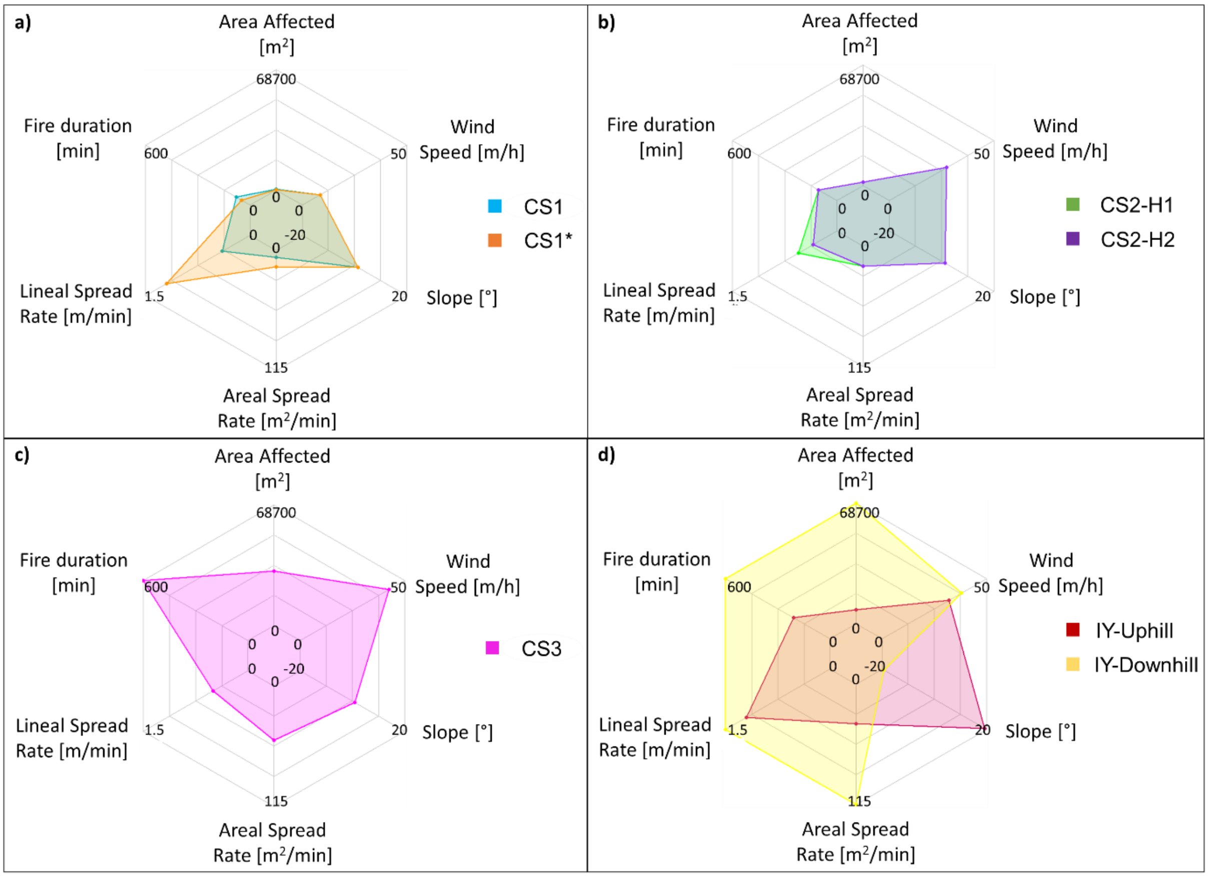

Fig. 6-11: Graphical representation of the average lineal and areal spread rates with respect to i) area affected, ii) fire duration, iii) wind speed and iv) slope. (a) CS1 vs CS1. (b) CS2 (H1) vs CS2 (H2). (c) CS3. (d) IY Uphill vs IY Downhill.*

Table 6-4 also allows one to observe the impact of the wind conditions on the fire spread rates, especially considering the flat terrain in all three case studies. CS3 had the strongest wind conditions and that was manifested on the areal and linear spread rates, which are 51.2 m2/min and 0.5 m/min. While the linear spread rates are 25% and 47% higher than CS1 and CS2(H2) respectively, the areal spread rates are 640% and 160% higher than CS1 and CS2, respectively. Additionally, it also believed that the spread rates would have been much faster if there was not a road (R2) between the two sections that were affected in CS3. Focusing on the results obtained in previous research, the average linear fire spread rate for the IY fire (downhill) stands out. Considering the wind speed and the fact that the fire is spreading downhill, the linear spread rate appears to be very high. However, it was mentioned in [15] that the fire intensity rapidly increased when the fire reached a line of Eucalyptus trees. It was implied that branding coming from these trees could have ignited other dwellings, producing a faster fire spread rate.

6.5.4 Home survivability

Another interesting topic to consider is the home survivability in IS fires. For CS1 and CS3 it was seen that some dwellings located on the perimeter of the affected area were not burnt. Although it is unknown if firefighting efforts could have been the reason for lack of spread, in both cases it was possible to observe certain spacings between dwellings that could have helped to prevent fire spread. Based on the resolution of the imagery used and on [142], it is estimated that there could be errors of ±20 cm with respect to the distances measured.

For CS1, the fire did not spread to adjacent dwellings, (zone B, C and D in Fig. 6-12), that were relatively near the affected area. As mentioned above, it is believed that the fire did not spread to the adjacent dwellings due to the spacing observed in the settlement configuration. The transversal spacing, noted as D1 - D6 in Fig. 6-12, ranged from 1.3 to 5.4 m. In the longitudinal direction of the fire spread the spacing between dwellings is almost negligible, whereas the lateral spacings (D1 - D6) limited spread. However, to the north of the burn scar it is possible to see separations of between 1.5 and 2.1 m (D7 and D8) which the fire easily crossed.

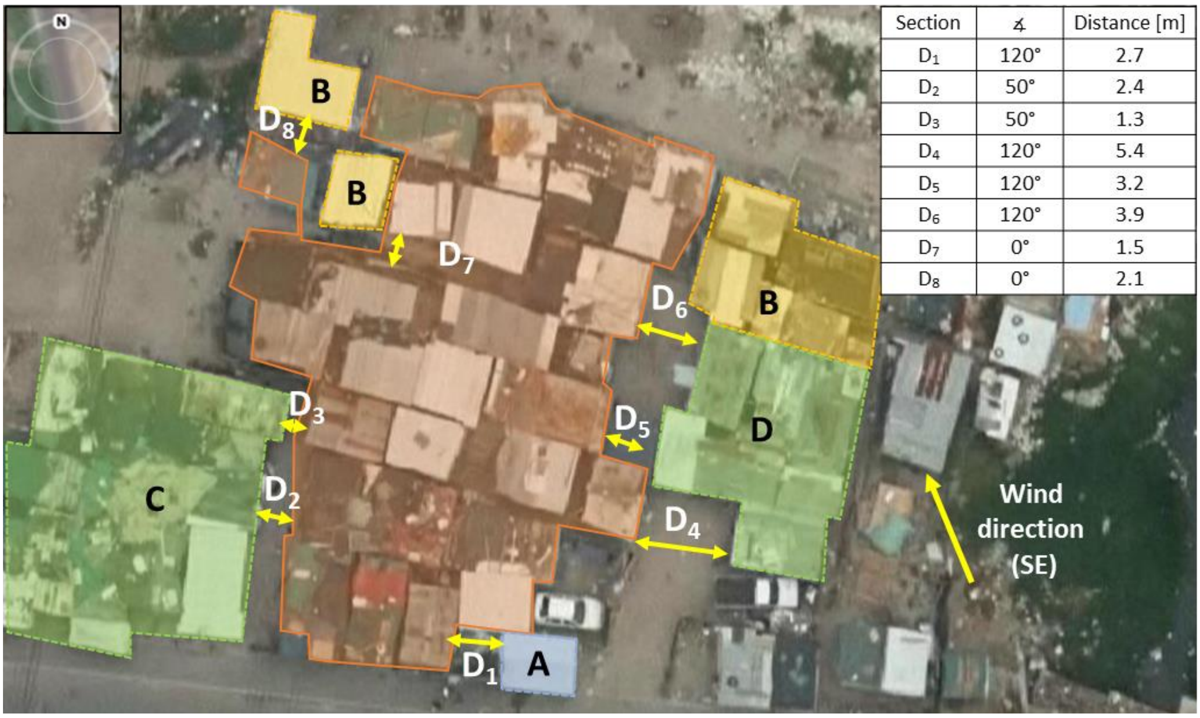

Fig. 6-12: Spacing for unburnt dwellings in CS1. ∡ represents the angle relative to the fire spread direction. The fire scar is shown in orange. Homes in Zones A, B, C and D were not affected by the fire.

For CS3, three areas where dwellings survived the fire were identified. Fig. 6-13 depicts these areas. A total of 10 roofs/structures remained standing after the fire. As shown in Fig. 6-13, all the homes are located on the perimeter of the burn scar, one dwelling (H_1) is on the left of the settlement, four dwellings are in the top-right of the settlement (H_2-H_5), and five dwellings are in the middle-right of the settlement (H_6-H_{10}). Fig. 6-13 also presents the separation distances between those homes and their closest neighbouring dwellings, and the width of the three roads (R_1, R_2, R_3) and two alleys (A_1,

A_2) located in the affected area. It is important to note that no homes within the burn scar survived, irrespective of construction type, geometry, or fuel load.

H_1 has a separation of 2.5 and 2.6 meters to its top and bottom closest neighbouring dwelling. It is interesting to observe that even when the alleys' width ranged from 1.4 to 2.9 meters (which is similar to the separation distances that H_1 had), the fire still spread to the top adjacent dwellings. Clearly the direction of the fire spread also had an impact on this situation. Fig. 6-13 illustrates that the unburnt dwelling was located at the left flank of the fire, while A_1 and A_2 are located at the head of the fire. More data regarding the influence of fire spread modes, construction materials, number and size of the dwellings' openings, presence of flammable materials between the dwellings, firefighting efforts, and wind conditions when the fire reached these homes, is required to make detailed statements regarding home survivability. Work such as the one done by Bellemare et al. [143] to study the efficiency of fuel breaks for wildland fires under different wind and slope conditions could be conducted in the future for ISs.

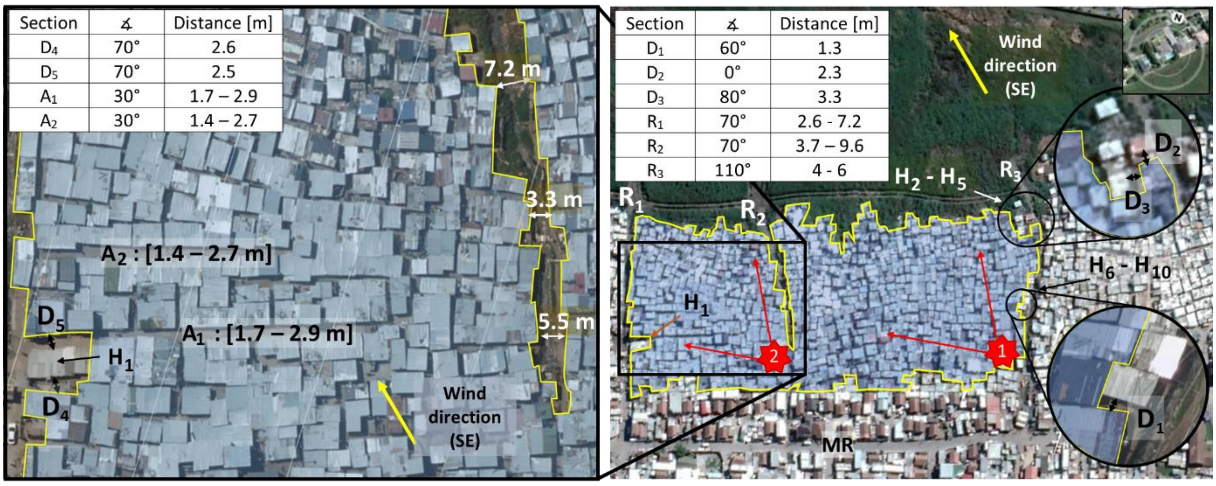

Fig. 6-13: Spacing for unburnt dwellings in CS3. ∡ represents the angle relative to the fire spread direction.

6.5.5 Uncertainties

A main limitation of this study is related to the many uncertainties associated with (a) the determination of the fire's duration, (b) the accuracy of the information provided by the firefighters, (c) the wind conditions at the scene during the fire. This section attempts to quantify these uncertainties.

6.5.5.1 *Duration of the fire*

The calculated spread rates are heavily reliant on the estimations of the ignition and extinction times. It is difficult to accurately determine these times without the residents' and firefighters' statements. It could be expected that the ignition time may be close to the time that the phone call was made. Once a dwelling of fire origin reaches flashover it should be evident for the settlement's inhabitants that a fire is happening and that they should contact the fire brigade. Additionally, from previous experimental work, it is known that the time to go from flaming combustion inside the dwelling to flashover could be as little as 3 minutes or less [13]. In [124] it was seen that the residents' became aware of the fire before flashover was reached, but they engaged in other activities before contacting the fire brigade and the phone call was done at least five minutes after ignition (Fig. 6-3). While for CS1 the error in the estimation of the ignition time could be around 10 minutes, for CS2 it could be much longer since the fire happened at night. For CS3, according to one of the residents' statement and the information given at the time of the phone call, the ignition was at least one hour before the call. The extinction time, on the other hand, could be related to the time at which the fire unit in charge indicates that no further assistance is needed, by saying 'STOP'. However, the extinction time does not necessarily represent the time in which the fire affected the total number of dwellings. It was seen in [124] that the time in which fire spread occurred is less than the total fire duration (the fire reached the back of the settlement at 11:06 and it was extinguished at 11:23). It is necessary to analyse more fires to be able to determine the error associated with the calculated fire spread rates. It is believed that initial fire spread rates are the most uncertain, with spread rates later into the fire becoming more certain as typically more information is available.

6.5.5.2 *Information provided by the firefighters*

In general, this work relies on the firefighters' input. Most of the data collected comes from firefighters' statements and reports. That information is used to (a) validate the fire origin and pattern formation sequence hypotheses developed, (b) estimate the average fire spread rates, (c) reconstruct timelines, and (d) identify the official fire causes. It is known that data might not be completely reliable. However, it is the only source of information that is available in most IS fires. Although the inaccuracies affect the results presented in this work, improvements can be made to reduce them. More detailed data about the fire cause and fire spread can be collected. Fire incident reporting systems from other countries could be implemented as discussed in [144]. Additionally, the way data is collected, reported and/or processed can be improved by using on site data collection tools and new fire incident management technologies.

6.5.5.3 *Wind conditions*

As mentioned, the wind conditions reported in the FRSIR are estimations made by the firefighters. Since the wind conditions have a critical influence on the fire spread, a more accurate and consistent manner for capturing this data can benefit the fire origin and pattern formation sequence analysis. It is recommended that the firefighters could use a handheld unit or mobile weather station to monitor the ambient conditions.

6.6 Conclusions

This paper presented the application of the Framework for Fire Investigations in Informal Settlements (FFIIS) to three real fire events that took place in informal settlements in South Africa. All three case studies were classified as large post-flashover fires. The analysis provided important insights into the applicability of the FFIIS for these types of fires. Through the application of the FFIIS it was possible to develop hypotheses that define the area of fire origin and pattern formation sequence with a reasonable level of certainty. This implies that the fire pattern for large post-flashover fires in ISs can be treated in a similar manner to that of wildland fires patterns, as proposed in the FFIIS. Additionally, the investigation of real fire events allowed one to: i) estimate the average fire spread rates, ii) study the impact of separation distances between dwellings on the fire spread, iii) and to identify the limitations of the FFIIS. In the case studies, fire spread rates ranged between 0.34-0.55 m/min and 6.9-51.2 m^2/min. Difficulties associated with identifying the actual start time of the fire significantly influence the accuracy of these predictions. Furthermore, instantaneous spread rates will often be significantly higher than averaged rates for an entire incident. In CS1, fire spread did not occur across lateral distances above 1.3 m. Ten homes that were not ignited around the perimeter of CS3 were discussed, and reasons for home survival may include location with respect of the fire spread, spacing between dwellings, and/or firefighting efforts.

It is important to note that this work is not sufficient to fully determine the effectiveness or the applicability of the FFIIS in general as there are a wide variety of conditions that influence fire spread in ISs. Further application of the FFIIS to different types of real fire incidents in IS is required to identify possible changes or improvements that need to be done in order to obtain better results for each of the fire categories, (i.e. pre-flashover fire, post-flashover fire, large post-flashover fire), as described in [10]. As the database of verified data on fire spread grows, it may be possible to apply statistical procedures to estimate fire spread rates during an incident to provide decision-making tools for the fire services. Furthermore, predictive computational models could potentially be developed for large-scale events. Data from incidents implicitly account for many factors that are difficult to include in experiments and physics-based models such as human activities, high levels of material variability, many different ignition modes, and similar aspects.

The application of the FFIIS to a large number of real IS fire incidents could also allow one to identify correlations between the different factors that influence the fire development and the fire outcome, such as wind and/or topography conditions and fire spread rates and spacing between dwellings and fire spread.

6.7 Acknowledgements

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Chapter 7: Towards understanding fire causes in informal settlements based on inhabitant risk perception

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Declaration by the candidate:

The nature and scope of the candidate's contribution were as follows:

Nature of contribution	**Extent of contribution**
Writing the manuscript, establishing methodology, analysing data, and preparing figures and tables.	87%

The following co-authors have contributed to as follows:

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Date:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 7,
2. no other authors contributed to Chapter 7 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 7 of this dissertation.

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This chapter is an exact copy of the journal paper referred to above

Contribution of chapter to dissertation

After the work carried out in Chapter 5 and Chapter 6 revealed the difficulty in obtaining information pertaining to the fire cause of IS fires, a different approach was taken in this chapter. This chapter analyses a survey conducted after a large-scale fire. The survey considered questions related to the fire risk perception in the settlement. Associating the concept of fire risk perception with fire cause the work seeks to gain knowledge about fire cause in IS.

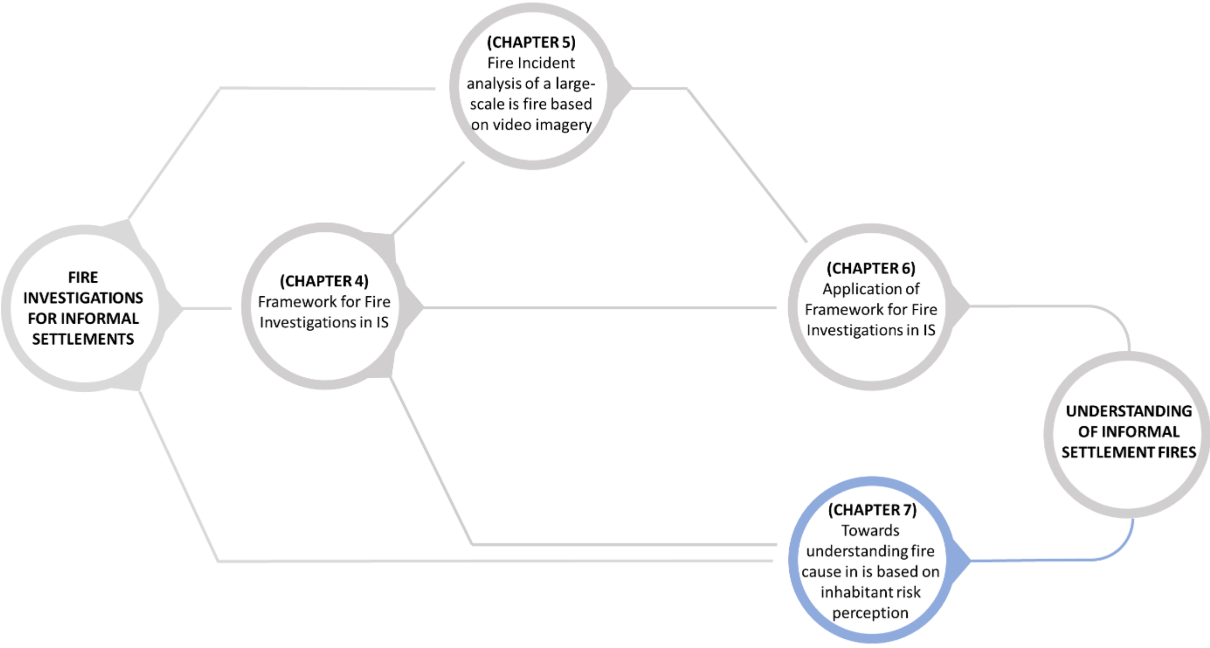

Fig. 7-1: Contribution of Chapter 7 to dissertation.

CHAPTER 7: TOWARDS UNDERSTANDING FIRE CAUSES IN IS

7.1 Abstract

Informal settlements (ISs) are a high-risk environment in which fires are often seen. In 2019 alone, 5544 IS fires were reported in South Africa. One of the main problems, when investigating an IS fire, is determining the fire cause. In the last 15 years, approximately 40% of the fire causes were classified as 'undetermined' in South Africa. Furthermore, the cases where the fire causes have been determined, do not provide the necessary information to comprehend why the fire started. This paper seeks to gain better insight with respect to fire causes by analysing the fire risk perception of IS inhabitants. To this end, a survey that was conducted in 2017, consisting of data from 2178 IS households, that were affected by a large-scale fire, was analysed. The survey consisted of questions relating to the fire risk perception with regards to the settlement in general, to the inhabitants own household, and about measures that could reduce fire risk. The analysis suggests that (a) the survey's risk target had a strong influence on risk perception, (b) the inhabitants' fire risk perception of their settlement is similar to that of firefighters in previous research, (c) the risk mitigation demands are more focused on decreasing the consequences of the fire than on the occurrence of a fire event, (d) the national fire statistics are not capturing the causes of real fire incidents, and (e) improvements to the documentation process after a fire event could provide critical information for the implementation of prevention measures.

Keywords: informal settlements; fire cause; fire risk perception; risk management; disaster; slums

7.2 Introduction

Informal settlements (ISs) (also known by more derogatory names such as slums, shantytowns, ghettos, etc.), are typically characterised by poverty, poor infrastructure, and high dwelling density [2]. These factors create a high-risk environment in which fires, flooding, and other hazards are often seen [122,145]. Focusing on fire risk, the following socio-economic conditions enhance the probability of having a fire event: hazardous lighting, cooking and heating methods; informal electric supply; and alcohol abuse [122]. Furthermore, there are factors such as poor construction materials, close proximity between the dwellings, poor accessibility (that hinder firefighters' operations), and lack of water supply, that influence the fire spread rates.

In 2019 alone, 5544 IS fires were reported in South Africa [7]. Fire departments attended to these fires and completed a Fire & Rescue Service Incident Report (FRSIR) for each incident. Even though the fire cause should be stated in the FRSIR, its determination is a complex endeavour, considering the lack of physical evidence left at the scene [10]. Hence, it is not a surprise that in the last 15 years an average of 37% of fire causes were classified as 'undetermined' [8]. The remaining 63% of fires, where the fire causes have been determined, generally do not provide the necessary information to comprehend why the fire started.

According to the NFPA 921 [59], fire cause can be defined as "the circumstances, conditions, or agencies that bring together a fuel, ignition source, and oxidizer (such as air or oxygen) resulting in a fire or a combustion explosion". NFPA 921 [59] also indicates that to determine the fire cause it is necessary to identify the factors (ignition source, first fuel ignited, circumstances) that allow the fire to have occurred. The official fire causes used in the FRSIR, with the data compiled by the Fire Protection Association of Southern Africa (FPASA), are smoking, electrical fault, open flames, cooking, heating, lighting, arson, undetermined, unrest, welding and cutting, or others. It is unknown if the definitions of the official fire causes are only focussed on the ignition source or if it considers the other two factors mentioned in [59], namely the first fuel ignited and circumstances. As an example, consider a fire that starts with a cardboard lining being ignited by flames coming from a paraffin stove that was unattended. The use of unsafe cooking methods, leaving the stove unattended, and placing the stove too close to combustible materials would be the factors that led to the fire. Would this fire cause be categorized as cooking or open flames according to FPASA guidelines? It is likely that this will depend on the person completing the report.

Cicione et al. [9] listed the main fire causes associated with IS fires in South Africa according to (a) fire brigades, (b) IS residents and (c) the statistics provided by the FPASA. The results exhibit a high level of discrepancy from one source to the other. Firefighters perceive the misuse of alcohol, the use of open flames, and arson as the most probable causes of fire. On the other hand, the inhabitants perceive cooking techniques and equipment, children left home alone, and the use of candles as the most probable causes of fire in ISs. These results can be interpreted as different groups of people having different risk perceptions. Risk perception can be defined as the “subjective assessment of the probability of a specified type of accident happening and how concerned we are with the consequences” [146]. Additionally, it is interesting to note that inhabitants’ answers include fire cause factors such as ignition sources (open flames, candles), and circumstances (irresponsible behaviour).

With the above-mentioned in mind, it is clear that there is a real need to gain a better understanding with respect to fire causes in an informal settlement. The authors postulate that this can be done by understanding the fire risk perception of IS inhabitants. Risk can be defined as the product of the probability of an event occurring and the consequence of the event [147]. Hence, fire risk considers conditions, situations, or/and behaviour that could affect the probability, and the consequences of the fire event. It is also important to note here that not all individuals will have the same risk perception of a specific risk. There are several factors that can influence individuals’ risk perception such as the individual’s exposure to the risk [148–150], demographics of the individual, and the risk target [11,12,14,15]. In [151] it is stated that risk target refers “to whom the risk is supposed to pertain”. According to Sjöberg [149], risk perception depends not only on the properties of the hazards as social context also plays a significant role.

Pharoah [122] described, in-depth, the fire risk of an IS in Cape Town. The author worked with the Monitoring, Mapping and Analysis of Disaster Incidents in Southern Africa (MANDISA) database that allowed her to develop a better understanding of the fire risk profile. The database compiled data from the disaster management unit and the fire services [122]. Zweig et al. [123] conducted a survey consisting of 852 IS households in the Wallacedene settlement which is located in Cape Town, South Africa. Their aim was to obtain insights with respect to the fire risk in the settlement, taking into consideration the fact that this settlement had just gone through an electrification programme. The impact of experience on the risk perception of wildland fires has been studied by McGee et al. [152]. The authors conducted surveys and 40 people that had experienced a wildfire were interviewed. They concluded that, in general, their risk perception remained the same and for some even decreased after the incident. Vandeventer [148] noted that these types of fire research findings have been inconsistent. Arvai et al. [150] investigated the contribution of several factors to the risk perception of wildland fires. The authors noted that people emphasize the influence of uncontrollable factors such as extreme temperatures and wind. Another important finding in [150] was the fact that wildland fires were perceived as “unpredictable, not foreseeable, and hence not controllable”, thus, it was perceived that the implementation of prevention measures could not make a difference to the outcome.

This paper seeks to gain a better understanding of the fire causes in ISs, by studying the fire risk perception of IS inhabitants. To this end, the authors analysed the data collected after the Imizamo Yethu (IY) fire that affected approximately 2200 dwellings in 2017 [15]. Thula Thula Hout Bay, a non-profit organisation that actively supports and partners with the local community, especially providing post-disaster relief, conducted surveys of households in the area to determine the level of fire awareness of the inhabitants after the IY incident. The survey considered three questions related to fire risk perception, two directed at the greatest fire risk in IY, and one focused on the measures that could reduce the fire risk. The remainder of this work presents (a) a background to the IY complex, (b) details about the survey, (c) the results, and (d) the discussion of the findings.

7.3 Imizamo Yethu Informal Settlement

As mentioned above, ISs present certain characteristics that make them extremely vulnerable to large conflagrations. These conditions vary from settlement to settlement; therefore, it is important to have a better understanding of the IY informal settlement in particular. In the subsections that follow, the location and demographics, the living conditions, and a summary of some of the fires that had occurred in IY are presented.

7.3.1 Location and Demographics

The Imizamo Yethu informal settlement is located on a mountain slope in the Hout Bay Valley in Cape Town South Africa. The last Census in South Africa was conducted in 2011, which showed that the IY settlement had a population of 15,538 people in an area of 0.571 km^2, meaning that the settlement density is approximately 27,227 people/km^2 [153]. This is more than 43 times the population density of the rest of Hout Bay and almost three times higher than the city centre of Cape Town. Fig. *7-2* visually illustrates this situation, where on the left is Tierboskloof (an upper-income suburban area) and on the right is IY formal and informal housing [154]. According to [153], in 2011, IY's population consisted of 55% males and 45% females, of which 91.6% of residents were Black Africans. A large variety of languages could be found in the settlement including English, Zulu, Afrikaans, and Xhosa (the latter being the predominant first language in 60% of the households).

Fig. 7-2: Contrast between the density in Tierboskloof (left side) and the formal and informal housing in IY (right side) [116].

7.3.2 Living Conditions

The data used in this section uses information provided by Thula Thula's survey that is discussed in the section below. The data collected by the organisation made it possible to characterize the living conditions of the households that were surveyed in IY as presented in Table *7-1*. The household conditions match with the IY informal housing showed in Fig. *7-2* (top-right). Most of the dwellings were constructed with corrugated iron and wood (98%) and had a floor area less than 30 m^2 (94%), while only 14% had a separation of more than 1 m to the closest adjacent dwelling. Access to running water is limited, as 76% of the households stated that they fetched water from a communal tap, which in some cases (16%) was located more than 25 m away from the dwelling. Furthermore, 41% of the households had access to formal electricity, while a concerning 31% had informal electricity (i.e., electricity obtained from neighbours or directly from nearby infrastructure). The access to electricity, formal and informal, in the settlement is reflected in the preferred source of energy, as over 40% of the households used electricity for cooking and lighting purposes. 55% of the households stated that they do not use any source of energy for heating purposes, followed by 22% that use paraffin. This makes sense considering that heaters consume much more electricity than other electric devices. However, the residents mentioned that when the electrical supplies are interrupted (power cuts), people had to use more dangerous sources of energy, such as candles and paraffin. It is unknown if the interruptions in the electrical supply were due to (a) running out of allocated free units, (b) running out of paid for units, (c) load shedding, or (d) problems with the electrical infrastructure. Finally, with respect to household habits, 53% indicated that at least one member of the household drank, 34% stated that at least one of the family members smoked, and 67% of the households never cooked after 22:00 h. Table 1 provides an overview of this data.

Table 7-1: Living conditions in the surveyed households (n = 2178).

		Living Conditions in IY			
Housing Conditions	Construction materials	**Corrugated iron and wood**		**Brick, corrugated iron and wood**	
		98%		2%	
	Floor Area	**1–15 m²**	**15–30 m²**	**More than 30 m²**	
		55%	39%	6%	
	Proximity to adjacent dwellings	**Directly attached**	**Less than 1 m**	**More than 1 m**	
		48%	38%	14%	
Basic Services	Access to running water	**In the household**	**Within 25 m from the household**	**More than 25 m from the household**	
		24%	60%	16%	
	Electricity	**Formal**	**Informal**	**No electricity**	
		41%	31%	28%	
Sources of Energy	Cooking method *	**Electric stove**	**Paraffin stove**	**Electric/ Paraffin stove**	**Gas bottle**
		46%	17%	13%	7%
	Lighting method *	**Electricity**	**Candles/ Electricity**	**Candles**	**Paraffin lamp**
		41%	17%	12%	10%
	Heating method *	**No heating**	**Paraffin stove**	**Electricity**	**Coal stove**
		55%	22%	10%	9%
Household habits	Cooking after 22:00 h	**Never**	**Few times a year**	**Few times a month**	**Few times a week**
		67%	12%	10%	11%
	Smokers in the household	**Yes**		**No**	
		34%		66%	
	Alcohol consumption in the household	**Yes**		**No**	
		53%		47%	

** Only the top 4 answers are listed, with the remaining answers corresponding to a combination of energy sources or less used energy sources, with individual answers being values of between 1 and 5%.*

7.3.3 Imizamo Yethu Fires

The fire that took place in March 2017, lasted 13 h, destroyed 2194 dwellings, and left approximately 9700 people homeless. This large-scale fire event was analysed in depth by Kahanji, et al. [15], and although it was possible to reconstruct the event by estimating fire lines at different times and fire spread rates, the fire cause could not be established. This is something that usually happens in IS fires due to the rapid fire spread, the lack of physical evidence [10], and inhabitants being hesitant to give information [9,15]. Additionally, in [15] some recommendations were made to reduce the fire risk of the IY settlement. However, three years later (on 6 September 2020), another large fire took place, destroying 263 dwellings and affecting around 1500 inhabitants [155]. Fortunately, there were no fatalities in this fire; however, according to the chairperson of the South African National Civic

Organisation (SANCO) in Hout Bay, eight people have died in IY due to fire events since 2017 [155]. One of the affected residents stated that this is the third time that his household has been burnt in a fire (2014, 2017, and 2020). "Every three years, is this bad luck?" he wonders [155]. However, considering the number of fires that take place every year specifically in ISs all over the world, such situations could be expected. According to the Thula Thula survey, when asked 'Has your household experienced a fire before?' only 23% of the households replied 'never' while 49% said 'one time', 18% 'two times', 7% 'three times' and 3% 'four or more times'.

For wildland fires, it is expected that after a fire has occurred, it would take at least a number of years before another fire occurs in the same area again (since most of the combustible material has been burnt). This is not applicable in IS fires, where there is a rapid rebuild rate after a fire [10,124]. Table *7-2* presents some of the fires that have occurred in IY since March 2017. These fires were large enough to appear in newspapers, but it is likely that there are many more that were not covered by the media. It can be seen that only a month after the large fire in March 2017, another fire occurred, affecting families that just finished building their new dwellings [156]. One of the victims stated, "It is difficult to change one's behaviour, but we always advise members to prepare food before going to shebeens" [156], drawing attention to the fact that cooking while drunk is possibly one of the riskiest actions in ISs. A 'shebeen' refers to a local tavern or informal restaurant where alcohol is often consumed. Fig. *7-3* depicts the aftermath of the first fire mentioned in Table *7-2*. It is possible to observe the high level of destruction, as all the combustible materials have been burnt and only metal sheets are left.

Fig. 7-3: Fire aftermath IY March 2017 (Images used courtesy of Bruce Sutherland, City of Cape Town).

Table 7-2: Fires in IY since 2017 as reported in the media.

Date	Dwellings Affected	Displaced People	Fatalities	Reference
11/03/2017	2194	±9700	4	[15]
16/04/2017	±100	±400	1	[156]
20/08/2017	20	±60	0	[157]
27/08/2017	52	±130	1	[158]
12/02/2018	95	±350	0	[159]
01/07/2018	+15	No info	2	[160,161]
21/08/2018	No info	±60	0	[162]
26/02/2019	±20	+70	0	[163]
06/01/2020	7	30	0	[164]
06/07/2020	±50	±200	0	[165]
06/09/2020	263	±1500	0	[155]

7.3.4 Survey

This section describes the survey conducted by Thula Thula Hout Bay, which consisted of 2178 households located in the Imizamo Yethu IS. The survey was carried out in 2017, over a period of five months (August to December). The survey's structure, the data processing, and the data's limitations are presented in the sections that follow.

7.3.5 Survey Structure

The survey consisted of 24 questions, as shown in Table *7-3*. It collected information about (a) the demographics of each household, (b) dwelling characteristics (construction materials, floor area, etc.), (c) fire protection equipment in the household, (d) lifestyle (smoking and drinking habits), (e) fire risk factors in the settlement and in the particular household, (e) measures to reduce the fire risk, and (f) access to basic services (water, electricity). While most of these questions allow for the characterisation of the settlement, and were used in the previous section, only Q6, Q7, and Q8 provide information about risk perception. It is important to note that the responses from the community to risk perception questions were not prompted/structured, which led to people giving feedback that does fit within traditional categories. However, this also highlights people's understanding of fire risk. Open questions were used in that case allowing the interviewee to name one or more potential fire risk activities, conditions, behaviours, and preventive measures.

Table 7-3: Questions included in Thula Thula survey.

Question	Information	Question	Information
Q1	Family size	Q13	Electricity
Q2	Gender and Age	Q14	Cooking method
Q3	Highest education level in the household	Q15	Lighting method
Q4	Nationality	Q16	Heating method
Q5	Number of Disabled people(s) in household	Q17	How often does it happen that someone cooks late at night (after 10?)
Q6	**What do you consider to be the greatest fire risk in IY?**	Q18	Is there anyone in the house who drinks?
Q7	**What do you consider to be the greatest fire risk in your household?**	Q19	Are there any smokers in the house?
Q8	**What are the things you would like to do to reduce fire risk?**	Q20	Has your household experienced a fire before?
Q9	Type of housing structure	Q21	Fire detector?
Q10	Size (floor area) of house	Q22	Fire blanket or bucket of sand/water?
Q11	Proximity to the neighbouring house	Q23	Fire extinguisher?
Q12	Proximity to running water	Q24	Fire retardant paint on walls?

7.3.6 Data Processing

The answers provided for Q6, Q7, and Q8 (Table *7-3*) were so diverse that they had to be categorized. Table *7-4* presents the 25 categories that were considered for the fire risk related questions. The categories include unsafe conditions, sources of energy and/or devices, irresponsible and deliberate behaviour. It is possible to see that 'open flames' appears more than once in Table *7-4*. This is because some households indicated the specific use of open flames (e.g., open flames while cooking, heating, and/or lighting).

Table *7-5* presents the 21 categories that were considered for the suggested preventive measures (question 8 in Table *7-3*), in this work. The categories include safer living conditions, safer sources of energy and/or devices, responsible behaviour, education, and training.

Table 7-4: Categories for the inhabitants' risk perception answers.

Category	Includes	Category	Includes
Arson	1) Arguments between people 2) Jealousy 3) Relationship problems 4) Witchcraft	Irresponsible drinking behaviour	1) Alcohol abuse 2) Cooking when drunk 3) Using candles or paraffin lamps when drunk
Poor accessibility	1) Small streets 2) Blocked streets	Irresponsible behaviour	1) Carelessness 2) Being irresponsible
No response—Does not know			
Electrical components	1) Electric boxes 2) Electric panels 3) Plugs	Irresponsible use of electrical devices	1) Overloading 2) Forget to unplug or switch off appliances 3) Using illegal or cheap appliances
Electric stove			
Electric supply interruption	1) Load shedding 2) Having to use hazardous sources of energy such as candles or paraffin when there is no electricity. 3) Running out of free electricity units	Lack of fire awareness	1) Lack of education about fire, electric usage, dangerous behaviours.
Gas stove		Lack of parental control	1) Kids left alone with flammable items 2) Kids left alone 3) Kids playing with matches
Gas/Gas heater/Gas bottle			
Houses closely built next to each other		No electrical supply	
Informal electric supply	1) Illegal connection 2) Unsafe electrical connections 3) Too many dwellings using one meter box 4) Unsafe electrical boxes	Nothing	
		Open flames *	
		Overcrowded	
		Smoking	
Irresponsible cooking	1) Leaving the stove unattended 2) Late cooking and falling sleep 3) Not switching off the electric stove after cooking	Unsafe heating methods	Open flames *, paraffin, coal
		Unsafe lighting methods	Candle, paraffin lamp

* Open flames can be considered as a category and subcategory, this will depend on the level of detail provided by the interviewee.

Table 7-5: Categories for the inhabitants' suggested preventive measures.

Category	Includes	Category	Includes
Being Responsible		Proper houses	1) Better materials 2) Better construction
Better access	1) More roads 2) Wider roads	Remove flammable items	
No response—Does not know		Safer cooking methods	
Education	1) Educate about fire risk 2) Educate about electricity usage 3) Firefighting training	Safer lighting	
		Solar panel	
Fire detector		More space between houses	
Fire protection devices	1) Fire extinguisher 2) Fire blanket 3) Bucket of water/sand	Super blocking	
		Responsible cooking	
Fire retardant paint		Responsible drinking/Reduce alcohol consumption	1) Eliminate taverns from IY 2) Close taverns earlier 3) Reduce substance consumption
Formal Electricity			
Improve firefighters' operations	1) More firefighters 2) Faster firefighters' response 3) Improve the relationship between firefighters and the community	Responsible use of electrical appliances/Safe appliances	1) No overloaded plugs 2) No overloaded electrical boxes 3) Unplug electrical appliances after using them
Nothing		Water supply	1) Having more hydrants 2) Tap water in every household
Parental control			

7.3.7 How to Go from Risk Perceptions to Fire Causes?

The survey data, presented above, focusses on the fire risk perception of the inhabitants of IY. However, this work aims to gain more knowledge about the fire cause factors. Fig. *7-4* depicts how the information obtained from the survey can be linked to fire cause factors. The elements that will increase the probability of a fire occurring are essentially the fire cause factors previously described. The consequences will depend on the fire severity. The IS's conditions that affect the fire severity will either allow a fast-spreading fire or affect the firefighting and evacuation activities.

The answers provided by the residents, Table 7-4 and Table 7-5, reflect their concern in three main areas (a) possible ignition sources (smoking, cooking), (b) circumstances that can lead to the fire or that increase the probability of one occurring (irresponsible drinking behaviour, lack of parental control) and (c) factors that will have an impact on fire spread (houses that are closely built to each other, informal houses). It is possible to associate the first and second areas to the official fire causes specified in the FRSIR ('unrest' and 'welding and cutting' were excluded because they were not mentioned by the residents). Table 7-6 presents the official fire cause associated with the ones obtained from the risk perception of the IY residents (Table 7-4). Table 7-6 shows that the possible fire causes observed by the residents provide much more detail. Additionally, the data illustrates that due to the lack of detail, there could be a problem with accurately fitting the fire cause in one of the nine categories. A clear example of this are the categories 'open flames', 'cooking', 'heating', and 'lighting', since open flames are used for cooking, heating, or lighting purposes. The lack of detailed information is one of the main obstacles to developing preventive measures in ISs. Finally, even though the third area is related to the consequences of a fire, it still offers interesting insights on problematics that are often seen in ISs.

Table 7-6: Official fire cause vs. Fire cause observed by the residents.

Official Fire Cause	Fire cause Observed by the Residents	
Smoking	Smoking	
Electrical fault	Informal electrical supply Electric components Irresponsible use of electrical devices Electrical supply interruption	
Open flames*	Open flames * Cooking * Heating *	
Cooking *	Irresponsible cooking Unsafe cooking method Gas stove Electric stove	Gas Gas bottle No electrical supply Paraffin Open flames *
Heating *	Unsafe heating method	
Lighting *	Unsafe lighting method	
Suspected arson	Arson	
Undetermined		
Others **	Irresponsible drinking behaviour Irresponsible behaviour Lack of fire awareness Lack parental control	

** These items can be considered as a category and subcategory depending on the level of detail provided by the interviewee.*
*** These factors could be present in any of the other categories.*

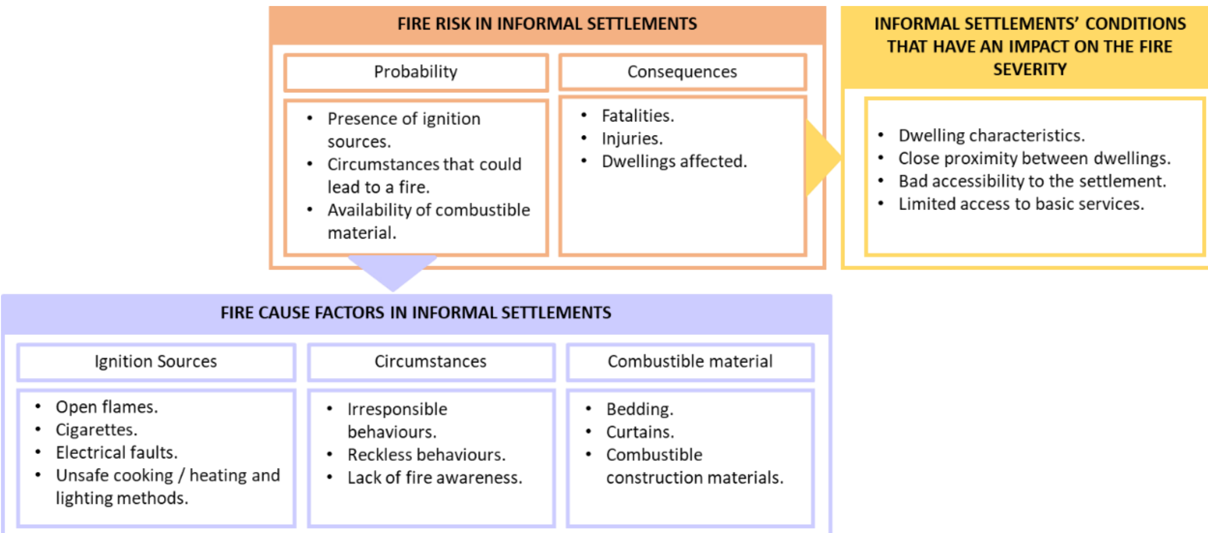

Fig. 7-4: Relation between fire risk perception and fire causes.

7.3.8 Limitations

The major limitation of this study is the fact that the survey was not conducted with the aim of gaining information about the fire causes in IS fires. Additionally, factors that could influence the inhabitants' risk perception were not accounted for. For example, it is not only important to ask how many fires a household had previously experienced. It is also necessary to collect additional information. Were they intimately related with the fire? When did the fire occur? Were they at home when the fire took place? Over what period did the fires occur? Understanding the different experiences within the affected settlement could be useful to understand the risk perception of the residents. Finally, the data collection process only considered the IY IS, which makes the findings of this work less robust compared to a scenario where the survey included a variety of settlements with different weather and living conditions, locations, access to basic services, demographics, etc.

7.4 Results

As introduced above, the survey had two questions related to fire risk perception in the IY IS. One was directed at the settlement (general risk) and the other at the household (personal risk). The fact that the survey included two risk targets allow this work to test the "unrealistic optimism" phenomenon [13,149], in which personal risk is underestimated in comparison with the general risk (i.e., people think that the risk that they create is significantly lower than that caused by others in the general community). This section presents (a) the main risks in IY identified by the inhabitants, (b) the main risks in households, and (c) a comparison between the answers for each risk target. An in-depth discussion regarding the inhabitants' risk perceptions is presented in the section that follows.

7.4.1 Fire Risk Perception in Imizamu Yethu

When asked 'What do you consider to be the greatest risk in Imizamo Yethu?' 51% of the households considered that it is 'Irresponsible drinking behaviour', followed by 'Unsafe lighting method' at 33%, 'Irresponsible cooking' at 19%, 'Unsafe cooking method' at 17%, and 'Irresponsible behaviour' at 15%. Table *7-7* presents in detail the answers given by the residents.

Table 7-7: Fire risk perception in IY (n = 2178).

Fire Risk in Imizamo Yethu	Percentage [%]	Fire Risk in Imizamo Yethu	Percentage [%]
Irresponsible drinking behaviour	51.1	Paraffin	1.8
Unsafe lighting method	33.3	Arson	1.7
Irresponsible cooking	18.9	Unsafe heating method	1.6
Unsafe cooking method	16.9	Informal houses	1.5
Irresponsible behaviour	15.4	Overcrowded	1.3
Informal electric supply	13.0	Open flames	1.0
Houses closely built next to each other	7.1	Electric supply interruption	1.0
Smoking	5.0	Gas stove	0.6
No electrical supply	4.8	Lack of parental control	0.6
Lack of fire awareness	4.7	Poor access	0.3
Irresponsible use electrical devices	2.7	Electric stove	0.3
No response—Does not know	2.1	Nothing	0.2

7.4.2 Fire Risk in the Household

When asked 'What do you consider to be the greatest risk in your household?' 33% of the households considered it to be 'Unsafe lighting method', followed by 'Electric stove' with 23%, 'Informal electric supply' with 22% and 'Unsafe cooking method' with 15%. Table *7-8* presents in detail the answers given by the residents.

Table 7-8: Fire risk perception in the household.

Fire Risk in Your Household	Percentage [%]	Fire Risk in Your Household	Percentage [%]
Unsafe lighting method	32.6	No response—Does not know	1.9
Electric stove	22.5	Paraffin	1.8
Informal electric supply	22.0	Smoking	1.4
Unsafe cooking method	14.7	Irresponsible behaviour	0.9
Gas stove	8.4	Lack parental control	0.6
Electric components	7.0	Houses closely built next to each other	0.6
Nothing	5.8	Irresponsible drinking behaviour	0.6
Irresponsible use of electrical devices	4.5	Informal houses	0.5
Gas/Gas heater/Gas bottle	3.7	Open flames	0.3
Irresponsible cooking	2.8	No electrical supply	0.2
Unsafe heating method	2.4	Overcrowded	0.1

7.4.3 Measures to Reduce Fire Risk

When asked 'What are the things you would like to do to reduce fire risk?' 33% of the households considered that it would be 'Formal Electricity', followed by 'Proper houses' at 26%, 'Spaces between houses' at 18% and 'Educate' at 10%. Table *7-9* presents in detail the answers given by the residents.

Table 7-9: Measures to reduce fire risk in IY.

Measures to Reduce Fire Risk	Percentage [%]	Fire Risk in Your Household	Percentage [%]
Formal Electricity	33.9	Water supply	3.1
Proper house	25.8	Fire protection devices	3
Spaces between houses	18.2	Nothing	2.9
Educate	9.6	Being Responsible	2.8
Better Access	6.8	Safer cooking methods	2.2
Irresponsible use of electrical appliances/Safe appliances	5	Solar panel	1.3
No response—Does not know	4.7	Fire detector	1.1
Super blocking	4	Remove flammable items	0.9
Responsible cooking	3.9	Parental control	0.6
Responsible drinking/Reduce alcohol consumption	3.6	Improve firefighters' operations	0.6
Safer lighting	3.3	Fire retardant paint	0.5

7.5 Discussion

The analysis of the survey data provides insights into the fire risk perception of IS inhabitants and how they relate to fire causes in informal settlements. Additionally, it allows for the identification of shortfalls in the current data. These topics will be discussed in detail in this section.

7.5.1 Risk Perception

This section analyses the risk perception of IY's inhabitants. The inhabitants' risk perception of the rest of the settlement (general risk) will be presented first, followed by the risk perception of their own household (personal risk). Then a comparison is made to be able to appreciate the differences between them. Finally, the suggested preventive measures are discussed.

7.5.1.1 *General Risk—Inhabitants' Risk Perception of Other Residents*

The main concerns of the inhabitants are irresponsible behaviour and unsafe sources of energy, with irresponsible drinking behaviour being the leading concern. This matches two of the main fire cause factors (i.e., alcohol related and open flames) mentioned in [9] by firefighters. Although there is no official information about the influence of alcohol consumption on the number of fires, it is known that it has a significant impact on the number of casualties in residential fires [111]. Focusing on Cape Town, South Africa, in 2001 alcohol intoxication was identified in 53% of the adults whose death was caused by burns [166]. Clearly, it would be important to find a way to monitor the influence of alcohol consumption on the number of IS fires.

7.5.1.2 *Personal Risk—Inhabitants' Risk Perception of Their Own Household*

Surprisingly 6% of the households indicated that in their dwelling there was no condition, situation, or behaviour that could lead to a fire. One would then assume that those dwellings probably never experienced a fire (or inhabitants were unwilling to provide detailed answers to the surveyors); however, 70% of them experienced at least one fire incident and 16% three or more fires. It could also be the case that in the previous fire events in which the inhabitants were involved, the fire did not start in their households.

It is interesting that 23% of the households perceived 'Electric stoves' as a risky appliance, since electricity is often considered a safe source of energy. A possible explanation for this could be the use of informal electricity, although 64% of the residents that own electric stoves indicated that they had formal electricity supply. Additionally, some residents mentioned that electric appliances were 'illegal' or 'cheap'. In [123], it was mentioned that these appliances, and electrification in general, could create a false sense of security that might generate riskier behaviour, such as unattended cooking.

7.5.1.3 *General Risk Versus Personal Risk*

When analysing the results of the survey it is interesting to note the effect of the risk target on the perception of the risk. Fig. *7-5* presents a comparison between the answers given for the different risk targets. The graph was divided into sections to group irresponsible behaviour and conditions inherent to ISs. When the target was the IY settlement, the answers tended to show a focus on people's irresponsible behaviour. In contrast, when the target was the household (of people living within the IY settlement) the concern was directed to unsafe sources of energy and devices. This could be related to the risk denial or unrealistic optimism phenomenon. In this case, factors that are beyond their control, (i.e., unsafe lighting and cooking) are over-emphasised and factors within their control (i.e., behaviour such as irresponsible cooking or irresponsible drinking) are underestimated. It has been acknowledged by Sjöberg that the unrealistic optimism phenomenon is more pronounced in lifestyle risks such as alcohol consumption or smoking [167]. Fig. *7-5* clearly depicts that situation, while there are factors that present a similar level of risk perception such as unsafe lighting or cooking methods, or the usage of paraffin, others such as irresponsible drinking behaviour and irresponsible cooking vary significantly. Additionally, in [167] it is stated that general risk perception is more important for policy attitudes.

7.5.1.4 *Measures to Reduce Fire Risk*

Sjöberg [168] acknowledged that risk mitigation demands are not always aligned with risk perception. He states that, even though the risk is a combination of probability and consequences, when perceiving a risk, the probability of that event happening is predominant, while for the risk mitigation measures, the consequences play a more significant role. That is shown in the survey where three of the top five measures shown in Table *7-9* (proper houses, spaces between houses, and better access), were not acknowledged when consulted about the fire risk. Those measures do not have a direct impact on the occurrence of a fire event, but on fire spread. It has been acknowledged that the living conditions in ISs have a great impact on fire spread to adjacent dwellings [1,5,22], which is clearly one of the main consequences that these types of fires produce.

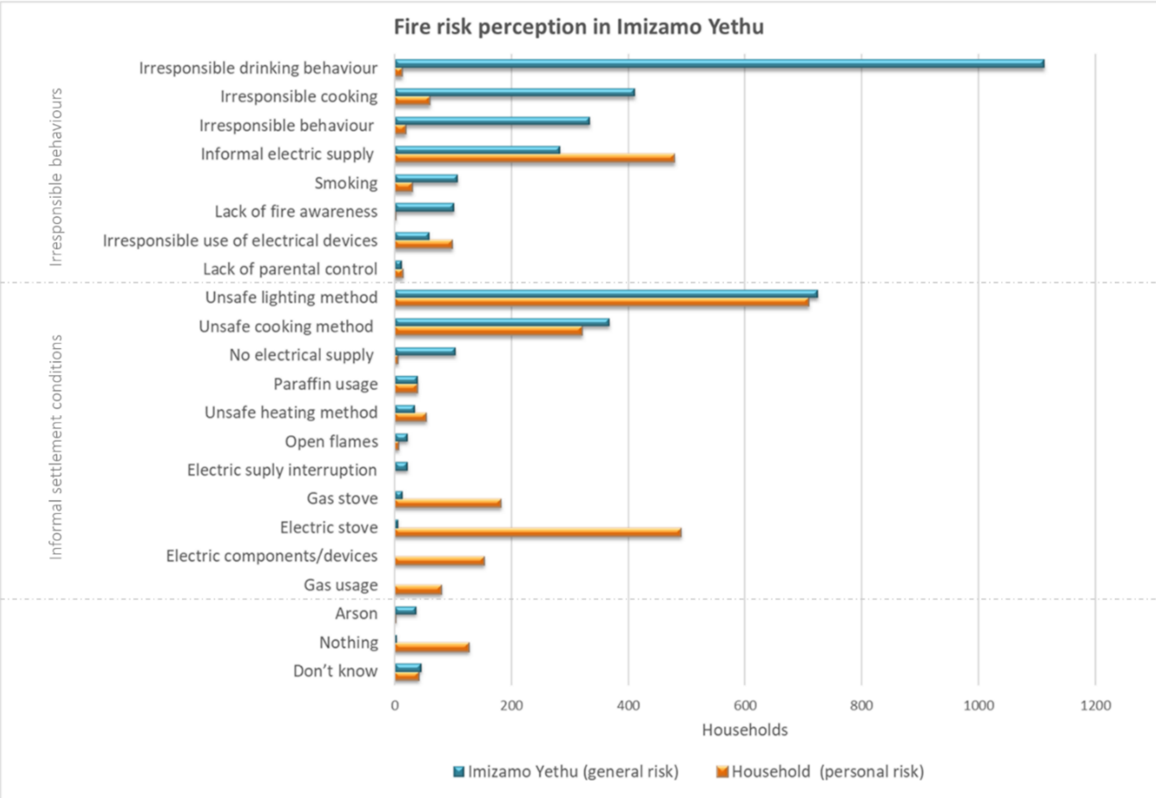

Fig. 7-5: IY inhabitants' risk perception. General risk vs. personal risk.

7.5.2 Fire Cause

7.5.2.1 *Official Fire Causes Versus Fire Cause Factors Observed by the Residents*

As mentioned above, the fire cause factors identified by the inhabitants are much more detailed than the official fire causes selected by firefighters (see Table *7-6*). However, the FRSIR allows the firefighter to add details about the fire cause. Furthermore, sometimes firefighters have more details that they do not include in reports (e.g., if they suspect that the fire started as a consequence of a person being under the influence of alcohol or drugs the information is often not included). Table *7-10* illustrates this situation. The details can be entered in an open text field in the FRSIR. This gives more freedom to the user, but at the same time makes the compilation process harder, which might be one of the reasons why this information is not included in the national statistics. As seen in Table *7-10*, the information that the firefighters collect at the fire scene could be relevant to develop evidence-based interventions.

Table 7-10: Information firefighters collect at the fire scene as recorded in the FRSIR.

Official Fire Cause	Details	Additional Info (Not Documented)
Electrical Fault	Suspected power surge of electrical current to faulty plug socket.	Informal electrical supply.
Cooking	Stove overturning and igniting bed, bedding, etc.	Witnesses indicate the man was under alcohol influence He was cooking on a paraffin stove.

Fig. *7-6* compares the official fire causes in informal settlements as compiled by the FPASA [7] with the inhabitants' risk perception results from this work and with the firefighters' opinions based on a previous survey [9]. For the comparison, 9 of the 11 official fire causes were considered. Two additional categories, (gang-related and irresponsible drinking behaviour), were included, even though they are not shown in the national statistics. While 'gang related' could be considered as 'arson' it is interesting to notice that this aspect was not mentioned by any of the surveyed households. It is possible that in IY in particular, gangs are less of a problem, but in other IS this could be an important factor to bear in mind. The influence of alcohol consumption is also relevant, being one of the main concerns for the IY inhabitants and for the firefighters interviewed in [9]. In recent work, Arce et al. [169] interviewed Costa Rican firefighters to understand IS fires in that country. It is interesting to notice that several of the fire causes mentioned match with the ones observed in this work.

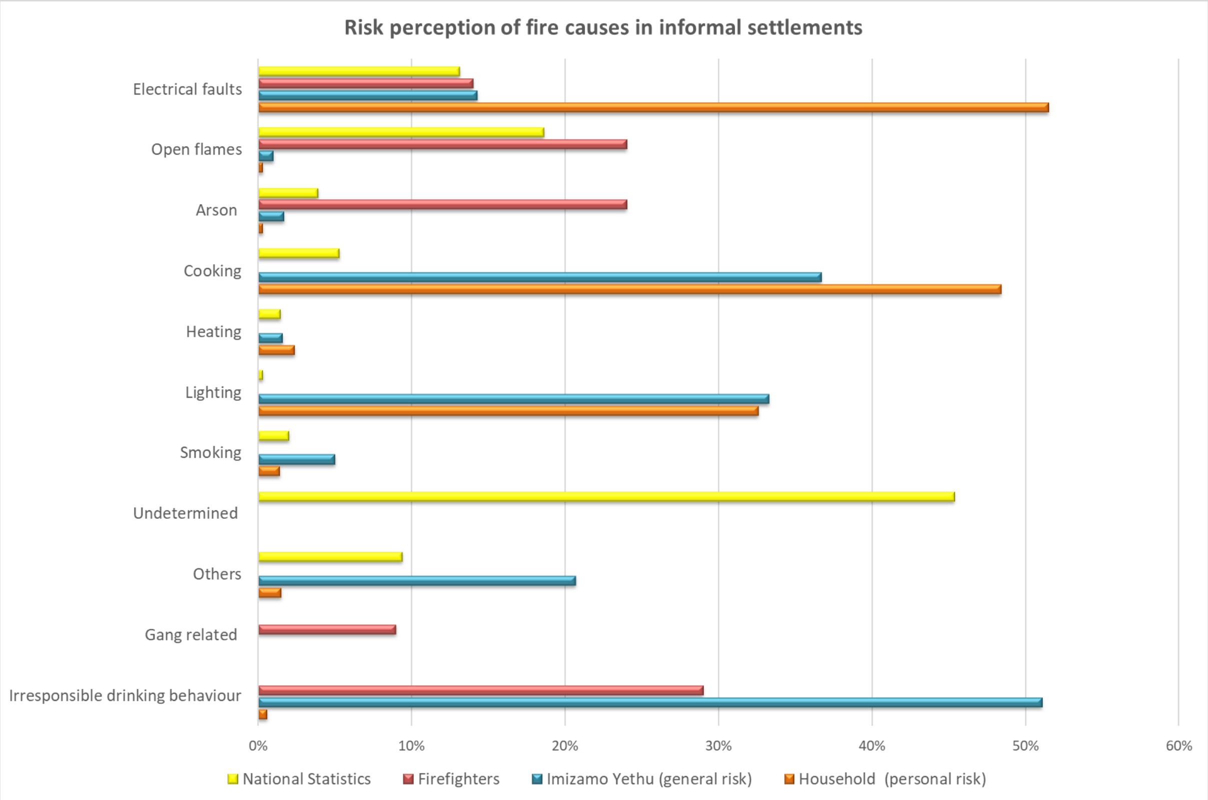

Fig. 7-6: Comparison of fire cause in IS perception.

7.5.2.2 *Recommendations for Improving the National Data Collection*

It is recommended that for fires in IS more information could be added to the FRSIR that would allow one to better understand the details pertaining to the cause of the fire. Efforts should be directed at those categories in which uncertainties are present. In the case of an electrical fault, it is necessary to know the type of electric supply the household had and what type of device or component failed. For open flames, it is important to know what they were being used for (i.e., cooking, lighting, heating).

For cooking, heating, and lighting, it is important to know the source of energy and the type of device that was being used. Additionally, it is important to document if the fire originated due to a device or component failing or due to people's irresponsible behaviour.

To improve the FRSIR, it is suggested that it would be possible to take, as an example, the National Fire Incident Reporting System (NFIRS) [170]. The reporting modules can provide guidelines to incorporate valuable information to the FRSIR. Among others, the NFIRS requires information about (a) ignition, (b) cause of ignition, (c) human factors contributing to ignition, (d) equipment involved in ignition, and (e) equipment power source (Table *7-11* provides more details). It might seem that this information is difficult to obtain in an IS fire due to the lack of physical evidence. However, the firefighters, through witnesses' testimonies, already have access to part of it (see Table *7-10*).

Table 7-11: Extract of NFIRS's Chapter 4-Fire Module (NFIRS-2) [170].

Factor	Details	Factor	Details
Ignition	Area of fire origin Heat source Item first ignited Type of material first ignited	Human factors contributing to ignition	Asleep Possibly impaired by alcohol or drugs Unattended person Physically disabled Multiple persons involved
Cause of ignition	Intentional Unintentional Failure of equipment or heat source Act of nature Cause under investigation Cause undetermined after investigation	Equipment involved in ignition	Brand, Model, Serial #, Year
		Equipment power source	i.e., Electrical, Gas fuels, liquid fuels, solid fuels

7.6 Conclusions

The work has provided novel insights regarding fire causes by understanding the fire risk perception of the IY IS complex inhabitants. By analysing the residents' fire risk perception, it was possible to see the influence that the risk target has on the answers. Depending on the risk target, certain factors are over- or under-estimated (e.g., alcohol abuse, irresponsible behaviour). Interestingly, when focusing on general risk, the inhabitants' perception is similar to that which firefighters had in previous research. However, their perceptions still present high levels of discrepancy with the national statistics. This gives significant reason to believe that the national fire statistics are not capturing the causes of real fire incidents and that the fire cause determination information is severely lacking and potentially highly inaccurate. Some of the factors that could contribute to this situation are (a) the lack of evidence left at the fire scene, (b) the limited time and resources available to the fire department to allow them to conduct a fire investigation, (c) safety concerns in more hostile settlements, and (d) the limited information that is documented after a fire. The latter is the aspect that offers the most opportunities for improvement. It is proposed that additional information be collected during post-fire investigations, including more details about ignition, cause of ignition, human factors contributing to ignition, and equipment involved in the ignition. Additionally, the feedback of inhabitants should not be dismissed as they have intimate knowledge regarding daily happenings in settlements that influence risk and risk drivers. Ultimately, the lack of accurate fire cause data hinders the development of evidence-based interventions. Through improving fire cause knowledge, it is likely that interventions can target the areas that are causing the greatest number of fires and damages due to fires. Fire safety guidelines being developed [21] can be improved as strategies and interventions being proposed can be supported, or negated, by quantitative analyses.

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Chapter 8: Discussion and additional findings

This chapter provides additional information and discussions that were not included in the published papers of this dissertation (Chapter 4 to Chapter 7). This data provided below has been excluded in the preceding chapters due to the limited space available, because it was not aligned with the contents presented in the work, and/or it was not possible to develop the topic in the required level to be included in the publications. However, this information is still novel and relevant to the understanding of IS fires so has been provided below to support future developments regarding the overall topic.

8.1 Chapter 4: Developing a Framework for Fire Investigations in Informal Settlements

The analysis of the fire statistics in South Africa allowed one to understand the data that is being collected and the relevance of IS fires. After the submission of the paper the author kept monitoring the statistics, focussing on the City of Cape Town, looking at detailed information such as the number of fires per month. This allowed to one observe the impact that the different restrictions associated with COVID-19 had on the number of fire incidents. From 26 March to 30 April 2020, South Africa was in 'alert level 5', changing to 'alert level 4' in May 2020, and moving to 'alert level 3' from 1 June to 17 August 2020. The restrictions implemented during this time that could have an impact in the number of fires are shown in Table 8-1.

Table 8-1: Restrictions during the different alert levels in South Africa that may have influenced fire incident occurrences [171]

Restrictions	**Alert Level 5**	**Alert Level 4**	**Alert Level 3**
Curfew	Every person is confined to his or her place of residence, unless strictly for the purpose obtaining an essential good or service, collecting a social grant, pension or seeking emergency, life-saving, or chronic medical attention	From 20h00 to 05h00	From 22h00 to 04h00
Gatherings	All gatherings are prohibited, except for funerals (limited to 50 people)	All gatherings are prohibited, except for funerals (limited to 50 people)	Permitted but limited to 50 persons or less for indoor venues and 100 persons or less for outdoor venues, but not more than 50 percent of the capacity of the venue
Movement	No inter-provincial movement	No inter-provincial movement	No inter-provincial movement
Alcohol	Sales are prohibited	Sales are prohibited	Sales allowed from 10h00 to 18h00 from Mondays to Thursdays. On site consumption until 20h00
Tobacco and nicotine products	Sales are prohibited	Sales are permitted	Sales are permitted

Fig. 8-1 presents the number of fires in Informal and Formal settlements from January to August during 2018, 2019 and 2020. It can be seen that since the restrictions were implemented, there was a strong decrease in the number of fires in IS, especially during April and May. However, for formal settlements there was a significant decrease only in May of 2020, but not beyond. Recent data from cities around the world indicate the lockdowns typically had a negligible influence on the number of reported fire incidents [172]. Hence, this tends to indicate restrictions associated with alcohol sales and consumption caused the significant decrease in the number of incidents recorded, supporting the feedback from residents regarding the prevalence of inhabitants in fire incidents, as provided in Chapter 7.

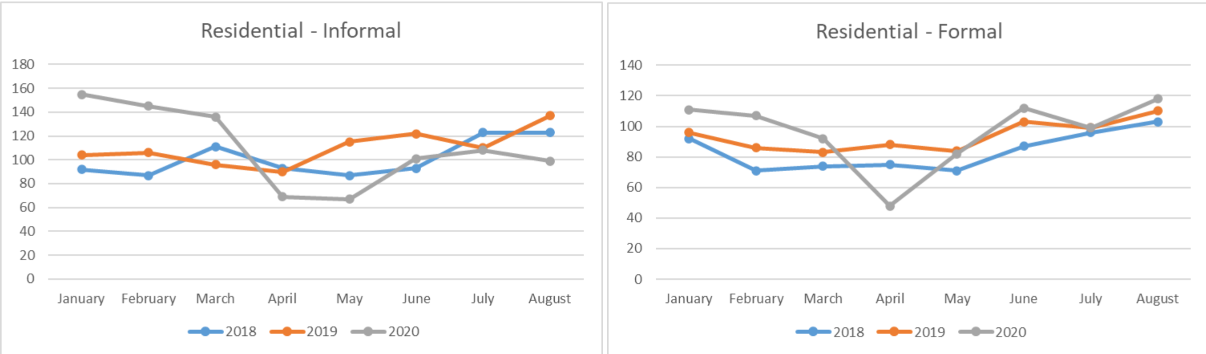

Fig. 8-1: Number of fires in Informal and Formal Settlements from January to August in 2018, 2019 and 2020.

8.2 Chapter 6: Application of the Framework for Fire Investigations in Informal Settlements to large-scale real fire events – Consideration of fire formation patterns, fire spread rates and home survivability

As mentioned in Chapter 6, one of the most important sources of information are firefighters' statements. During the multiple interviews interesting topics that are usually not documented were discussed. Some of these topics are (a) lack of water supply, (b) delay with regards to fire notification, (c) accessibility, and (d) hostile environments. While some of these issues are commonly known, the latter has not received much attention. In [15] Kahanji et al it is mentioned that community members cut hoses in order to redirect water to their dwellings. However, in this work other problems were voiced. Firefighters mentioned that in the last years they have seen an increase in the number of attacks towards them when attending to IS fires. These attacks include stoning, threats, robs, etc. These situations create a new area of concern when dealing with IS fires. Further research is required to quantify and understand this problem.

8.3 Chapter 7: Towards understanding fire causes in informal settlements based on inhabitant risk perception

8.3.1 Thula-Thula survey

In Chapter 7 it is mentioned that Thula-Thula conducted a survey with 24 questions. Only those questions related to inhabitants' risk perception and living conditions were presented and used for the analysis. Furthermore, there were two questions that were excluded: 'What would you do if a fire broke out in your house?' and 'Do you know emergency number (107)?'. The first was not considered since there were no details about what member of the family will perform each activity, or the order in which the different tasks would be performed. This made it impossible to identify priorities and the extent to which activities would be carried out. The second question was excluded since in South Africa there is not a single number to contact the fire department, and it will depend on the district you are in. 107 is the number for general emergencies and it can only be reached via cell phone, and is not the number promoted by the City of Cape Town for emergencies. This section presents the results of the questions that were not included in Chapter 7.

Table 8-2 focusses on the demographics (Q1 to Q5 in Table 7-3) and fire protection devices (Q21 to Q24 in Table 7-3), while Table 8-3 presents the results for the actions people would undertake in case of a fire.

Table 8-2: Results of the questions from Thula-Thula survey that were not presented in Chapter 7. (n=2178)

Family Size (Q1)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**>10**	**0**
	457	604	455	318	183	75	36	14	12	6	10	8

Gender and Age (Q2)	**Boys**	**Girls**	**Men 18-30**	**Women 18-30**	**Men 31-60**	**Women 31-60**	**Men +60**	**Women +60**
	976	1000	1016	948	1327	982	40	57

Highest education level in the household (Q3)	**No schooling**	**Primary school**	**High school**	**Professional education**	**University bachelor**	**University master**
	36	255	1733	103	48	3

Nationality (Q4)	**SA**	**Malawi**	**Namibia**	**Zimbabwe**	**Other**	**No Information**
	1565	311	153	73	46	30

Does your household have?	**Yes**	**No**
Disable people (Q5)	26	725
Fire detector (Q21)	360	1818
Bucket (water or sand) or fire blanket (Q22)	2013	165
Fire extinguisher (Q23)	51	2127
Fire retardant paint (Q24)	132	2046

Table 8-3: Results to the question 'What would you do if a fire broke out in your house?' (n=2178)

Action	No. of households	Action	No. of households
Fire-fighting action	1401	Something to minimize danger	331
Evacuate	706	Help others	330
Warn others	688	Clear exit routes	37
Contact fire brigade	468	Move furniture/ appliances	24
Save personal effects	378	Make way for fire brigade	18

8.3.2 Improvements to the survey

One of the limitations identified in this work was the quality of the data. As mentioned in Section 7.3.8 the survey was not designed to understand fire causes in IS fires. With this in mind, this section describes the improvements that could be done for futures surveys. In Table 8-4 it is proposed that there should be two different approaches, (a) one when the community is being consulted about a particular fire event and (b) one for a general or hypothetic scenario. While the latter study can be used to understand the fire risk perception of IS's inhabitants, the study of a specific fire can provide important insight about the IS residents' behaviour in fire as seen in Section 2.5. Additionally, the surveys should be designed considering different methods of capturing and measuring attitudes and opinions, depending on the objective of the study. These methods include questionnaires, Likert scale, open ended questions, etc [173]. The design of the research instrument will allow one to improve the quality of the dataset; therefore, other types of statistical analysis could be applied to it to study correlations between responses.

Table 8-4: Additional questions to be consider in future research

Additional Question	Purpose
General or hypothetic scenario	
Do you have access to a phone?	Determine the ability of residents to report fires
What is the fire brigade number?	Check if the residents know how to contact the fire brigade.
Has a fire ever started in your household?	It complements the question 'Has your household experienced a fire before?'
Has your household experience any casualties due to a fire?	It complements the question 'Has your household experienced a fire before?'
Particular fire event	
Location with respect to the fire	It provides a context for their answers.
Who was with you?	To determine the influence that having kids, spouse, family, friends, etc. can have in the behaviour.
How did you become aware of the fire?	To identify cues that trigger a response.
What did you do before evacuating? (If possible, list all the actions in order and with estimated time spent on them)	To understand the residents' behaviour during a fire
Did you return? Why?	To study the reasons for re-entry behaviour
Do you know where the fire started?	To obtain more information about the fire
Do you know what caused the fire?	To obtain more information about the fire

8.4 Possible solutions to the IS fires problem

In this section possible solutions to the IS fires problem are presented. These solutions are based on the findings of this work and do not consider an upgrade to IS conditions, as that is unrealistic (in 2004, the South African Department of Housing manifested their intention of eradicate IS in South Africa by 2014 [174]). A detailed report entitled "Fire Engineering Guideline for Informal Settlements" is provided by Walls et al. [21] and provides an extensive discussion on the topic.

The analysis of the video footage (Chapter 5) provided critical information for understanding the fire incident in a holistic way. It was possible to see that (a) the intervention of the residents can have a critical impact in the fire development, (b) the lack of water supply in the area greatly affects the firefighters' operations, (c) people appear to know what to do in case of a fire. From the application of the FFIIS to the three case studies (Chapter 6) it was observed that (a) there could be long delays in the notification of the fire to the fire brigade, and (b) firefighters not only face technical difficulties when responding to the fires. Finally, from the analysis of the inhabitants' fire risk perception (Chapter 7), it was seen that (a) residents have low fire risk awareness (with respect to their own household), (b) the sources of energy used in IS and people's behaviours such as alcohol consumption seem to play a big role in the number of IS fires, (c) the national statistics are not accurately capturing the causes of real fire incidents.

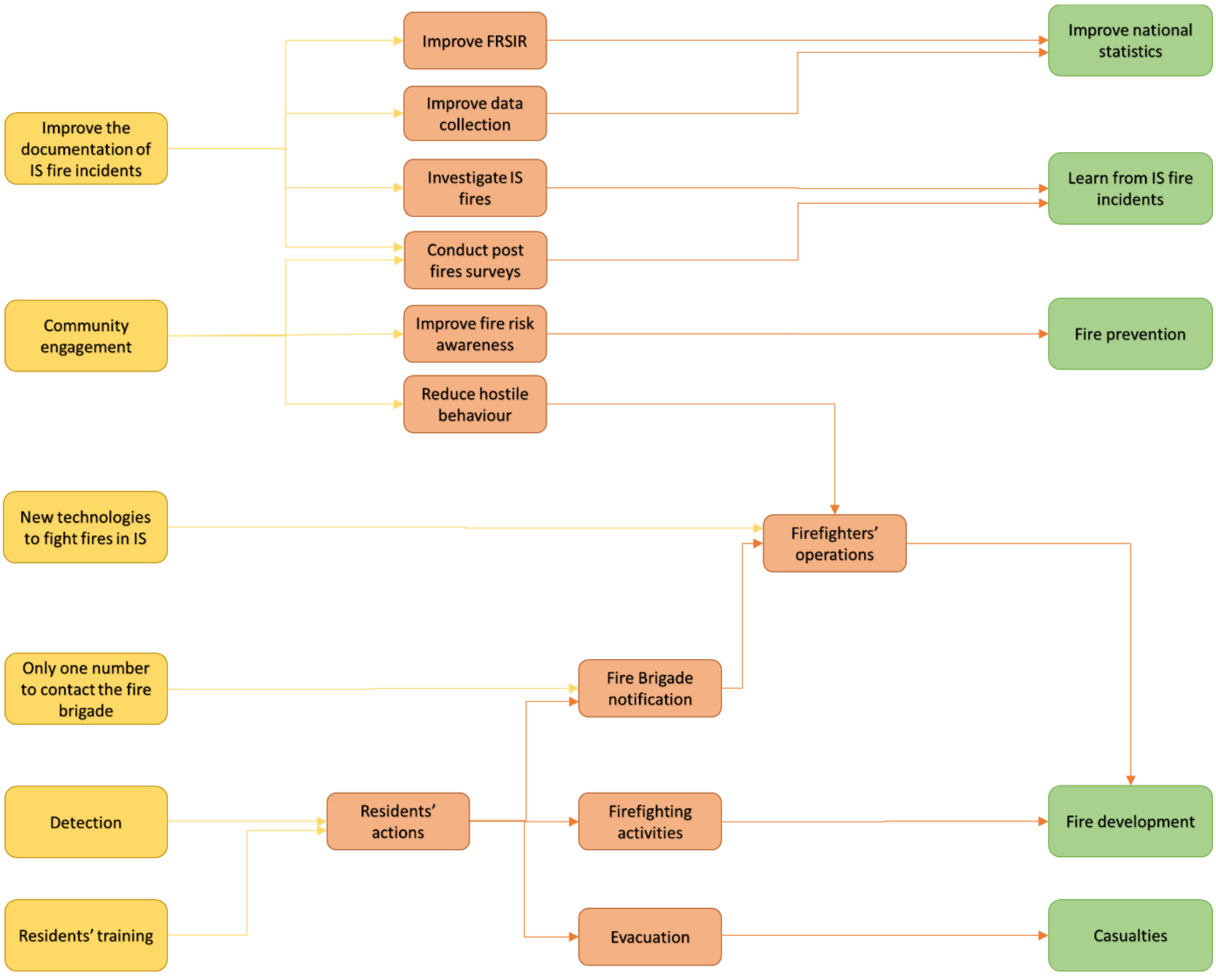

Fig. 8-2: Possible solutions to improve fire safety in IS.

From these findings it is possible to identify different solutions that could improve fire safety in IS. Fig. 8-2 illustrates six potential solutions (yellow boxes) that could be implemented in IS. (1) While improving the documentation of IS fires does not directly impact the number of fires or casualties, it is a useful tool to identify new problems that could be developing. It is expected that the other five solutions could have an impact in the number of fires, the severity of the fire and the number of casualties. Since IS residents play a critical role in the fire cause and fire development, the most important solutions are (2) community engagement and (3) resident training. (4) The implementation of detection systems could decrease occupants' response times (as seen in Section 0). However, this is not new in IS in South Africa. In February 2017 a pilot project was implemented in Cape Town and approximately 1400 devices were installed, as discussed by Zweig et al. [123]. The settlement was monitored for approximately one year. Although it was seen that the fire alarms were efficient in reducing the consequences of the fire (number of casualties and dwellings affected), it was also seen that in some cases the devices were removed due to large numbers of nuisance alarms. Often the devices were triggered due to cooking, showering, and smoking. Furthermore, some devices were affected by dirt accumulation and insect infestation. This situation highlights how challenging is to increase the fire safety in ISs, and that characteristics like size of the dwellings, occupants' behaviours, pollution, etc. must be taken into account. Finally, the firefighters' operations would be benefited by (5) the implementation of a single fire and emergency number and (6) the use of new technologies or equipment meant of fighting IS fires.

Chapter 9: Conclusions

Fires in ISs are a major concern in low-income countries. Not only do they cause property and monetary losses, but they are responsible for high fire fatality rates. In the recent years, there has been an increasing interest in understanding fires in IS. However, the research to date has tended to be theoretical or based on idealised experiments rather than on analysing real fire incidents. The purpose of this work was to gain understanding of what happens in real IS fire events such that evidence-based responses can be developed in the future.

9.1 Conclusions and recommendations from previous chapters

A Framework for Fire Investigations in Informal Settlements (FFIIS) was developed in 0. The framework applies well-known forensic fire investigation principles for compartment and wildland fires to informal settlements. This chapter has explored the question **'*How can a fire investigation in an IS be conducted?*'** raised in 0. The FFIIS defined three categories (pre-flashover, post-flashover and large post-flashover fires) and proposed guidelines to conduct fire investigations for each category. Furthermore, limitations, the data that could be collected and the information that could be obtained for each case were identified. One of the main limitations in IS fires is the lack of physical evidence left at the scene. This situation directly affects the identification of the fire cause, meaning that investigators must primarily rely on witnesses' testimonies. The application of the FFIIS to a well-known, and previously studied, large post-flashover fire such as the Imizamo Yethu incident not only identified the area of fire origin, but also assisted in understanding other aspects of the fire event such as the problems faced by the fire brigade and residents' actions.

The analysis of a real IS fire incident that was recorded by a CCTV camera was presented in Chapter 5. The high quality of the video showing the fire from the early stages until the extinguishment, coupled with having access to the fire incident report and to firefighters' testimonies, allowed for this IS fire to be analysed in a holistic way. Hence, this work provides novel data in terms of IS incidents. This chapter has explored the question **'What happens in IS fire incidents?'** raised in 0. The analysis provided information regarding the fire spread, the residents' actions and the firefighters' operations and their interaction. Fire spread rates were estimated, ranging from 0.4 to 2.3 m/min, or 4.3 to 36.5 m^2/min. Residents' actions were similar to what has been observed in residential fires. These actions include firefighting activities, information seeking and gathering of valuables. Factors that affected the firefighters' operations were also identified, with the lack of water supply being the most critical.

The FFIIS developed in Chapter 4 was applied to three IS fires that occurred in South Africa in Chapter 6. Following the classification proposed in the FFIIS (i.e., pre-flashover fire, post-flashover fire, large post-flashover fire), all three cases were classified as large post-flashover fires. This chapter has explored the question **'Is it possible to determine the fire cause, fire origin and fire spread of an informal fire event by conducting a fire investigation?'** raised in 0. The analysis provided important insights into the applicability of the FFIIS for these types of fires. The hypotheses proposed described the area of fire origin and pattern formation sequence with a reasonable level of certainty. However, there was insufficient information to develop hypotheses regarding the fire cause. This emphasises the difficulty associated with determining the fire cause, as acknowledged in the FFIIS. Additionally, in this chapter a) average fire spread rates were estimated, b) the impact of separation distances between dwellings on fire spread was studied, and c) the limitations of the FFIIS for large post-flashover fires were identified. The fact that one of the case studies was the fire analysed in Chapter 5 allowed the work to benchmark the findings obtained through the application of the FFIIS. As an example, the average spread rates estimated in this work were less than half than what was calculated in Chapter 5 using the video footage. Difficulties associated with determining the start time of the fire and the time that it took to spread to all the affected dwellings significantly influence the accuracy of predictions. Hence, predictions regarding fire spread rates can only be relied upon when direct observations of the fire line position are available.

The work carried out in Chapter 5 and Chapter 6 reveal the difficulty in obtaining information pertaining to the fire cause of IS fires. Hence, in order to gain a better understanding of this topic a different approach was taken. Chapter 7 presented the analysis of a survey conducted after the Imizamo Yethu (IY) fire that affected approximately 2200 dwellings in 2017. The survey included questions related to the fire risk perception in the settlement. Through the analysis of the residents' risk perception, this chapter has explored the question **'What are the causes of IS fires?'** raised in 0. The survey included two risks target, the IY settlement (general risk) and their own household (personal risk). The answers provided by the residents include unsafe conditions, unsafe sources of energy and/or devices, irresponsible and deliberate behaviour. It was found that the risk target had a strong influence on the risk perception. When the target was the IY settlement, the top five answers were 'Irresponsible drinking behaviour', 'Unsafe lighting method', 'Irresponsible cooking', 'Unsafe cooking method', and 'Irresponsible behaviour'. When the target was their own household, the top five answers were 'Unsafe lighting method', 'Electric stove', 'Informal electric supply', 'Unsafe cooking method', and 'Gas stove'. The general risk perception tended to focus on people's irresponsible behaviour. In contrast, when the target was the household (of people living within the IY settlement) the concern was directed to unsafe sources of energy and devices, meaning that factors that are beyond their control are overemphasised. The answers given for the general risk target are, to some extent, similar to the opinions that firefighters had in previous research. However, neither the risk perception of the residents (general risk or personal risk), nor the perception of the firefighters, show good correlation with the national statistics. This gives significant reason to believe that the national fire statistics are not capturing the causes of real fire incidents and that the fire cause determination information is severely lacking and potentially highly inaccurate. Several factors that could affect the accuracy of the fire cause determination were identified, where the limited information that is documented after the fire is of primary concern. The analysis of the residents' risk perception allowed for better understanding regarding the causes of IS fires.

9.2 Synthesising findings in this research

The work has addressed the main research question '**What happens in IS fire incidents?'** raised in 0 as the aim and motivation of this research project. Through the investigation of past fire events, it was possible to gain understanding on (a) the factors that affect the fire spread, (b) fire spread rates, (c) human behaviour, (d) firefighters' operations. It was seen that:

- Due to the home construction characteristics of ISs, once the fire in the dwelling of origin has reached a fully developed stage factors such as wind conditions, topography of the area, and the separation distances between dwellings influence the fire development. This agrees with hypotheses and findings in previous IS work which relied on experimental data, but typically lacked real world data for validation.
- In the first stages of the fire the residents' response can have a significant impact on the fire spread. As it was seen in Chapter 5, buckets brigade can help to extinguish the fire before it reaches flashover avoiding spread to adjacent dwellings. Such phenomena are almost impossible to quantify without significant amounts of information, including eyewitness accounts and camera footage.
- The rate of fire spread can significantly increase if brands start to produce secondary fires. This situation usually occurs when the fire reaches vegetation. Although observed, this phenomenon still needs to be quantified as negligible data is currently available.
- Barriers (fuel discontinuity) such as roads are extremely useful to limit the fire spread. These also allow for the fire department to have access to the fire. Although not necessarily a novel

finding, the results may help to encourage use of fuel breaks in settlements and emphasise the need for municipal enforcement when homes encroach on access ways.

- The residents' actions are typically similar to what has been seen in formal residential fires. However, it seems that IS residents are well prepared and coordinated when reacting to a fire incident, possibly in excess of those in formal dwellings. This is probably due to the many fires that IS inhabitants have experienced before. Additionally, it was possible to see dangerous behaviour by inhabitants when performing firefighting activities (e.g., standing on roofs and returning to fetch possessions), along with a large number of children near the fire scene during the incident. Such aspects placed increased pressure of firefighters to ensure the safety of residents while responding to incidents.
- The firefighters' response to IS fires can be affected by:
    - Late notification of the fire. The reason for this may include residents not knowing the fire brigade phone number or residents calling the police first.
    - Difficulties in reaching the affected area. The high dwelling density, narrow streets, people evacuating or saving their belongings, and blockages from cars or furniture can increase the time to arrive at the fire scene.
    - Lack of water supply. Usually, the areas where IS are located do not have a proper water supply or hydrant infrastructure has been damaged or cannot be found.
    - Hostility from the residents. In some cases, residents can cut the hoses to redirect water to their own dwelling and may even attack the firefighters. Although the latter was typically not encountered in the incidents analysed in this work, it was mentioned by several of the firefighters that were interviewed in Chapter 5 and Chapter 6.

A better understanding of IS fires, through the investigation of past fire events, can be used to:

I. Facilitate the design of prevention plans that respond specifically to informal settlements requirements. By having a better knowledge of the causes of IS fires it is possible to direct the efforts to those behaviours, activities or conditions. For instance, as data regarding fire cause becomes more accurate focus can be placed upon initiatives to addresses the most prominent causes, whether it be poor electrical wiring, the provision of electricity or arson.

II. Develop or validate fire spread models. By understanding how the different conditions interact and affect the fire spread models can be developed or improved.

III. Inform the community on how their actions influence the fire occurrence, the fire behaviour and the firefighters' operations. This will assist in advancing community engagement strategies and the development of fire safety material.

IV. Enhance firefighter response and training. By identifying the specific problems that firefighters face during IS fires it guides brigades in terms of preparation, training and /or modifying their response and operations.

V. Plan for incidents. The holistic understanding of fires in IS will allow municipalities to develop prevention, mitigation and recovery plans. By anticipating the potential magnitude of large fire disasters organisations can proactively prepare to prevent and respond to them.

VI. Develop community fire awareness. Identifying the main fire causes will allow municipalities, NGOs and fire departments to promote general fire awareness, and more importantly to raise awareness regarding specific risks.

VII. Develop community training mechanisms. As it was seen in this work, community members have a significant influence fire development. Having proper training could help to improve their response and to prevent fires from growing and spreading to other dwellings.

9.3 Future research

This work has provided the foundation for gathering more accurate data and for obtaining a better understanding of IS fire incidents. However, many questions have been raised by the work that need to be addressed. Future research related to this work should include:

I. The determination of the validity/representability of previous full-scale experiments. Many factors (e.g., inhabitant behaviour, firefighter interventions, fire behaviour which includes factors such as material between dwellings, real fuel loads, actual homes, etc.) will influence the extent to which existing experimental data on fire spread can be directly applied to real informal settlement incidents.

II. The application of the FFIIS to a large number of real fire incidents. This will allow researchers and fire departments to (a) determine the feasibility of implementing the FFIIS in different types of fires (i.e., pre-flashover, post-flashover, large post-flashover), (b) conduct a detailed comparison between IS fire spread rates and urban and WUI fires spread rates (especially those where timber homes are present, e.g., Japan), and (c) enhancing the FFIIS. From this work it was shown that conducting pre-flashover fire investigations is extremely difficult and so is unlikely to be done on a regular basis. Furthermore, the resources required to carry out such investigations are unlikely to be provided unless fatalities are reported.

III. Continuing with the study of human behaviour in fire in informal settlements. The research should be directed to understand residents' actions and their motivations. This can be done by interviewing the residents or by implementing questionnaires. Such research could significantly contribute to developing training material, communication philosophies, human movement models and municipal strategies in relation to communities. As emphasised before, the role of communities is key in addressing fire safety.

IV. The impact that IS conditions have in the firefighters' operations. By identifying the different factors that hinder their performance and the impact that these have on the fire spread will allow for the implementation of new strategies for IS fires.

V. The application of this work to other low-income communities such as refugee camps, for market fires (commonly occurring in various African countries), temporary shelters, homeless settlements within cities, in ISs in other countries with different conditions, and similar settlements. In refugee camps the density of homes, fuel loads, layouts and construction materials are likely to influence fire behaviour. Shelters are constructed from combustible materials such as tarpaulins and plastic layers, meaning that enclosures will burn through rather than experiencing typical enclosure fire behaviour. However, once fires affect larger numbers of homes it is likely that wildfire-type spread patterns will also occur. Nevertheless, spread rates, residents' behaviour, firefighting operations, etc. will probably be different to those presented in this work.

VI. Further analysis of the Fire & Rescue Service Incident Report. Details regarding the fire cause, the caller statement, the number of dwellings affected are currently not being processed and could potentially provide important information for the fire investigation. This will assist in quantifying the problem, responding to challenges and allocating resources more efficiently.

In particular, as the database of verified data on fire spread grows it may be possible to

I. Apply statistical procedures to estimate fire spread rates during an incident to provide decision-making tools for the fire services. This would be similar to contemporary models using when responding to WUI fires.

II. Develop predictive computational models for large-scale events. Correlations between the different factors that influence the fire development and the fire outcome, such as wind and/or topography conditions and fire spread rates and spacing between dwellings and fire spread, could be identified.

Chapter 10 : References

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Appendix A : Additional papers

In the development of this dissertation research papers focusing on informal settlement fire safety have been completed in conjunction with other researchers. The abstracts of papers included in this Appendix address issues closely aligned with the work in this dissertation but have not been included in the body of the work as they do not focus on the central theme of fire investigations in IS. The reader is referred to them for:

- understanding the effect of dwelling separation distance on informal settlement fire spread (A.1 The Effect of Separation Distance Between Informal Dwellings on Fire Spread Rates Based on Experimental Data and Analytical Equations);
- understand the effects of leakages and ventilation conditions on informal settlement fire dynamics. (A.2 An Experimental and Numerical Study on the Effects of Leakages and Ventilation Conditions on Informal Settlement Fire Dynamics);
- understanding the fire dynamics in double storey informal settlement dwellings along with the added fire risks associated with such structures. (A.3An experimental study of the fire dynamics of double storey informal settlement dwellings)

APPENDIX A

A.1 The Effect of Separation Distance Between Informal Dwellings on Fire Spread Rates Based on Experimental Data and Analytical Equations

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Globally, the number of informal settlement dwellings are increasing rapidly; these areas are often associated with numerous large fires. Unfortunately, until recently, very little research has been focused on informal settlement fire issues leaving any attempts to improve their fire safety lacking the evidence base to support effective-decision making. However, over the past 4 years, a limited number of researchers have looked at better understanding these fires through full-scale experimentation and numerical modelling; starting to provide the necessary evidence base and future research directions. It is with this background in mind that this paper seeks to provide a more fundamental understanding of the effect of dwelling separation distance on informal settlement fire spread based on full-scale experiments and analytical equations. In this paper two full-scale experiments were conducted. Both experiments consisted of multiple dwellings, with the main difference between the experiments being the separation distance. Fire spread times, heat release rates, door and window flow velocities, ceiling temperatures and incident heat fluxes were recorded and are reported for both experiments. Theoretical neutral planes are derived and compared to the experimental neutral planes, which show relatively good correlation. The paper continues by calculating the expected incident radiation and time-to-ignition, using the flux-time product method, of the two fire scenarios (i.e., the two experiments) through means of analytical equations, and these findings are compared to the experimental results. Through configuration factors, the paper shows the effect of separation distance, dwelling height and dwelling length on the times-to-ignition, where it is clear that the heat flux received by an adjacent dwelling decrease approximately exponentially as the distance between dwellings increases, and consequently, the time-to-ignition increases exponentially as the separation distance between dwellings increases.

A.2 An Experimental and Numerical Study on the Effects of Leakages and Ventilation Conditions on Informal Settlement Fire Dynamics

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The one billion people that currently reside in informal settlements are exposed to a high and daily risk of large conflagrations. With the number of informal settlement dwellers expected to increase in the years to come, more systematic work is needed to better understand these fires. Over the past 3 years to 4 years, researchers have explicitly started investigating informal settlement fire dynamics, by conducting full-scale experiments and numerical modelling research. It is with this background that this paper seeks to investigate the effects of leakages and ventilation conditions on informal settlement fire dynamics. Three full-scale informal settlement dwelling experiments were conducted in this work. The experiments were kept identical with only a small change to a ventilation or leakage condition from experiment to experiment. During each experiment the heat release rates, heat fluxes, temperature and flow data were recorded and are given in this paper. B-RISK's (a two-zone model software) predictive capabilities are then benchmarked against the full-scale experiments. B-RISK is then used to conduct a parametric study to further investigate the effects of leakages and ventilation on informal settlement dwelling fire dynamics. It was found that the ventilation conditions can significantly affect the radiation emitted from an informal settlement dwelling, and as a result increase or decrease the probability of fire spread to neighboring dwellings.

APPENDIX A

A.3 An experimental study of the fire dynamics of double storey informal settlement dwellings

(Under review)

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It is estimated that the number of people residing in informal settlements would increase from 1 billion globally, to 1.2 billion in Africa alone by 2050. It is not new information that informal settlements are becoming more dense annually, both in terms of the population and the number of dwellings per area, and that the number of large conflagrations in informal settlements are becoming more frequent. With settlements becoming denser, it leaves the inhabitants with no other choice but to start building up, and hence double storey informal settlement dwellings are becoming more common. Currently, there is no research in terms of better understanding the fire dynamics in double storey informal settlement dwellings along with the added fire risks associated with such structures. It is with this backdrop that this paper seeks to: (a) provide a better understanding in terms of the enclosure fire dynamics of double storey informal settlement dwellings; and (b) investigate the risks in terms of both fire spread and suppression requirements that these dwellings pose. In this paper, the results of the world's first full-scale double storey informal settlement experiment are presented, including enclosure gas temperature, heat flux measurements at a distance, and flow velocities through doors and windows. It was found that double storey dwellings are more prone to ignition compared to a single storey dwelling, and also produce higher heat fluxes than a single storey dwelling. Fire suppression is a major challenge, and a finding of the work is that firefighters will be exposed to significant risks if they are in the vicinity of these dwellings during a fire.

Appendix B Data collection for informal settlement fires

Note: the questions listed below are for data over-and-above that required of the Fire & Rescue Service Incident Report (FRSIR). The data obtained in the field, the FRSIR and the Occurrence Book will be considered together such that all data is obtained for an incident, including fire brigade response times, casualties, etc.

Field Collection

Basic Information

1. Date.
2. Address.
3. Type of Incident.
   i. Pre-flashover fire (one dwelling affected).
   ii. Post-flashover fire (more than one dwelling affected).

Fire Analysis

1. Description of the fire scene. (e.g., the volume of flames and smoke; the colour, height and location of the flames; the direction in which the flames and smoke are moving).
2. Potential point(s) of fire origin.
3. Potential fire cause(s).
   i. Cooking.
      a. Open flames
      b. Gas
      c. Electrical
   ii. Heating.
      a. Open flames
      b. Gas
      c. Electrical
   iii. Lighting.
      a. Open flames
      b. Gas
      c. Electrical
   iv. Open Flames.
      a. Cooking
      b. Heating
      c. Lighting
   v. Smoking.
   vi. Electrical Faults.
   vii. Arson.
   viii. Undetermined.
   ix. Unrest.
   x. Welding and Cutting.

Pre-flashover fire

1. Exterior pictures of fire patterns and damage.
2. Interior pictures of the dwelling (look for artefacts and patterns). If possible, photograph all walls, floor and ceiling.
3. Indicate how the fire was controlled. Describe the fire suppression techniques used.

Post-flashover fire

1. Estimated number of dwellings involved.
2. Pictures of the area.
3. Draw area affected in the map. If possible, draw fire line every hour of incident.
4. If possible, describe the fire scene every hour of incident.
5. Indicate how the fire was controlled. Describe the fire suppression techniques used.
6. Wind details.
7. Observations about wind, topography and other factors that could influence fire spread.

Property (only for the dwelling of origin)

1. Fire Protection Equipment.
   - i. Detectors.
   - ii. Fire Extinguisher.
   - iii. Blanket.
   - iv. Bucket of sand/water.
2. Configuration.
   - i. Single story.
   - ii. Double story.
   - iii. Back shack.

Fire Brigade Performance

1. How was the request to attend the fire incident received?
   - i. Dialled 10111. Police visited site and then called the fire brigade.
   - ii. Dialled 112 from cell phone (this number is for any emergency). Call was transferred to fire control who proceeded with dispatch.
   - iii. Dialled 107 from landline (this number is for medical and fire emergencies). Direct dispatch.
   - iv. Direct call to responding fire station. Direct dispatch.
2. Factors that affected the fire brigade performance and that had an impact in the growth and spread of the fire.
   - i. Delayed reporting of fire.
   - ii. Unable to contact fire brigade. (includes wrong number, phone problems).
   - iii. Information incorrect or incomplete.
   - iv. Blocked or obstructed roadway.
   - v. Poor or no access for fire department apparatus.
   - vi. Traffic delay.
   - vii. Poor access for firefighters.
   - viii. Natural conditions.
   - ix. Evacuation activity impeded fire department access.
   - x. Residents threatened fire brigade.

xi. Residents attacked fire brigade.
xii. Other (Specify).

Witness

1. Age.
2. Gender.
3. Location with respect of the fire.
4. Who was with you?
   i. Children under 12.
   ii. Children over 12.
   iii. Spouse/Partner.
   iv. Other relatives.
   v. Friends.
   vi. I was alone.
5. How did you become aware of the fire?
   i. Felt heat.
   ii. Saw flames.
   iii. Saw or smelt smoke.
   iv. Heard shouts.
   v. Was told.
   vi. Heard fire alarm.
   vii. Heard fire engines.
   viii. Other (Specify).
6. What did you do before evacuating? (List all the actions in order)
   i. Firefighting.
   ii. Contacted fire brigade.
   iii. Warned others.
   iv. Cleared exit routes.
   v. Saved personal possessions.
   vi. Helped others.
   vii. Did something to reduce fire risk (remove gas bottles, closed doors, turned off electricity, etc.).
   viii. Helped fire brigade.
   ix. Moved furniture/appliances.
   x. Did not evacuate.
7. Did you return? Why?
8. Do you know where the fire started?
9. Do you know what caused the fire?

Data from the FRSIR and Occurrence Book

Fire Brigade Performance

1. Dates and Times (DD/MM/YYYY)
   i. Alarm.
   ii. Dispatch.
   iii. First Water Application.
   iv. Fire Controlled.
   v. Last Unit Cleared.
2. Total number of apparatus in the scene.

i. For suppression purposes.
ii. For rescue and emergency medical service purposes.

Civilian Fire Injuries and Casualties

1. Age.
2. Gender.
3. Location with respect to the fire.
4. Severity.
   i. Minor.
   ii. Moderate.
   iii. Severe.
   iv. Life threatening.
   v. Death.
5. Primary apparent symptom.
   i. Smoke inhalation.
   ii. Burns.
   iii. Smoke inhalation and burns.
   iv. Cut laceration.
   v. Strain or sprain.
   vi. Shock.
   vii. Pain.
   viii. Other.
6. Primary area of body injured.
   i. Head.
   ii. Neck and shoulder.
   iii. Thorax.
   iv. Abdomen.
   v. Spine.
   vi. Upper extremities.
   vii. Lower extremities.
   viii. Internal.

Multiple body parts.

Fire Service Injury/Casualty

1. Name.
2. Gender.
3. Age.
4. Affiliation.
   i. Career.
   ii. Volunteer.
5. Severity.
   i. Minor.
   ii. Moderate.
   iii. Severe.
   iv. Life threatening.
   v. Death.
6. Cause of injury.

i. Fall.
ii. Jump.
iii. Slip/Trip.
iv. Exposure to hazard. Includes exposure to heat, smoke, or toxic agents.
v. Struck or assaulted by person, animal, moving object.
vi. Contact with object (firefighter moved into or onto object). Includes running into objects, stepping on objects, or grabbing a hot or electrically charged object.
vii. Overexertion/Strain.
viii. Other.
ix. Undetermined.

7. Activity when injured.
8. Location with respect to the fire.
9. Primary symptom.
   i. Smoke inhalation.
   ii. Burns.
   iii. Smoke inhalation and burns.
   iv. Cut laceration.
   v. Strain or sprain.
   vi. Shock.
   vii. Pain.
   viii. Other.
10. Primary area of body injured.
   i. Head.
   ii. Neck and shoulder.
   iii. Thorax.
   iv. Abdomen.
   v. Spine.
   vi. Upper extremities.
   vii. Lower extremities.
   viii. Internal.
   ix. Multiple body parts.
11. Did the protective equipment fail and contribute to the injury?
   i. Yes.
      a. Describe the problem.
   ii. No.

Appendix C Application letter for institutional permission

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APPLICATION LETTER FOR INSTITUTIONAL PERMISSION

INSTITUTION NAME & ADDRESS:	City of Cape Town Fire & Rescue Service
INSTITUTION CONTACT PERSON:	Chief Ian Schnetler
INSTITUTION CONTACT NUMBER:	+27 (0)21 590 1738
INSTITUTION EMAIL ADDRESS:	Ian.Schnetler@capetown.gov.za

TITLE OF RESEARCH PROJECT:	The development and application of forensic investigation procedures for informal settlements fires
ETHICS APPLICATION REFERENCE NUMBER:	15246
RESEARCHER:	Natalia Flores
DEPT NAME & ADDRESS:	Stellenbosch University / Civil Engineering / Structural Department Cnr Banhoek Road & Joubert Street, Stellenbosch 7600
CONTACT NUMBER:	0609454435
EMAIL ADDRESS:	nataliaflores@sun.ac.za

Dear Chief Fire Officer Schnetler

Kindly note that I am a PhD student at the Department of Civil Engineering (Fire Engineering Research Unit) at Stellenbosch University, and I would appreciate your assistance with one facet of my research project.

Please take some time to read the information presented in the following four points, which will explain the purpose of this letter as well as the purpose of my research project, and then feel free to contact me if you require any additional information. This research study has been approved by the Research Ethics Committee (REC) at Stellenbosch University and will be conducted according to accepted and applicable national and international ethical guidelines and principles.

1. A short introduction to the project:

Informal settlements (IS) are characterised by poverty, poor infrastructure, high dwelling density and similar factors. Fires in IS are a substantial problem in developing countries. In South Africa alone, 5940 IS fire incidents were reported during 2017 (although this still probably under predicts the number of actual fires). World data from 2016 shows that even though only 20% of the world's population reside in countries with a low/low-middle Socio-Demographic Index, nearly half of the fire related fatalities occurred in those countries. It is with this backdrop that this research project seeks to improve the understanding of informal settlement fires through the study of real fire events.

APPENDIX B

In the first phase of this research work, a framework to conduct fire investigations in IS was developed. This second phase will be focused on the study of real fire events. Recently, it was possible to have access to a video recording of a fire in an IS in Cape Town. The fire event was recorded by a CCTV camera located near the settlement. The video has a duration of 80 minutes and capture the fire incident from ignition in the dwelling of origin to the point of fire extinction. The fire investigation of this event could provide significant information to the fire safety engineering field.

2. The purpose of the project:

The aim of this research is to understand fires in informal settlements through forensic investigations. To achieve this goal the objectives of this research are to:

- Obtain information about (a) fire spread, (b) human behaviour in a fire event and (c) firefighters procedures, response and operations, from the video recording.
- Obtain first-hand accounts of the event from firefighters that attended to the fire scene.
- Conduct interviews with the firefighters that attended to the fire scene which will allow for a better understanding of the video.
- Understand the interaction between the fire, residents' behaviour and firefighters' actions.
- Describe in depth the fire event.

3. Your assistance would be appreciated in the following regard:

The primary investigator (Natalia Flores) along with his supervisor (Prof Richard Walls) requires your authorization to (a) access to the aforementioned CCTV footage, (b) use the Fire & Rescue Service Incident Report of the fire event and (c) utilise Fire & Rescue Service Incident Reports of several similar fire incidents. This data is not available to the public domain and will be treated as confidential (refer to Section 4). Additionally, Natalia Flores would like to conduct face-to-face interviews (or via video-conferencing due to COVID-19) with the Epping Fire Department firefighters (willing firefighters). No firefighter will be pressurised to participate in the face-to-face (or video-conference) interview.

The data will be analysed and a presentation will be given to the Epping Fire Department in order for them to see the findings. The findings will be published and will also be in the PhD student's (Natalia Flores) thesis. No personal information (e.g. names, ID numbers, etc.) will be published nor will it be in the PhD student's thesis. Station Commander Mark Smith, is involved with the work to assist with input and to ensure that the work is carried out in a way that will not negatively impact the City of Cape Town Fire Services. All publications stemming from the research will be submitted for approval prior to submission for publication.

4. Confidentiality:

As a safety measure, all data will be stored on a password protected laptop. Only the primary investigator (Natalia Flores) and the student's supervisor (Richard Walls) will have access to the databases and interview data. The laptop will not be left unattended without being locked in an office at the Faculty of Engineering. The laptop will be securely locked to an office table as an additional safety procedure.

If you have any further questions or concerns about the research, please feel free to contact me via email nataliaflores@sun.ac.za or telephonically at 0609454435. Alternatively, feel free to contact my supervisor, Richard Walls, via email rwalls@sun.ac.za or telephonically 0723724096.
Thank you in advance for your assistance in this regard.

Kind regards,
Natalia Flores (Principal Investigator)

Appendix D : Consent Form

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STELLENBOSCH UNIVERSITY
WRITTEN CONSENT TO PARTICIPATE IN RESEARCH

TITLE OF RESEARCH PROJECT:	The development and application of forensic investigation procedures for informal settlements fires
REFERENCE NUMBER:	15246
PRINCIPAL INVESTIGATOR:	Natalia Flores
ADDRESS:	Cnr Banhoek Road & Joubert Street, Stellenbosch 7600
CONTACT NUMBER:	0609454435
E-MAIL:	nataliaflores@sun.ac.za

Dear prospective participant,

Kindly note that I am a PhD student at the Department of Civil Engineering at Stellenbosch University, and I would like to invite you to participate in a research project entitled "The development and application of forensic investigation procedures for informal settlements fires".

Please take some time to read the information presented here, which will explain the details of this project and contact me if you require further explanation or clarification of any aspect of the study. This study has been approved by the Research Ethics Committee (REC) at Stellenbosch University and will be conducted according to accepted and applicable national and international ethical guidelines and principles.

1. INTRODUCTION

Informal settlements (IS) are characterised by poverty, poor infrastructure, high dwelling density and similar factors. Fires in IS are a substantial problem in developing countries. In South Africa alone, 5940 IS fire incidents were reported during 2017 (although this still probably under predicts the number of actual fires). World data from 2016 shows that even though only 20% of the world's population reside in countries with a low/low-middle Socio-Demographic Index, nearly half of the fire related fatalities occurred in those countries. It is with this backdrop that this research project seeks to improve the understanding of informal settlement fires through the study of real fire events. In the first phase of this research work, a framework to conduct fire investigations in IS was developed. This second phase will be focused on the study of real fire events. Recently, it was possible to have access to a video recording of a fire in an IS in Cape Town. The fire event was recorded by a CCTV camera located near the settlement. The video has a duration of 80 minutes and capture the fire incident from ignition in the dwelling of origin to the point of fire extinction. The fire investigation of this event could provide significant information to the fire safety engineering field.

2. PURPOSE

The aim of this research is to understand fires in informal settlements through forensic investigations. To achieve this goal the objectives of this research are to:

- Obtain information about (a) fire spread, (b) human behaviour in a fire event and (c) firefighters procedures, response and operations, from the video recording.
- Obtain first-hand accounts of the event from firefighters that attended to the fire scene.
- Conduct interviews with the firefighters that attended to the fire scene which will allow for a better understanding of the video.
- Understand the interaction between the fire, residents' behaviour and firefighters' actions.
- Describe in depth the fire event.

3. PROCEDURES

If you agree to take part in this study, you will be asked to tell your experience during the fire event including (a) the procedure that was followed, (b) problems you faced during the fire, (c) interaction with the residents. At the end of this document, you will find the questionnaire. The interview will be conducted at the Epping Fire Station while watching the recording of the fire.

4. TIME

It is expected that this activity will take between 45 to 60 minutes.

5. RISKS

It is not expected that you present any discomfort during your participation. However, if at any moment of the interview you feel uncomfortable, you can discontinue participation of the study.

6. BENEFITS

The understanding of informal settlement fires will benefit the community, fire brigades, municipalities and engineers. With the additional knowledge the fire safety interventions can be improved, including (a) prevention, meaning that the number of fires could decrease, (b) residents response, trying to control the fire in the initial stage, and (c) firefighters response in order to improve their procedures and response.

7. PARTICIPATION & WITHDRAWAL

You can choose whether to be in this study or not. If you agree to take part in this study, you may withdraw at any time without any consequence. You may also refuse to answer any questions you don't want to answer and still remain in the study. If you decide to withdraw before, during, or after the interview has been completed, your responses will be disregarded and any written notes or electronic copies related to your responses will be destroyed.

8. CONFIDENTIALITY

Any information you share with me during this study and that could possibly identify you as a participant will be protected. You will not be requested to provide any personal information during the interview/questionnaire, which can identify you as an individual. Your name will be replaced by ID code. Any form of correspondence between prospective participants and investigators will be kept confidential, and only the principal investigator and his/her supervisor will have access to this information.
The information gathered during this interview/questionnaire will only be used for research purposes, specifically related to my thesis and research papers.
When publishing the results of the study details about the fire event will be intentionally excluded to ensure confidentiality. These details include (a) the exact location of the event, (b) people's faces and (c) specific details about the firefighters and fire stations involved.

9. RECORDINGS

No recordings will be used during the interviews.

10. DATA STORAGE

The access to the data obtain from your participation will be restricted; all data will be stored on a password protected laptop. Only the primary investigator (Natalia Flores) and her supervisor (Richard Walls) will have access to the databases and interview data.

If you have any questions or concerns about this research project, please feel free to contact Natalia Flores via email nataliaflores@sun.ac.za or telephonically at 0609454435 and/or the supervisor, Richard Walls, via email rwalls@sun.ac.za or telephonically at 0723724096.

RIGHTS OF RESEARCH PARTICPANTS: You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché (mfouche@sun.ac.za / 021 808 4622) at the Division for Research Development. You have the right to receive a copy of this Consent form.

If you are willing to participate in this research project, please sign the Declaration of Consent below and hand it to Mark Smith.

APPENDIX C

DECLARATION BY THE PARTICIPANT

As the **participant** I hereby declare that:

- I have read the above information and it is written in a language with which I am fluent and comfortable.
- I have had a chance to ask questions and all my questions have been adequately answered.
- I understand that taking part in this study is voluntary and I have not been pressurised to take part.
- I may choose to leave the study at any time and will not be penalised or prejudiced in any way.
- If the principal investigator feels that it is in my best interest, or if I do not follow the study plan as agreed to, then I may be asked to leave the study before it has finished.
- All issues related to privacy, and the confidentiality and use of the information I provide, have been explained to my satisfaction.

By signing below, I ______________________________ agree to take part in this research study, as conducted by Natalia Flores.

____
Signed at *(place)*

____
Date

____
Signature of Participant

DECLARATION BY THE PRINCIPAL INVESTIGATOR

As the **principal investigator** I hereby declare that the information contained in this document has been thoroughly explained to the participant. I also declare that the participant has been encouraged (and has been given ample time) to ask any questions. In addition I would like to select the following option:

	The conversation with the participant was conducted in a language in which the participant is fluent.
	The conversation with the participant was conducted with the assistance of a translator, and this "Consent Form" is available to the participant in a language in which the participant is fluent.

____
Signed at *(place)*

____
Date

____
Signature of Principal Investigator

Appendix E : Questionnaire

QUESTIONNAIRE

The interview schedule will comprised a combination of free-flow narrative and a semi-structured interview. While watching the video, you will be asked specific questions but feel free to comment and to add any information that you consider relevant at any point of the recording. The interview will consider the following questions:

- What problems did you faced while trying to extinguish the fire?
- Were there any fire hydrants in the area?
- What were the main sources of water to extinguish the fire?
- How does the settlement layout (i.e. closeness between dwellings, accessibility) affect your performance?
- How was the interaction with the residents?
- Were there any residents not cooperating?
- Were the hoses of the firefighters cut or slashed by residents in order to direct the water towards their homes?
- The effect of people running from the fire with some of their belongings getting in the way of people trying to combat the fire.
- Did other organization (i.e. metro police, traffic department) helped during the fire?