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A preliminary investigation to develop a semi-probabilistic model of informal settlement fire spread using B-RISK

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Abstract

In South Africa alone, there are more than 5000 informal settlement fires a year, where a single incident can leave up to 10000 people homeless. The government and local authorities of countries with informal settlements, that extend over large areas, have no tools to simulate fires to identify high risk areas, or to quantify the magnitude of an incident to which they may need to respond. It is with this backdrop that the paper seeks to develop a semi-probabilistic method to determine fire spread rates in informal settlements. Data from a full-scale fire experiment is used to validate the fire spread rates predicted by B-RISK from which a simplified semi-probabilistic analysis method is developed that can estimate fire spread rates in informal settlements. B-RISK simulations are then compared to an actual informal settlement fire incident to assess its predictive capabilities. The paper also discusses how the effect of wind has been included and what additional features could be incorporated to obtain more realistic informal settlement fire spread predictions. This work provides the first step in a complex problem where it is difficult to accurately define input parameters.

Keywords: informal settlements, fire spread, ignition time, item-to-item ignition

1. Introduction

Informal settlements, also commonly known as shantytowns, slums or ghettos, are often razed by large fires [1]. Informal settlements are extremely vulnerable to fire spread because they are inherently characterized by poor infrastructure, lack of basic services, poorly constructed structures and are generally overcrowded [2]. Informal Settlement Dwellings (ISDs) are makeshift structures that are typically constructed from materials in the immediate surroundings of the inhabitant [3]. Informal settlements and ISDs, along with how they behave in fire, are extensively discussed in [3–6]. Although numerous fire spread interventions have been proposed and implemented over the past decade [7], informal settlement fires still cause the one billion vulnerable people that reside within these settlements extreme losses (i.e. economic losses and death) on a daily basis [8]. Whilst fire related fatalities have decreased in high income countries, they have increased in lower-to-middle income countries. Additionally, it is expected that the population that reside in informal settlements will increase to 1.2 billion in Africa alone by 2050 [2]. It is thus a cause for serious concern to see how little work is done in terms of fire safety in these communities.

Aiming to better understand informal settlement fires and to assist local authorities in their attempts to select the most suitable fire spread interventions, recent studies have investigated the fire dynamics within ISDs and fire spread between ISDs [3,5,9–11]. Cicione and Walls [9] looked at a simplified method to model ISD fire spread using Fire Dynamics Simulator

(FDS) simulations. They found that even with powerful software such as FDS, it is difficult to predict fire spread rates between dwellings. Additionally, there are a significant number of unknowns that are inherent in informal settlements. These include: during an incident, there are suppression efforts by residents and firefighters; combustibles are present between, or on top of dwellings; dwellings are poorly constructed so structural collapse occurs quickly after ignition; dwellings have variable ventilation conditions; evacuating residents move their possessions, resulting in mobile fuel loads that can be transferred into open 'fuel break' areas; there are large variations in the construction products and the household content found; wind can significantly influence fire spread rates; settlements are ever-changing meaning that geometries are difficult to accurately quantify; gas canisters and liquid fuels may be stored in the homes leading to small explosions; etc. Hence, in order to make any progress, it is necessary to significantly simplify the problem. The work done in these previous studies [3,5,9,10] are used as a basis for the semi-probabilistic analysis proposed in this work.

It is with this backdrop that this paper provides a preliminary method to estimate informal settlement fire spread rates using B-RISK (version 2019.043), although other software, such as Wildland-Urban Interface Fire Dynamics Simulator [12] could also have been used. The hope is that the method developed can be generalized over time and refined so that it can aid firefighters, municipal managers and community service organizations when dealing with these unique fires. Ultimately, this work seeks to provide a semi-probabilistic model that could assist authorities of countries with large informal settlements with a tool to simulate fires to provide predictive capabilities that can help in identifying high risk areas, or quantify the magnitude of an incident to which municipalities may need to respond. Single deterministic answers regarding fire spread rates are not possible, and their usefulness is questionable, but decision-making tools for quantifying fire risk would be invaluable. In order to develop this semi-probabilistic model, the paper starts by developing an ISD spread scenario (i.e. a baseline scenario), using B-RISK (a zonal model), for an ISD fire spread experiment [3] with known fire spread rates. The experimental data is then used to validate the initial B-RISK scenario input properties and are then used to create a semi-probabilistic scenario in B-RISK. The software is then run for a real informal settlement fire and the results are compared to the actual event to assess the performance of the software.

2. Experiment used for baseline B-RISK scenario

The baseline scenario that is assessed through B-RISK is based on an experiment consisting of three steel clad ISDs. The experiment was conducted at the end of 2017 by the University of Stellenbosch at the Breede Valley Fire Department, South Africa [3]. Fig.1 gives the dimensions and details of the full-scale experiment, from which the geometries in the baseline simulation have been created. The fuel load in each dwelling consisted of nine timber (Pine) cribs, with 36 timber pieces (40×60×900 mm) per crib and was internally lined with cardboard to mimic reality. The moisture content of the timber and cardboard was not measured but can be assumed to be typical of normal ambient conditions. Fig. 1 was taken from [9]. The wind speed on the day of the experiment was negligible according to [3], thus it is ignored for the baseline scenario. For more details regarding this experiment the reader is referred to [3].

The experimental fire spread rates are given in Table 1. The spread rates are taken as the time between the start of flashover in each ISD, in which flashover was arbitrarily identified by a ceiling temperature of 300 °C, i.e. approximately when the cardboard lining material ignites [13,14] since this leads to the rapid onset of flashover, as discussed in [3,6].

For enclosures with non-combustible boundaries, flashover typically occurs when the upper layer reaches 500-600 °C, which corresponds to a radiative heat flux at the floor level of 15-20 kW/m^2 [15]. Thus, the initial fire growth time in the dwelling of origin is eliminated as this will vary from dwelling to dwelling, and event to event. Table 1 also gives a summary of the results obtained in [3]. The peak heat flux values in Table 1 were measured during the fully developed stage of the fire.

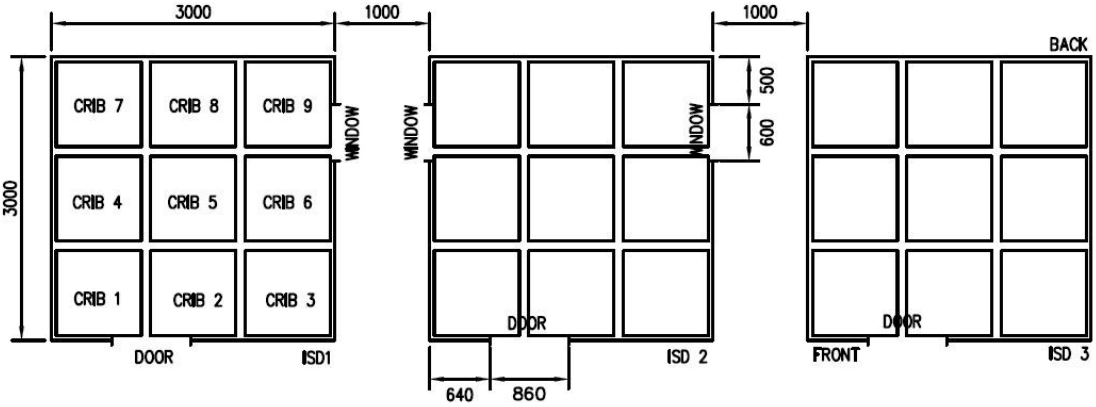

Fig. 1. Overview of the experimental dimensions of (figure from [9], with permission from John Wiley and Sons)

Table 1: Summary of details from the steel triple ISD experiment [3,9]

	ISD 1	**ISD 2**	**ISD 3**
Spread mechanism	Dwelling of origin	Flame impingement on the cardboard	Flame impingement on the cardboard
Fire spread time [s]	**N/A**	**210 (between the start of flashover in ISD1-ISD2)**	**182 (between the start of flashover in ISD2-ISD3)**
Time from flashover to collapse [min]	8.5	6.3	8.4
Heat flux 1 m from the door [kW/m^2]	59	79	66

3. Radiation and target ignition in B-RISK

This section gives a brief introduction to the B-RISK radiation and ignition model used in this work. For a more in-depth explanation of B-RISK, the reader is referred to [16]. This section also describes a simple method implemented to account for the effect of wind.

3.1. Radiation

B-RISK models the ignition of secondary items through radiation from either the hot gas layer in an enclosure or from one or more already burning items. However, this work treats the objects as being outside and not within an enclosure so that no hot layer is present. To ensure a hot layer is not created in the simulations, the ‘enclosure’ is given a sufficient number of vents to allow the hot air to escape to the ‘outside’. Thus, the focus will be on an initial item igniting secondary items, i.e. the ISD of origin ‘item 1’ ignites the vertical surfaces of adjacent ISDs ‘secondary or target items’ by means of radiation. Previous research [17] investigated the performance of different flame radiation models, namely: the spherical model (also known as the point source model, PSM), three different cylindrical models and a planar model. It was found that the PSM gave the best correlation with actual experimental heat flux results, and thus it is chosen for inclusion in the design fire generator (DFG) [18] submodel. The mathematical formula for the PSM is as follows:

$$\dot{q}''_{fl} = \dot{Q}\chi_R cos\theta / 4\pi R^2 \qquad (1)$$

where $\dot{q}''_{fl}$ is the heat flux received by the target item from the flaming item [kW/m^2], $\dot{Q}$ is the total heat release rate of the burning item [kW], χ_R is the radiative fraction and R is the horizontal radial distance from the center of the flaming region of the burning item (known as the point source) to the nearest point of the target item [m]. Fig. 2 shows the geometry assumed in this study where, in this case θ is zero, but it is shown for illustration purposes. The flame height z_{fl} [m] is calculated using Heskestad’s [19] correlation given by:

$$z_{fl} = 0.235\dot{Q}^{2/5} - 1.02D_f. \qquad (2)$$

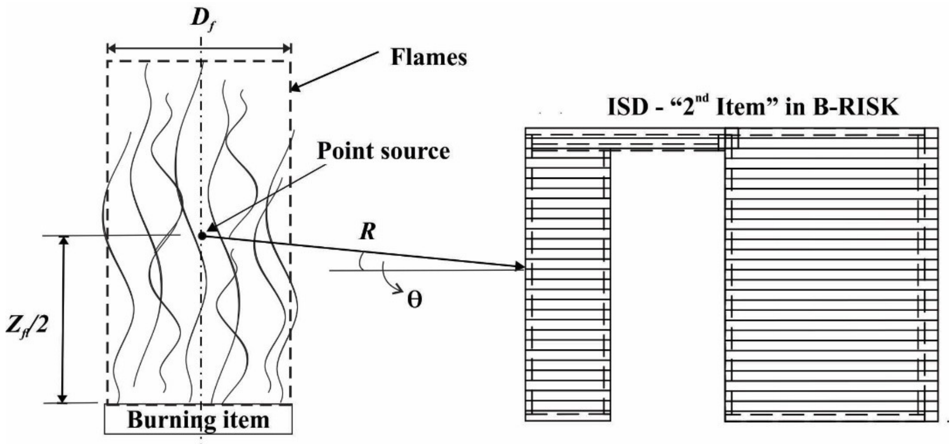

Fig. 2. PSM geometry between burning and target items, adapted from [20]

3.2. Effect of wind speed

Wind is a key factor affecting fire spread rates during informal settlements fire incidents [21]. Since B-RISK mainly deals with enclosure fires, the need to adjust the radiation model for fire spread between objects to account for wind has been unnecessary to date. However, for the purpose of simulating fire spread in informal settlements, it is necessary to incorporate the effect of wind on flames in B-RISK. This work proposes a preliminary method to account for wind and is programmed into B-RISK for use in a later section to simulate a real informal settlement fire. It should be noted that since the main focus of this paper is to investigate a preliminary semi-probabilistic analysis to simulate fire spread in informal settlements, some simplifications have been made in terms of incorporating wind into B-RISK, i.e. that wind direction and the wind speed are constant throughout the simulation. However, in reality the wind direction and speed can change during a fire incident and, this should be incorporated in future versions of the method developed in this work.

Research by Thomas [22] and AGA [23] reported plume and flame shape properties of a single fire source in the presence of wind. More recently, Oka et. al [24] developed a formula (Eq. 3) to predict flame tilt angles for urban fires that is more applicable for practical use, where the empirical model developed for flame tilt angles is based on the balance of mass between the fluxes given by the upward hot current and the cross-wind. The formula is as follows:

$$\tan \alpha = 2.73 Fr^{\frac{2}{5}} \cdot Q^{*-0.1(1+2.5y)} \cdot \left(\frac{W}{r^*}\right)^{-0.5} \quad (3)$$

where α is the angle between the vertical line from the center of the burning item to the intersection of the wind-tilted flame axis, Fr is the Froude number given by u^2/gD (where u is the wind speed [m/s], D is the short length of the rectangular burning item [m] and g is the acceleration due to gravity [m/s^2]), $Q^*$is the dimensionless heat release rate given by $\dot{Q}/(\rho_a C_p T_a g^{1/2} D^{5/2})$ (where $\dot{Q}$ is the heat release rate [kW], ρ_a is the density of ambient air [kg/m^3], C_p is the specific heat of constant pressure [kJ·kg^{-1}·K^{-1}] and T_a is the ambient temperature [K]), $y = 2$ for $0.05<Q^*<0.38$ and $y = 2/3$ for $0.38<Q^*<12.8$, W is the long length of the rectangular burning item, and $r^* = \sqrt{\text{burning item floor area}/\pi}$. Thus, in the presence of wind, the updated radial distance between the point source and the burning object (R') can be calculated as follows (see Fig. 3):

$$R' = R - \frac{z_{fl}}{2} \cdot \sin \alpha \quad (4)$$

Refer to Fig. 3 below for a visual depiction of the variables used in Eq. 4. Since B-RISK only takes the radiation distance as the horizontal distance (in plan) between the two items, the point source height has not been modified.

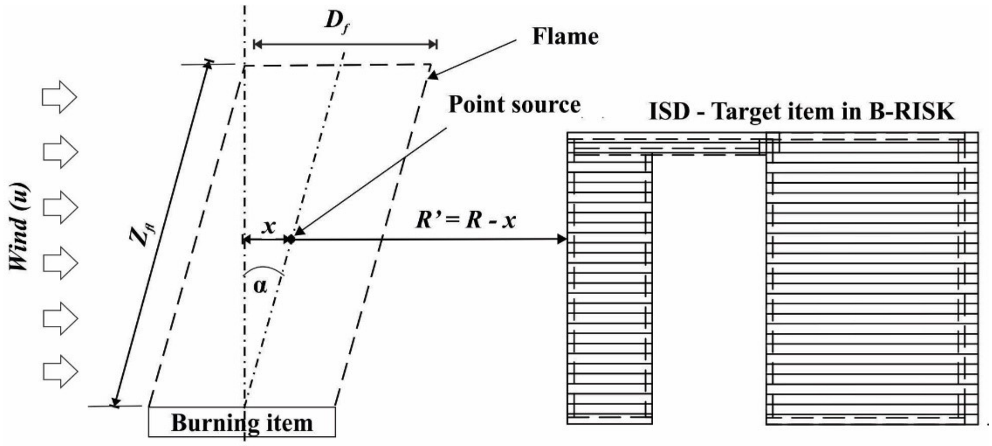

Fig. 3. PSM geometry between burning and target items when exposed to wind

3.3. Ignition

Following on from the work of Fleury [17] and the selection of the PSM within B-RISK, Baker *et al.* [25] published work examining the process of selecting an ignition criteria methodology for the submodel by establishing a set of essential criteria that the ignition method needs to meet. Baker *et al.* [25] determined that the flux-time product (FTP) method was sufficiently appropriate to simulate the ignition of secondary items, and it has been used in numerous other works [18,26–28]. The FTP method is a simplified approach to estimate ignition of combustible items subjected to an incident heat flux. The method was first derived by Smith and Satjia [29], which other researchers later extended. The method was then generalized by Shields *et al.* [30] such that:

$$FTP = t_{ig}(\dot{q}'' - \dot{q}''_{cr})^n \quad (5)$$

where t_{ig} is the time-to-ignition, $\dot{q}''$ is the incident heat flux emitted by the burning item (i.e. $\dot{q}''_{fl}$ calculated using Eq. 1), $\dot{q}''_{cr}$ is the critical heat flux [kW/m^2] and n is known as the FTP index and can be obtained by plotting $1/t_{ig}{}^{1/n}$ against $\dot{q}''$, and iteratively vary n to get the best linear trend line fit [26]. The FTP index depends on the thermal thickness of the material. As a guideline, a material is assumed to be thermally thin if n = 1, when n = 1.5 the material is thermally intermediate, and when n = 2 the material is thermally thick [26].

The FTP method was originally limited to piloted ignition, however Baker *et al.* [25] extended the method by deriving an empirical approximation for spontaneous ignition based on the presence of a hot layer within an enclosure. It is therefore not applicable to the present study as a hot layer is not permitted to be established in the model. Thus, in this work, the focus will be on dwelling ignition by means of piloted ignition of vertical surfaces (i.e. as a result of flame impingement from dwelling to dwelling for closely spaced ISDs in reality). The FTP index is derived from cone calorimeter data of the cardboard lining used in the experiments described above, since cardboard is typically used for lining material in informal settlements [3]. The cardboard of an adjacent dwelling is typically exposed to the radiation emitted by the burning dwelling as a result of poor construction methods, or gaps as a result of the flutes of the corrugated sheets [6]. It should be noted that this is a conservative assumption and that some dwellings are lined with other materials (e.g. timber) that have a higher critical heat flux.

Currently there is negligible data on firebrand generation during large informal settlement fires, although it is likely to occur. Discussions with firefighters and observations during large-scale experiments (which may lack the materials required to create brands) have provided insufficient data. Hence, firebrand behavior has been neglected in the current work, and research is required to understand this phenomenon.

4. B-RISK baseline scenario

Before the inputs of the baseline scenario are discussed, it is important to note how the ISDs experiment has been modelled and what simplifications are made. In order to simulate the ignition of secondary dwellings in B-RISK, they must be simplified to items with a specific shape (i.e. the volume of the ISD in this case) and a specific heat release rate (i.e. the heat release rate of the ISD in this case).

The purpose of this scenario is to validate the ignition (FTP) input parameters by comparing the B-RISK simulation results to the experimental results discussed above. The inputs are then used to run a semi-probabilistic analysis (using Monte Carlo with stratified sampling, where the ISDs were stratified based on dwelling floor area) on the Imizamo Yethu informal settlement fire [21], by randomly populating ISDs (the ‘items’ in B-RISK) in an informal settlement and simulating the scenario for a number of iterations. It should be noted that the ignition predictions in B-RISK are not influenced by the material properties, combustion properties of the item or the enclosure boundaries, other than the properties used in Eq. 1 and Eq. 5 [26]. Thus, the ignition predictions are only dependent on the radiation from the flame of the burning item(s) using the PSM and FTP formulae given by Eq. 1 and Eq. 5, respectively. Where multiple items are burning, the incident heat (Eq. 5) on an adjacent item (not yet ignited item) is the sum of that received from all the burning items, irrespective of orientation, which is a conservative assumption.

4.1. Input specification

Fig. 4 depicts the geometric setup of the B-RISK baseline simulation, with the descriptions referring to what is discussed above. In this case the room ('domain') used is 13×5×6 m (L×W×H) and the three ISD items are given a size of 3×3×2.3 m (L×W×H), i.e. the actual size of the dwellings with each having a floor area of 9 m^2. As mentioned above, the wind speed was negligible during the experiment and it is thus not considered for the baseline simulation.

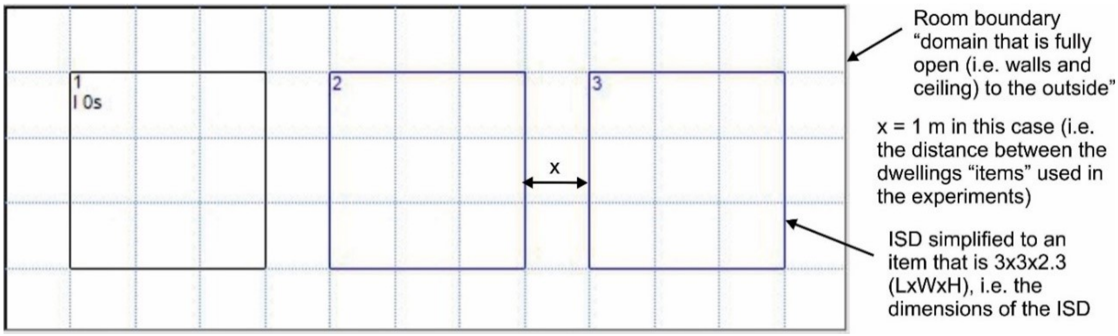

Fig. 4. Room setup in B-RISK (where ISD1-3 are modelled as items)

The next step is to define the combustion and ignition properties of the ISD items. The combustion properties are taken as those of the timber cribs used in [3], whereas the ignition properties are based on the cardboard lining used in [3]. The soot yield of 0.015 g/g, CO_2 of 1.33 g/g and radiant loss fraction χ_R of 0.3 are taken from Table 3-4.14 of the SFPE Handbook [31]. The heat of gasification (1.8 kJ/g) has been selected from Table 3-4.7 of the SFPE Handbook [31], based on similar representative materials. Assuming a combustion efficiency of 1, the effective heat of combustion equals the gross heat of combustion heat of combustion (18 kJ/g) of the timber used in [3].

Unfortunately, the heat release rates (HRRs) were not measured during the experiment. Thus, similar to [6,9], the HRRs are calculated by the following formula [32]:

$$\dot{Q} = \dot{m}\Delta H_{\text{eff}} \qquad (6)$$

where $\dot{m}$ is the mass loss rate measured in kg/s (of the timber cribs in this case) and ΔH_{eff} is the effective heat of combustion (kJ/kg). The maximum HRR of the ISDs is taken as the maximum HRR of the timber cribs used as the fuel, based on the assumption that the cardboard lining contributes only a minor amount. The mass loss rate of the timber cribs, $\dot{m}$, would normally be taken as the lesser of the surface-controlled mass loss rate, porosity-controlled mass loss rate, and the ventilation-controlled mass loss rate. However, here it is assumed that the mass loss rate is governed by ventilation [3,6,33–35], such that for the steel clad dwellings the mass loss rate is given by [32]:

$$\dot{m} = 0.12A_v\sqrt{H_v} \qquad (7)$$

where A_v is the sum of the areas of the openings in which A_v = 2.29 m^2, A_v = 2.65 m^2 and A_v = 1.93 m^2 for ISD1, 2 and 3, respectively (A_v includes the openings created by the flutes). H_v is the weighted average of the heights of the openings and in this case H_v = 1.72 m, H_v = 1.57 m and H_v = 1.93 m for ISD1, 2 and 3, respectively. The weighted average is given by:

$$H_v = (H_1A_1 + H_2A_2 \ldots.)/A_t \qquad (8)$$

where H_1 and A_1 is the height and area of the first opening, H_2 and A_2 is the height and area of the second opening and A_t is the sum of all the openings.

The growth phase is assumed to correspond with the experiment [6] (i.e. as seen by the time-temperature curves), which were very similar to a t-squared fire with an ultra-fast growth constant *(k)*, thus a t-squared fire with *k* = 75 has been used in the baseline simulation. Fig. 5 depicts the time-temperature curves of ISD1-3 of the steel-clad dwelling experiment along with the calculated HRR curves. For the steel clad dwellings, structural collapse was assumed to be 7.1 minutes (i.e. the average of the values listed in Table 1) after the fully developed fire stage was reached [34].

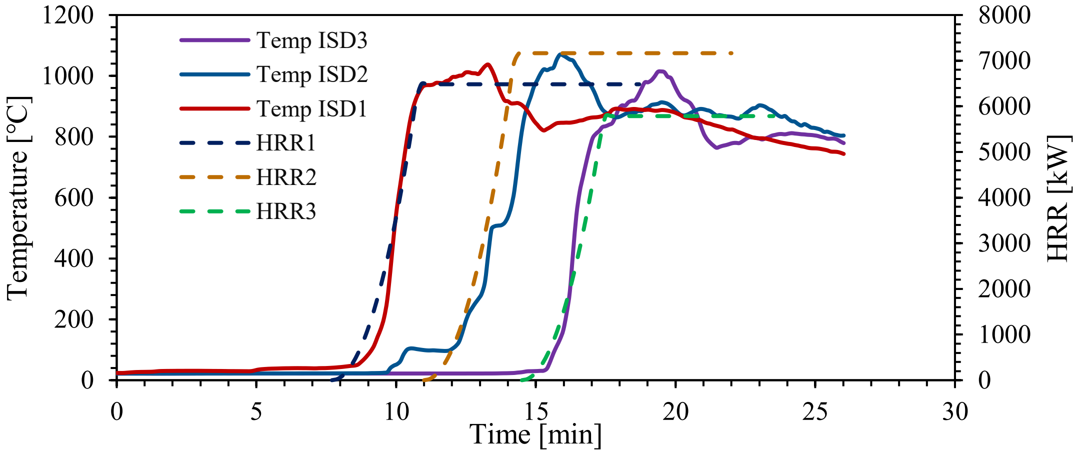

Fig. 5. HRR and ceiling temperatures versus time for ISD1-3

The last step is to define the ignition mechanism of the ISDs' items, and it is assumed to be the ignition of the cardboard lining. As mentioned earlier, by plotting $\dot{q}''$ against $1/t_{ig}{}^{1/n}$, both the value for n and FTP can be obtained by iteratively varying n to obtain the trendline with the highest correlation coefficient (R^2). Piloted ignition measurements from the cone calorimeter for the cardboard used in the large-scale experiments can be seen in Fig. 6.

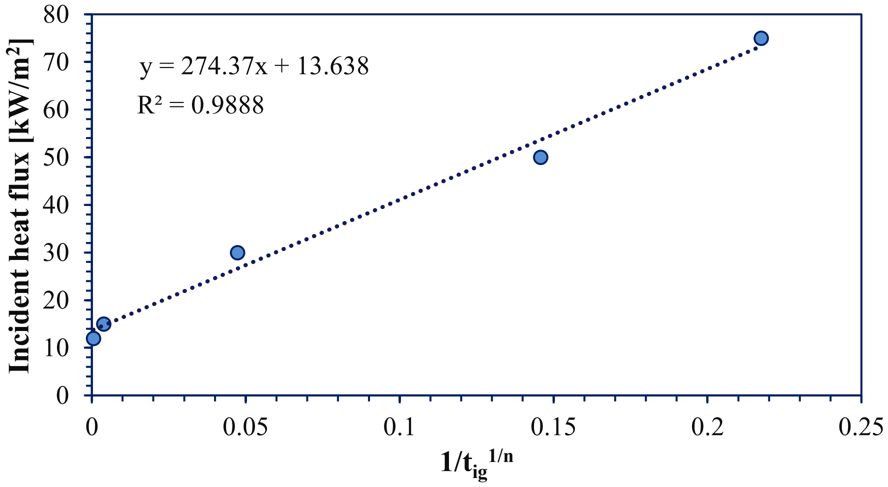

Fig. 6. Correlation of ignition times and incident heat flux (cone calorimeter data from [14])

Wang *et al.* [14] found that the critical heat flux (CHF) of cardboard is somewhere between 11 kW/m^2 and 12 kW/m^2, thus it is assumed that the CHF is 11.5 kW/m^2. The value of n is found to be equal to 1.39 with R^2 = 0.9888 and FTP is found to be equal to 2446 [kW/m^2]^n.

Using the above mentioned as direct inputs to the B-RISK baseline scenario yield the results discussed in the next section.

4.2. Results and discussion

Table 2 summarizes the experimental and B-RISK simulation spread rates of the dwellings. The percentages reported in brackets, indicate by what percentage the simulation overpredict (+) or underpredict (-) the spread rate. For the simulations, the spread rates are taken as the time between ignition of ISD item 1 to the ignition of the particular item under consideration, whereas the spread rates of the experiment are taken as the time between the start of flashover in ISD1 to the start of flashover in the particular dwelling under consideration. From Table 2 it is clear that the B-RISK simulation with no wind slightly underpredicts the experimental data in terms of ignition times. The effect of wind is also assessed using the baseline scenario, with the wind direction being from left to right of the setup as depicted in Fig. 4. It is clear that as the wind speed increases the spread rate increases, indicating that the wind functionality added to B-RISK works as expected. For higher wind speeds, the spread rates start to converge, simply indicating that for these particular dwelling sizes and HRRs, the tilt angle is starting to approach the maximum tilt angle, at a wind speed of approximately 10 m/s. In order to get the best correlation to the experimental results, the simulation has been calibrated by decreasing the value of n. It is found that $n = 1.57$ gives the best correlation to the experimental results, thus it is decided to use $n = 1.57$ for the case study simulations that follow.

Table 2: Summary of baseline simulation results versus experimental results

Experiment/Model	Time to ignition after the ignition of ISD1 [s]	
	ISD2	**ISD3**
Experiment (Negligible wind)	210	392
B-RISK simulation (No wind)	231 (-10%)	433 (+10.46%)
B-RISK simulation (1 m/s wind)	145 (+30.95%)	283 (+27.8%)
B-RISK simulation (5 m/s wind)	138 (+34.29%)	269 (+31.4%)
B-RISK simulation (10 m/s wind)	138 (+34.29%)	269 (+31.4%)
B-RISK (No wind, n = 1)	178 (+15.2%)	338 (+13.8%)
B-RISK (No wind, n = 1.57)	208 (+0.95%)	395 (-0.77%)

5. Semi-probabilistic simulation of the 2017 Imizamo Yethu fire

The purpose of this section is to use the input data used in the baseline scenario, but with n = 1.57 and apply it to a real informal settlement. The results are then compared to a fire incident that occurred in the settlement of interest. It should be noted that the slope of the settlement is not accounted for as the current version of B-RISK does not have the functionality to account for this. Additionally, B-RISK currently cannot account for fluctuations in wind speed or fluctuations in wind directions, as mentioned earlier. In terms of the Imizamo Yethu fire, the wind speed fluctuated between 7.8 m/s (28 km/h) - 12.8 m/s (46 km/h), and the wind direction changed by a full 180 degrees during the incident. Thus, these factors may be incorporated in future versions of B-RISK, as more case studies become available for calibration.

5.1. Imizamo Yethu 2017 fire

Imizamo Yethu is an informal settlement in the Hout Bay Valley, on the Atlantic Ocean side (west) of the Cape Peninsula, and within the jurisdiction of the City of Cape Town. The settlement is situated on steep (average 12° slope) mountain land with poor access thus limiting the ability of emergency services to reach the upper parts of the settlement as the road access deteriorates with steepness of slope [36]. Imizamo Yethu is notorious for its lack of basic services and infrastructure. The exact number of occupants is unknown but is estimated in the region of 16000 to 36000 [37] with a settlement density ranging from 228 – 262 dwellings per hectare. Imizamo Yethu has a long history of fire [38] and, prior to the 2017 fire discussed in this paper, a fire in 2004 destroyed 1200 informal dwellings and left as many as 5000 residents homeless.

As described in detail by Kahanji *et al.* [21], on the night of Saturday 11 March 2017, at around 00h00, a fire started in Imizamo Yethu and was finally extinguished thirteen hours later at around 13h00 on Sunday 12 March 2017. This devastating fire resulted in four deaths, two fire fighter injuries, 2194 structures destroyed and approximately 9700 people displaced [21]. Kahanji *et al.* [21] divided the burn scar into zones on the basis of fire fighters' reports of the location and time of the fire front. The fire started in Zone A (Fig. 7) and it appears that the inhabitants in the dwelling of origin perished in the blaze. Fire fighters arrived on the scene and the fire appeared to be almost under control, but a resident cut the fire fighters hose to direct water to their own home and from this point on, the fire quickly grew, pushed by wind and topography. The wind changed direction between 01h00 and 03h00 from Northeast to Southwest which then pushed the fire beyond Zone A and into Zones B and C. In this work, the semi-probabilistic model will be focused on fire spread modelling within Zone A (average 9° slope), thus the rest of the fire report is not summarized here, however a description of the fire in Zones B – E can be accessed in Kahanji *et al* [21].

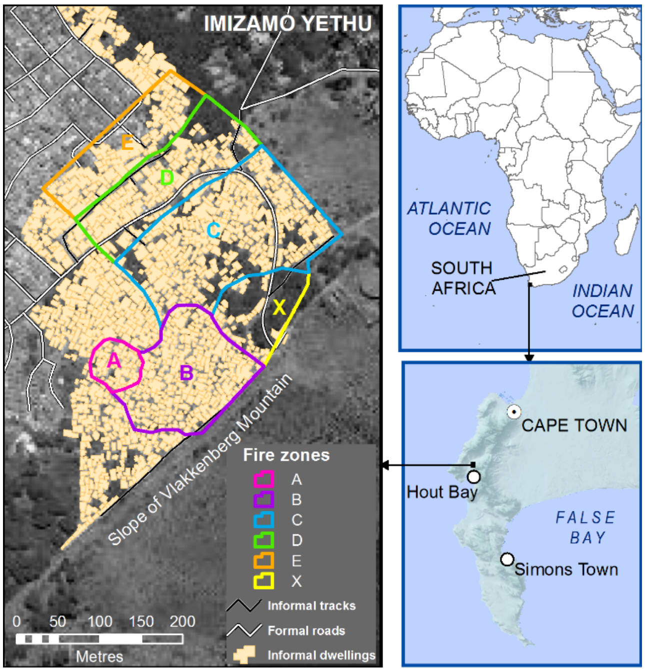

Fig. 7. The Location of Imizamo Yethu and the fire of 11 March 2017, showing the fires zones as determined by Kahanji et al. [21].

5.2. Zone A

The fire zones delineated by Kahanji *et al.* [21] were determined roughly from the fire fighters' reports at settlement scale without individual dwellings being considered. It can be seen in Fig. 8 that this delimitation results in some dwellings being considered partly in and partly out of the fire extent and dwellings straddle the boundary between zones. When considering the detail require for modelling fire spread, Zone A's boundaries have been redefine, and the boundary has been adjusted along dwelling boundaries so that dwellings are either completely included or completely excluded from Zone A. Thus, the revised area of Zone A (Fig. 9) is 3312 m^2. Dwellings were digitized in ArcGIS 10.5 at a scale of 1:200 from City of Cape Town high resolution (~8 cm resolution) aerial photography captured on February 2017, approximately one month before the fire. Some dwellings are built very close or even touching each other, making delimiting individual dwellings challenging. Generally, where a gap, however small, between dwellings could be detected, dwellings were digitized as individual dwellings. Further, very large continuous structures were delimited into multiple dwellings based on shape of the structure and identification of differing roof sheeting. A large tree in Zone A partially obscured roofs of dwellings and the outline of these dwellings was estimated by extending the roof boundaries where visible. Area statistics for all dwellings in Zone A were calculated and the frequency distribution of the size of dwellings were plotted, as depicted in Fig. 10.

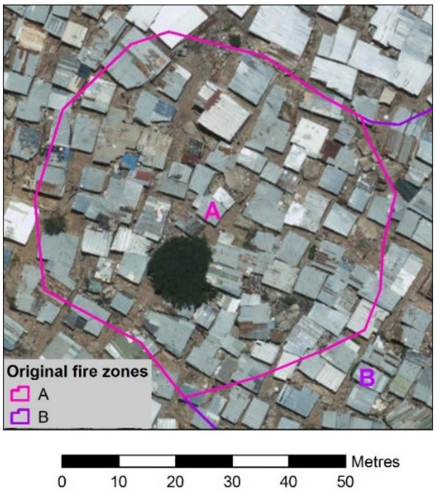

Fig. 8. Original fire Zone A

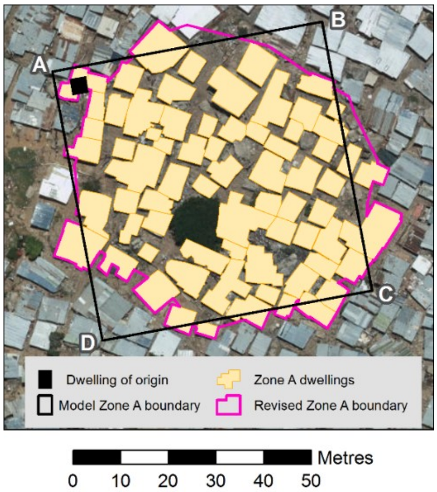

Fig. 9. Revised fire Zone A

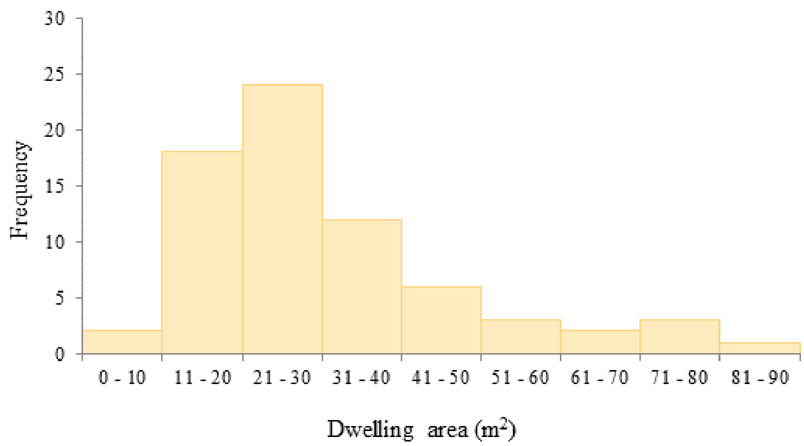

Fig. 10. Frequency distribution of the size of dwellings in Imizamo Yethu Zone A

From these statistics, together with the calculated area of Zone A, the following metrics can be obtained: (a) the dwelling density: Total dwelling area represented as a percentage of Zone A area is 65.28%, (b) the household density: Number of individual dwellings within Zone A, upscaled to number of dwellings per hectare is 214 dwellings/ha, a figure close to the reported settlement density of 228 – 262 dwellings/ha, and (c) the dwelling roof area (which is assumed to be equal to the floor area) ranges from ~7 m^2 to 86 m^2 (although it is possible that the large dwellings represent more than one household) with the frequency distribution peaking at around 22 m^2.

5.3. Semi-probabilistic model setup

To represent Zone A, an area of 58 m × 58 m (see Fig. 9) populated with 71 ISD items Fig. 10) at locations randomly allocated by B-RISK, as depicted in Fig. 12, within the Zone is simulated. The ISD item size distributions are taken from Fig. 10. Thus, only the locations of the 71 items are varied from simulation to simulation, with all other inputs remaining constant. Assigning probabilistic distributions to variables such as *n*, FTP, HRRPUA etc., to account for more of the variables in informal settlements would be beneficial. It should however be noted that the current version of B-RISK does not have the functionality to assign a probabilistic distribution for all of these variables and should thus be coded into B-RISK. Since this is only the first attempt and since space is limited, it is recommended for future work. Since the opening sizes and the number of openings per dwelling for the case study scenario are not known, some assumptions are needed. Thus, it is assumed that the dwellings are always ventilation controlled, such that the HRR curve assigned to the dwellings are the HRR curves as depicted in Fig.5 multiplied by a factor f_A which is the ratio of the area of the dwelling under consideration to the area of the dwelling representing the original HRR (the original item being one of the dwellings used in the triple steel clad experiment). Thus, it is assumed that H_v (Eq. 7) remains approximately constant, but that A_v (Eq. 7) increases proportional to the dwelling floor area. Table 3 lists the number of dwellings with their associated dwelling size, HRR curve (decided in such a way that each curve is used roughly the same number of times) and f_A.

Table 3: Model inputs summarizing assumptions for dwelling characteristics

Dwelling size (L×W×H)	**Number of dwellings**	**Original HRR curve used**	f_A
3.5 m × 3.5 m × 2.3 m	1	ISD1	1.4
3 m × 3 m × 2. 3m	5	ISD1	1.0
3.5 m × 3.5 m × 2. 3m	9	ISD1	1.4
4 m × 4 m × 2. 3m	13	ISD2	1.8
4.5 m × 4.5 m × 2. 3m	15	ISD3	2.3
5 m × 5 m × 2. 3m	11	ISD1	2.8
5.5 m × 5.5 m × 2. 3m	2	ISD2	3.4
6 m × 6 m × 2. 3m	3	ISD2	4.0
6.5 m × 6.5 m × 2. 3m	5	ISD2	4.7
7 m × 7 m × 2. 3m	2	ISD3	5.4
8 m × 8 m × 2. 3m	4	ISD3	7.1
9 m × 9 m × 2. 3m	1	ISD3	9.0

5.4. Results and discussion

Two scenario variations (i.e. one with wind and one without wind) have been executed with the resulted averages displayed in Fig. 11. Currently B-RISK does not generate an output file for the spread time between dwellings. Thus, since the spread rates were captured by hand, only 100 simulations were run to illustrate the functionality of the model. Note that the location of the first item ignited was always fixed to the bottom left of the domain. The fire spread rates here are different than above and is given in m^2/hr. This has been calculated by dividing the total domain area by the time it took to ignite all the items (similar to what was done in [21]). The wind speed of 8.9 m/s used, is based on the actual wind speed during the fire incident of 8.9 m/s (32 km/h) as reported in [21] with a wind direction of 45 degrees, as depicted in Fig. 12. The error bar for Zone A is based on the start time of the incident. In this case, it is assumed that the fire started at 00:00 (although it could have started slightly earlier or later). The spread rate for Zone C and D are also added to Fig. 11 to show the range of spread rates that occurred during the incident. The error bars of the B-RISK results are the standard deviation of the simulations. The black dwelling in the bottom left corner of Fig. 12 represents the dwelling of origin (the position was fixed for all simulations).

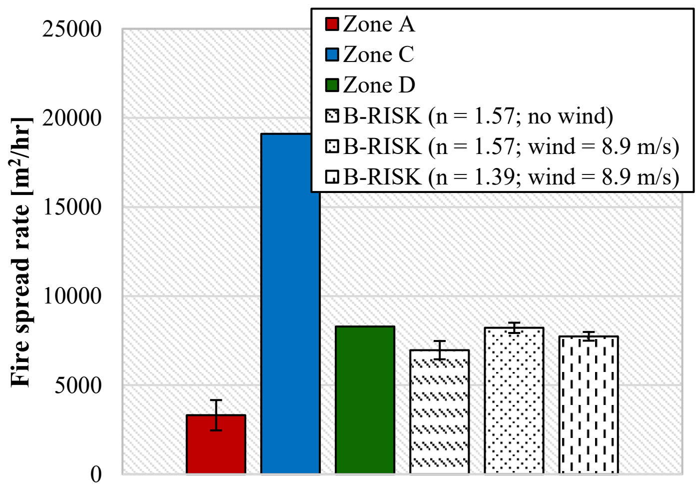

Fig. 11. Fire spread rates of Zone A, C and D and the B-RISK simulation

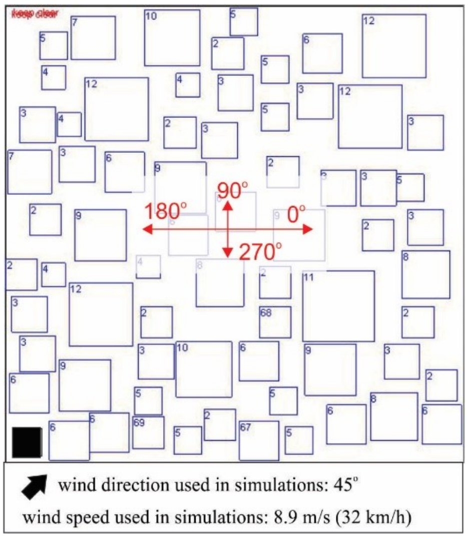

Fig. 12. Wind direction angles and an example of random item population

Based on the B-RISK simulations, a wind speed of 8.9 m/s increases the spread rate by 1252 m^2/hr on average, consistent with the baseline scenario and showing that wind functionality added to B-RISK works as expected. The actual fire spread rate in Zone A of 3312 m^2/hr is slower than the predicted B-RISK spread rate (wind included) of 8216 m^2/hr. This could be due to multiple reasons, such as: B-RISK not accounting for human intervention (i.e. fire brigade and inhabitants); Zone A boundaries being approximate boundaries based on fire fighters' interviews; not only cardboard is used for lining materials in reality (with more data this can be calibrated). The B-RISK error bars shown are relatively narrow – there are still many uncertainties not included in the analysis such as the materials and their ignition and combustion properties, uncertainty in the flame shape and size, view factors etc. The only uncertainty included in the analysis is the randomization of the ISD locations, and there are additional uncertainties associated with the assumed ISD density. The predicted spread rate of 8216 m^2/hr is however plausible when compared to the 8300 m^2/hr spread rate of Zone D. Zone C had a spread rate of 19100 m^2/hr, indicating that much higher spread rates are also possible. The higher spread rate, in Zone C, can be as a result of many reasons such as an increase in wind speed, as the fire gets bigger it results in more rapid spread and human intervention has less of an effect as the fire grows. Considering all the variables and unknowns, the predicted spread rate of 8216 m^2/hr is a good first step in the development of this semi-probabilistic method to simulate fire spread in informal settlements. Interestingly, a simulation executed with n = 1.39 (the original n value for the cardboard), shows a fire spread rate of 7740 m^2/hr which is closer to the actual incident, compared to the spread rate of 8216 m^2/hr obtained with n = 1.57.

6. Future considerations

This paper develops a preliminary semi-probabilistic model of informal settlement fire spread using B-RISK, through making a number of assumptions. As more data becomes available from informal settlement dwelling experiments and from real fire incidents, the model discussed can be calibrated and updated to account for more variables, and to make it more practical for municipalities and fire brigades to use as a tool for risk and strategy planning. For future work it is recommended that variables such as FTP, n, HRR, etc. are randomly generated from a probabilistic distribution, in order to account for more of the unknowns associated with informal settlements. Additionally, the following needs to be implemented/considered in future versions: (a) the ability to vary wind speeds and directions, (b) graphical outputs of the fire spread patterns, (c) the ability to auto-populate different ignition criteria (i.e. to account for a number of possible lining/cladding materials), (d) the ability to slope the floor of the ‘domain’, (f) the ability to specify variations in the ‘room’ and ‘item’ shapes, and (e) the ability to include vegetation or random combustibles between dwellings as one would typically find in informal settlements.

7. Conclusions

This work provides the first step towards the development of tools to simulate fire spread in informal settlements, in order to provide municipalities with predictive capabilities in identifying high risk areas, or to quantify the magnitude of an incident to which municipalities may need to respond to. This first step includes the development of a methodology using B-RISK, determining ignition criteria that best fit ISDs, implementing a simplified method to account for wind, and the execution of a validation and case study scenario. The baseline scenario, with a total spread time of 392 s, shows a good correlation compared to the experimental results, with a total spread time of 374 s. The baseline scenario inputs are thus used to model the case study scenario, where it is found that the B-RISK simulation over-estimates the fire spread rate in Zone A by 5004 m^2/hr. However, since the simulation neglect factors such as human intervention, it was expected that the simulation would over-predict the spread rate. The predicted spread rate seems plausible when compared to other zones (Zone C and D). Considering the complexity of the problem and the difficulty to accurately define input parameters, this paper is a first step to simulate fire spread in informal settlements. With more than one billion people residing in informal settlements there is a need to understand and improve fire safety in these areas.

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9. References

[1] UN Office for Disaster Reduction, UNISDR Terminology on Disaster Risk Reduction, Geneva, Switzerland, 2009. https://doi.org/978-600-6937-11-3.

[2] UN-Habitat, Slum Almanac 2015/2016: Tackling Improvement in the Lives of Slum Dwellers, Nairobi, 2016.

[3] A. Cicione, R.S. Walls, C. Kahanji, Experimental study of fire spread between multiple full scale informal settlement dwellings, Fire Saf. J. 105 (2019) 19–27. https://doi.org/10.1016/j.firesaf.2019.02.001.

[4] P. Zweig, R. Pharoah, R. Eksteen, R.S. Walls, Installation of Smoke Alarms in an Informal Settlement Community in Cape Town, South Africa – Final Report, 2018.

[5] R.S. Walls, C. Kahanji, A. Cicione, M. Jansen van Vuuren, Fire dynamics in informal settlement "shacks": Lessons learnt and appraisal of fire behavior based on full-scale testing, in: 11th Asia-Oceania Symp. Fire Sci. Technol., Taiwan, 2018.

[6] A. Cicione, M. Beshir, R.S. Walls, D. Rush, Full-Scale Informal Settlement Dwelling Fire Experiments and Development of Numerical Models, Springer US, 2019. https://doi.org/10.1007/s10694-019-00894-w.

[7] R.S. Walls, R. Eksteen, C. Kahanji, A. Cicione, Appraisal of fire safety interventions and strategies for informal settlements in South Africa, Disaster Prev. Manag. 28 (2019) 343–358. https://doi.org/https://doi.org/10.1108/DPM-10-2018-0350.

[8] FPASA, SA Fire Loss Statistics 2015, 2017.

[9] A. Cicione, R.S. Walls, Towards a simplified fire dynamic simulator model to analyse fire spread between multiple informal settlement dwellings based on full-scale experiments, Fire Mater. (2020) 1–17. https://doi.org/10.1002/fam.2814.

[10] R. Walls, P. Zweig, Towards sustainable slums : understanding fire engineering in informal settlements, Sustain. Vital Technol. Eng. Informatics. (2016) 1–5.

[11] M. Beshir, Y. Wang, L. Gibson, S. Welch, D. Rush, A Computational Study on the Effect of Horizontal Openings on Fire Dynamics within Informal Dwellings, Proc. Ninth Int. Semin. Fire Explos. Hazards (ISFEH9. (2019) 512–523. https://doi.org/10.18720/spbpu/2/k19-122.

[12] W. Mell, A. Bova, G. Forney, Models for Fire Spread in the Wildland-Urban Interface, (2012) 1–61.

[13] E. Kim, N. Dembsey, Engineering Guide for Estimating Material Pyrolysis Properties for Fire Modeling, 2012.

[14] Y. Wang, C. Bertrand, M. Beshir, C. Kahanji, R. Walls, D. Rush, Developing an experimental database of burning characteristics of combustible informal settlement dwelling materials, Fire Saf. J. (2019). https://doi.org/https://doi.org/10.1016/j.firesaf.2019.102938.

[15] D. Drysdale, An Introduction to Fire Dynamics, 3rd ed., John Wiley & Sons, LTD, 2011.

[16] C. Wade, G. Baker, K. Frank, R. Harrison, M. Spearpoint, B-RISK user guide and technical manual, BRANZ Study Report SR364, Porirua, New Zealand, 2013.

[17] R. Fleury, M. Spearpoint, C. Fleischmann, Evaluation of Thermal Radiation Models for Fire Spread Between Objects, in: Fire Evacuation Model. Tech. Conf., Baltimore, Maryland, 2011. http://www.ir.canterbury.ac.nz/handle/10092/4959.

[18] G. Baker, P.C. Collier, C. Wade, M. Spearpoint, C.M. Fleischmann, K. Frank, S. Sazegara, A comparison of a proiri modelling predictions with experimental results to validate a design generator submodel, in: 13th Int. Fire Mater. Conf., San Francisco, CA, USA, 2013.

[19] G. Heskestad, Fire Plumes, Flame Height, and Air Entrainment, in: SFPE Handb. Fire Prot. Eng., 4th ed., Quincy, MA, USA, 2008: pp. 2–1 to 2–20.

[20] G. Baker, M. Spearpoint, C.. Fleischmann, C. Wade, Development of a Radiative Fire Spread Submodel for an Enhanced Zone Model, in: 8th Asia-Oceania Symp. Fire Sci. Technol., International Association of Fire Safety Science, 2010.

[21] C. Kahanji, R.S. Walls, A. Cicione, Fire spread analysis for the 2017 Imizamo Yethu informal settlement conflagration in South Africa, Int. J. Disaster Risk Reduct. (2019). https://doi.org/10.1016/j.ijdrr.2019.101146.

[22] P.H. Thomas, The Size of Flames from Natural Fires, in: 9th Int. Combust. Symp., Combustion Institute, 1963: pp. 844–859.

[23] American Gas Association, Report IS 3-1, 1974.

[24] Y. Oka, O. Sugawa, T. Imamura, Y. Matsubara, Effect Of Cross-Winds To Apparent Flame Height And Tilt Angle From Several Kinds Of Fire Source, in: Fire Saf. Sci., 2003: pp. 7:915-926. https://doi.org/10.3801/IAFSS.FSS.7-915.

[25] G. Baker, M. Spearpoint, C.. Fleischmann, C. Wade, Selecting an ignition criterion methodology for use in a radiative fire spread submodel, Fire Mater. 35 (2011) 367–381. https://doi.org/10.1002/fam.1059.

[26] S. Sazegara, M. Spearpoint, G. Baker, Benchmarking the Single Item Ignition Prediction Capability of B-RISK Using Furniture Calorimeter and Room-Size Experiments, Fire Technol. 53 (2017) 1485–1508. https://doi.org/10.1007/s10694-016-0642-y.

[27] G. Baker, R. Fleury, M. Spearpoint, C.M. Fleischmann, C. Wade, Ignition of Secondary Objects in a Design Fire Simulation Tool, in: Fire Saf. Sci., 2011. https://doi.org/10.3801/IAFSS.FSS.1.

[28] H. Peel, C. Wade, M. Spearpoint, Comparison of partially lined timber room experiments with the modified B-RISK flame spread capability, 14th Int. Conf. Exhib. Fire Sci. Eng. - Interflam. (2016) 4–6.

[29] E.E. Smith, S. Satija, Release rate model for developing fires, J. Heat Transfer. 105 (1983) 281–287. https://doi.org/10.1115/1.3245575.

[30] T.J. Shields, G.W. Silcock, J.J. Murry, Evaluating ignition data using the flux time product, Fire Mater. 18 (1994) 243–254. https://doi.org/10.1002/fam.810180407.

[31] A. Tewarson, Generation of Heat and Chemical Compounds in Fires, in: SFPE Handb.

Fire Prot. Eng., 4th ed., 2002.

[32] V. Babrauskas, Heat release rates, in: M.J. Hurley et. al (Ed.), SFPE Handb. Fire Prot. Eng., 5th ed., Springer, 2016: p. 829. https://doi.org/10.1007/978-1-4939-2565-0.

[33] N. de Koker, R. Walls, A. Cicione, Z. Sander, S. Loffel, J. Claasen, S. Fourie, L. Croukamp, D. Rush, 20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements, Fire Technol. (2020). https://doi.org/DOI 10.1007/s10694-019-00945-2.

[34] A. Cicione, R. Walls, Estimating time to structural collapse of informal settlement dwellings based on structural fire engineering principles, in: SEMC Conf., CRC Press, 2019.

[35] R. Walls, G. Olivier, R. Eksteen, Informal settlement fires in South Africa : Fire engineering overview and full-scale tests on " shacks ," Fire Saf. J. 91 (2017) 997–1006.

[36] M. Rosenberg, Community Based Fire Risk Reduction - Case Study of Imizamo Yethu, Hout Bay, (2013).

[37] Governance Department of Cooperative Affairs South Africa., African Centre for Disaster Studies, Southern Africa Society for Disaster Reduction, Per National Disaster Management Centre South Africa., J. Disaster Risk Stud. 3 (2011) 443–452.

[38] E.W. Harte, I.R.W. Childs, P.A. Hastings, Imizamo Yethu: A case study of community resilience to fire hazard in an informal settlement Cape Town, South Africa, Geogr. Res. 47 (2009) 142–154. https://doi.org/10.1111/j.1745-5871.2008.00561.x.