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A PRELIMINARY DESIGN OF NUMERICAL EXPERIMENTS STUDY ON THE INFLUENCE OF FACTORS AFFECTING THE FIRE SPREAD IN BRAZILIAN INFORMAL SETTLEMENTS (FAVELAS)

Calisa Katiuscia Lemmertz
Rodolfo Prediger Helfenstein
Department of Mechanical Engineering, Federal University of Rio Grande do Sul, Porto Alegre, RS,Brazil
calisa.lemmertz@ufrgs.br, rodolfo.helfenstein@ufrgs.br

David Rush
School of Engineering, The University of Edinburgh, Edinburgh, Scotland, United Kingdom
d.rush@ed.ac.uk

Felipe Roman Centeno
Department of Mechanical Engineering, Federal University of Rio Grande do Sul, Porto Alegre, RS,Brazil
frcenteno@mecanica.ufrgs.br

Abstract. *Informal Settlements (IS), also known in Brazil as favelas, are under constant risk of large scale fires, which may affect hundreds of people at the time. Some of the Informal Settlements' main characteristics, which are commonly seen in IS all over the world, such as close proximity of the dwellings, irregularity of lanes and alleys, and large availability of combustible material contribute to a larger fire spread rate when compared to other urban areas. From previous works, it is already known that the presence of atmospheric wind can enhance the severity of a fire and contribute to its spread. For this reason, in this study, we analyze the factors that contribute the most to the fire spread in informal settlements subjected to atmospheric wind. To do this, a screening study applying design of experiments for numerical simulations was conducted. For the design of the numerical experiments, the space-filling design known as Latin Hypercube Design (LHD) technique was applied and the results were analyzed using Gaussian Process. It is known that fires frequently spread to adjacent structures by heat flux or flame impingement, thus, the studied parameters (responses) were the hot gas temperature inside the fire dwelling, the incident radiative heat flux in a neighboring dwelling, and the flame horizontal projection ejected through the fire dwelling's opening. The studied factors were the wind speed and direction, and the separation distance between dwellings. The dwellings were modeled as thermally-thick compartments, which better represent masonry dwellings, commonly found in Brazilian Informal Settlements. The simulations were performed in a CFD code called Fire Dynamics Simulator (FDS) and the IS was represented by an array of nine dwellings to allow the wind flow to be affected by the presence of these obstacles (dwellings), creating "wind tunnel effects". This study allowed us to understand which of the studied factors have a more important influence on the fire spread, and also how the interactions between these factors affected the fire spread in Informal Settlements. Knowing the dynamics of the fire spread in Informal Settlements will help us in the future to propose interventions that may reduce the risk of fire spread in these communities.*

Keywords: *Fire Spread, Informal Settlements, Atmospheric Wind, FDS, Design of Experiments*

1. INTRODUCTION

Informal Settlements (IS), also known in Brazil as favelas, are under constant risk of large scale fires. This is a consequence of some of their main characteristics, such as close proximity of the dwellings, irregularity of lanes and alleys, and large availability of combustible material, which contribute to a larger fire spread rate when compared to other urban areas.

The presence of wind during the fire incident also contributes to the increase in fire spread and fire severity. According to Lemmertz et al., 2021, a number of historical large scale urban fires, such as the Great London Fire (1666), the Great Chicago Fire (1871), The San Francisco Fire (1906), the Valparaíso Informal Settlement Fire (2014) and Imizamo Yethu Informal Settlement Fire (2017) happened under severe wind conditions. However, still little research has been made to study the effects of the wind conditions in Informal Settlement fires.

The effect of wind (speed and direction) on the Heat Release Rate (HRR) required to reach flashover was investigated by Centeno et al., 2020. They conducted numerical simulations of small-scale thermally-thin and thermally-thick compartments in a wind tunnel using the software Fire Dynamics Simulator (FDS), and assuming constant and prescribed HRRs. It is important to highlight that since the HRR was constant and prescribed, this study did not account for the effect of the wind on the burning rate. It was found that the HRR required to reach flashover increased with wind speed for thermally-thin compartments, while it decreased for thermally-thick compartments. They concluded that those results were associated to the heat transfer losses through walls and by wind-induced pressures at the doorway, the former being the driving mechanism for thermally-thin compartments and the later for thermally-thick compartments.

FDS models were also used by Lemmertz et al., 2021 to analyze numerically the effect of the atmospheric wind in the fire dynamics and heat transfer through walls in full-scale under-ventilated post-flashover compartment fires. Different wind speeds, wind directions and compartment boundaries (thermally-thin and thermally-thick, to represent different types of IS dwellings) were analyzed and a constant and prescribed HRR was assumed. The numerical experiments shown that both wind conditions (speed and direction) affected significantly the temperatures and heat fluxes through compartment walls and that for constant HRRs, the windward wall (internal and external) temperatures and the hot gas temperatures were inversely proportional to the wind speed. It was also observed that compartments with different wall thermal characteristics were affected differently by the atmospheric wind: the thermally-thin compartments presenting more uniform gas temperature profiles and having their net wall heat fluxes more affected by the wind.

Rush et al., 2021, investigated how fire spread parameters (such as, flame length and external heat flux) are affected by different wind conditions and different IS dwelling layouts. They used FDS models, which consisted in different arrays (four and eight dwellings) of full-scale thermally-thin dwellings (steel sheets boundaries). The fire source was modeled using a simplified burner with prescribed, but not constant HRR (which does not allow observing the influence of the wind on the burning rate) and the wind was modeled through the Monin-Obukov similarity theory. From the results, a very complex interaction between the dwellings separation distance and wind conditions was observed. They noticed that the atmospheric wind may produce a “wind-tunnel" effect that affected the analyzed fire spread parameters. They observed the peak heat fluxes, flame lengths, and temperatures at wind speeds between 10-15 m/s, which do not correspond to the maximum wind speed analyzed in their study, and the longest flame lengths were observed for the cases with the wind blowing in the back wall of the fire dwelling, with an important dependence on the wind speed.

Gibson et al., 2022, investigated the influence of the wind conditions and the spatial layout of dwellings on fire spread in IS in Cape Town. They analyzed both, together and separately, data on fire incidents, dwelling footprints, and the wind conditions during a fire. It was observed that the majority of fires occurred in the windy times of the year (around December), with the most destructive fires taking place during moderate wind conditions (approximately 8 m/s). They concluded that this may happen, since at higher wind speeds, the wind will not decrease the distance between the flame and adjacent dwelling any further, but a reduction in flame height will reduce the radiation to neighboring dwellings.

Lemmertz et al., 2022 (Under review), conducted a numerical study using the software FDS to understand the influence of the wind conditions (speed and direction) and wall thermal characteristics on the time to reach the onset of flashover, fire dynamics and fire spread in informal settlements. The simulations were conducted considering a full-scale IS dwellings burning wood cribs for different wind speeds and directions, analyzing the fuel mass loss rate, hot gas temperature, global equivalence ratio, radiative heat flux outside the door and time to flashover. It was observed that regardless the wind direction the increase in wind speed considerably reduced the time needed to reach flashover. They concluded that this happens due to the wind enhancing the burning rate of the wood cribs, and consequently accelerating the hot gas temperature rise. Wind also accelerated the occurrence of under-ventilated condition and then, combined to a shorter time to reach flashover, flame ejection through the door happened earlier. The radiative heat fluxes measured outside the door also increased with the increase in wind speed. Wall thermal characteristics presented a great influence on the studied parameters, with thermally-thin bounded dwellings presenting a more severe fire scenario. They concluded that both wind speed and wall thermal characteristics significantly affect the severity of informal settlement fires and can increase the risk of fire spread.

The present work aims to conduct a preliminary design of numerical experiments study on the influence of factors affecting the fire spread in Brazilian informal settlements (favelas) in the presence of atmospheric wind. The effects of 3 parameters (wind speed, wind direction and separation distance between dwellings) will be analyzed for 3 different responses, the hot gas temperature inside the fire dwelling (FD), incident heat flux in the front nearest dwelling (ND7) and the flame horizontal projection ejected through the door of the FD.

2. METHODOLOGY

According to Mathews, 2006, Design Of Experiments (DOE) is a methodology for studying any situation that involves a response (output) that varies as a function of one or more independent variables (inputs). It is an essential tool for addressing complex systems, where more than one variable may affect a response and two or more variables may interact with each other.

Although the original DOE techniques, usually referred as classical DOE techniques, were developed for physical experiments, the designed experiments can also be successfully applied to computer simulation models of physical systems [Montgomery, 2017]. However, it is important to highlight that there are some differences between data generated by a physical experiment and data generated by a deterministic numerical experiment. Physical experiments measure a stochastic response corresponding to a set of treatment input variables, which frequently involve nuisance input variables that may or may not be recognized and cause some of the variations in the experimental response, while a deterministic numerical experiment (i.e. CFD models) will produce identical results repeated for the same set of inputs [Santner et al., 2003]. That is why using DOE techniques specifically developed for deterministic simulations is so important.

According to Viana, 2016, classical experimental designs, such as central composite designs or D-optimal designs, have been used for simulations, however, this practice has proven to be sub-efficient and, these days, less and less frequent.

Space-filling designs are often thought to be particularly appropriate for deterministic computer models, because spread the design points out nearly evenly or uniformly throughout the region of experimentation and do not contain any replicate points [Montgomery, 2017]. For this reason, to conduct this study, a numerical experiment was planned through a space-filling design called Latin Hypercube Design (LHD). The Design matrix for this study was prepared using the software JMP 16, and the experimental points can be seen in Figure 1(a). Generally, as a rule of thumb, it is recommended that the number of runs (numerical experiments) in a LHD would be 10 times the number of the studied parameters (factors). In this case it would be equal to 30 runs. However, the software developer recommends starting with a smaller number of runs and testing how it fits and only if necessary, augmenting the design. So, for this preliminary study, we decided to start with 15 runs.

The numerical experiments were conducted through a CFD code namely Fire Dynamics Simulator (FDS) for dwellings with the internal size of a full-scale ISO 9705 room exposed to different wind speeds (varying from 1 m/s to 10 m/s), wind directions relatively to the fire dwelling opening (0° to 180°, where 0° corresponds to the wind blowing in the negative y direction (back wind) and 180° on the positive y direction (front wind)), different separation distances (SD) were tested, from 0.5 m to 3 m.

The software FDS is a free and open source computational fluid dynamics (CFD) model, developed by the National Institute of Standards and Technology (NIST) and VTT Technical Research Center of Finland, which resolves the fluid dynamics problem by solving the Navier–Stokes equations adapted to buoyancy driven low Mach numbers (Ma < 0.3), using a second order scheme in time and space. In this study, the default FDS turbulence and combustion models were applied and the Radiative Transfer Equation (RTE) was solved through the Finite Volume Method (FVM) with a gray gas model. More information about the mathematical model solved by FDS can be found in McGrattan et al., 2020a.

2.1 Problem statement and numerical modeling

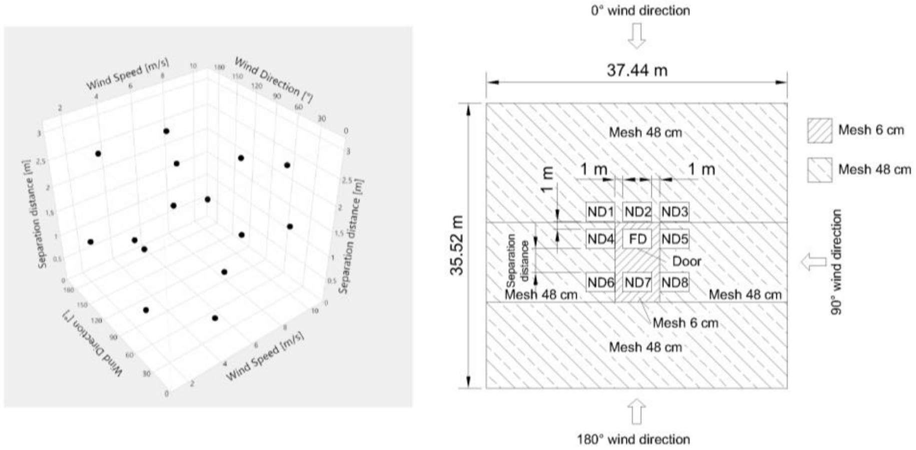
The dwellings' geometry used in these simulations corresponds to a full-scale standard ISO 9705 room (internal dimensions 2.4 m (W) × 3.6 m (L) × 2.4 m (H)) with a doorway of 0.8 m (W) × 2 m (H) in the middle of the larger wall (front wall), similar to the geometry that has been used in several studies of informal settlement fires. The fire dwelling walls were modeled as asbestos cement (thermally-thick) sheets, materials usually found in informal settlement dwellings. The thermal properties of the materials applied to the compartment solid boundaries in the study were obtained from Drysdale (2011) and are conductivity ($k = 0.15$ W/(m·K)), specific heat ($c_p = 1050\ \mathrm{J/(kg \cdot K)}$), density ($\rho = 577\ \mathrm{kg}/m^3$) and thickness ($\delta = 13\ \mathrm{mm}$). The boundary emissivity for both cases was assumed constant and equal to 0.94.

To represent the influence of other dwellings an array of 9 dwellings was modeled, with the fire dwelling (FD) in the middle, as presented in Figure 1 (b). The neighboring dwellings were modeled as inert solids with geometry similar to the fire dwellings, but with no openings; this was made to simplify the model, allowing the use of a coarser mesh (48 cm) in the regions where there are no fire or measurement points. This reduces considerably the computational time required, and suffices for a preliminary study. The domain layout and mesh resolution can be found in Figure 1 (b).

The fire source was modeled by means of a simple pyrolysis model of a wood crib placed at the back of the compartment, using the ignition temperature model for pyrolysis, similarly to previous works of Lemmertz et. al., 2022 (under review) and Beshir et al., 2021. The Pine wood properties used in the fire source modeling are presented in Table 1. The pine wood's bulk density was assumed 535 kg/m³, and was adapted to 455 kg/m³ according to the method proposed by Kallada Janardhan and Hostikka, 2019. The heat release rate per unit area (HRRPUA) of the pine wood was obtained from the cone calorimeter study conducted by Wang et al., 2020, under the heat flux of 75 kW/m², with a peak HRRPUA of 111 kW/m^2.

The geometric characteristics of the corrugated asbestos sheets and the poor construction of informal settlement dwellings cause leakages. These leakage areas are substantially smaller than the mesh resolution, so for its modelling the HVAC function in FDS has been used. For the long walls the leakage area was assumed as 0.03187 m² and for the short walls 0.02125 m^2.

All the simulations were run until 300 s and reached the post-flashover steady state fire condition before 275s. The software FDS produces transient results, that present some oscillatory behavior caused by the turbulence, for this reason, all results presented here were obtained through a time average between 275-300 s, which corresponds to the steady state post-flashover fire condition.



(a) (b)

Figure 1 – (a) Experimental points (b) Domain layout and mesh resolution

Table 1 – Pine wood properties for fire source modelling

Chemical composition	$C_{3.4}H_{6.2}O_{2.5}$ [Hostikka e McGrattan, 2001]
Ignition temperature	250°C [Bartlett et al., 2019]
Heat of combustion	20MJ/kg [Bartlett et al., 2019]
Soot Yield	0.015 [Robbins e Wade, 2008]
Bulk density	535kg/m³ [Bartlett et al., 2019]
Specific heat	1.3 kJ/kg.K [Bartlett et al., 2019]
Conductivity	0.2 W/m.K [Bartlett et al., 2019]

The atmospheric wind was modeled in FDS as an Atmospheric Boundary Layer through the Monin-Obukhov similarity theory, assuming an aerodynamic roughness length (z0) of 1.0 m, which corresponds to a landscape characteristic of suburbs, villages and forests, and neutral thermal stability. The reference wind speeds are implemented at a reference height of 10 m above the ground, which corresponds to the standard height where the wind parameters are measured in meteorological stations.

2.2 Domain and Mesh resolution

In order to allow an adequate development of the wind field within the numerical domain, it is recommended that any obstructions (i.e. the dwellings) should be kept reasonably far from the domain boundaries [McGrattan et al., 2020b]. For this reason, all domain boundaries were extended outwards 5 times the characteristic height of the buildings (2.4 m), which correspond to a domain extension of 12 m in each direction. Those extensions make the domain considerably large, and using the same refined mesh required by the compartment region would lead to unfeasible simulation's run times. For this reason, coarser meshes were applied outside the burning region. The domain was divided into 10 meshes within 2 levels (5 meshes in each level). The domain dimensions and mesh resolutions applied to level 1 (inferior level) can be seen in Figure 1(b), where the compartment region has a 6 cm mesh resolution and the domain extensions a 48 cm mesh resolution. The meshes in the level 2 (superior level) are similar to those presented in Figure 1(b), however all with 48 cm mesh resolution. It's important to highlight that the domain is tridimensional and the meshes are uniform in the three directions (x, y and z).

Two methods were applied to ensure that the proper mesh resolution was employed in the present numerical simulations. The first one was the analysis of the non-dimensional parameter D^*/δ_x, largely employed for FDS simulations, and the second was the Measurement of Turbulence Resolution (MTR).

It is widely known by the fire safety community that for simulations involving fire plumes, the non-dimensional parameter D^*/δ_x gives a good estimative of how well the flow field is resolved [McGrattan et al., 2020a,b]. The use of this criterion has also shown a good performance on wood cribs simulations in FDS [Zhang et al., 2015]. D^* is the characteristic fire diameter given by Equation (1) and δ_x is the nominal size of a mesh cell.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty T_\infty c_p \sqrt{g}}\right)^{2/5} \tag{1}$$

where $\dot{Q}$ is the heat release rate in kW, ρ_∞ is the ambient air density in kg/m^3, T_∞ is the ambient air temperature in K, c_p is the ambient air specific heat in kJ/(kg·K) and g is the acceleration of gravity in m/s^2.

As suggested in the literature, values of D^*/δ_x of the order of 10 provide adequate grid resolutions [McDermott et al., 2010,Salley e Kassawara, 2007]. Table 2 presents the values of D^* and D^*/δ_x for the three uniform mesh resolutions tested in the compartment region ($\delta_x = 0.12$ m, $\delta_x = 0.06$ m and $\delta_x = 0.03$ m), assuming a HRR of 4000 kW, which is in accordance with the maximum HRR in the simulations.

Table 2 - Non-dimensional mesh resolution criterion analysis

HRR (kW)	D* (m)	D*/δ		
		0.12 m	**0.06 m**	0.03 m
4000	1.67	13.95	**27.90**	55.79

As can be seen in Table 2, all tested meshes were adequate according to this criterion and as a traditional mesh sensitivity analysis was impracticable given the domain size and computational power limitations, the 0.06 m mesh was selected similarly to what was done by other researchers [Beshir et al., 2021,Cicione et al., 2020, Lemmertz et al., 2022 (under review)], where the mesh size selection was made based on the wood crib geometry, in accordance to the method proposed by Kallada Janardhan and Hostikka, 2019. Cicione and Walls, 2021 also conducted a mesh sensitivity study to model the fire spread between multiple dwellings using conditions similar to this study and found that a 0.1 m mesh size was good enough to represent important parameters, such as, hot gas temperature, heat fluxes and the lining materials burning behavior.

To ensure that the selected mesh was adequate to model the problem, especially considering the implementation of the wind field, the Measure of Turbulence Resolution (MTR) was also examined, similarly to what has been done by several authors in the literature. The methodology to calculate the MTR can be found in McGrattan et al., 2020b. The criterion suggested by Pope, 2004, states that the MTR value must be less than or equal to 0.2, which corresponds to the resolution of 80% of the turbulent kinetic energy in the flow field. McDermott et al., 2010 observed that a MTR mean values near 0.2 provide satisfactory results for mean velocities and species concentrations in non-reacting, buoyant plumes.

In this study, the mean MTR was calculated based on 12 points of interest scattered inside the fire dwelling to verify the mesh quality in the fire dwelling region (6 cm mesh size) and based on 16 points outside the fire dwelling (48 cm mesh size), 4 upstream of the dwelling, 4 at each lateral and 4 downstream. The mean MTR values calculated for the study case #6 (wind speed 3.57 m/s, wind direction 0° and separation distance 1.04 m), based on the average of the measurement points, was 0.1 for the compartment region and also 0.1 for the domain extensions, which is much less than 0.2 and confirms the adequacy of the mesh resolution even considering wind in the simulations.

2.3 Numerical model validation

The FDS numerical model for a single informal settlement dwelling in still air condition was validated by Lemmertz et al., 2022 (under review), comparing the numerical results to the experimental results of Beshir et al., 2022 (under review) and was used as a baseline for this study. The model captured the HRR post-flashover accurately with a maximum variation of 16% and the post-flashover gas layer temperature (measured in the top thermocouple of the left front thermocouple tree) matched the experimental results with around 2-3% variation, the radiative heat fluxes from the door at a distance of 2.0 m and 1.6 m from the front wall at 2.5 m height, slightly underestimated and overestimated (±10-15%) the heat flux, respectively. This model was capable to represent adequately the experiment.

3. PRELIMINARY RESULTS AND DISCUSSIONS

In this study three responses were analyzed: (1) the hot gas temperature inside the fire dwelling (FD); (2) the incident radiative heat flux measured in the middle of the front nearest neighboring dwelling's wall (the dwelling placed right in front of the fire dwelling door (i.e. ND7 in Figure 1)) and (3) the average flame horizontal projection length of the flame ejected through the fire dwelling's door. Table 3 presents the experimental matrix obtained through the Latin Hypercube Design and the results obtained for these 3 responses through the fifteen numerical simulations. The results of these responses were analyzed through Gaussian Process using the software JMP 16, to determine which parameters present major impact on the fire spread and if the interaction between these parameters were important (indicating a coupled and complex phenomenon). According to the JMP 16 manual for predicting and specialized modeling [SAS Institute Inc., 2018], the Model Report presented for Gaussian Process analysis shows a functional ANOVA table for the model parameter estimates and it is an analysis of variance table where the variation is computed using a function-driven method.

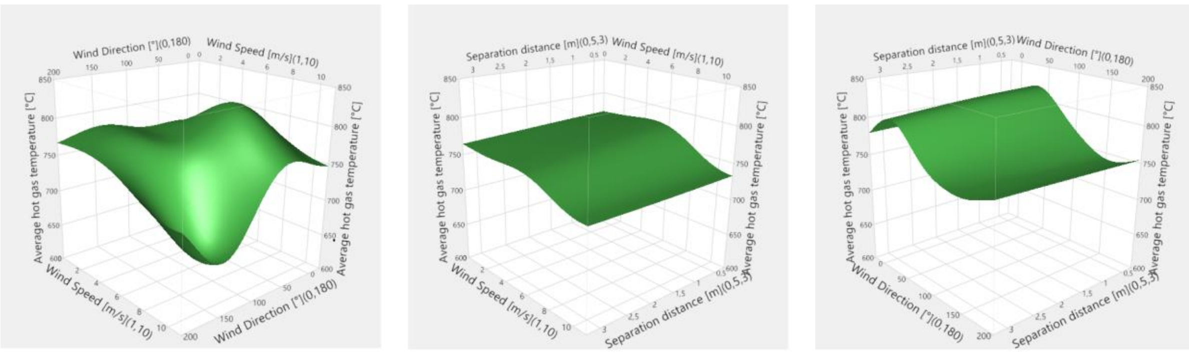
3.1 Hot gas temperature inside the fire dwelling

The average hot gas temperature inside the FD was analyzed, to do this, the gas temperature inside the compartment was measured by four thermocouple trees, one near each corner (distanced 0.25 m from the walls), being each tree composed by 10 thermocouples, at heights 0.6, 0.9, 1.2, 1.5, 1.8, 1.95, 2.1, 2.2, 2.3 and 2.35 m from the floor. The average hot gas temperature was obtained from the time average (between 275-300 s) of the results obtained by the top thermocouples in each of the four thermocouple trees (2.35 m from the floor).

The Gaussian Process analysis fitted using a Gaussian correlation function pointed that the hot gas temperature was more influenced by the wind direction main effect (sensitivity of 0.47 on a scale from 0 to 1) followed by the interaction between the wind direction and the wind speed (0.28) and the wind speed main effect (0.25). The importance of the effect caused by the interaction between wind speed and direction is clearly demonstrated in Figure 2 (a), as we can observe, a combination of high wind speeds and high wind direction angles (front wind) produced the lowest observed hot gas temperatures. Through Figures 2 (b) and (c) we can see that both wind speed and direction have significant effects on the hot gas temperature, however their interaction with the separation distance produce practically no effects.

Table 3 – Experimental matrix and responses results obtained from the numerical simulation runs.

Run	Wind speed [m/s]	Wind direction angle [°]	Separation distance [m]	Average Hot Gas Temperature [°C]	Average radiative heat flux (ND7) [kW/m²]	Average flame horizontal projection [m]
#1	1	128.57	1.57	780.15	17.08	2.64
#2	6.79	64.29	0.68	800.56	43.1	2.79
#3	6.14	25.72	1.93	814.78	15.58	3.17
#4	4.21	154.29	0.86	764.63	31.58	1.12
#5	5.5	115.71	1.75	754.04	16.65	2.41
#6	3.57	0	1.04	793.4	26.16	3.31
#7	8.07	12.86	3	784.98	7.2	1.68
#8	9.36	102.86	2.29	714.15	10.11	1.3
#9	4.86	90	2.82	764.54	7.3	2.8
#10	10	39.57	1.39	777.75	25.84	3.01
#11	1.64	51.43	2.11	769.72	11.13	3.03
#12	7.43	180	2.46	720.98	9.25	1.48
#13	8.71	141.43	1.21	669.22	23.59	1.18
#14	2.93	167.14	2.64	776.63	8.12	2.05
#15	2.29	77.14	0.5	773.05	50.34	1.94



(a) (b) (c)

Figure 2 – Response surfaces for Average hot gas temperature (a) as a function of Wind speed and direction (b) as a function of Wind speed and Separation distance and (c) as a function of Wind Direction and Separation distance.

It was also observed that the temperature increased slightly with the increase in wind speed, until around 5 m/s and then decreased with the increase in wind speed. The increase in the wind direction angle presented a tendency of decrease in the temperature, while the separations distance had practically no effect in the temperature.

The results in Figure 2 (a) make clear the importance of using Design of experiments to analyze the interactions between factors in experiments, since we can observe an important interaction between wind speed and direction, which may not be observed using an one-factor-at-a-time method (OFAT), where all other factors are fixed in a specific level, while the factor of interest is varied.

3.2 Radiative heat flux on the neighboring dwelling

The incident radiative heat flux (RHF) that reaches the dwelling placed right in front the fire dwelling door (ND7) was measured in a point in the middle width of its wall, 1 m above the floor. As the separation distance between the dwellings changes, also the distance between the fire dwelling (FD) door and this measurement point changes (target). This measurement of the RHF is a good measurement to help identifying the risk of fire spread to adjacent buildings, since fire spread frequently happens due to flame impingement and radiative heat fluxes.

The Gaussian Process analysis (using Gaussian correlation function) indicated that the separation distance was the most important parameter to affect the RHF incident on the neighboring dwelling (ND7). This was expected, since increasing the separation distance increases the distance between the fire dwelling (FD) and the target (ND7), decreasing the incident radiative heat flux in this target. The relation between the increase in the separation distance and the decrease in the radiative heat flux incident in the neighboring dwelling is very strong (0.93), for this reason the wind factors (speed and direction) as well as their interactions have just a small effect in the RHF that reaches the ND7. Figure 3 presents the measurements of the incident radiative heat flux in the neighboring dwelling as a function of the separation distance, the relation between the factor and the response is so strong that the tendency can be observed even without fixing the other factors, as is usually done in OFAT analysis. From Figure 3, we can observe that until 2 m, the separation distance had a very important effect on the RHF, however, for larger separation distances the reduction in the RHF still exists, but is less evident.

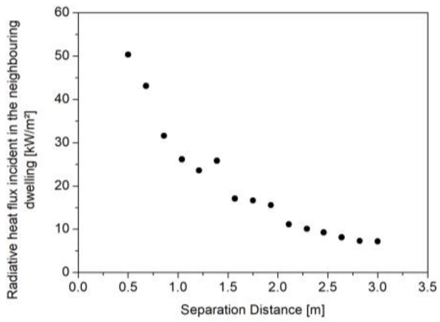


Figure 3 – Measured radiative heat flux as a function of the separation distance

Figure 4 presents the Response surfaces obtained through the Gaussian Process Analysis. As we can see from Figure 4 (b), the interaction between wind speed and separation distance is more significant for low separation distances, presenting higher RHF for low wind speeds and lower RHF for high wind speeds. From figure 3 (c), we can observe that for lower separations distances the higher RHF were observed for side winds (direction angle around 90°) and lower values were observed for front and back winds. For high separation distances the behavior was distinct, increasing with the increase in the wind direction angle.

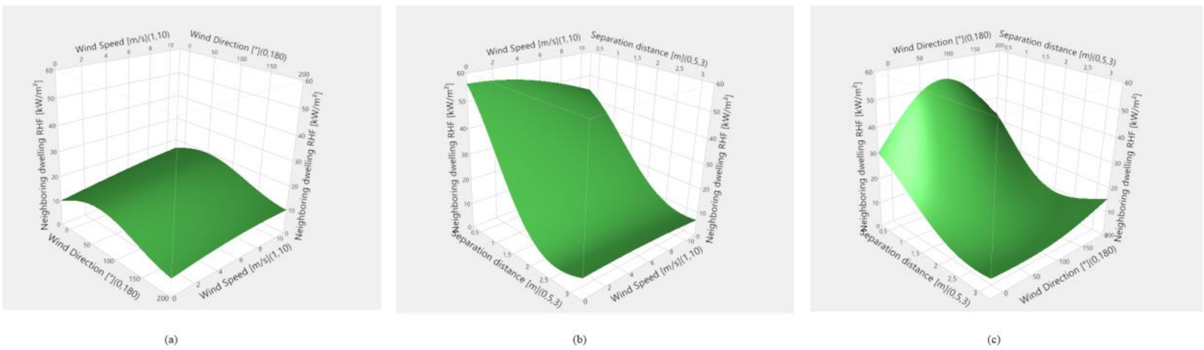


Figure 4 – Fitted response surfaces using Gaussian Process for the radiative heat flux incident in the front nearest neighboring dwelling (a) as a function of Wind speed and direction (b) as a function of Wind speed and Separation distance and (c) as a function of Wind Direction and Separation distance.

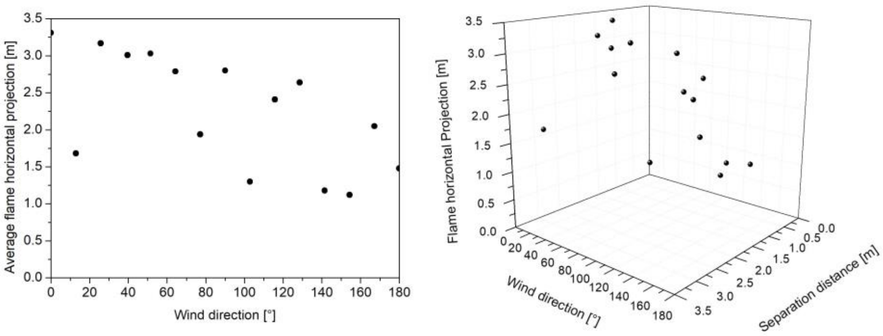
3.3 Average flame horizontal projection outside the door

As discussed before, the flame impingement and the radiative heat flux to the surroundings are both very important mechanisms of fire spread to adjacent structures. For this reason, the average flame length outside the door was measured. The measurements were made using the graphic interface of the software FDS (namely Smokeview) at every 1s from 275-300 s, and assuming a flame edge of 550 °C [Bullen e Thomas, 1979].

The Gaussian Process analysis pointed out that the most important factor that affected the average flame horizontal projection was the wind direction main effect (0.54), followed by the interaction between wind direction and separation distance (0.14) and the wind speed main effect (0.13). The separation distance as a main effect had just a small influence in the flame projection.

The wind direction is important for the flame length since it is capable to deflect the flame backward (for front winds), sideward (for side winds) or even extend its length (for back winds) depending on the wind direction. Also, small separation distances can affect the flame length since there is flame impingement in the neighboring dwelling which in turns blocks the flame, projecting it upwards and making it more subjected to the wind direction effects.

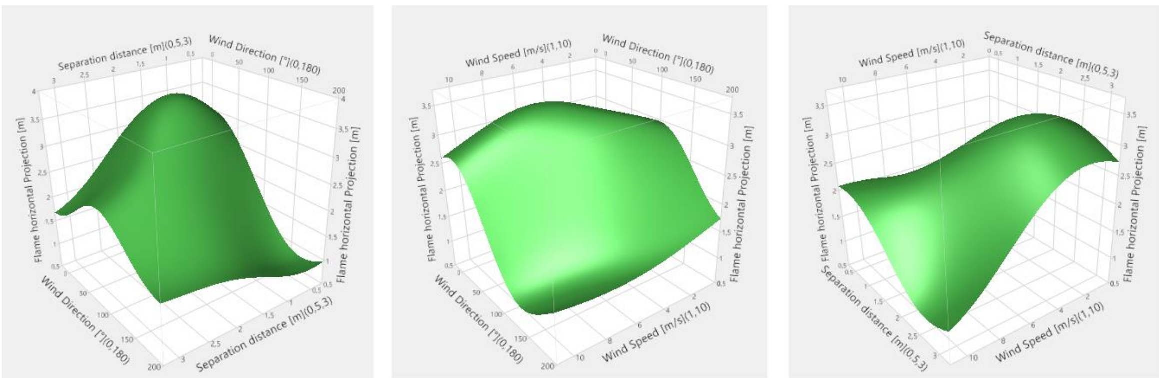
As we can see from Figure 5, the increase in the wind direction angle, decreases the flame horizontal length projection. This happens since small wind direction angles (around 0°) correspond to back winds, which have the effect of extending the flames towards the ND7, producing larger flame projections. The intermediate wind direction angles (around 90°), correspond to side winds, these wind streams flow in the alley between the FD and ND7 and deflect the ejected flame laterally, reducing its horizontal projection in the Y direction (towards ND7). The larger wind direction angles (around 180°), correspond to front winds, which deflect the flame backward in the direction of the fire dwelling, reducing even more its projection.



(a) (b)

Figure 5 – Average flame horizontal projection as a function of the wind direction and as a function on wind direction and separation distance.

Figure 6 presents the response surfaces generated by the Gaussian Process for the Average flame horizontal projection, considering 2 factor interactions.



(a) (b) (c)

Figure 6 – Response surfaces for (a) Flame horizontal projection as a function of Wind direction and separation distance (b) Flame horizontal projection as a function of Wind direction and Wind speed and (c) Flame horizontal projection as a function of Separation distance and Wind speed

From Figure 6 (a) it's clear that the largest flame projections happen for back winds (direction angle around 0°) and smaller separation distances, while for front wind (direction angle around 180°) and small separation distances, the flame projection is the smallest. So, for back wind, the increase in the separation distance decreases the flame projection, while for front wind, the increase in the separation distance increases (but in a less important proportion) the flame projection.

Although in a small degree, the interaction of wind speed and direction (0.06) and the interaction between wind speed and separation distance (0.07) also had some impact in the flame projection, as can be seen in figures 6 (b) and 6 (c). From Figure 6 (b), we can see that the smallest flame projections were observed for the cases with front wind (180°) and high wind speeds, while the longest flame projections were observed for the cases with back wind (0°) and intermediate wind speeds. From Figure 6 (c), we can conclude that for small separation distances, the increase in wind speed increases the flame projection, while for large separation distances the increase in wind speed decreases the flame projection. The largest flame projections were observed for a combination of large separation distances and low wind speeds, while the smallest flame projections were observed for large separation distances and high wind speeds.

4. CONCLUSIONS

This study employed design of numerical experiments to assess the influence of the factors affecting the fire spread in Brazilian informal settlements (favelas) in the presence of atmospheric wind. The effects of 3 parameters (wind speed, wind direction and separation distance between dwellings) was analyzed for 3 different responses (hot gas temperature inside the fire dwelling, radiative heat flux in the front nearest neighboring dwelling and flame horizontal projection ejected through the fire dwelling's door). The experimental matrix was obtained through a space filling design, known as Latin Hypercube Design (LHD) and the analysis was conducted through Gaussian Process.

From this analysis, the following conclusions were obtained:

Hot gas temperature: The parameter that had the most important influence in the hot gas temperature was the wind direction main effect (0.47) followed by the interaction between the wind direction and the wind speed (0.28) and the wind speed main effect (0.27). It was observed that the temperature increased slightly with the increase in wind speed, until around 5 m/s and then decreased with the increase in wind speed. The increase in the wind direction angle also presented a tendency of decrease in the temperature, while the separations distance had practically no effect in the temperature. Due to the interaction between wind speed and direction, a combination of high wind speeds and high wind direction angles (front wind) produce the lowest observed hot gas temperature, while the combination of intermediate wind speeds and low wind direction angles (back wind) produce the highest temperatures.

Neighboring dwelling incident radiative heat flux: The separation distance was the most important parameter to affect the radiative heat flux incident in the neighboring dwelling (RHF), with a very strong influence (0.93), followed by the wind direction (0.03) and the interaction between separation distance and wind direction (0.03). The RHF decreased with the increase in separation distance. This indicates that this is an extremely important parameter to be considered in the prevention of fire spread in informal settlements. As observed, the radiative heat flux in the neighboring dwelling was much less affected by the wind conditions than by the separation distance, however, side winds (direction angles around 90°) presented higher RHF, especially for small separation distances. For high separation distances the behavior was distinct, increasing with the increase in the wind direction angle.

Flame horizontal projection: The most important factor that affected the flame projection was the wind direction main effect (0.54), followed by the interaction between wind direction and separation distance (0.14) and the wind speed main effect (0.13). The wind direction is important for the flame length since it is capable to deflect the flame backward, sideward or even extend its length depending on the wind direction.

As can be observed by the results in this study, some important conclusions can be made by the analysis of the interactions between the studied factors. These tendencies in the results that are observed when analysing the factors interactions may not be observed when using simpler methodologies such as the one-factor-at-a-time method (OFAT), so high risk conditions caused by a combination of factor (factor interactions) may not be identified by these simpler methodologies. The Gaussian Process analysis beside allowing the identification of the important factor that affect certain responses in a complex phenomenon, also allows to create surrogate models to predict these responses in the future, however to obtain high quality models, the experiment should be augmented (the number of experimental points should be increased).

So, the present study demonstrated the applicability of Design of numerical experiments to identify the most important factors, as well as their interactions, that affect the fire spread in Informal Settlements.

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