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Human Factors in the Model of Urban Fire Spread in Madrid (Spain) Focused on the Poor Population

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Abstract: This study aims to highlight the great potential advantages of bringing human and organizational factors (HOF) into the planning for building fire safety in deprived neighbourhoods (whose populations suffer from a lack of safety culture). Physics-based models were used to analyse fire-spread behaviour in a block of the district of Tetuán, located in the centre of Madrid (Spain), in which a high number of substandard dwellings presented a greater fire risk. GIS tools were used to model the real geometry of the buildings. The numerical models introduced more realistic fire load data related to the characteristics of the population living in these dwellings, which is also a parameter that directly affects the probability of ignition, defined as a Poisson distribution. Generally, the results show that vertical fire spread becomes faster for all buildings, which also contributes to increasing the number of affected rooms. The introduction of HOF in these numerical models can help citizens to better understand fire risk in their own dwellings, raising their risk awareness and subsequently improving their resilience to possible fire accidents.

Keywords: human and organizational factors; fire spread; GIS; urban fires; deprived population; resilience

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1. Introduction

Humanity has had to live with potential dangers from time immemorial. However, global trends in demographics, information, politics, warfare, climate, environmental damage and technology have led to entirely new, varied and complex levels of risk [1].

Human and organizational factors (HOF, hereafter) have become paramount in enhancing safety culture in many critical or complex systems. According to the International Ergonomics Association [2], HOF is a multidisciplinary field that refers to the interactions among system components and humans, taking into consideration human behaviours at all levels, such as individual, situational or group, while relating organizational, institutional, cultural or political elements to safety. Nowadays, HOF are widely considered in the design of systems, tasks, activities, environments, equipment and technologies. Furthermore, HOF are also connected to the design of instructional materials and training programs that optimize human and systems efficiency and effectiveness, safety, comfort, and health [3].

People's characteristics such as age, gender, ethnicity, skills or abilities, education, health and socio-economic status, preferences, attitudes, beliefs and readiness influence the safety culture [4]. Previous works have highlighted the importance of identifying and hierarchizing the different factors or actions that allow better safety practices to be able to quantify safety culture in various sectors, organizations and segments of society [5]. Moreover, the type and magnitude of cognitive, sensory, and physical demands placed on people by different equipment or technologies (security, maintenance requirements, institutional support, etc.) constantly vary and evolve over time [3]. Similarly, building regulatory systems have been changing recently, from a functional or performance basis to the introduction of new societal objectives, such as sustainability and climate change resiliency. They are considered a complex socio-technical system (STS, hereafter), in which the interaction of actors, institutions and innovation is essential to manage risk adequately [6].

HOF are key variables when assessing fire risk in the built environment. In fact, after a fatal fire, investigations generally prove that technical errors are not the only cause [7]. Many different entities are involved during a fire event in a building. Building residents, occupants, building owners, staff, emergency responders, etc. may have different responses, affecting the risk. Among others, occupants can delay evacuation trying to reduce the fire, may not obey fire alarms, can store excessive flammable materials or allow unacceptable occupancy levels. These two latter factors are prevalent in substandard housing. They are also related to other characteristics such as the use of hazardous cooking or heating facilities, which make urban fire disasters frequently correlated with poverty [8]. The rate of fires is high in buildings with substandard housing conditions, which has been directly linked to higher levels of deprivation and lower socio-economic status [9,10]. Risk is also a social construct, where values, beliefs, education and knowledge shape the perception of risk [6]. Therefore, this study aims to highlight the great potential advantages of bringing HOF to the planning for building fire safety in deprived neighbourhoods, whose populations suffer from a lack of safety culture.

In this work, fire spread is assessed in a particular block of buildings in a neighbourhood in the centre of Madrid (Spain), where the number of dwellings under substandard living conditions is high. Physics-based models are employed, which include the different modes of spread, developed from physical laws and empirical data [11–14], and allow the introduction of specific conditions related to their residents or occupants. In addition, using geographic information system (GIS) tools, the models can be defined with the real geometry of the buildings that may help citizens improve their safety culture, raise their risk awareness, and enhance their resilience to fire events.

2. Materials and Methods

2.1. The District of Tetuán

A detailed description of the district is included to understand how the characteristics of the dwellings and the population clearly contribute to presenting a higher fire risk.

According to the disposable index ratio between the richest and poorest, Spain is one of the most unequal countries in the EU [15]. This structural inequality in the labour and housing markets produces marginalization and spatial concentration of lower-income people, often with an ethnic minority background [16].

In particular, it is highlighted in [17] that five of the 21 districts of Madrid show clear defined and contrasting socio-economic conditions. They can be grouped into two categories: lower class (Tetuán and Vallecas) and middle and upper classes (Centro, Salamanca and Chamberí). The analysis by districts is based on the rigid spatial segregation and social stratification of Madrid. Interestingly, the topography of Madrid seems to be connected to its wealth. In particular, the district of Tetuán straddles an invisible border with Madrid's financial district. Tetuán is a diverse, asymmetric and intercultural district that presents the following social problems:

- Urban aspects. The urban design of this area hinders coexistence and social cohesion, promoting isolation. The district is characterized by the following: narrow winding streets, not very accessible to pedestrians, public transport or emergency services; unwelcoming public spaces in poor condition; lack of equipment and services; abandoned or unused lots; loss of business activity; decreasing economic vitality. On the other hand, according to the 2011 census, 7.5% of the district's population are living in overcrowded households, which is well above the Madrid average (4.1%). This phenomenon is connected with the average surface area of west Tetuán's housing stock (74.1 m^2), which is substantially lower than that of Madrid (80.7 m^2). The area gathers tiny homes in poor conditions, so it is common to find homes that do not meet

the minimum habitability standards. Furthermore, almost 4% of the houses have less than 30 m^2 of useful surface [18].
- Population structure and coexistence. Approximately 19% of the population is older than 65 years; the over-ageing rate (over-80 population split by over-65 population) is 37%, higher than Madrid city's average (35%). This fact implies the existence of a high number of elderly and sick people: actually, 13% of the district's households comprise people aged 65 and over who live alone. However, the ageing of the population has been somewhat mitigated by the progressive settlement of migrant families, which implies the incorporation of many children and parents of working age into the area. In fact, the concentration of foreign population in the district is 21% (15% average in Madrid city). The main nationalities that reside in this area are from Latin America (Paraguay, Dominican Republic, Ecuador and Venezuela). These two groups' use and understanding of public spaces, the over-ageing indigenous population and the young migrant newcomers, have generated conflicts of coexistence [19,20].
- Low cultural level and school failure. Regarding the academic background, 22% of the population of Tetuán over 25 years old have the mandatory minimum level of studies, and 13% do not reach primary education. If it is disaggregated by sex, 11% of men have unfinished primary studies, while the percentage rises to 15% in women. Regarding the school environment, it is important to highlight the lack of secondary education centres in the district; this implies the need for the displacement of secondary school students (with the subsequent consequences). A significant percentage of young people present stories of school failure, interruption of studies, the need for early incorporation to work to contribute to the precarious family economy, a reorientation towards short training programs, and even a lack of opportunities that leads them to enter the black (and/or illegal) economy. Many young people spend a large part of their free time on the streets. The absence of motivation in studies, leisure activities, education or work, together with other factors such as the lack of identification with the host culture, lead some of these young people to join street groups (Latino gangs, for example) that are "welcoming" to the exclusion and perception of discrimination that these young people feel [19–21].
- Precarious labour market conditions. A total of 26% of Tetuán workers have a temporary contract, and 28% work part-time. The unemployment rate in the district (12%) is higher than the city average (10%). Unemployment is especially pronounced in those over 45 years of age (this range includes 54% of the unemployed, both in the city of Madrid and in the district of Tetuán) and affects women to a greater extent (56% of the total unemployed) than males (44%). The percentage of unemployed foreigners in Tetuán (17%) is higher than that of the City of Madrid (15%). For this group, unemployment affects men significantly more than women. This is logical given that the former used to be mainly engaged in construction, a sector in crisis, while the latter focused on the care sector, a "refuge niche" characterized by the precariousness of its conditions. These types of jobs are exhausting, with never-ending workdays and negatively influence family life and neighbourhood cohesion [19,20].

2.2. Resilience in Urban Planning

At the local, national and international levels, resilience has even become a priority in urban planning, having been included as one of the main objectives in the 2030 Agenda for Sustainable Development of the United Nations Development Programme [22]. This concept has been primarily associated with the urban areas' ability to face or prevent disruptive events such as natural disasters, violence or terrorism [23]. Nevertheless, some authors have introduced a more comprehensive approach, relating resilience to a broader range of social, economic and ecological impacts. In [24], "social resilience" is defined as "the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental changes". Considering that humans are the primary drivers of environmental change, it is crucial to introduce the study of HOF for improving the safety of complex STS. It will create more liveable, sustainable and resilient cities and will reduce their environmental and social impacts across the whole planet. The human factor is undeniably a critical element in risk assessment, since it denotes the human contribution to risk.

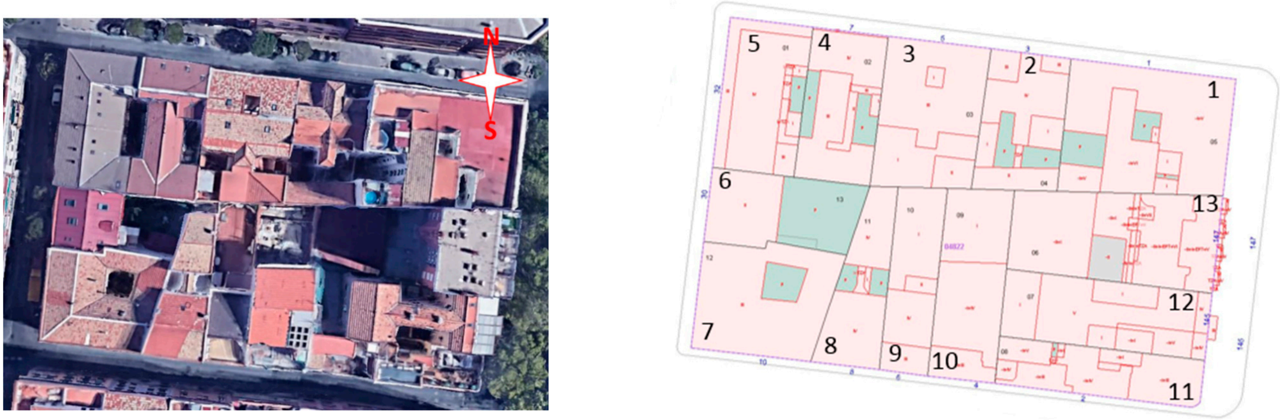
Thus, from a resilience perspective, HOF integration can imply the design of training programs and instruction manuals to ensure that individuals have the information and the needed skills to feel more confident in fire safety culture. Furthermore, a HOF approach can also have input into the broader organizational environment to help design and implement certification protocols and fire safety programs [3].

2.3. Case Study

Fire-spread behaviour in a whole block with 13 different buildings is assessed with the use of physics-based models. This block includes dwellings that actually present substandard living conditions, presenting a higher fire risk mainly due to overcrowding, defective materials, hazardous uses of heating and cooking facilities or unsafe electrical connections (Figure 1). For example, once a fire breaks out, the burning of cables releases a high amount of dioxins, toxic and harmful gases [25].

Figure 1. Deteriorated construction materials and unsafe electrical connections.

The block contains a total of 193 dwellings and is located between Bravo Murillo, Carolinas, Topete and Alvarado streets, as can be seen in Figure 2. The main characteristics of the different buildings are summarized in Table 1. The real geometry and data have been gathered from the Cadastral Electronic Site [26], Figure 2b. The block of buildings has been modelled using the free and open-source software for GIS applications, QGIS [27].



(**a**) (**b**)

Figure 2. Block in the District of Tetuán, Madrid: (**a**) Satellite view; (**b**) Electronic Cadastral Site data: 13 buildings.

Table 1. Main characteristics of the buildings.

Building	Year of Construction	Average Number of Floors	Dwellings Per Floor	Average Surface Area Per Dwelling [m^2]
1	1925	6	5	75
2	1910	4	3	46
3	1920	3	5	47
4	1970	3	6	35
5	1920	4	5	42
6	1915	2	2	54
7	1945	3	4	67
8	1930	4	3	52
9	1988	4	1	104
10	1955	4	3	73
11	1920	4	4	54
12	1940	5	2	104
13	1993	7	4	78

To assess fire spread, the internal geometry of buildings and partition into different dwellings is paramount. An algorithm is proposed in [14], implemented in the GAMA software [28], for buildings division into apartments and corridors, introducing the non-flammable conditions of walls and ceilings of typical constructions in Mediterranean countries. In this work, this algorithm has been deeply modified to big-city blocks that are very common in Spanish cities. In the former case, buildings were separated between green spaces, streets or roads. In our case, the blocks are made up of numerous buildings, with different heights and common walls between them. Thus, the following new features have been implemented in the partition algorithm:

1. For every building, the number of apartments has been defined according to the Cadastral data. This number and distribution are kept for all floors;
2. Entrances from the different streets are introduced;
3. The layout of the building corridors has been adjusted so that they can reach every apartment;
4. Some main apartment doors have been established at the corners of the corridors.
5. All apartments have at least one window;
6. Some isolated storage rooms have been considered for buildings 2, 3 and 10.

Due to the year of construction, some of these buildings present irregular shapes, such as narrow corridors, tiny light-wells or interior airshafts. These particular courtyards can be used by those living on the ground floor or can be shared by the neighbourhood community. As can also be observed in Figure 2a, most buildings have tile roofs, although penthouses and terraces are also common. In the actual work, the top floor of each building has been modelled as a uniform floor to simplify the geometry. Thus, the general partition scheme can be summarized as follows:

1. The minimal bounding rectangle that contains building's foot- print is divided into squared cells of the average room size for that particular building;
2. Main entrances, using the defined cells, are established according to the Cadastral data;
3. From the main entrances, the lengths of the corridors are established so that all apartments can have a main door;
4. Definition of the different apartments by accumulating the rooms around the corridor. A minimum of two rooms per apartment is allowed;
5. Windows are created in the internal courtyards and in the external part of the outer walls;
6. Doors are generated for each apartment.

The internal partition generated for every building is shown in Figure 3. In every building, the consecutive apartments have been highlighted in the same tonal colours.

Corridors are represented in yellow. The small brown squares and the light blue rectangles represent the doors and the windows, respectively. No partition of the internal courtyards has been introduced.

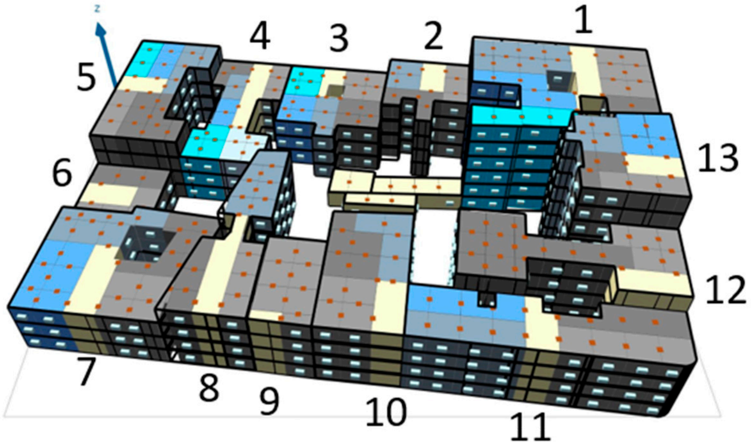


Figure 3. Internal partition of the 13 buildings of the block.

In order to consider the variability of the dwellings, especially focused on the substandard living conditions of some of the buildings, a wide variation around the mean prescribed values of the fire load density has been defined to all rooms, i.e., a variation of 50%. In Spain, the Building Technical Code [29] establishes a mean value of 650 MJ/m^2 for residential dwellings and 730 MJ/m^2 for business premises. The latter prescribed value has been introduced in those rooms on the ground floor that face the street, due to the high number of small shops that can be found in this area. In addition, fire propagation is considered after reaching the fully developed phase, which starts within the range of 25% to 30% of the total room fire load.

Several studies regarding the ignition frequency per floor area depending on the type of building can be found in the literature [30]. The ignition frequency per floor area for small buildings was observed to have a strong dependence on the size of the apartments. Additionally, with the numbers of annual fire occurrences and building floor area, the probability of fire occurrence in different occupancies was estimated in [31]. In this work, with the aim to analyse the influence of human factors, the probability of fire ignition is described by applying a Poisson distribution function to the entire block of buildings. This function is defined in terms of the discrete values of fire load density obtained for each of the rooms of the case study. The fire load is proportional to the room size, and therefore, a much lower probability of fire in those larger rooms, generally associated with better living conditions, is expected.

A wind speed value of 6 m/s is introduced with a wind direction of 60°, which corresponds to the highest frequencies measured in the closest meteorological station (Hortaleza [32]).

2.4. Fire Spread Model

Compartment fires, or fires in enclosed spaces such as rooms, generally follow these steps: ignition, growth, flashover, fully developed phase and decay. If sufficient fuel and oxygen are available, it will continue to grow, and the temperature will rise. Fires with enough oxygen for combustion are fuel controlled or well-ventilated [33].

When all combustible contents are involved in a fire, flashover occurs, and the heat release rate reaches the highest value during the fully developed phase. Then, fire spread follows to other adjacent rooms, upper floors or proximate buildings. Based on the literature [13,14,34] and considering only ignition and radiation mechanisms, fire behaviour highly depends on the characteristics of the room, such as the size of windows or doors.

Thus, the mass burning rate of fuel, $\dot{m}_r$ (kg/s), in a room, based on experimental results, can be calculated as:

$$\dot{m}_r = K_n 0.18 A_o \left(1 - e^{0.036\Omega}\right) \sqrt{H_o (W/D)} \tag{1}$$

with K_n as 1 for rooms with only one window and 1.7 in the case of two [35]; A_o and H_o are the opening area and height, respectively; W and D are the room width and depth, respectively. Additionally,

$$\Omega = \frac{A_T - A_o}{A_o \sqrt{H_o}} \tag{2}$$

where A_T is the total area of the compartment. When ventilation is high enough, fuel is assumed to burn freely. In this case, for example, domestic furniture has a fire duration of about 20 min. Then, for a particular floor area, A_F, and a fire load density, L'', the mass burning rate of fuel is evaluated as:

$$\dot{m}_r = A_F \dot{L}''/1200 \tag{3}$$

For ventilation-controlled fires, the temperature, T_r (°C), inside the room can be evaluated with

$$T_r = T_{ambient} + 6000\left(1 - e^{-0.1\Omega}\right)\left(1 - e^{-0.05\psi}\right) \tag{4}$$

whereas for ample ventilation conditions, the room temperature is calculated as:

$$T_r = T_{ambient} + 1200\left(1 - e^{-0.04\psi}\right) \tag{5}$$

with,

$$\psi = \frac{(A_T - A_o)L''}{\sqrt{A_o A_F}} \tag{6}$$

Finally, the fire phase at time t is obtained with $L_t = A_F L''/\dot{m}_r$. Generally, if $0.3 \leq L_t \leq 0.8$, the fully developed phase is reached, and the fire is allowed to spread to adjacent and upper rooms by direct ignition through flammable doors or by the flames impinging from windows.

When flames are ejected from a window, they may cause ignition in rooms on upper floors or to adjacent buildings. They are generally considered one of the most important mechanisms of fire spread from the fire origin [36]. This spread mechanism depends on the shape and distribution of windows on the building and on the geometry of the emerging flames. The latter can be characterized by the height of the flame tip above the top of the window, the horizontal outward projection of flame from the exterior wall, and its width [34].

Based on [37], the height H of the flame tip above the top of the window and the horizontal projection x of the centreline of the flame without any wall above the window can be calculated as:

$$H = 12.8\left(\dot{m}_r/w_w\right) - h_w \tag{7}$$

$$x = 0.6 h_w (H/h_w)^{1/3} \tag{8}$$

where w_w and h_w are the width and the height of the window, respectively. The flame width is assumed to be equal to the window width, and the flame thickness equal to $2h_w/3$. For free burning conditions, considered when wind speed u is above 5 m/s, slightly wider flames are ejected from the downwind window. In this case, the flame thickness is equal to the window height. Then,

$$H = 23.9 u^{-0.43} (\dot{m}_r/\sqrt{(A_o)} \tag{9}$$

$$x = 0.605\left(u^2/h_w\right)(H + h_w) \tag{10}$$

In addition, the radiation received by adjacent buildings is evaluated based on a configuration factor that depends on the external flame and the adjacent building. These geometrical factors are obtained with the 3D spatial operators of the GAMA software [14,28]. The times for ignition are 1, 7, 10, 25 and 30 min, for 30, 20, 17.5, 15 and 12.5 kW/m^2, respectively.

2.5. Simulation Procedure

The complete simulation procedure can be observed in Figure 4. The input data is highlighted in green. From the Electronic Cadastral Site, the real geometry of the block is introduced in Qgis, which is adjusted with the partition algorithm to satisfy the restrictions commented above. Once the buildings are correctly partitioned, the geometry of every room is introduced to the fire model. Their orientation and openings area are considered for the input of the wind conditions. In the same way, fire load distribution is introduced according to the expected values of substandard living conditions (Section 2.3).

The probability of fire ignition is calculated from the Poisson probability density function, which is generally used for counts of rare events. This is the case of counting the number of fires in a given territory and time period. Fire occurrences are spatially clustered, and human factors and organizational elements such as ownership, human accessibility, population density in overcrowded rooms or the excessive accumulation of materials are important determinants of spatial locations of fires. Thus, the probability of the initial ignition is defined as:

$$\Pr(X = k) = \frac{\lambda^k e^{-\lambda}}{k!} \tag{11}$$

where k (being 0, 1, 2, 3 . . . .) denotes the number of fire occurrences per m^2 within the entire block of buildings.

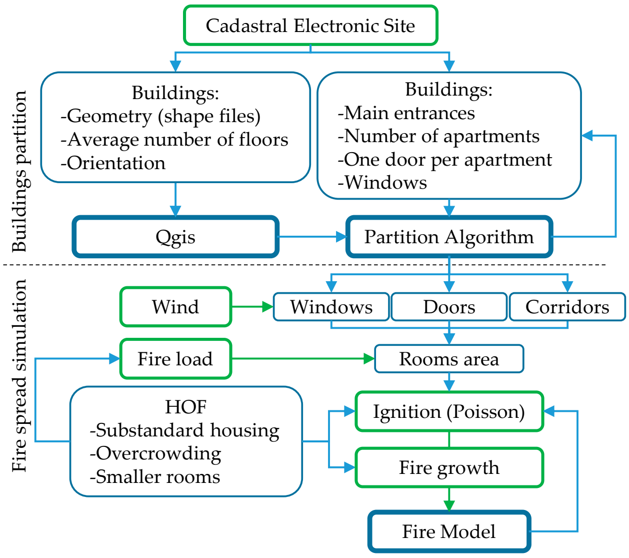
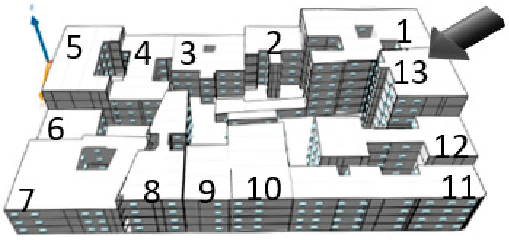
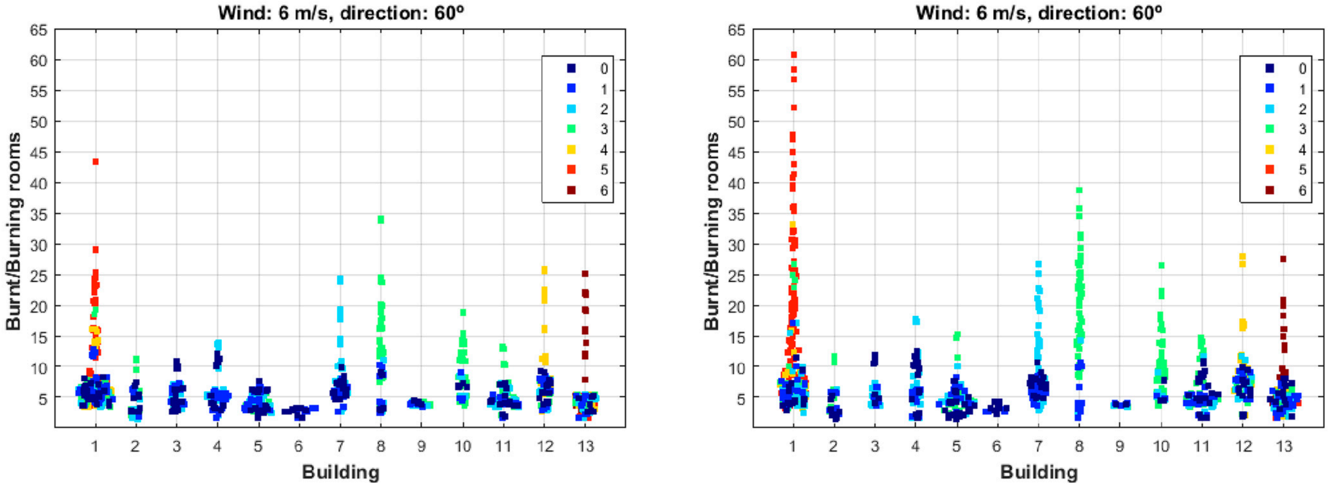


Figure 4. Input data and simulation procedure.

3. Results

A total number of 1000 simulations have been performed, and their results can be observed in Figure 5. Those obtained from a random distribution of fire ignitions in the same case study, with the mean prescribed values of fire load according to the national standards, throughout the total number of dwellings are shown in Figure 5a. The results from a Poisson distribution of fire ignitions with the random distribution of fire load density commented above can be observed in Figure 5b. The final number of rooms that have been completely burnt out or that are still burning after 60 min from ignition are represented. The different markers in Figure 5 represent the highest floor the fire has reached after the period of time, "0" being the ground floor. A bee swarm chart has been chosen to display the results to show the possible repetitiveness of fire spread, as the same amount of affected rooms can be obtained for different initial fire locations. It has to be mentioned that the total number of affected rooms by fire has been chosen as a relevant measure of the damage caused, considering this number will directly impact the life of residents.





(**a**) (**b**)

Figure 5. Burnt and burning rooms for 1000 different fire scenarios: (**a**) Random distribution of fire ignitions/prescribed mean values of fire load density; (**b**) Poisson distribution of fire ignitions/random distribution of fire load density.

Buildings 1, 7, 8, 10, 12, and 13 are the most affected. In fact, buildings 1, 12 and 13 have the largest surface areas (2251 m^2, 1042 m^2 and 2195 m^2, respectively) and the highest number of total rooms (162, 85 and 98, respectively), which confirms the relevant values of fire spread achieved. However, both features of buildings 7, 8 and 10 do not follow those of the former buildings. Specifically, building 8 has a total surface area (623 m^2) below the total mean average (925 m^2). In addition, with only a medium value in the number of total rooms (56), it is the building with the second-highest fire spread. Building 8, from 1930, has a quite irregular shape, which is frequent in the centre of Madrid, where apartments that face internal courtyards are separated by a corridor from those facing the streets. This type of construction increases the number of windows, which enhances the amount of ventilation and, thus, the heat released by the fire, which favours its spread to adjacent rooms or to upper floors. Building 10, despite its regular shape, contains an important number of windows which boosts fire propagation through the rooms, becoming particularly fast to upper floors.

When comparing both cases (Figure 5a,b), the number of affected rooms by fire is clearly increased when introducing the variability in the values of fire load density and the Poisson distribution of fire occurrence. The numerical model is flexible enough to introduce more realistic fire load data related to the characteristics of the population living in these dwellings, which is also the parameter that directly affects the probability of ignition. Fire spread is enhanced in most of the buildings, with special relevance in buildings 1 and 8. It is important to mention how, in building 1, vertical fire spread is also boosted, so that fire reaches the maximum height of the building, i.e., the 6th floor, which might hinder specific emergency and firefighting works.

Fire spread is also increased in buildings 7 and 10. However, it is mainly in the latter where fire spread is more vertical, as an appreciable reduction in the number of fire scenarios within the lowest floors.

No significant differences can be found in buildings 12 and 13. Generally, the results show that vertical fire spread becomes faster for all buildings, which also contributes to increasing the number of affected rooms.

4. Discussion and Conclusions

In this work, fire spread is assessed in a block of a deprived neighbourhood in the centre of Madrid. Due to their year of construction, some of the buildings in this block have irregular shapes, which entails an internal division of small apartments. In addition, a high percentage of the inhabitants of this block live under substandard housing conditions, generally being overcrowded and not meeting the minimum habitability standards. Frequently, excessive storage of flammable materials is observed, mainly caused by the number of persons sharing the same household. These factors have been introduced in the model by three main assumptions. Firstly, a variable fire load, with respect to the design value recommended by the Spanish Technical Code, is introduced. In addition, the fire growth behaviour has been adapted so that the fully developed phase can also be reached in a shorter period of time and consequently enhance a faster fire spread. Finally, the higher risk of the initial ignition is related to the smaller rooms through the Poisson distribution.

The results show that the damage by fire is clearly increased when considering these specific characteristics of overcrowding (Figure 5b), which is common in the district and related to its poorest population. These values are compared with the accepted and prescribed values associated with Spanish society's average socio-economic status (Figure 5a). As can be observed, when considering the conditions of substandard housing in which vulnerable groups reside, the spread of fire is enhanced in most buildings, with a significant increase in the speed of vertical propagation. The latter is especially relevant in the tallest buildings, where the fire is observed to reach the maximum height of the building in a higher number of possible scenarios. According to Figure 5, the map of fire spread throughout the buildings can be directly used in fire risk analysis, since it would help us not only to pinpoint "hot spots" (high fire occurrence probability) but also to identify areas that should be considered for greater attention with respect to fire risk. It also has to be mentioned how the observed and visually inspected living conditions in this district would correspond to a wider variation in the proposed values of the fire spread model herein assessed. Temporary cardboard walls to obtain more rooms, accumulation of blankets and mattresses or the use of fire in the kitchens are frequent.

Safety culture refers to the interaction between the requirements of the Safety Management System and people's awareness based on their attitudes, values and beliefs, and demographic characteristics (such as socio-economic status, age, gender, ethnicity, education and family size). It is possible to integrate HOF from a resilience perspective: (1) fostering a good level of reactivity after an event in order to reduce the probability of its repetition, and (2) being proactive in risk analysis in order to anticipate the right actions to produce and reduce the risks at an acceptable level. Thus, HOF should acquire a relevant status in the analysis of fire safety, inciting policymakers to design specific safety actions and put in place the corresponding training. The demographic variables, when focusing on the most vulnerable, can be used as determining factors to promote fire safety behaviour and lifestyle in urban areas. The perception of the need for an immediate response to fire incidents can be enhanced through implementing collaborative preventive actions, fire safety promotion campaigns and cross-disciplinary efforts [38,39]. Increasing the population's knowledge about fire safety would enable them to better understand the characteristics of fire, the ignition conditions, the consequences of a fire outbreak situation, and the correct methods of extinguishing or evacuating their dwellings.

The study enhances the understanding of the HOF involvement dimension in fire safety behaviour and lifestyle. By coupling physics-based models with GIS tools, this type of fire spread analysis can help to better study possible fire scenarios and assess how fire can seriously damage buildings. With a more realistic fire load distribution introduced in the case study, according to the substandard living conditions, an important increment of damage can be observed.

Moreover, these results are related to the resilient perspective of the HOF integration. The use of these numerical models can support citizens to understand fire risk in their specific real dwellings by raising their risk awareness or even through specific training programs and subsequently improving their resilience to possible fire accidents. Furthermore, emergency services can also use these numerical models as a preventive tool to analyse the most vulnerable urban areas, which have been historically affected by fire incidents. We conclude the study by suggesting that one important task for policymakers might be to help design and implement fire safety education programs in urban neighbourhoods, and to customize these programs according to the socioeconomic characteristics of the population living in different districts.

It is a shared responsibility to strengthen the fire safety condition in urban neighbourhoods, with a special focus on those considered marginal, which are generally exposed to a higher fire risk. Knowledge could heighten their understanding and make a huge difference in their perception of fire safety.

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Nomenclature

Variables	**Definition**
A_o	Opening area (m^2)
A_F	Floor area (m^2)
A_T	Total area of the compartment (m^2)
D	Room depth (m)
H	Flame tip height (m)
H_o	Opening height (m)
L''	Fire load density (kg/m^2)
L_t	Fire phase at time t
T_r	Room temperature (°C)
$T_{ambient}$	Ambient temperature (°C)
w	Room width (m)
$\dot{m}_r$	Mass burning rate of fuel (kg/s)
h_w	Height of the window (m)
k	Number of fire occurrences per m^2
u	Wind speed (m/s)
w_w	Window width (m)
x	Horizontal projection of the flame centreline

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