Review of Fire Risk Factors for Fire Risk Assessment in Urban Areas: The Case of Ahmedabad, India

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Abstract Fire incidents have increased drastically due to rapid urbanization. More than 9000 fire incidents causing large casualties were recorded in 2020, as documented by the India risk survey 2021. Thus, it becomes of utmost necessary to assess the risk associated with urban areas, especially metro cities. The present work critically reviews fire risk assessment studies of urban areas. It involves the review of critical factors affecting the urban fire, Indian standards and code used in practice, factor integration techniques for preparation of risk maps, and optimization of the fire station. The factors affecting fire hazards are bifurcated into satellite data, metrological data, bio-physical data, planning and regulation data, and other ancillary data. Based on the review, the eleven parameters significantly influence the city under consideration are derived. Further, as a case study, the land utilization of Ahmedabad City is studied. The isochrones map is developed for the city, and fire stations are marked. The generated map shows the coverage area by a particular fire station. The map also highlights the area at higher risk where the timely response to calls for service is difficult from the nearest fire stations. This study provides an essential contribution for new researchers, assessing the fire risk of buildings and old structures in urban cities. The study can help administrators, city planners, and civil society organizations plan to provide facilities, minimize fire hazards, and solve related issues to decrease fire risk.

Keywords Urban fire · Fire risk factors

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D. Patel et al. (eds.), *Innovation in Smart and Sustainable Infrastructure*, Lecture Notes in Civil Engineering 364, https://doi.org/10.1007/978-981-99-3557-4_44

1 Introduction

Inadequate infrastructure planning and construction execution relevant to fire prevention and mitigation considerably increase the potential for fire, fire ignition, and spread. Fire affects people, extends to loss of property and resources, and degrades air quality. Due to burn-related injuries or fire, more than 1,80,000 people die every year across the world. More than 95% of these deaths and injuries happen in developing nations, where risks increase due to rapid urbanization. In developing countries, fire policy and mitigation strategies are constrained due to insufficient or inadequate information. Prime Minister of India warned in April 2022 that the temperature is rising rapidly in India, so the Government of India needs to focus on the urban fire issues. According to the India risk survey 2021, in recent years, the fire risk has increased, specifically in urban areas, as India's urban population improved by 1.34%, from 34.9% in 2020 to 35.4% in 2021. And the population density is 464.1 people per sq. mt. Dense urban clusters mean a higher probability of casualties as fires has a domino effect. The India Risk Surveys 2021 has placed India at 4th position in fire incidents. There were over 9300 reported cases of fire casualties with more than 9000 fatalities in India in the year 2020; it makes the severe cause of consideration for sustainable infrastructure (Kaur et al. 2021). According to a survey, around Rs. one thousand crores are lost per year due to fire.

One of the primary reasons for these fire casualties is fast urbanization and the shortage of fire protection norms and protection protocols. According to National Crime Records Bureau records, residential buildings noticed 58% of fire-related casualties in 2019 in preference to 2% in factories. In 2021, there were at least 15 notable cases of fire regarding incidents in COVID hospitals; due to this Supreme Court directed all states to implement fire protection audits of dedicated COVID hospitals (Kaur et al. 2021). In 2016, National Building Code (NBC) suggested that building residents conduct regular fire protection inspections to ensure they meet their standards. However, for commercial buildings, it is far up to statutory authorities so as the State Factory Inspectorate and various outside entities, depending on their nature, to audit for fire safety purposes. In 2020, the Ministry of Health issued regulations requiring certification of third-party fire protection. In December 2020, the Supreme Court instructed all states to conduct fire audits, and the National Disaster Management Authority (NDMA) has set fire protection standards for hospitals and other public facilities.

These two most highly urbanized states, Maharashtra and Gujarat, account for about 30% of the country's fire accident deaths. Ahmedabad is among the largest city in Gujarat and was formerly Gujarat's capital. Ahmedabad is still the judicial capital, as the Gujarat High Court is located there. The estimated population of Ahmedabad is more than 8.1 million in the city. Thus, Ahmedabad is the fifth-largest city and the seventh-largest metropolitan area in India. It is clear that tall buildings are rising, resulting in a growing volume span. High-rise buildings have diverse structures and functions, as well as a variety of facilities, high-density personnel, and complex fire safety measures (Li et al. 2018). The prediction of fire occurrences depends on many environmental and human factors, presenting a nonlinear and complex problem (Jafari Goldarag et al. 2016). Each parameter has its significance on the fire described in the particular paper. The fire risk map will be generated based on geographical information system (GIS) (Castro and Chuvieco 1998).

Suggesting the critical urban fire risk factors requires an in-depth review of the existing fire risk factors of wildfires and urban fires to understand the strength and weaknesses of all the risk factors. The study will also describe each fire risk factor to identify the reason for considering the particular factor for the risk assessment. Developing a fire risk assessment method with referred critical risk factors needs a detailed review of existing risk assessment approaches to get the maximum accuracy of the output of the urban risk assessment. Given these objectives, the study of existing critical fire risk factors and risk assessment methods are presented in the review. For the future scope of the study, the review has also included some methods for urban fire optimization to locate the maximum service coverage area with minimum travel time. For completeness, the review has also provided a methodology for urban fire risk assessment. Further, Ahmedabad City, India, is taken for the case study to assess the city's risk, and maps are generated using Landsat data to understand this study better. The primary outcome of this review is to propose several urban fire hazards and vulnerability factors that can be used for the urban fire risk assessment.

2 Literature Review & Methodology

The review analysed considerable research on wildfires and urban fires to assess the various fire risk factors and suggested urban fire risk hazards and vulnerability factors. However, the current study has reviewed some methods to assign weightage to the critical risk factors to perform the urban fire risk assessment with the aim of developing of detailed risk map that allows for a better response and mitigation of the effects of urban fires.

2.1 Review of Indian Standards and Codes

The Indian standards and codes, such as the National Building Code of India, IS: 11460-1985, IS: 1643-1988, for fire safety in building, during construction, while planning, in temporary structures, etc. These documents provide technical information and guidelines to improve fire safety by specifying the fire safety management, operational management, and emergency rescue operations that should be implemented. Part 4 of the National Building Code of India focuses on fire and life safety. The code specifies construction, occupancy, and protective factors required to minimize the fire's danger to the property and life (Bureau of Indian Standards 2016). IS:11460-1985 is a code for fire safety of libraries and archives which gives details regarding the planning, designing, and construction of library buildings and archive buildings according to the IS: 1553-1976 and IS: 2663-1977, respectively (Bureau of Indian Standards 2005). IS: 1643-1988 is a code of practice for fire safety of buildings (general): exposure hazard covers the necessity regarding the building spacing to provide appropriate protection against the exposure hazard. Exposure hazards express the risk of the spread of fire through the open space in a building (Bureau of Indian Standards 1988). IS: 8758-2013 is a code for fire precautionary measures in constructing temporary structures and pandals. IS: 8758- 2013 focuses on the fire safety of locations, construction, and maintenance of temporary structures and pandals (Bureau of Indian Standards 2013).

Based on the review of referred documents, several fire safety recommendations are provided for temporary structures, permanent structures, technical details, during construction, after construction, etc.

2.2 Fire Risk Factors

Since the primary outcome of this study is to provide urban fire risk factors that can be used to develop a method for urban fire risk assessment. After the extensive literature review, it has been observed that there is a massive necessity for fire risk assessment and the optimization of fire stations in urban areas in India. Also, various primary fire hazard and vulnerability factors affect the fire risk assessment, as described in Table 1.

Table 1 describes the series of fire risk factors that affect the behaviour of wildfires and urban fires. The table also explains how these fire risk factors affect the fire risk and its behaviour. These risk factors are used to analyse the forest and urban areas' fire risk. The fire risk assessment maps are generated based on these critical risk factors.

The review proposes a methodology that needs to be adopted while performing an urban fire risk assessment, as Fig. 1 suggests. The first step is to collect various data that affect fire behaviour. After completing the first step, each parameter should weightage using suitable multi-criteria decision-making techniques. Based on the weightage of the fire risk factors, the risk maps are to be generated using the ArcGIS Desktop software. For the validation of the prepared urban fire risk zone map, the past five years' fire event data can be a map on the fire risk assessment.

2.3 Fire Risk Assessment

Fire risk is the likelihood of the occurrence of fire. Fire incidents are rapidly increasing in the forest as well as in urban areas. Fire causes damage to the environment, people, and valuable property.

The fire risk assessment study has been done for Dhaka city in the GIS framework, which develops the methodology to generate fire hazard factors and risk maps. To

Table 1 Various fire risk factors are as follows

FRF	Description	Sources
FRF1—wind speed	Influence fire behaviour An increase in wind speed can spread smoke rapidly	Cai and Chow (2012), Nelson (2002)
FRF2—Population	The population is among the primary reasons behind several fire incidents Population data can be used to estimate future demand for fire emergency services	Lamat et al. (2021), Kiran et al. (2018)
FRF3—land use land cover	LULC can be categorized into different classes: water body, built-up area, vegetation, open land, forest land, etc.	Lamat et al. (2021)
FRF4—temperature	High temperature leads to drying moisture and influences the occurrence of fire	Bonora et al. (2013), Peacock et al. (1999)
FRF5—slope	In case a fire occurs at the bottom of a steep gradient or slope, it will spread faster upwards as it can pre-heat the imminent fuels with rising hot air, and upward drafts are much more likely to create spot fires	Kushla and Ripple (1997)
FRF6—road network	Fires are generally ignited close to roads in all LULC classes This impact is consistent with previous studies in several ecosystems, which revealed a high spatial clustering of human-caused fire ignitions around accessibility networks	Ricotta et al. (2018)
FRF7—earthquakes	Fires, frequently associated with broken gas and electrical lines, are a general side effect of earthquakes	Tsukagoshi et al. (n.d.), Zolfaghari et al. (2009)
FRF8—ignition sources	Electric sparks, mechanical sparks, static electrical sparks, and lightning	Syphard (2019), Lautenberger et al. (2015)
FRF9—vegetation type	There is a range of vegetation types across India Vegetation type affects the frequency of ignition and time-to-ignition, duration of flaming, and censurability	Ganteaume et al. (2011)
FRF1—cooking	Fire incidents in Indian homes are verified due to cooking. The existence of cooking oils and appliances used for preparing food, along with the existence of liquefied petroleum gas (LPG) as an origin of energy, make it an ideal combination of fire hazards in the kitchen	Jain et al. (2013)
FRF11- MRTS	A major fire in a metro tunnel can cause damage to the infrastructure in terms of economic and life loss. A large number of users are potentially exposed to these risks	Poon and Lau (2007)

(continued)

Table 1 (continued)

FRF	Description	Sources
FRF12—structural material	Effects of fire vary with the different structural materials such as concrete, wood, and steel	Gan et al. (2019)
FRF13—infrastructure	Infrastructure includes the position of gas and fuel stations, industrial zone, residential zone, commercial zone in the city, etc.	Gernay et al. (2016)
FRF14—plot area ratio	Floor Space Index or Floor Area Ratio liberalized population density. FSI also plays a role in restricting the height of the structure. It also affects the space around the building	Bureau of Indian Standards (2016)
FRF15—zones	The zone, residential, commercial, industrial, etc., have different fire risks	

establish a method, different fire hazard zones have been categorized based on past fire incidence. A total of five fire zones are categorized from highly hazardous to least hazardous. Electrical faults cause maximum numbers of fire incidence in Dhaka city. In the less hazardous zone, the cause of the fire is gas, and in the least hazardous Zone, the cause is machine heat, cooking, candles, etc. For risk analysis of fire hazards, an expert system is developed which follows the framework of the 'Fire Risk Assessment Method for Engineering,' proposed by Erik (1992). The fire risk analysis is defined as the result of the potential risk P by the protection level D and acceptance level A. The Fire Hazard Software is used. The software uses graphical user interfaces (GUI) to ease the analysis. The conclusion says that in highly hazardous areas like industrial areas, warning systems, fire extinguishers, warning systems, and automatic sprinklers should be provided (Alam and Baroi 2004).

Another extensive analysis study on urban fire risk was done, and Haikou city has taken it as a case study. The analysis has been done concerning the risk of fire casualty in urban areas, vulnerability, and urban anti-fire capability. The statistics data on fire accidents between 2000 and 2009 says that fire accidents are about to increase and can be more complicated. The analytical hierarchy process (AHP) method has been implemented to analyse urban fire risk. Also, the gray correlation degree method gives weight to each coefficient of parameter or indicator. The weighted sum can get depending on the weighted coefficient, and evaluation correlates with actual indicators. And finally, values of urban fire risk, urban vulnerability, and urban anti-fire capability can be identified. Thus, the research concludes that the gray correlation degree method can be applied for urban fire risk assessment (Zhang 2013).

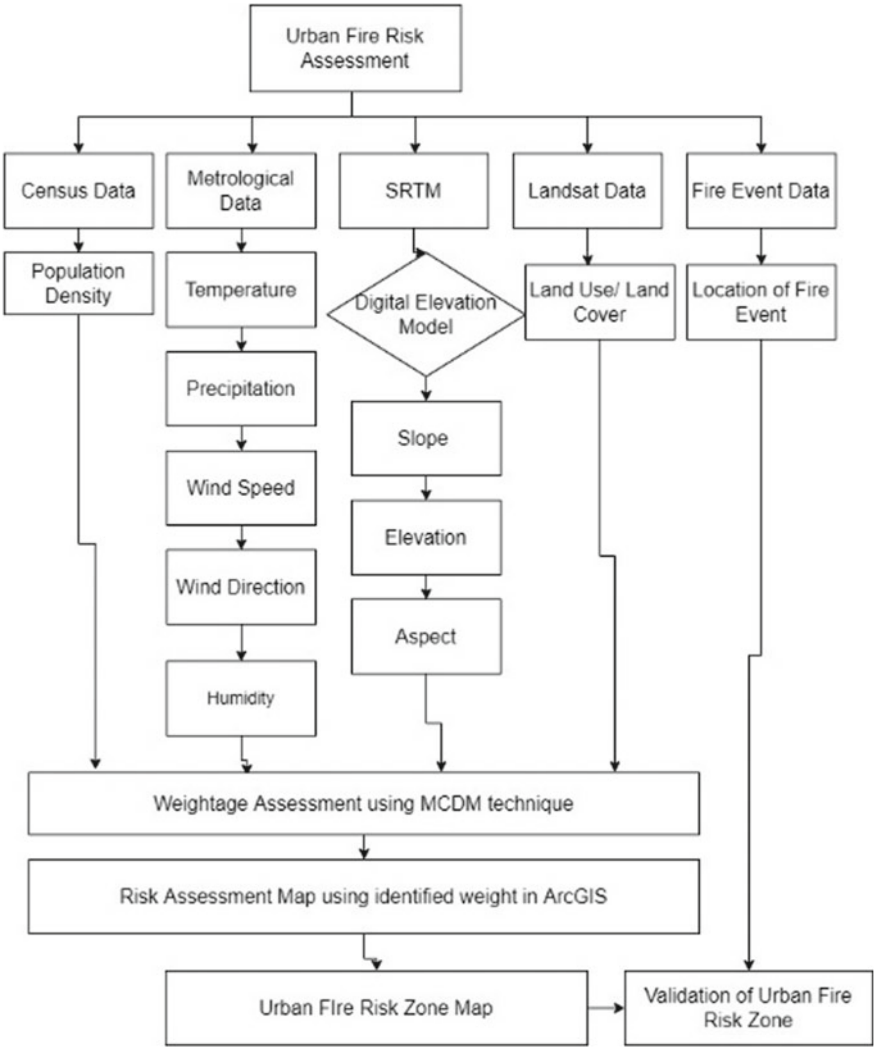


Fig. 1 Critical factors for fire risk assessment

2.4 Optimization of the Fire Station

Well-organized formation of urban fire stations is necessary for a timely response for rescue service at the place of the fire accident. Locating urban fire stations is a multi-dimensional issue that includes many parameters, including population, water availability, fire risk, and the preference of decision-makers (Badri et al. 1998; Church and Li 2016; Murray 2013). The problem associated with fire station location has been considerably studied using the geographical information system (GIS) and mathematical models (Aktaş et al. 2013; Eiselt and Marianov 2015; Liu et al. 2006; Murray 2013; Aktaş et al. 2013; Liu et al. 2006; Murray 2013). The access may reduce the overall time or distance from the fire station to the risk site; the p-median problem (PMP) is widely used (Hakimi 1964). For service coverage, methods such as location set covering problem (LSCP) and maximal covering location problem (MCLP) have been extensively utilized for analysing the location of existing and new fire stations (Church and Revelle 1972; Toregas et al. 1971). Integration of access and service coverage addresses a more extensive range of concerns. Therefore, the bi-objective spatial optimization model develops to consider access and service coverage. The empirical study was done in Nanjing, China, on fire station location planning, and the fire accident data was taken from 2002 to 2013. The proposed spatial optimization model uses the locating set covering problem (LSCP) and p-median problem (PMP). The model aims to decrease the number of fire stations with minimum travel distance or time. The possible location of the fire station is represented in the center of demand areas. In terms of service coverage, various studies have specified that the straight-line distance can be a satisfactory substitute for network travel time, and it has been generally accepted in fire station siting (Cudnik et al. 2012; Eiselt and Marianov 2015; Murray 2013). The conclusion of the research is that the bi-objective optimization model gives the best location of fire station including the access and service coverage.

3 Case Study on Ahmedabad

Gujarat's largest city and the seventh-largest metropolis in India, Ahmedabad, was founded on the eastern bank of the river Sabarmati in 1411 AD as a walled city. The city has traditionally been one of the most important trade and commerce centers in western India. Furthermore, it is one of the major industrial and financial centers in India, contributing about 14% of all stock exchange investments and 60% of state productivity. There are several national, regional, and global institutions of scientific and educational excellence in the city. There are many exquisite monuments, temples, and modern buildings that reflect the city's architectural tradition (Doshi n.d.).

As discussed in the introduction, Ahmedabad is one of the fastest-growing cities in India, with a population above 8 million. So, the fire risk to the people and property is high. Therefore, it is a massive requirement to obtain the critical fire risk factors for the city. And further, there is the requirement of fire risk assessment planning and access and service coverage. Hence, for Ahmedabad City, the factors influencing fire are classified under various categories such as Shuttle Radar Topography Mission (SRTM), metrological data, census data, Landsat data, and planning and regulation data (Fig. 2).

The LULC map of Ahmedabad has created using the QGIS software. To create the LULC map, the Landsat images have been used. The Landsat images are taken from the United States Geological Survey. Data processing has been done on the Landsat image in which the five land use classes have classified. These five land use classes are river, pond, water clogged area (RPWC), residential, commercial, and

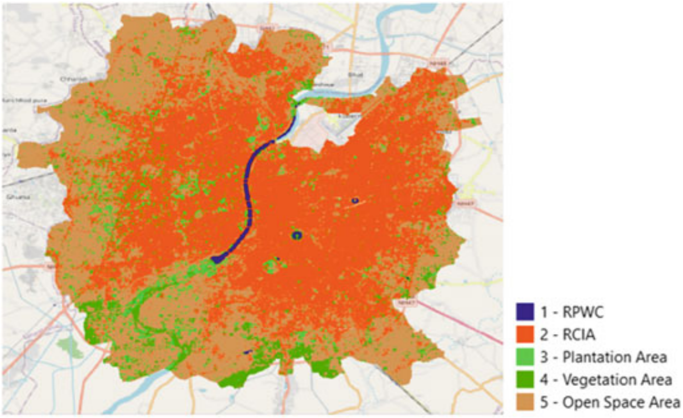


Fig. 2 LULC map of Ahmedabad (RPWC: river, pond, water clogged area, RCIA: residential, commercial, industrial area)

industrial area (RCIA), plantation area, vegetation area, and open space area. Three algorithms are used: minimum, maximum likelihood, and spectral angle mapping. After these, the sieve corrections are done at levels 4 and 8 to get the maximum accuracy of the LULC map. The area under these five different classes is obtained. The map represents that the maximum area of the city is covered by built-up, and the minimum area is under the class of plantation and vegetation area. There are 19 fire stations in Ahmedabad, as shown in Fig. 3.

The data of the fire station is collected from the fire department of the Amdavad Municipal Corporation's fire office in Ahmedabad. These 19 fire stations are located using the latitude and longitude of the respective fire station in the geographical information system. And when further analysis has been done on the city, like service coverage area, it has found a massive problem with access to fire risk sites. Also, there is no fire station in the newly developed areas of the city. The purpose of locating these 19 urban fire stations is to identify the service coverage area of each fire station. To map the service coverage area with respect to the optimum time, the review has taken the flash over time.

Figure 4 represents the natural fire growth over time. In the growth phase, first of all, the material is inflamed by the influence of an event and creates tiny flames of fire. These local flames grow step by step, and their thermal reflex causes more consumption of the blazing material or flame enhancement increases and reaches the flaming temperature. It may develop entirely and achieve the conditions of hot flashes point. In the burn step, when the flames of fire reach the roof, the distribution begins under the roof. Subsequently, flammable gases will reach the flame temperature, and the whole closed space will fire in a very short time (Bagheri et al. 2017).

As modernization is increasing day by day, especially in urban areas. Various modernization factors also affect the fire, for example, the material curtain fabric, furniture, floor material, etc. All these modernization factors are responsible for the

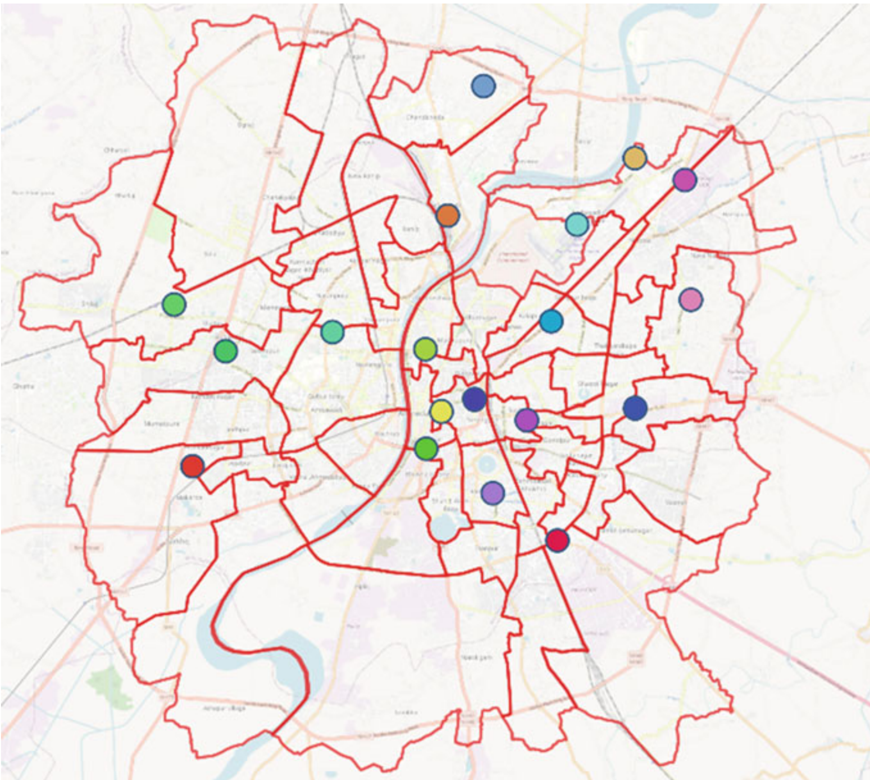
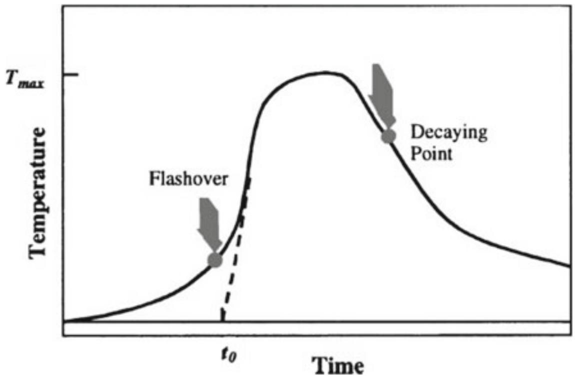


Fig. 3 Location of the fire station

Fig. 4 Natural fire development (Ma and Ma 2000)



change in fire growth. Therefore, there is a requirement to know the flashover time considering the modernization factors. Hence, the study has reviewed new research performed by the Fire Safety Research Institute (FSRI) that illustrates the difference between natural and synthetic furnished rooms in terms of burn efficiency (Anon 2020). It has been determined that natural and synthetic furnished rooms have similar flashover times since FSRI released the original comparison video in 2009 (Anon 2020). The average optimum time for a natural furnished room is greater than 30 min, whereas the average optimum time for a synthetic furnished room is three minutes and thirty-eight seconds. Therefore, the study has taken three different times for service coverage areas to assess the risk to the city. The time taken to map the service coverage area is 2, 5, and 8 min. The service coverage area concerning the time of each fire station is specified in Fig. 5.

ORS tool is used in QGIS Desktop 3.20.2 software to create the service coverage area map for different times. Figures 6, 7, and 8 show the area not included in the service coverage from the fire station. From Fig. 6, the 2 min service coverage area can be seen. And it also shows that significantly less area is covered in 2 min and the

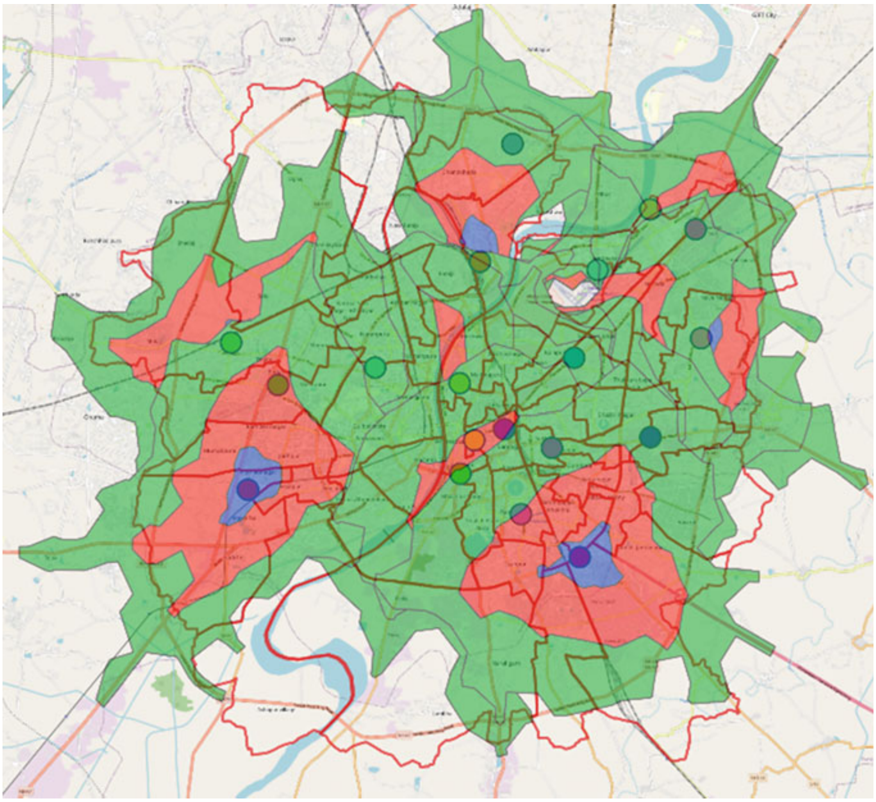


Fig. 5 Service coverage from the fire station

rest of the areas are at risk. Considering the flash over time, a further 5-min service coverage area map is developed. Figure 7 shows that many areas are at risk, such as Sarkhej, Shilaj, Bhadaj, Chanakyapuri, Tragad, Narol Gam, Hanspura, Vastral, and some areas of Vatva GIDC as well. These areas have a very large population, so the people are at high risk. The area also covers historical monuments such as Sarkhej Roja and the most prominent industrial areas like Vatva GIDC, which are at high risk. Further, 8 min is taken as the maximum response time, and it has been observed that the maximum area of the city is covered. However, still, there are uncovered areas such as Ghuma, Lambha, New Ranip, Ognaj, and Adalaj. The population density is also high in these areas, and historical monuments like Adalaj stepwell are at very high risk. Hence, the emergency service cannot reach that area. Therefore, our work focuses on Ahmedabad City to find the optimum location for a fire station with minimum distance, travel time, and maximum service coverage area.

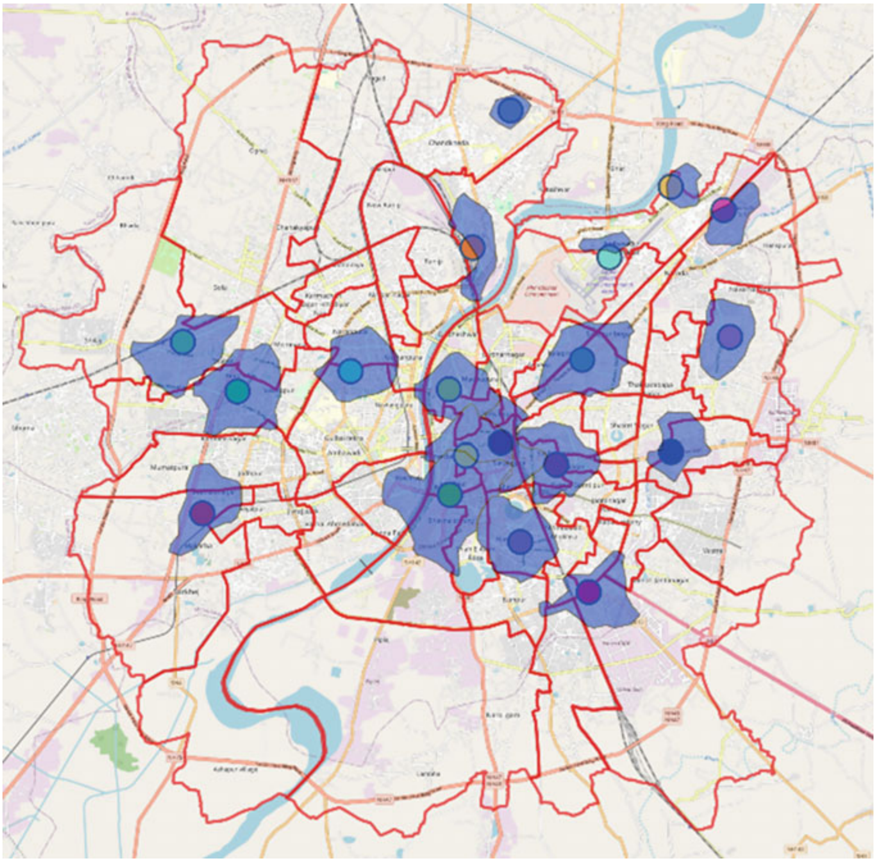


Fig. 6 2 min service coverage

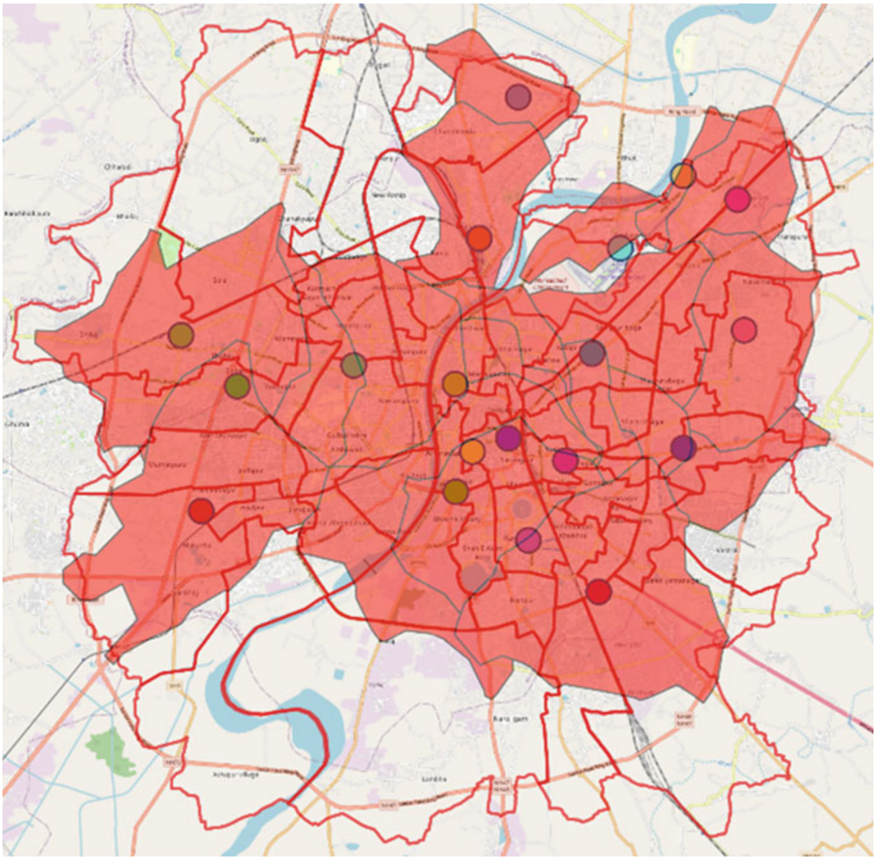


Fig. 7 5 min service coverage

4 Conclusions

In order to understand the importance of fire risk assessment and fire station optimization, a comprehensive review has been conducted on fire risk assessment globally, including many cities such as Haikou, Bangladesh, Dhaka, Bangladesh, and Nanjing, China. Existing methods for urban fire risk assessment and fire station optimization were reviewed to understand their importance of it. The present study has examined the critical factors for urban fire risks. The review concludes the critical risk factors with effective factor integration techniques. The study proposes eleven dominant factors contributing to fire risk in Ahmedabad city. As the maximum area of the city is covered by the built-up, thus the primary critical factors that influence the city's fire risk are land use and land cover) and population. The secondary factors are planning and regulation data such as zone and plot area ratio. Further critical factors are temperature, road network, cooking, ignition sources, MRTS, structural material, and

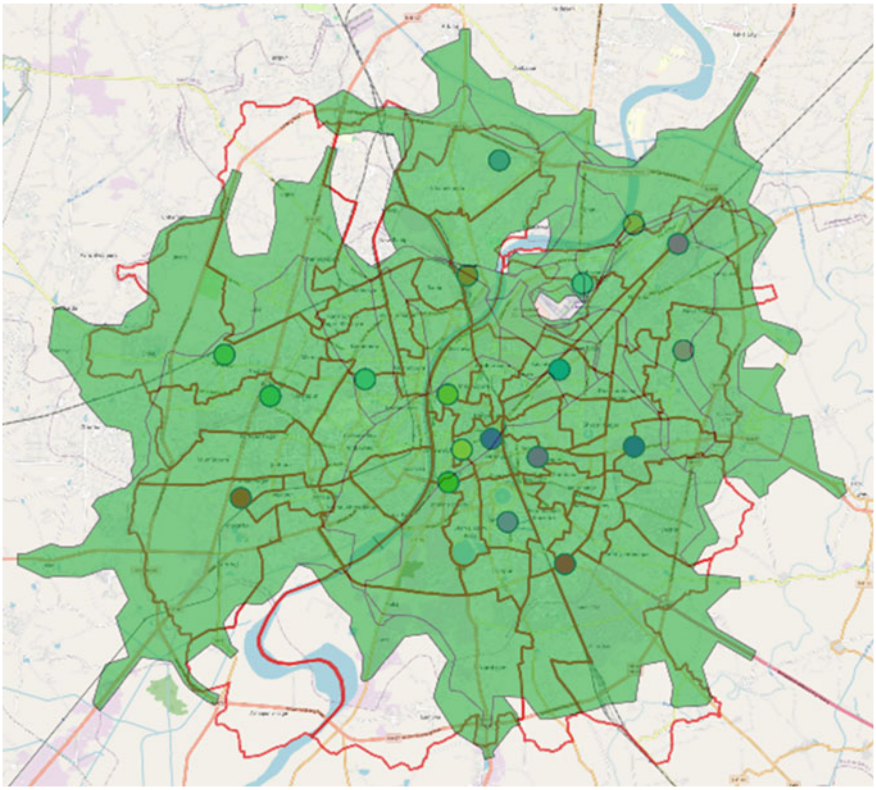


Fig. 8 8 min service coverage

city infrastructure. These critical factors are analysed using the factors integration techniques. In the review of the integration method, it has been observed that most researchers have used the analytical hierarchy process to assign weightage to the critical factors. In addition to improving decision-maker learning, AHP utilizes consistency measures to enhance the efficiency of the decision-making process. Whereas the analytical hierarchy process has certain limitations as the weight of certain critical factors also affects the other requirements. Therefore, to overcome this limitation of AHP, Decision Making Trial and Evaluation Laboratory (DEMATEL) can be used to assign the weightage to the critical factors. The weightage given to the parameters can either be in terms of ranges from 1 to 9 or in terms of severity such as low, moderate, high, and very high. Based on these weighted fire risk factors, urban fire risk map can be developed using fire risk assessment methods. Another objective of the review focuses on the optimization of the fire station.

Ahmedabad is a rapidly growing city in Gujarat. Hence, there is a considerable problem with service coverage from a fire station to the risk site. From Fig. 5, it can be seen that most fire stations are located inside the S.P Ring Road. Thus, it is difficult to reach the risk site if the fire occurs outside the S.P. Ring Road. Hence, Figs. 6, 7, and 8 are developed using the QGIS software. These images represent the service coverage area from the fire station, and it can be seen that there is an area where the emergency service cannot reach even after the 8 min. Therefore, the fire stations must be strategically located to provide maximum service coverage with a minimum possible number of fire stations in Ahmedabad.

5 Future Scope

A further extension of this study can involve evaluating the finding of different multi-criteria decision making and machine learning algorithms to determine the best method for assessing the weightage for fire risk factors. Additionally, location optimization techniques can be studied based on a fire risk assessment map.

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