A GIS-based Framework of Fire Risk Assessment and Emergency Route Planning for Heritage Buildings

Yutong Qiao[1], Chi Chiu Lam[2*], Mun On Wong[3*]

Abstract: This paper presents a Geographic Information Systems (GIS) based framework of fire risk assessment and emergency route planning for heritage buildings in historic centers. The framework addresses the specific challenges faced by heritage buildings, such as fragility, insufficient risk awareness, and inadequate emergency response. In the framework, potential risk factors are first identified and categorized through a literature review, forming a fundamental instrument for assessing the vulnerability of heritage buildings. Next, GIS technology is adopted to visualize the risk levels on spatial maps. Open-source route data is further collected and merged into a virtual prototyping engine to develop an emergency route simulation application. Specifically, a city-level navigable network is constructed to calculate the possible emergency routes between heritage buildings and fire stations using Dijkstra's algorithm. The proposed framework is carried out with a case study of two heritage buildings (i.e., the Ruins of St. Paul's and Kuan Tai Temple) in Macao, which showcases that the framework can indicate quantitative fire risk levels and optimized routes to enhance fire safety and heritage conservation.

Keywords: Emergency route planning; Fire risk assessment; Geographic information system; Heritage building.

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1 Introduction and related works

Heritage buildings in historic centers are valuable cultural resources that allow people to perceive and understand the rich history and culture of a region. These heritages are not only treasured for their art of architecture, but also serve as important landmarks and symbols of cultural identity. The preservation and protection of these heritage buildings face various unique challenges due to their ages, construction materials, and architectural features, in which fires are one of the critical threats that may incur irrecoverable damage. A prominent example highlighting the devastating impact of fires on heritage buildings is the fire incident at Notre Dame in Paris [1]. The fire incident resulted in significant damage to the iconic Notre Dame Cathedral, including the collapse of its spire and the destruction of its roof. The Wan'an Bridge fire incident in Pingnan, Fujian is another recent example of a heritage building on fire [2], leading to the burning and collapse of this Chinese longest wooden arch bridge. These accidents have highlighted the need to implement effective fire risk assessment measures and emergency route planning systems for protecting heritage buildings.

However, insufficient risk awareness and emergency preparedness may exacerbate the vulnerability of heritage buildings to fire incidents. Specifically, various factors may contribute to the increment of fire risks and further affect the fire response operations, such as outdated electrical systems, the presence of combustible materials, and the restriction of emergency routes. To address these issues, Geographic Information Systems (GIS) have emerged as powerful tools in the field of heritage building fire protection. GIS enables the integration, analysis, and visualization management of various data sources, thereby facilitating a comprehensive understanding of fire risks and efficient emergency route planning. For instance, GIS was utilized to present a location map of fire hydrants and fire extinguishers in heritage buildings, which was beneficial for firefighters to quickly identify available fire resources in emergency situations [3]. Moreover, GIS was leveraged to analyze historical fire events in heritage buildings [4]. The fire modes and the outdoor spread trends recorded in previous fire events provided information reference for fire prevention measures. In addition, by considering factors such as building materials, layouts, and ventilation systems, GIS can model and simulate the spread of fires within heritage buildings, providing quantitative results to identify high-risk areas and develop effective evacuation strategies [5].

Although GIS systems have great practical potential in this field, there are still significant research gaps that need to be addressed. First, little attention has been paid to conducting comprehensive identification of fire risks specific to heritage buildings. For the fire risk assessment of heritage buildings, the conventional methods [6] often refer to the standards used in the construction of new buildings and the restoration of existing buildings, while ignoring the unique characteristics and fragility of heritage buildings. Second, the use of geospatial data to improve route planning for heritage buildings in emergency response scenarios is still not fully utilized. A more precise fire emergency route planning strategy for heritage buildings is needed to mitigate the damage caused by fires. This strategy should comprehensively consider the surrounding firefighting resources, such as the fire stations, the locations and quantities of available fire hydrants, the locations of building entrances and exits, as well as the car parking locations for fire trucks.

Therefore, this paper aims to develop a GIS-based framework to address these research gaps and provide a systematic approach to fire risk assessment and emergency route planning for heritage buildings. The objectives of this study are: (1) to establish a fire risk assessment model for heritage buildings and conduct comprehensive assessments; (2) to develop a pathfinding simulation using open-source geospatial data to analyze the accessibility of emergency routes; (3) to conduct an exploratory case with two real-life heritage buildings to assess the applicability of the framework. The proposed framework is expected to provide a quantitative assessment tool and a GIS-driven route simulation to help the urban governance stakeholders gain a better understanding of fire protection and heritage conservation.

2 Methodology

The methodology of this study is divided into two main parts: fire risk assessment and emergency route planning, as shown in Figure 1. The study combines the analysis of risk factors related to heritage buildings and the use of geographic information system technology to develop effective emergency route plans.

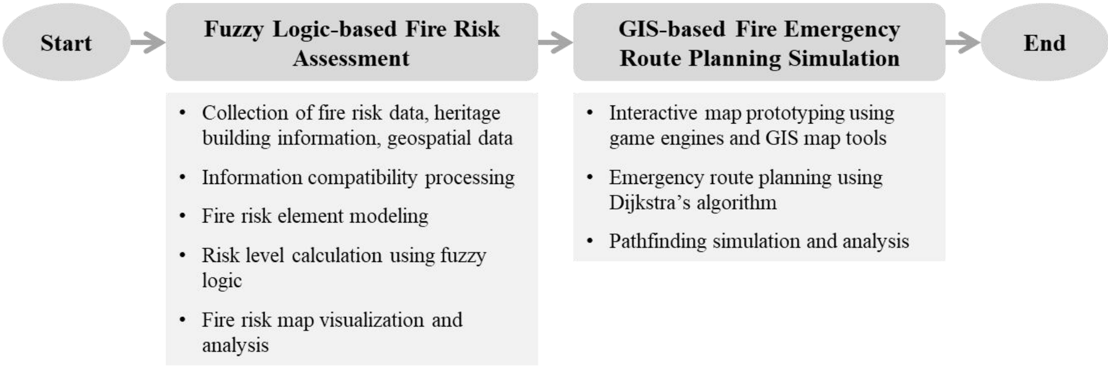


Figure 1. Flowchart of the research

2.1 Fire Risk Assessment

In order to conduct a comprehensive fire risk assessment of heritage buildings, risk element modeling has been preliminarily constructed via a literature review [7]. The risk model consists of four categories, namely the hazards, internal characteristics of heritage buildings, fire safety management, and surrounding environments and traffic, as shown in Figure 2. The hazards category includes ignition sources, flammable materials, and secondary damages to heritage buildings during fire suppression. Regarding internal characteristics of heritage buildings, evacuation routes, indoor fire safety equipment, and internal structures are incorporated. For the fire safety management category, formulation of safety management organizations and predictive warning capabilities are identified as important factors. Apart from the above three categories, this study centers on the assessment factors in the category of surrounding environments and traffic, given that these factors are highly related to geospatial information and can be efficiently collected with the assistance of GIS tools, thereby benefiting spatial analysis and high-risk area identification.

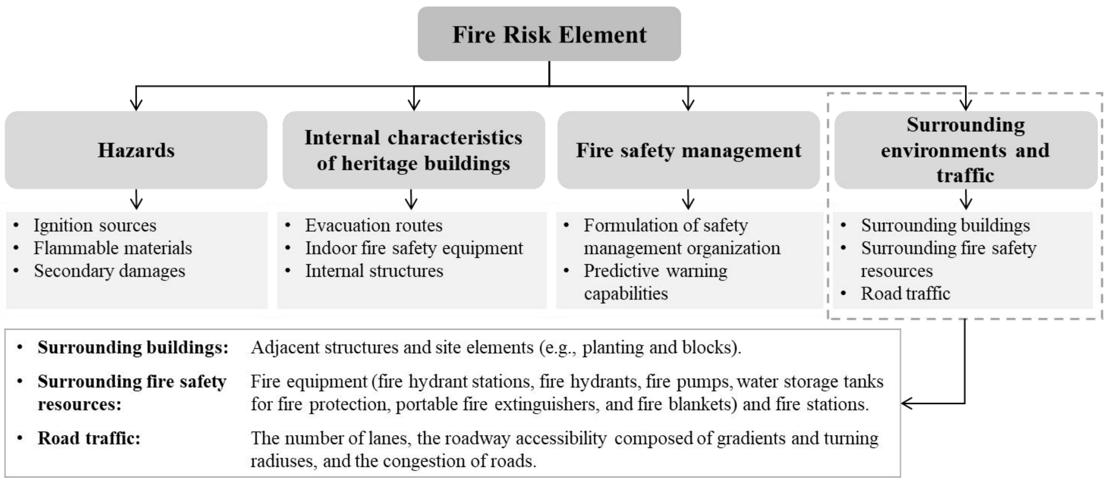


Figure 2. Risk element model

The surrounding environment and traffic of heritage buildings primarily cover three aspects, i.e., the surrounding buildings, surrounding fire safety resources, and road traffic. First, the surrounding buildings refer to the consideration of nearby dangerous structures with a great risk of fire spread (e.g., gas stations), which help quantify the potential influence on the fire outbreak of the targeted heritage buildings and stipulate protection strategies [8,9]. Second, the surrounding fire safety resources focus on the availability and accessibility of fire safety equipment, such as fire hydrants, fire pumps, fire water tanks, portable fire extinguishers, and fire stations. By considering the presence and functionality of these resources near heritage buildings, the assessment can identify areas where fire safety measures may be insufficient, thereby contributing to the overall risk assessment. Third, the road traffic aspect assesses the condition of the emergency roads leading from the fire stations to the heritage buildings. This includes the number of lanes, the roadway accessibility composed of gradients and turning radiuses, and the congestion of roads. By considering these factors, road conditions and terrain can be better understood to identify suitable emergency routes and enhance rescue operations.

After formulating the fire risk assessment model, the relevant information is collected by making use of the GIS databases such as OpenStreetMap (OSM) [10] and Macao geospatial portal [11] as well as the materials captured by the site visit. Next, fuzzy logic [12] is applied to quantify the importance of these risk factors. It is a mathematical technique for dealing with uncertainty and imprecision and can be used to assign weights or importance levels to different risk factors. By employing fuzzy logic, a more comprehensive assessment on the vulnerabilities of heritage buildings can be conducted. Equation 1 illustrates the core process of the fuzzy logic-based assessment, in which the rated values of risk factors ($\boldsymbol{v}$) and their quantified importance ($\boldsymbol{w}$) were calculated to indicate the risk level (R) of the heritage buildings. The parameter n refers to the number of different risk factors. Consequently, the result (R) presents a numerical value that shows the risk levels ranging from 0 (the lowest risk) to 9 (the highest risk) in reference to Saaty's scale [13].

$$R = \boldsymbol{v} \cdot \boldsymbol{w}/n = [v_1, v_2, ..., v_n] \cdot [w_1, w_2, ..., w_n]^T/n \quad (1)$$

Besides, this study also considers whether the assessed heritage buildings have experienced fire incidents. Additional data on historical fire events and fire spread patterns are collected to analyze the causes of fire and the development trend of the situation, gaining a better understanding of the vulnerabilities and potential threats that need to be addressed in heritage buildings.

Consequently, the evaluation results from the risk assessment are visualized on a GIS map using Mapbox [14]. Various fire risks are presented in different colors (Figure 3) to indicate the identified risk areas and high-risk heritage buildings. In this way, the spatial representation of fire risk levels should vividly demonstrate the risk and vulnerability distribution of the heritage buildings.

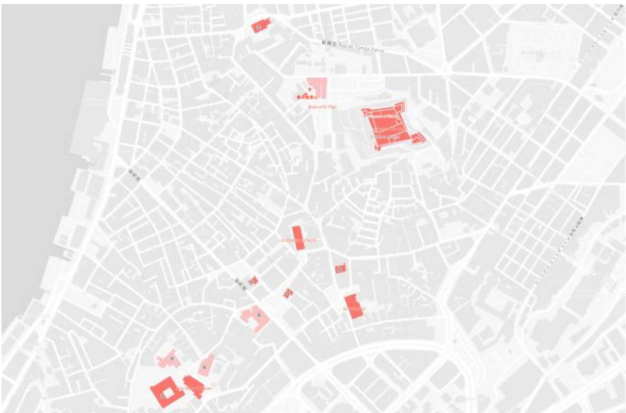


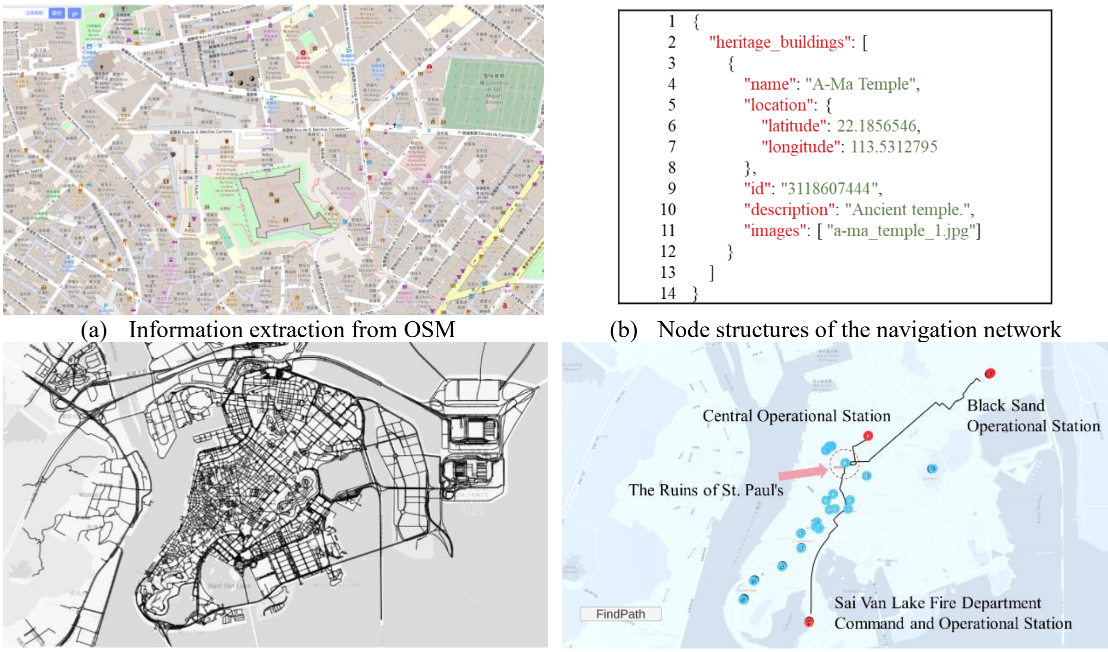
Figure 3. Fire risk map

2.2 Emergency Route Planning

The emergency route planning aims to simulate the shortest routes for fire responders to reach heritage buildings in case of a fire incident. Several steps are involved in the planning simulation. First, the route information, including the attributes of road networks, traffic patterns, and accessibility, is collected from an open-source OSM GIS platform (Figure 4 (a)). The collected road data contains a set of routes, in which numerous geospatial nodes with the coordinates of latitudes and longitudes are grouped sequentially to form the directional route (Figure 4 (b)). In addition, the road data also includes the types of roads and thus indicates the accessibility for the transport of bulky fire trucks.

Next, an interactive navigation network map is constructed. This study adopts a virtual prototyping engine called Unity [15] and a 3D geospatial tool called Mapbox SDK [14] to develop the interactive map. Mapbox SDK provides various base maps, data sources, and customization options for creating dynamic maps flexibly, and Unity is a popular game engine that enables realistic rendering, physics simulation, and user interaction. By integrating Mapbox SDK and Unity together, this study can create a rich and interactive map that showcases the navigation network in a multi-dimensional environment. In particular, built-in scalable base maps are adapted to allow users to manipulate the interactive map and observe both the city-level road networks and the building-level features. On the basis of the scalable base maps, a network-based navigation graph is constructed by processing the nodes and edges of the road data. Self-developed scripts are created to iterate all the route data provided by OSM, determine the connectivity between any two arbitrary nodes, and calculate their distances, forming the weighted edges of the navigation graph. Figure 4 (c) shows the navigation graph of a selected area consisting of heritage buildings and interconnected road networks.

Later, an emergency pathfinding simulation is established. This study combines the interactive map with common shortest pathfinding algorithms (e.g., Dijkstra's algorithm [16]) to calculate the shortest route between fire stations and heritage buildings. A user interface is also developed to visualize the route results and present relevant information about the heritage buildings. As a result, the route simulation is merged into the interactive map, as shown in Figure 4 (d).



(a) Information extraction from OSM

(b) Node structures of the navigation network

(c) Navigation network

(d) Pathfinding simulation

Figure 4. Implementation of route planning simulation

By employing geospatial maps and pathfinding simulations, emergency route calculations are provided in the framework to assist firefighters in deploying resources and conducting fire suppression efficiently. Moreover, the result of emergency route planning can complement the risk assessment. For instance, if heritage buildings are identified to have limited access points or to be structurally weak, emergency route plans need to have special considerations by satisfying the passage of additional fire engines. In addition, if the heritage buildings are located far from the fire stations, the fire risk assessment may prioritize fire prevention measures with enhanced firefighting systems to compensate for the potential delays in emergency response. Together with the risk assessment and emergency route planning, the proposed framework provides a new instrument for stakeholders to make informed decisions on emergency preparedness and proactive protection measures.

3 Case Analysis and Results

The proposed framework for fire risk assessment and emergency route planning was applied to a case study conducted in Macao, with a focus on two heritage buildings in the Historic Center [17]. The Ruins of St. Paul's and Kuan Tai Temple, known for their historical and cultural significance, were chosen as representative examples of heritage buildings in this study. The case study intended to implement the GIS-based framework and assess its feasibility in assessing fire risks and planning emergency routes for heritage buildings.

Through the risk assessment analysis, various risk factors associated with heritage buildings were evaluated. The surrounding environment of the Kuan Tai Temple was found to have a higher risk level (5.57) due to its proximity to densely populated areas, narrow streets, and limited access to emergency vehicles. Specifically, the presence of joss sticks within the Temple posed a considerable risk, given that the open flames are one of the most common sources of ignition in temples. Moreover, the Temple was made of brick and wood, which increased its vulnerability as well as required special firefighting techniques to avoid secondary damage. However, the existing firefighting facilities and evacuation signs equipped in the Temple were relatively fundamental. In addition, historical fire incidents around Kuan Tai Temple indicated a higher likelihood of fire outbreaks in that area.

By contrast, the Ruins of St. Paul's showed a fewer risk level (3.07), with relatively better accessibility and road conditions. The heritage had no open flames or candles and thus gained a lower risk level in the category of potential fire hazard. Also, the heritage had clear escape routes and marked exits, along with fire detection systems and sprinklers for early detection and containment of fires. The surrounding environment was well-maintained, but due to being a tourist landmark, it faced a high flow of people. The management of the heritage was well-formed by following the measures regulated by the Macau Cultural Bureau. Moreover, the historical records demonstrated that the Ruins of St. Paul's had a relatively lower vulnerability as it had undergone recent renovations. These findings highlight the needs for tailored risk mitigation strategies based on the specific characteristics and challenges of each heritage building. The findings also identify highly vulnerable heritage buildings to aid in prioritizing fire safety improvements and strengthen preventive measures.

The assessment result was then integrated into a geospatial map to provide a clear representation of the identified risk areas and high-risk heritage buildings. In this way, stakeholders could easily identify vulnerable areas requiring immediate attention and allocate resources. Figure 5 presents the fire risk map of the two selected heritage buildings.

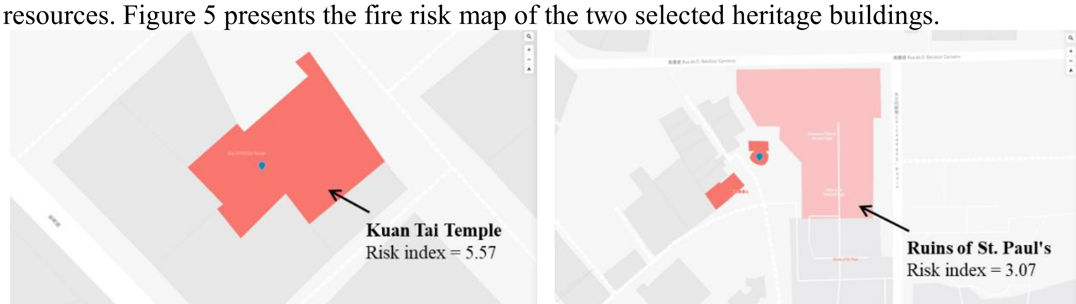


Figure 5. Part of the fire risk map

Next, emergency route planning was conducted to find the shortest routes for fire departments to reach the heritage buildings in case of fire incidents. By integrating road information data, reconstructing the navigation network, and implementing the pathfinding algorithm, the optimal emergency routes were calculated to take the road types and the distances to all fire stations into consideration. The results in Table 1 indicated the response priority of different fire stations to different heritage buildings, in which both the Ruins of St. Paul's and Kuan Tai Temple were closest to the central operation station. From this perspective, the results implied that the daily coordination between the two heritage buildings and the central operation station could be further strengthened in order to better respond to heritage fire incidents.

Table 1. The distance of the shortest route from pathfinding

Heritages	The distance between heritage buildings and fire stations (unit: meters)		
	AP: Areia Preta Operational Station	CO: Central Operational Station	SVL: Sai Van Lake Operational Station
Kuan Tai Temple	2356.02	942.22	1357.44
Ruins of St. Paul's	1969.00	468.58	1777.23

The case study showcased the several benefits of the proposed framework for fire risk management of heritage buildings. The semi-quantitative fire risk assessment incorporated fuzzy logic and GIS mapping to generate a comprehensive understanding of fire risks and vulnerabilities specific to heritage buildings. In addition, the integration of urban geographic data and simulations of emergency route planning offered optimized results that helped reduce potential damage and realize timely rescue operations. Hence, the proposed framework is expected to provide analytical insights for stakeholders in multiple disciplines and facilitate their collaborations in heritage building preservation, urban planning, and fire safety.

Limitations and directions for future investigation were also revealed by the case study. One direction for future work is to verify the effectiveness of the proposed framework by comparing the optimal route generated by simulation with the actual route taken by fire response personnel in fire incidents occurring in heritage buildings. This would require collecting data on fire events and their corresponding routes, and evaluating the consistency and deviation between the simulated and actual outcomes. Another direction is to merge additional data sources, such as historical records and cultural heritage information into the framework to enhance its applicability for tackling the distinct challenges faced by heritage buildings, such as structural complexity and limited accessibility. Moreover, the dynamic nature of urban environments, including the changing traffic patterns, real-time traffic data, urban development, and population density fluctuations, should also be considered in future work to enhance the accuracy and adaptability of the framework over time.

4 Conclusion

In this paper, a GIS-based framework for fire risk assessment and emergency route planning for heritage buildings is presented. The framework addresses the research gaps in fire risk assessment specific to heritage buildings and the limited use of urban geographic data in emergency route planning. It encompasses two main components: fire risk assessment and emergency route planning. The risk assessment incorporates the evaluation of heritage building attributes, fuzzy logic-based quantification of risk factors, comprehensive risk assessment analysis, and visualization of results on a geospatial map. The emergency route planning extracts critical route information from OpenStreetMap, reconstructs the navigation networks using a game engine, and further develops pathfinding simulations based on the Dijkstra algorithm to calculate the shortest routes between the heritage buildings and the nearby fire stations.

The feasibility of the framework is evaluated by conducting a case study with real-life heritage buildings in the Historic Center of Macao. The result reveals valuable insights into the specific fire risks faced by heritage buildings and provides a spatial representation of risks and vulnerabilities. Additionally, the application of the GIS-based framework for emergency route planning facilitates the calculation of optimal routes for timely fire emergency response. Hence, the proposed framework serves as an instrument for heritage building stakeholders, including heritage site managers, preservation organizations, and emergency responders, to enhance their fire risk awareness and improve emergency response preparation. Further work focuses on refining risk assessment methodologies and integrating real-time data sources to enhance its practicability and adaptability in emergency situations of heritage buildings.

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