A Framework of Integrating HBIM and GIS for Automated Fire Risk Assessment of Heritage Buildings

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Abstract –

Historic buildings face multi-faceted fire risks that threaten their conservation. A comprehensive fire risk assessment is essential to prevent fires and protect cultural heritage. Conventional practices rely on surveys and site visits, which are inefficient in capturing up-to-date information digitally and analyzing the risk levels quantitatively. This paper proposes a framework integrating Historic Building Information Models (HBIM) and Geographic Information Systems (GIS) to enable automated, data-driven fire risk assessment of historic buildings. The framework consists of two key phases: quantitative fire risk modeling and automated risk assessment. The risk modeling defines unified indicators in accordance with fire safety regulations to quantify the risks exposed to the heritage buildings internally and externally. Both inherent building characteristics (e.g. fire resistance rating) and external spatial characteristics (e.g. adjacent access and spatial separation) were assessed. Next, the automated assessment utilizes HBIM and GIS to extract building and surrounding area information, compute the quantitative risks, and develop an interactive visualization platform to facilitate stakeholders in decision-making. The feasibility of this framework is verified through a case study of Mandarin's House in Macau. The results indicated the framework is capable of quantifying the risk related to fire-resistant materials (0.66), external access (0.75) and separation (0.76). The results demonstrate that the proposed framework could contribute a unified fire risk model quantification method and a BIM and GIS-combined mechanism for automated risk assessment to support the proactive conservation of valuable cultural heritage assets.

Keywords –

Historic Building Information Modeling (HBIM); Geographic Information System (GIS); Fire Risk Assessment; Heritage Building

1 Introduction and Related Work

Heritage buildings carry rich historical and cultural values. However, they still face multiple risks of fire. The combustible building materials and lack of fire protection systems make them vulnerable to fire hazards [1]. In addition, electrical, heating and other systems in these historic structures can become ignition sources due to insufficient maintenance [2]. This renders heritage architecture especially susceptible to fire threats. For instance, the original Church of Mater Dei in Macao was destroyed by recurrent fires in history, leaving only ruins. The Zhengjiao Chanlin Buddhist Pavilion at A-Ma Temple also caught fire again after restoration. This indicates that even refurbished heritage buildings remain prone to fire risks [3]. Comprehensive fire risk assessments are one of the proactive measures to identify underlying fire hazards and evaluate the vulnerability of buildings to fire emergencies, and thus are imperative for fire prevention and heritage conservation.

Effective Fire risk assessment can help determine the fire risk level of buildings and provide guidance for fire protection measures and emergency plans. Fire risk assessment for heritage buildings is particularly challenging, as it involves various factors, such as the building materials, structures, occupancies, firefighting systems, surrounding environments, and access routes. Moreover, heritage buildings may have complex and irregular shapes and sometimes undertake restorations, making it difficult to collect accurate and up-to-date data for fire risk assessment.

Traditionally, fire risk assessment for heritage buildings is mainly based on qualitative methods such as questionnaire surveys, site visits, and expert judgments. These methods heavily rely on human efforts to collect and process the fire risk-related information of the building, such as the combustibility of the materials, the presence of ignition sources, the availability of fire protection systems, and the accessibility of fire vehicles. Then, according to relevant criteria and standards, the fire risk level of the building is calculated and classified.

However, these methods have several limitations. Firstly, fire risk assessment is time- and labor-consuming, prone to errors and uncertainties, resulting in the inefficient acquisition of up-to-date information and inconsistent assessment results affected by assessors' experience. Secondly, there is a lack of comprehensive risk assessment models grounded in regulations and practices to quantify and evaluate fire risk factors for heritage buildings. Thirdly, assessment results are ambiguous, lacking data visualization and user-friendly interactive tools to support firefighting decision-making and planning.

Therefore, there is a need for a more efficient and reliable method for fire risk assessment of heritage buildings [4]. In recent years, with the development of digital technologies such as Building Information Modeling (BIM) and Geographic Information Systems (GIS), new methods have emerged to facilitate fire risk assessment of heritage buildings. BIM is a digital representation of the physical buildings that contain various attributes and parameters such as materials, structures, fire-resistant ratings and space functions, which can help analyze the building's fire hazard [5,6]. GIS is a data management and analysis system that incorporates various spatial information regarding buildings and road networks, such as locations, orientations, distances, and relations, offering rich geographic data of the external environment to support the analysis of the building's fire vulnerability [7,8].

By integrating BIM and GIS, both building internal and external information can be utilized to assess the fire risk of heritage buildings, further providing suggestions for fire prevention measures and emergency plans [9]. However, previous research on the integration of BIM and GIS has mainly focused on route planning and spatial visualization, while their usage for automated and quantitative fire risk assessment is still in its infancy. Many key factors, such as the intrinsic properties of the building and the surrounding terrain features, have not yet been systematically explored. Therefore, there are still many untapped opportunities for fire risk assessment combining BIM and GIS. Moreover, the mechanism of identifying relevant data in BIM and GIS and utilizing the data for risk quantification deserves further exploration in order to establish automated fire risk assessments for heritage buildings.

This paper proposes and validates an integrated historic BIM (HBIM) and GIS framework for automated fire risk assessment of heritage buildings, which can overcome the limitations of conventional methods by improving the efficiency of data acquisition and reducing manual efforts. The framework combines building inherent features from HBIM models and the external space characteristics from GIS to quantify the risk levels of heritage sites. The framework is applied to a case study of the Mandarin's House, a Chinese heritage building in Macao listed in the UNESCO World Heritage Site [3,10]. The results validate that the proposed framework can effectively quantify and visualize the fire risk levels in multifaceted aspects and provide data-driven analytics for fire prevention and emergency management of heritage buildings.

2 Overview of the Framework

The proposed framework of HBIM and GIS-integrated automated fire risk assessment of heritage buildings consists of two phases: quantitative fire risk modeling and automated risk assessment. Figure 1 shows the overview of the framework.

Quantitative fire risk modeling aims to define and quantify the fire risk factors of heritage buildings based on the building parameters from HBIM models and the spatial data sets from GIS. The fire risk factors are divided into two categories: building inherent features and external space characteristics. For each category, a set of indicators is selected and weighted according to the relevant regulations and best practices in the field of fire safety and heritage conservation. Then, risk indices are established as numerical values to calculate and indicate the fire risk level of the heritage building.

The second phase is automated risk assessment, which analyzes and visualizes the fire risk of heritage buildings based on the risk indices. It consists of three steps: HBIM-based internal risk analysis, GIS-based external risk analysis, and automated risk assessment and visualization. The HBIM-based indoor risk analysis leverages HBIM models of heritage buildings to extract data of building components. GIS-based external risk analysis uses GIS data of heritage sites to identify and evaluate the spatial factors that influence the fire vulnerability of the buildings, such as the adjacent structures and firefighting parking routes. Last, automated risk assessment and visualization integrates the HBIM and GIS data and develops an interactive platform to visualize the 3D BIM models, 2D GIS base maps, meshes of neighbor structures, and routes along with the associated risk results. The visualization platform serves as a graphical interface for stakeholders to understand the potential dangers exposed to the heritage buildings and further facilitate fire prevention and emergency management.

3 Quantitative Fire Risk Modeling

In general, factors affecting heritage fire risks can be categorized into four groups, i.e., fire hazards, heritage building characteristics, surrounding environments, and fire safety management [11]. Specifically, heritage building characteristics, including

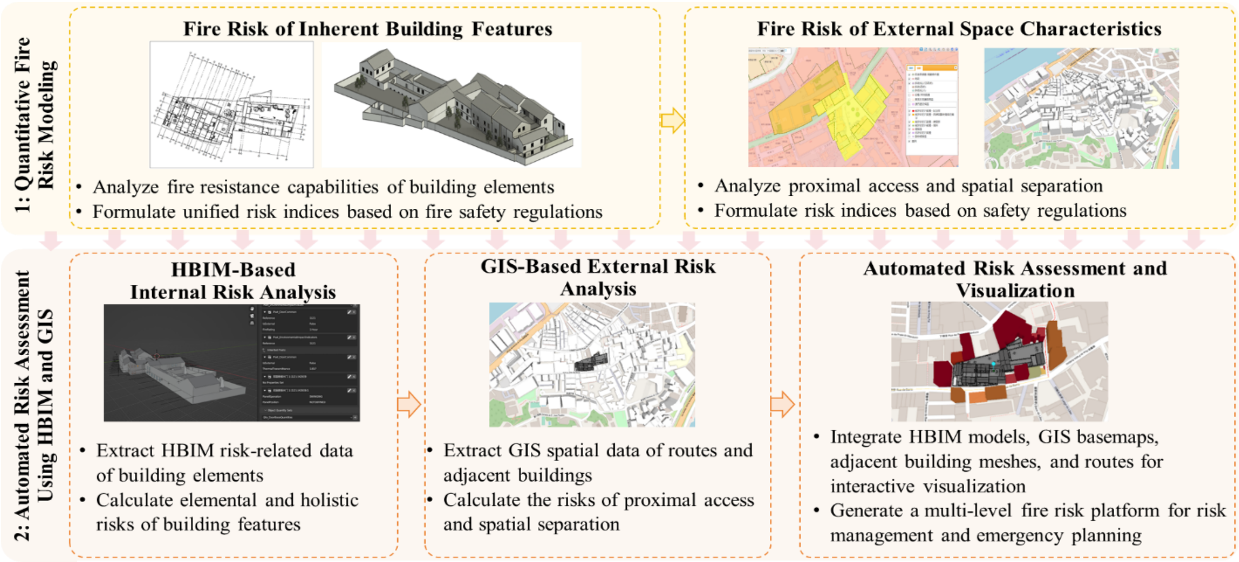

Figure 1. Overview of the framework

building inherent features, means of egress, portable firefighting devices, integrated fire service installations, and water supplies, are primarily related to the intrinsic attributes of heritages, and thus are highly related to HBIM modeling. Also, the surrounding environments cover the aspects of external space characteristics, road traffic, firefighting resources, external water supplies, and surrounding potential dangers, which fit well with the scope of GIS analysis. As an initial exploration, this study would focus on building inherent features and external space characteristics. To quantify the fire risks of these two factors, relevant regulations and codes in different countries and regions are reviewed and referenced [12–15].

3.1 Fire Risk of Building Inherent Feature

Building inherent features refers to the attributes of building elements that affect the fire spread and propagation. In this study, the concept of fire resistance rating (FRR) is employed as the indicator of building inherent features to measure the duration (in hours) of building elements for withstanding fires passively. According to [13], the FRR can be ranged as 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4 and 6 hours, in which a higher value of FRR represents a better fire-resistant performance. To comprehensively quantify the fire risks of entire buildings, the FRR of various building element classes, including walls, roofs, floors, doors, columns, windows, slabs, and stairs, would be obtained individually and then calculated aggregately to form a united fire risk index. For consistency, the study defines the fire risk index to represent the potential risks of the heritage building suffering from fires, with values ranging from 0 (lowest risk) to 1 (highest risk). Correspondingly, the relation between the fire risk index of different building elements and their FRRs is denoted as in Equation (1):

$$R_{ij} = 1 - FRR_{ij}/FRR_{max} \qquad (1)$$

where R_{ij} is the fire risk index of the i-th building element in the j-th class in terms of building inherent features, FRR_{ij} is the fire-resistance rating (unit: hour) of the building element, and FRR_{max} is the maximum regulated FRR (i.e., 6 hours in [13]).

Next, to holistically assess the fire risks of each building element class and the entire heritage building, the weighted fire risk index is introduced by multiplying the individual fire risk index with the volume of the building element, as shown in Equation (2). The volume of building elements is considered as it can reflect the utilization ratio of elements with different FRRs to approximate their fire-resistant performance to the whole building.

$$\begin{cases} V_j = \sum V_{ij} \\ R_j = (\sum R_{ij} \times V_{ij})/V_j \\ R_{BIF} = (\sum R_j \times V_j)/\sum V_j \end{cases} \qquad (2)$$

where V_{ij} is the volume of the i-th building element in the j-th class, V_j and R_j is the aggregated volume and fire risk index of the j-th building element class, R_{BIF} is the holistic fire risk index in terms of building inherent features.

Consequently, through decomposition and weighed aggregation of building elements, R_{BIF} can be utilized to represent the fire-resistance capabilities of the holistic heritage buildings.

3.2 Fire Risk of External Space Characteristics

External space characteristics refer to the spatial conditions that determine the exposure and isolation of heritage buildings and affect the spread and severity of fires, which include proximal access and spatial separation. Proximal access is considered as it affects how the way fire trucks can be accessed and parked near the fire-affected heritage buildings. Spatial separation evaluates whether the heritage building has sufficient fire separation distance to its adjoining buildings to prevent fire propagation across buildings.

To quantify the risks of the proximal access, the quadrilateral sides of heritage buildings would be first investigated. More specifically, according to [14], if the side is directly next to a road with a width no less than the minimum width for emergency vehicular access (i.e., 4 meters in [13]), it is suitable for fire response operation. In this manner, all the quadrilateral sides would be examined to verify their suitability. In case all the quadrilateral sides are not suitable, [15] also regulated that the alternative roads within a closely accessible area (i.e., 30 meters in [14]) serve as a secondary option to assist in emergency operations.

Correspondingly, this study introduces the fire risk index of proximal access to comprehensively take the quadrilateral sides and the closely accessible area into account. As indicated in Equations (3) and (4), the fire risk index is related to the number of suitable quadrilateral sides when there exists at least one suitable side (i.e., $\exists\, w_s \geq W_{EVA}$), otherwise, it would be determined by the suitability of the roads in the closely accessible area (i.e., either $\exists\, w_r \geq W_{EVA}$ or $\forall\, w_r < W_{EVA}$). Hence, the values of the fire risk index of proximal access could be 0 (lowest risk), 0.25, 0.5, 0.75, 0.875, and 1 (highest risk).

$$R_s = \begin{cases} 0, & \text{when } w_s \geq W_{EVA} \\ 1, & \text{when } w_s < W_{EVA} \end{cases} \tag{3}$$

$$R_{pa} = \begin{cases} \sum R_s/4, \text{when } \exists\, w_s \geq W_{EVA} \\ 0.875, \text{when } \forall\, w_s < W_{EVA} \;\&\; \exists\, w_r \geq W_{EVA} \\ 1, \text{when } \forall\, \{w_s, w_r\} < W_{EVA} \end{cases} \tag{4}$$

where R_s is the fire risk index of an individual quadrilateral side of a heritage building, w_s and w_r are the widths of the quadrilateral side and the roads in the accessible area, W_{EVA} is the regulated minimum road width for emergency vehicular access, and R_{pa} is the fire risk index of proximal access.

For spatial separation, the height and the minimum distance of the surrounding buildings directly adjacent to the heritage building is considered. According to [13], the regulated minimum fire separation distance varies. It depends on whether either the heritage building or its adjoining buildings are high-rise. This is detailed in Equation (5):

$$D_{min,i} = \begin{cases} D_{min,H}, & \text{when } \exists\, \{H_h, H_{a,i}\} > H_{hr} \\ D_{min,L}, & \text{when } \forall\, \{H_h, H_{a,i}\} \leq H_{hr} \end{cases} \tag{5}$$

where H_h and $H_{a,i}$ are the building height of the heritage and the i-th adjoining building, H_{hr} is the regulated height in the definition of high-rise buildings (i.e., 27 meters for residential buildings in [11]). $D_{min,H}$ and $D_{min,L}$ are the regulated minimum fire separation distances when at least one high-rise building exists and when no high-rise building exists (in [13], $D_{min,H}$ is 9 meters and $D_{min,L}$ is 6 meters for conservative calculation). $D_{min,i}$ is then calculated as the minimum fire separation distance between the heritage and the i-th adjoining building.

Correspondingly, the fire risk index of spatial separation of each adjoining building is introduced by considering whether the minimum fire separation distance is satisfied or not, as shown in Equation (6). The holistic fire risk index of spatial separation of the heritage building is eventually calculated by averaging the results of all the adjoining buildings, as indicated in Equation (7):

$$R_{ss,i} = \begin{cases} 0, & \text{when } D_i \geq D_{min,i} \\ 1 - D_i/D_{min,i}, & \text{when } D_i < D_{min,i} \end{cases} \tag{6}$$

$$R_{ss} = \sum R_{ss,i}/N \tag{7}$$

where D_i is the actual fire separation distance between the heritage and the i-th adjoining building, $R_{ss,i}$ is the fire risk index associated with the adjoining building, N is the total number of adjoining buildings, R_{ss} is the holistic fire risk index of spatial separation.

Eventually, the total risk of external space characteristics (R_{ESC}) is then calculated as a weighted combination of the risks of the proximal access and the spatial separation using a coefficient φ, as shown in Equation (8). Theoretically, the coefficient φ represents the importance ratio between the proximal access and the spatial separation. However, no quantitative evidence was found in the existing literature for comparing their importance, which in turn suggests a further investigation with firefighting experts to determine the specific values suitable for the local countries or regions. For simplicity, this study adopts $\varphi = 0.5$, assuming that proximal access and spatial separation are equivalently important. As a result, R_{ESC} represents a unified fire risk index that comprehensively considers the potential impacts of proximal access and spatial separation on the heritage building in the surrounding environment.

$$R_{ESC} = \varphi R_{pa} + (1 - \varphi) R_{ss} \tag{8}$$

4 Automated Risk Assessment Using HBIM and GIS

4.1 HBIM-based Internal Risk Analysis

After modeling the fire risk of the building's inherent feature, relevant building data such as the fire-resistant rating and volume of various building elements needs to be obtained for risk analysis. In this study, the HBIM of heritage buildings is utilized as a digital tool to access and manage fire risk-related information. More specifically, Industry Foundation Classes (IFC) [16] is selected for data exchange as it is a standardized open-source data schema widely used in the architecture, engineering, construction, and operations industry. To acquire the fire-resistant rating, the property 'FireRating' in the property set 'Pset_FireRating' defined in the IFC 4 schema is extracted [16]. In addition, volumes of various building elements are obtained individually using the property 'Volume' in the property set 'Pset_BuildingElementPhysical'. To enable automated data extraction, self-developed scripts are compiled using IfcOpenShell and Pandas libraries [17,18] to iterate all the building elements and retrieve their fire-resistant rating and volumes, serving the preprocessed data for further risk quantification.

4.2 GIS-based External Risk Analysis

For the risks of external spatial characteristics, this study adopts OpenStreetMap (OSM) [19] for data acquisition and ArcGIS software [20] for data processing and visualization. OSM contains the critical spatial data regarding adjacent buildings and roads of the heritage building, such as the width of roads, the height and footprint of buildings, and the longitudinal and latitudinal coordinates of common spatial features. Accordingly, the OSM data of the heritage building region is first collected using the Overpass Turbo wizard [21], and then relevant attributes are extracted and compiled into tables. The OSM data and tables are further imported into ArcGIS Pro for spatial analysis and visualization. To calculate the risks of proximal access, the width of roads can be directly retrieved from the OSM data, i.e. 'width' of the 'highway' objects in OSM. Regarding the calculation of spatial separation, the height of the heritage building and adjoining buildings can be also obtained from the OSM data ('height' or 'levels' of the 'building' objects in OSM), and the fire separation distance can be determined by utilizing the geometric boundary of the buildings. Specifically, this study adopts the built-in function named *Near* in ArcGIS to measure the shortest distance between the heritage and its adjoining building. As a result, all the input data required by the quantitative risk models (i.e., Equations (1) – (8)) can be efficiently collected using HBIM models and GIS systems to support further automated risk assessment.

4.3 Automated Risk Assessment and Visualization

The HBIM model and GIS data are integrated into a common environment in ArcGIS Pro. To align the HBIM model to its geographical location, built-in functions (*Join* and *Relate*) are used to connect the 3D IFC model to the 2D base map. Furthermore, layers regarding the roads and 3D meshes of the adjoining buildings are created by employing the OSM data. To enable automated risk assessment, custom Python scripts are created to access the HBIM and GIS data and calculate the risk index of the building's inherent feature R_{BIF} and the external spatial characteristics R_{ESC}. For visualization, the results are further associated with the HBIM model, the GIS basemaps, the road layers, and the 3D adjoining building meshes, in which users can query the attributes and the results by interacting with the graphical representation. Different colors are set to display the severity of fire risks for more intuitive visualization. Eventually, the analytical HBIM and GIS-combined scene are published via ArcGIS Online to allow users to access results and support them in risk assessment and subsequent decision-making.

5 Case Study

5.1 Application to heritage building

To validate the feasibility of the proposed framework, a case study was conducted on a heritage building in Macao. The Mandarin's House is selected, which is a typical Lingnan-style courtyard house built around 1881 [9], with traditional Chinese brick and timber architectural features and intricate decorative details.

A LOD 200 HBIM model of Mandarin's House was created in Revit [19] (as shown in Figure 2). The model included basic architectural elements like walls, columns, doors, windows, and roofs. The HBIM model was exported as an IFC data model, which was further imported into ArcGIS Pro. The OSM data of the surrounding area was also collected and imported into the same geographical scene. Python scripts were developed to extract the relevant building components and properties from the IFC data model and the OSM spatial data. The scripts also computed the fire risk index based on the proposed equations. Specifically, in the calculation of building inherent features, 582 building elements in total were processed to retrieve their FRRs and calculated their elemental fire risk index, e.g., 236 walls (fire risk index: 0.58), 123 doors (0.84), 116 windows (0.92). Regarding the external spatial characteristics, the boundary of the heritage building was simplified as a quadrilateral polygon, in which the width of the four sides was extracted to check if they satisfied the requirements of the minimum width for emergency vehicular access or not. Also, 21 roads within the 30-meter area were also obtained as the secondary options for alternative proximal access. In addition, the fire risk index of the 16 adjoining buildings was investigated to calculate their fire risk indices according to their heights and fire separation distances. To visualize the results, an analytical scene was published into a web scene viewer via ArcGIS Online.

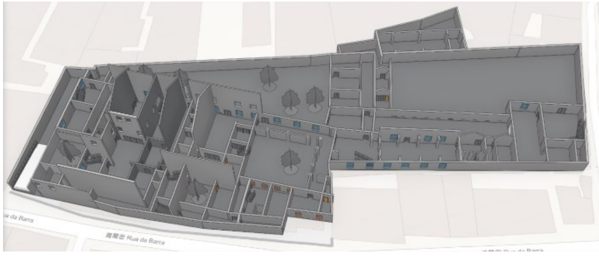

Figure 2. The ground floor of Mandarin's House

5.2 Results and Discussion

The case study demonstrated the application of the proposed framework for a fundamental fire risk assessment utilizing BIM and GIS methodologies. Tables 1 to 3 summarize the quantitative results of the fire risk assessment for both building inherent features and external space characteristics. The results indicate that the fire risk index of the inherent features of Mandarin's House is 0.66, representing a moderate fire risk level. In addition, the fire risk index of diverse building element classes and their volumes are presented in Table 1. The holistic result revealed that walls and slabs notably impacted the overall fire risk, given their substantial volumetric ratios.

Table 1. Fire risk results for building inherent features

Building/ element class	Element volume (m^3)	Volumetric ratio	Fire risk index
1: Column	6.97	0.13%	0.75
2: Door	109.06	2.11%	0.84
3: Ramp	7.56	0.15%	0.75
4: Roof	272.06	5.27%	0.83
5: Slab	1506.62	29.16%	0.78
6: Stair	2.17	0.04%	0.75
7: Wall	3164.26	61.24%	0.58
8: Window	98.03	1.90%	0.92
Mandarin's House	**5166.74**	100.00%	**0.66**

Table 2. Fire risk results of spatial separation

Building name	Building height (m)	Actual distance (m)	Mini. fire separation distance (m)	Fire risk index
1: Wo Fong Building	27.00	0.00	6.00	1.00
2: Lei Heng Building	34.40	0.00	9.00	1.00
3: King Yip Building	32.40	0.00	9.00	1.00
4: No.12-16, Barra Street	32.40	0.00	9.00	1.00
5: No.12, António da Silva Crossing	23.20	0.00	6.00	1.00
6: Wan Seng Building	20.40	0.00	6.00	1.00
7: Weng On Building	20.00	0.69	6.00	0.89
8: Kun Seng Pavilion	35.70	0.74	9.00	0.92
9: Weng Leng Building	20.40	1.64	6.00	0.73
10: Wang Fu Building	31.90	3.00	9.00	0.67
11: Kou Fu Building	31.40	3.00	9.00	0.67
12: No.2, Barra Street	23.20	3.50	6.00	0.42
13: Hou Kio Building	34.00	4.00	9.00	0.56
14: No.5A - 5E, Barra Street	34.00	4.00	9.00	0.56
15: Heng Vo Building	37.40	4.00	9.00	0.56
16: No.4, Barra Street	23.20	4.50	6.00	0.25
Mandarin's House	**11.00**	N/A	N/A	**0.76**

Table 3. Fire risk results of proximal access

Road Name	Road width (m)	W_{EVA} (m)	Fire risk index
Side 1: Barra Street	4.00	4.00	0.00
Side 2: António da Silva Crossing	3.00	4.00	1.00
Side 3: no road	0.00	4.00	1.00
Side 4: no road	0.00	4.00	1.00
Mandarin's House	N/A	**4.00**	**0.75**

Next, the fire risk index of the external space characteristics is 0.76 (proximal access: 0.75, spatial separation: 0.76), indicating a high fire risk level. Specifically, the calculation of proximal access showcased that two out of four sides had no roads next to the heritage site, and among the remaining two sides, only one side satisfied the requirement of road width for emergency vehicular access. Given that there existed a suitable side next to Mandarin's House, this study did not further consider the alternative roads within the 30-meter accessible area. Regarding the spatial separation, half of the adjacent buildings are less than one meter from Mandarin's House, implicating very high risks of fire propagation among these buildings and the heritage site. From another perspective, it is critically challenging to protect the heritage site from fire emergencies in such a high-density city like Macao.

The results of this case study provided a quantitative assessment of the fire risk for Mandarin's House in terms of building inherent features and external spatial characteristics. The results identify the most vulnerable and critical risks of the heritage building, thereby assisting heritage conservation and fire protection parties in prioritizing fire prevention and mitigation measures. For instance, in Mandarin's House, the window elements get a high level of risk (0.92), which suggests that further proactive measures are required to protect these vulnerable assets. In addition, from the perspective of external characteristics, the adjacent buildings that are extremely close to Mandarin's House are all distributed in the northern and eastern regions of the heritage, implicating that additional fire barriers could be strengthened correspondingly (Figure 3). Hence, the proposed framework serves as a data-driven approach to evaluate the internal and external risks of heritage building in an efficient, automated, and quantitative manner. The proposed framework and the HBIM and GIS-combined visualization platform can be potentially expanded to other heritage buildings and further help stakeholders govern and manage the fire risks of historic centers worldwide.

Limitations also exist in quantitative risk modeling and automated risk assessment. First, the scope of this study only focused on building inherent features and external space characteristics, while many other factors such as ignition sources, emergency exits, fire extinguishers, smoke detection systems, firefighting resources, and road traffic have not been systematically investigated. Site visits and interviews with stakeholders could reveal additional vulnerabilities not captured in the models. Second, the risk models had made certain assumptions and simplifications, and the critical parameters are referenced from regional codes and guidelines. Hence, the risk models need to be carefully interpreted to accommodate the relevant requirements when applying them to other countries or regions. In addition, surveys or questionnaires with stakeholders may provide professional judgement to rationalize the risk formulation based on local conditions. Last, it was found that data from HBIM models and GIS systems was occasionally inaccurate or missing, which would adversely influence the reliability of the quantitative risk results. This highlights the necessity of developing solutions for the semi-automated acquisition of geometric data of buildings to guarantee reliable inputs that do not overly depend on the modeler's manual inputs. Therefore, future work should construct more standardized and automated data collection updating mechanisms (e.g., reality capture and aerial survey techniques) to improve the reliability of the result. In addition, more heritage buildings with different types (e.g., churches and palaces) should be considered in future studies to verify the generalizability of the proposed framework.

6 Conclusions

This paper proposes and validates a framework that establishes quantitative fire risk models and integrates HBIM and GIS techniques to develop automated fire risk assessments of heritage buildings. Specifically, the fire risk models cover both internal and external factors, including building fire resistance, proximal access for fire trucks, and spatial separation against fire propagation. By referencing fire safety regulations and practical guidelines, the quantitative modeling of fire risks can effectively provide clear and unified indices to help stakeholders better understand the diverse threats facing heritage sites. Therefore, the fire risk models can form a fundamental instrument to support stakeholders in prioritizing their tasks and allocating resources to mitigate the most crucial risks in a targeted and informed manner.

In addition, an HBIM and GIS-combined mechanism is developed in this study to enable automatic data extraction, risk analysis, and interactive visualization. The information requirements of risk quantification are identified and matched with BIM and GIS data sources, where critical information is extracted programmatically to support the subsequent risk computation. Eventually, an interactive visualization platform is developed to

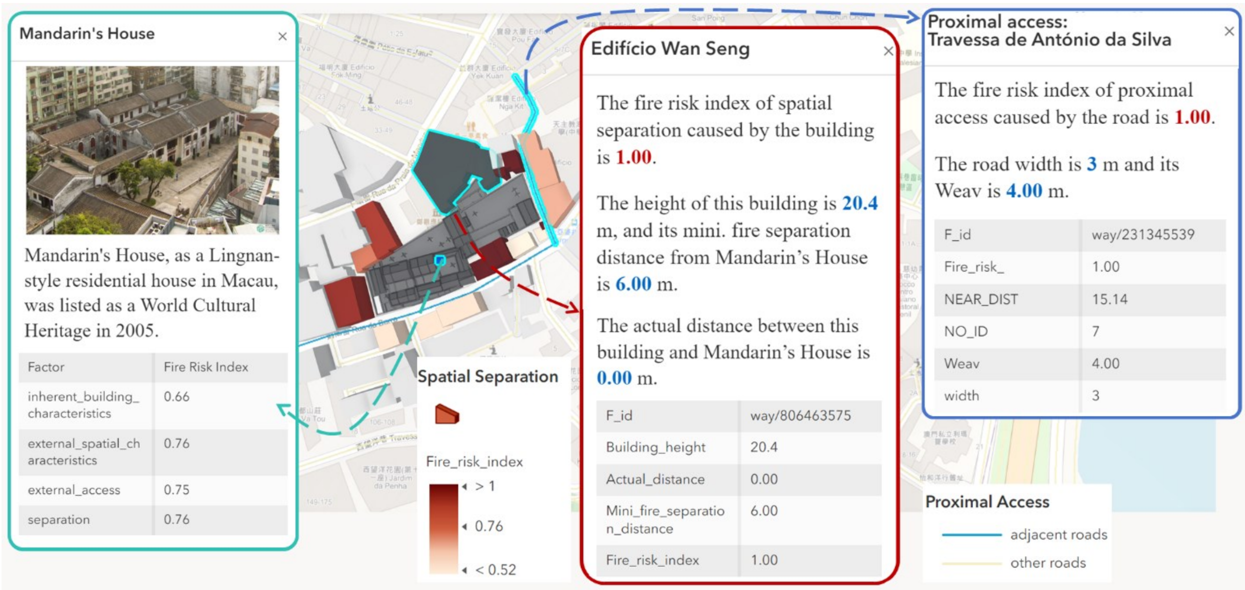

Figure 3. Visualization of spatial fire risk patterns

present the fire risks in different colors to help recognize their spatial distributions.

Through the case study of Mandarin's House, the proposed framework is validated to quantify the multi-faceted risks exposed to the heritage site efficiently and effectively. Furthermore, the result discloses that the spatial separation aspect gained a high level of risk and thus deserves more attention for proactive mitigation. Overall, the proposed framework enables data-driven analytics to reveal spatial patterns of fire risk in heritage buildings, thereby forming a solution to facilitate fire prevention and emergency management.

Future work would further investigate other fire risk-related factors of heritage buildings and incorporate various data collection methods to enhance the reliability of the results.

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