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A statistical analysis of occurrence and association between structural fire hazards in heritage housing

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ABSTRACT

Reported in this paper is a novel application of statistical analysis of structural fire hazards that were found in heritage housing stock in a metropolitan area. The structural fire hazards in terms of non-compliances to the building regulations are digitised and then subjected to statistical analysis to obtain estimates of probabilities of occurrence under various conditions. The concepts of Hamming distance, Jaccard distance, virtual distance and pairwise Phi correlation coefficients are employed in the analysis to estimate the association between the fire hazards. Estimates of the probability distribution over the number of joint occurrence of hazards and pairwise joint probabilities are also obtained. In addition the 3-tuple and 4-tuple joint probabilities are analysed. Finally, logistic regression models are established to correlate each fire hazard with the others. The results show that not only the probability of occurrence of structural fire hazards is high, but probability of multiple occurrence is also significant. There are indications that some structural fire hazards are correlated. The findings of this study may assist certifying authorities, building surveyors, fire safety engineers and fire services in identifying fire hazards in heritage buildings and developing alleviating and effective strategies or solutions to protect life safety of building occupants as well as the cultural heritage values of the relevant building stock.

1. Introduction

Fire is one of the most frequent and common threats to public safety and social development among various kinds of disasters [1,2]. Particularly, the destruction by fire is a major threat to the conservation of heritage buildings as well as their contents worldwide [3–5]. Building fires are the result of human occupation and activity. Interestingly, it is the continuing usage and maintenance that is regarded as an effective means of conservation of heritage buildings [6,7]. Old buildings may undergo renovations or refurbishments to adapt the changes in lifestyle and technology. For example, air conditioning units or skylights may be added to existing buildings to provide comfort for building occupants or to improve energy efficiency. These kinds of renovations inevitably alter or have impacts on the structure of the existing buildings and their fire safety measures.

A distinctive feature of heritage housing in suburban areas of major metropolitan cities in Australia is the adjoined and/or close proximity of multiple properties [8]. Fire spread between these kinds of properties is a potential hazard, which needs to be addressed in order to ensure both the continued viability of the remaining heritage housing stock and the life safety of the occupants. As heritage housing is a valuable cultural and dwindling asset in most parts of the world, the level of protection against a major fire in closely-spaced heritage housing precincts deserves careful consideration.

A recent study by Hardie et al. [9] investigated the presence of a set of identified fire hazards within a sample of 47 heritage social housing properties in Sydney. The study's major contribution was the collection of data on the structural fire hazards, but unfortunately, the study did not explore deeper relationships between the hazards.

In this article, a thorough assessment of the probability of each structural fire hazard being present or absent, and the association between each hazard is provided. To complete the analysis, sophisticated statistical methods for binary random variables are used, such as confidence intervals for proportions, binary metrics, multi-dimensional scaling, and logistic regression.

This article provides the two major contributions: 1) the computation of associations between various structural fire hazards, and 2) the revelation of a given set of sophisticated analysis methods that were developed in other fields of study, that can be applied to fire hazard analysis. The article proceeds as follows: Section 2 contains a description of the problem and related work, Section 3 contains a description of the data. In Section 4, the individual fire hazards are examined. Sections 5 and 6 describe the metrics and pairwise relationships of fire hazards. Finally, Section 7 examines the effect of the set of fire hazards

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Nomenclature

AIC	Akaike information criterion
C	correlation matrix
C_k	cumulative probability of joint occurrences of k multiple fire hazards
D	distance function
D_k	probability of joint occurrences of k multiple fire hazards
g	logistic link function
HD	Hamming distance
i,j,k,l	indices
JD	Jaccard distance
L	likelihood
M	total number of fire hazards
m	number of terms included in the logistic model
N	sample size or length of string
P	probability
P_j	probability of occurrence of jth fire hazard in a building
R	fire hazards
$R_{i,k}$	the realisation of hazard R_i in kth sampled building
$\bar{R}_i$	the mean of R_i over all sampled buildings
S_{Rj}	standard deviation in R_j
VD	virtual distance as defined in Eq. (5).
VS	virtual similarity
X, Y, Z	arbitrary binary strings

Greek

β_j	regression coefficient (j=0, 1, ..., M)
$\phi_{i,j}$	Phi correlation coefficient between fire hazard pair R_i and R_j
π_i	estimated probability P_i, or the marginal probability, of fire hazard i being present

on each individual fire hazard.

2. Background

Fire hazards usually appear in different forms. In the study by Hardie et al. [9], structural fire hazards are defined as the features in the building structure that are not compliant with the current building regulations, and defects in building fire safety measures as a result of poor maintenance. Fire separation between adjacent dwellings is prescribed by many building regulations as one of the fundamental strategies to prevent fire spread in close spaced properties. Hardie et al. [9] conducted an observational survey to look at the occurrence of noted defects, or non-compliance with the Building Code of Australia [10], in fire separation between attached or closely spaced occupancies. The survey selected a sample group of 47 heritage listed public housing properties in densely built up areas of Sydney. The sampled group consisted of 18 detached or stepped frontage houses and 29 row houses.

Most of these properties were built largely using brick which had less potential for fire spread than closely spaced timber housing. However, fire can spread through any significant gaps in the non-combustible walls, as well as, through any combustible material that bridges the gap between the adjacent brick buildings. The properties in the survey were inspected for any potential gaps or breaches in fire isolation and potential bridging pathways for fire between the separate occupancies, which may have occurred as a result of building refurbishments or upgrading over the lifetime of the heritage buildings. In total, ten fire hazards were identified and their frequencies of occurrence were estimated. Eight of the ten identified fire hazards were structural related [9], which are listed in Table 1 together with their estimated occurrence probabilities.

The separating walls are the walls between adjoining properties. They are required to have fire ratings by the building code [10]. When the walls are breached by penetration by combustible or non-fire rated materials or gaps (R_1 to R_4), the breaches are regarded as fire hazards. Similarly, the features denoted by R_5 to R_8 do not comply with the relevant clauses the building code and, hence, regarded as fire hazards. For detailed description of the eight structural fire hazards listed in Table 1, reference is made to the article by Hardie et al. [9]. Their study also showed that multiple fire hazards might co-exist in individual given buildings. These hazards represent the structural weaknesses and potential routes for fire spread in the event of fire.

The identified fire hazards were likely the results of building refurbishment that were undertaken without proper certification by appropriate building surveyors or the authorities having jurisdictions. Many may have been the result of unsympathetic service upgrades undertaken in a series of small refurbishments over time, which did not at the time require certification or inspection. Based on the result of their study, Hardie et al. [9] recommended that authorities having jurisdictions should consider the introduction of a building surveying audit wherever a refurbishment is undertaken in a heritage housing property, regardless of the extent of the refurbishment. Such audits will enhance heritage protection as well as life safety of building occupants.

Hazard identification is the first step in risk analysis and management [11,12]. The study by Hardie et al. [9] represents such an important step. Following this step is the systematic quantification of hazards in terms of their likelihood of occurrence. Such quantification is warranted for risk assessment, policy making and developing solutions to implement the policies and rectify the identified hazards. Recent literature has seen advancement in the Artificial Neural Networks (ANN) and Building Information Modelling (BIM) approaches to rapid risk assessment for fire service operations and fire risk management [13,14]. Statistical data of structural fire hazards in existing buildings can be of assistance to the development of ANN and BIM models. The most recent work by Silva et al. [15] demonstrated the valuable contribution of the probabilistic analysis to the evaluation of the risk of building component failure in the building lifecycle assessment. It represents the increasing trend of quantitative approach to building research.

Structural fire hazards in existing buildings, particularly in heritage buildings, are inherent defects that are deemed non-compliant to current prescriptive building regulations. Various solutions can be developed to remedy these defects. A straightforward solution could be to alter the building structures and make them compliant to the prescriptive building regulations. However, this kind of solution may run into conflict with the protection of the heritage values of the buildings. Therefore, performance based design solutions or fire safety engineering solutions under the performance based building codes are

Table 1
The eight structural fire hazards and their occurrence probability.

Fire hazard	Notation	π_i
Timber penetrations through the separating wall	R_1	0.47
Box gutters penetrating the separating wall	R_2	0.15
Gaps and other penetrations in the separating walls	R_3	0.11
Separating wall stopping short of the roof	R_4	0.21
Skylights installed within 900 mm of the adjoining property	R_5	0.17
Combustible facades bridging between attached houses	R_6	0.09
Combustible separating walls between adjacent balconies of attached houses	R_7	0.11
Common eaves construction	R_8	0.24*

* This fraction was calculated over the sampled 29 row houses. Over the total sample size of 47 (including single dwellings) this value is 0.15.