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Fire Load Density Distribution in School Buildings and Statistical Modelling

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Abstract. Reported in this paper is an exercise that contributes to the fire load database for fire severity analysis. The movable fuel load data was collected by the weight-inventory method from a specific building type, namely school buildings located within the metropolitan area of Sydney, Australia. The data was analysed to obtain statistical descriptions of fire load density in terms of probability density distributions. The results were compared with the similar data obtained from other countries. It was found that while basic statistical characteristics show similarities globally, some other characteristics, particularly the 90th percentile, may differ from one country to the other. This outcome suggests that fire load selection for design fires in fire safety engineering design and assessment should be better based on local data and a careful review of the unified approach in the international fire engineering guidelines is warranted.

Keywords: Fire load density distribution, Design fire, Histogram, Regression model, Statistical analysis

1. Introduction

Fire load is one of the important parameters in fire safety engineering design and assessment [1]. Traditional fire engineering design for building occupant life safety and fire resistance design for building structure protection are often based on deterministic timeline analysis of available safe evacuation time *vs* the required safe evacuation time or fire resistance level *vs* fire severity. In this kind of approach, one or limited number of design fires are selected as design references. To deal with uncertainties in the design, safety factors are introduced to augment the design values and make them err on the safer side [2]. Such an approach has, in most cases, resulted in adequate protection of building occupants and structures. However, there have been questions as to what is the appropriated value of

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the safety factor and how much are we erring on the safer side. These questions stem from the desire to develop reliable and cost-effective performance-based fire safety engineering solutions.

Recent decades have seen the advancement in building fire regulations with of a trend toward risk informed performance based building codes [3]. This kind of regulations allow for more objective and quantifiable performance requirements to be introduced. However, to support such a development, it is essential that appropriate verification methods and databases are established.

Against the traditional deterministic approach, the risk based, or the probabilistic approach has been termed as the second generation performance-based engineering approach to fire safety design by some scholars (e.g., Khorasani et al. [4]). This approach has the advantage over the deterministic approach in that it delivers quantifiable risk parameters in the assessment of engineering design solutions. It is capable of dealing with complex phenomena which are influenced by parameters exhibiting random characteristics.

Fire load density is a parameter that behaves randomly. It not only depends on the type of occupancy, but also varies drastically within the same type of occupancy. Office buildings appear to be the most surveyed classification [5–8] followed by residential dwellings [9, 10], shopping centres [11, 12] and hotels [13]. Attempts were made by many researchers to characterise the surveyed data with various probability density distribution functions. For example, Melinek [12], Zalok et al. [10, 13], Kumar and Rao [14], Thauvoye et al. [15], Xie et al. [16], Hadjisophocleous and Zalok [17] tried to fit fire load data with normal, lognormal, Gumbel and other distributions for a range of building types including commercial, residential and office buildings. These researchers indicated that the lognormal distribution is a better fit than normal, Gumbel and other distributions. This outcome provided further support to the recommended model by CIB [18]. On the other hand, the normal distribution was found to have a good fit to the fire load for residential buildings by Bwalya et al. [19]. Khorasani [4] thought the Beta distribution provided a good fit for fire load in US office buildings. Zalok [20] found the fire load density in Canadian office buildings to follow the Gumbel distribution. Liu [21] regarded that both generalized extreme value and log-logistic distributions have a good fit for residential building fire load in Beijing, China. A summary of some selected fire load surveys and the regression modeling of probability density distributions obtained from the literature is given in Table 1.

School buildings belong to a special category where both occupant load and fire load could be high [22]. However, field surveys of fire load in school buildings are sparse in the literature, let alone the statistical modelling of the fire load data. As can be seen in the above Table 1, the available data in the literature mostly originated from the northern hemisphere and few have originated from the southern hemisphere. There is a likelihood that statistics of fire load densities differ from region to region as well as from country to country. In addition, it would be preferable to have information about the analytical method and evaluation criteria in the regression modelling such that confidence may be cast or uncertainty may be evaluated when applying the models in risk based fire engineering assessment.

Table 1
Summary of Fire Load Studies in the Selected Literature*

Source and date	Model	Country	Building class	Regression method	Evaluation method	Tool
[12] 1993	Lognormal and normal	UK, US	O	MLE	UN	UN
[19] 2004	Normal	Canada	R	UN	UN	UN
[13] 2005	Lognormal	Canada	C	UN	UN	UN
[17] 2008	Lognormal	Canada	C	UN	UN	UN
[15] 2008	Lognormal	Switzerland	C	TAE	C–S	UN
[15] 2008	Lognormal and Gumbel	France	P	QME	C–S	UN
[10] 2009	Lognormal	Canada	C	UN	K–S & P–V	R & Easy-fit@
[21] 2012	Gev and log logistic	China	R	MLE	K–S	MATLAB
[20] 2013	Gumbel	Canada	O	QME	K–S	Easyfit@
[4] 2014	Beta	US	O	BPA	UN	UN
[16] 2019	Lognormal and normal	China	O	BIT	UN	UN
[22] 2010	NA	Canada	S	NA	NA	NA

*O = office; R = residential; C = commercial; PB = public; S = school, NA = not available; UN = unknown; MLE = maximum likelihood estimation; MME = moment matching estimation; QME = quantile matching estimation; BIT = Bayesian inference theory; BPA = Bayesian probability approach; TAE = try and error; C–S = Chi-square test; K–S = Kolmogorov–Smirnov test; P–V = P-value test

The aim of the current study is to investigate probabilistic descriptions of the fire load density distribution in typical Australian school buildings. Fire load data were collected from a number of primary and secondary school buildings in Sydney metropolitan area. The collected fuel load data were segregated against enclosure types (e.g., library, laboratory, classroom, storeroom, etc.) and school types (e.g. primary and secondary). Meanwhile, the floor areas of these enclosures were surveyed. The collected data were converted into fuel load density and were subjected to statistical analysis using the R programming language. The criteria for selecting the probability density distribution function for fire load density were established on the basis of the nature of the parameter and its application in fire safety engineering design. Four candidature probability density distribution functions were selected for regression analysis and their goodness of fit were compared.

The results of the mean, standard deviation and certain percentile values of fuel load distributions are also analysed and compared with the data obtained from other countries in the world where similar studies were conducted. The outcome of this research will contribute to the international database for fire safety engineering practice.

2. Data Collection and Initial Processing

Combustible materials in building compartments can be largely divided into two categories: fixed fuel load and moveable fuel load [4]. The former is usually fixed with the building structures (such as walls, floor, ceiling and doors) and has less variability during the lifetime of the buildings. In contrast, the latter is associated with the portable building contents, has a much greater variability, hence, uncertainty from fire safety engineering design point of view and, therefore, received much attention in fire load survey studies [22, 23]. In the current study, focus is given to the fire load density evaluated from the moveable fuel load. Unless otherwise specified, fire load and related parameters in the remaining text refer to that of moveable fire fuel.

Fuel load data was collected from three schools located within the Sydney metropolitan area. One of the schools was a primary school and the others were combined primary and secondary (or high) schools. The buildings surveyed generally ranged between 3 to 90 years old with the majority of buildings being over 50 years. The size and extent of buildings varied from single storey blocks to four storey multi-compartment buildings. The compartments or rooms were classified according to their usage. The sample size, or the total number of rooms surveyed, was 85. An overview of the surveyed rooms is given in Table 2.

The combined weight-inventory method [24, 25] was employed in the current study to collect fuel load data from various enclosures in the school buildings. In this method, direct access to building compartments is required. Fuel mass in each compartment is either weighted directly or measured by volume then multiplied by density values obtained from the literature. In the meantime, the floor area, A, of the compartment is also measured. The fire load density, q, is then calculated from [22]:

Table 2
Overview of Surveyed Rooms

Room use	School-1 Number	School-2 Number	School-3 Number
Classroom-primary	19	4	8
Classroom-secondary	–	13	7
Science room	–	3	5
Visual arts studio	–	4	3
IT room	1	2	–
Library	1	2	2
Storeroom	6	–	–
Other[#]	4	1	–
TOTAL	31	29	25

[#] The ‘Other’ category includes: assembly halls, after school cares, tutor rooms and bag rooms

$$q = \frac{1}{A}\sum_i k_i m_i \Delta H_i \tag{1}$$

where m_i and ΔH_i are the mass and heat of combustion of the ith item in the compartment respectively, k_i is the proportion of the ith item that can burn, or the effective burning efficiency. In the current study, the value of 1 was assigned to all k_i as the worst case. The mass of an item is either obtained from the weighting or from the following scheme:

$$m_i = \begin{cases} \rho_i V_i & \text{forvolumetirc items} \\ \tau_i T_i & \text{for textile or surface items} \end{cases} \tag{2}$$

where ρ_i and V_i are material density (kg/m^3) and measured volume (m^3) of ith item respectively, τ_i and T_i are area density (kg/m^2) and measured area (m^2) of the ith item respectively, if the item is textile or surface material.

The properties (density and heat of combustion) of typical combustibles for the evaluation of fire load were acquired from the literature and are listed in Table 3.

3. Result and Analysis

3.1. General Statistical Analysis

A summary of the room classification and the general statistics of the moveable fire load density for each type of rooms as well as for the total of 85 samples is given in Table 3. Data from International Fire Engineering Guidelines (IFEG) [1] and Eurocode 1 [27] are also included in the table for comparison.

It can be observed from Table 4 that the fire load density in primary classrooms on average is approximately 1.5 times that of the secondary classrooms. In this regard, primary classrooms were noticed to contain more storage furniture (e.g. cabinets, bookshelves) as well as contents (e.g. computers, books and toys), whereas secondary classrooms typically contained one (1) piece of storage furniture (e.g. shelving unit) and limited content (e.g. computer and books).

In comparison, the mean and the 80th percentile fire load density values nominated by Eurocode for classrooms and libraries are higher than that obtained in

Table 3
Combustible Material Type and Properties for Fuel Mass and Fie Load Evaluation

Material	ΔH (MJ/kg)	Reference	ρ (kg/m^3)	References
Wood	18.6	[10]	450	[25]
Paper	17.0		450	
Plastic	22.1		1500	[26]
Textile	19.0		2.60 (kg/m^2)	

Table 4
Summary of Movable Fire Load Density According to Room Usage

		Fire load density (MJ/m^2)						
						Percentile		
Room use	Sample size	Min	Max	Mean	STD	80th	90th	95th
Classroom-primary	31	19.0	297	149	57.0	171	229	249
Classroom-secondary	20	55.0	274	107	47.0	127	139	163
Science room	8	42.0	163	69.0	41.0	79.0	114	138
Visual arts studio	7	61.0	149	100	28.0	114	128	138
IT room	3	84.0	440	206	202	302	371	405
Library	5	213	886	551	322	879	882	884
Storeroom	6	534	4860	2330	1680	3490	4180	4520
Other*	5	94.0	297	297	292	357	583	697
Overall	85	19.0	4860	316	710	232	525	884
Eurocode—Classroom	–	–		285	–	347	–	–
Eurocode—Library	–	–	–	1500	–	1824	–	–
IFEG [1]	–	–	–	–	–	360	410	450

*The ‘Other’ category includes assembly halls, after school cares, tutor rooms and bag rooms

the current study. Comparing the percentile values of the overall school result of the current study with that of IFEG, it is seen that the 90th and 95th percentile fire load density values of IFEG are lower than the corresponding results obtained in the current study. Whereas the 80th percentile value of fire load density of IFEG is higher than the current study.

The International Fire Engineering Guidelines (IFEG) (ABCB 2005) presents fire load data from studies undertaken in Switzerland (1967-69) and the Netherlands (1983). In addition, a large amount of variable (i.e. moveable) fire load data is provided relating to a broad range of occupancy types. With respect to school buildings, the fire load data presented by IFEG is reproduced in Table 5 (Switzerland) and Table 6 (Netherlands) below.

3.2. Probability Density Distribution Modelling

3.2.1. Probability Density Distribution Function Selection Fire load is a non-negative real valued parameter. Past studies that have been listed in Table 1 and beyond have shown that histograms of fire load data collected from various build-

Table 5
Fire Load Densities (Switzerland) (IFEG, ABCB 2005)

Type of occupancy	Fabrication (MJ/m^2)
School	300

Table 6
Fire Load Density in Different Occupancies (Netherlands) (IFEG, ABCB 2005)

Densities in mega-joules per square metre

		Percent fractile *		
Occupancy	Mean (MJ/m^2)	80	90	95
Schools	285	360	410	450

*The percent fractile is the value that is not exceeded in that percent of the rooms or occupancies

ings usually have a single peak and a long tail skewed toward the right, or the high end of the range. The considerations given to the selection criteria of the probability distribution functions are outlined below:

(1) The nature of fire load demands that the domain of the distribution function is $\mathbf{R}^+$, i.e., $x \in [0, \infty)$, and the function is non-monotonic and has a unimodal;
(2) The distribution gives a reasonable goodness of fit;
(3) The distribution is versatile and robust in its application. In other words, it is easy to use.

A preliminary screening of the probability distribution function using Criteria (1) resulted in four candidature functions: namely the general extreme value (Gev), lognormal, Weibull, and Gamma distributions.

A number of methods were then used to conduct regression analysis to fit various distributions to the raw fire load data. These include the maximum likelihood method, the method of moments, the cumulative method, …etc. in R language package [10].

Previous studies [10, 14, 15, 21] found extreme value (General, Gumbel, Weibull) distributions to provide a better fit as compared to other distributions. The expressions of these distributions are presented below.

1. The general extreme value (Gev) distribution [28] is widely used in the treatment of "tail risks" in fields such as finance and natural hazards [29]. The probability density function of the Gev distribution for the $k \neq 0$ case is given as:

$$f(x) = \frac{1}{\sigma}\left(1 + k\frac{x-\mu}{\sigma}\right)^{-\left(\frac{1}{k}+1\right)} \exp\left[-\left(1 + k\frac{x-\mu}{\sigma}\right)^{-\frac{1}{k}}\right] \tag{3}$$

where k, σ ($>$ 0) and μ are called shape, scale and location parameters respectively. The domain of the distribution is $x > \left(\mu - \frac{\sigma}{k}\right)$.

2. The Weibull distribution (also named the Type III extreme value distribution [20, 30]) has a probability density function given by:

$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} x \geq 0 \\ 0x < 0 \end{cases} \tag{4}$$

where $x \in [0, \infty)$, λ and k (> 0) are called scale and shape parameters respectively.

3. According to the literature [10, 12–17, 19], fire load density is often considered to be lognormal distributed. The probability density function of the lognormal distribution is given by:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2} \tag{5}$$

where $x \in (0, \infty)$, and μ and σ (> 0) are mean and standard deviation respectively.

4. The Gamma distribution function also has a non-negative domain ($x > 0$) and is, therefore, selected as a candidature function for regression analysis. The probability density function of the Gamma distribution is given by:

$$f(x) = \frac{\beta^{\alpha} x^{\alpha-1} e^{-\beta x}}{\Gamma(\alpha)} \tag{6}$$

where αandβ(> 0) are called shape and rate parameters, respectively.

In the context of the current study, x is fire load (MJ/m^2). The cumulative distribution function is denoted by $F(x)$. It is noted that other forms of distribution functions, such as normal, Beta and Gumbel distributions, have been used by researchers in the past (see Table 1). However, the domains of these distributions do no satisfy Criteria (1) and are, therefore, not explicitly expressed herein.

3.2.2. Regression and Goodness of Fit Analyses The identified distributions were fitted to the collected fire load density data by using various estimation methods, details of which can be found in [31–33]. These methods have been coded into R routine library which was employed to process the data. The estimated parameter values, the methods of estimation and the results of the goodness of fit analysis are summarised in Table 7. As can be seen from this table, the parameters for the Gev, Weibull and Lognormal distributions may differ a little, depending on the method of estimation. For example, two sets of mean and standard deviations were obtained from the maximum likelihood and method of moments estimators separately for the lognormal distribution. The corresponding goodness of fit tests also yielded two sets of values, though the differences are relatively small. In the case of Gamma distribution, the value of parameter α varied, however, significantly from 0.809 to 0.2.

It is noted that not all test results are necessarily produced by the R routines. For example, the MLE and LME routines did not generate K-S, CVM and A-D test results for Gev distribution. The MDE routine did not yield AIC, BIC and L-

Table 7
Summary of Regression Result and Goodness of Fit Analysis*

Distribution	Parameter values	Method of fitting	Goodness of fit test					
			AIC	BIC	LL	K–S	CVM	A–D
Gev	$\mu = 102.22$, $\sigma = 69.422$, $k = 0.594$	MLE	1067.0	1074.3	–530.51	–	–	–
	$\mu = 99.168$, $\sigma = 64.033$, $k = 0.742$	LME						
Weibull	$k = 0.793$, $\lambda = 258.91$	MLE	1139.2	1144.1	–567.61	–	–	–
		MDE	–	–	–	0.227	1.553	8.407
Lognormal	$\mu = 5.022$, $\sigma = 0.946$	MLE	1089.5	1094.4	–542.76			
	$\mu = 4.859$, $\sigma = 1.338$	MME	1107.2	1112.1	–551.62			
	$\mu = 4.854$, $\sigma = 0.577$	MDE	–	–	–	0.190	0.692	3.871
Gamma	$\alpha = 0.809$, $\beta = 0.003$	MLE	1149.6	1154.5	–572.80	–	–	–
	$\alpha = 0.200$, $\beta = 0.001$	MME	1230.5	1235.3	–613.22	–	–	–
	$\alpha = 3.441$, $\beta = 0.024$	MDE	–	–	–	0.285	2.009	10.13
Gumbel	$\mu = 143.67$, $\beta = 200.15$	LME	1220.6	1225.5	–608.29	–	–	–
Normal	$\mu = 315.74$, $\sigma = 705.90$	MLE& MME	1360.3	1365.2	–678.16	0.382	4.143	20.34

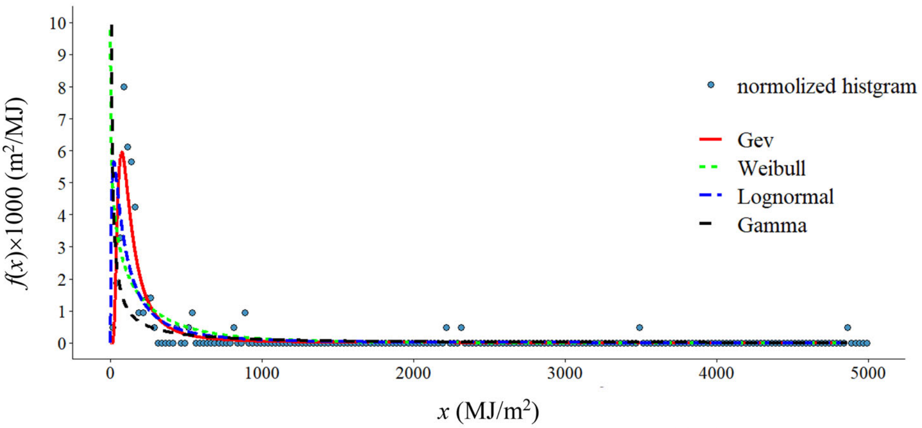
*MLE = Maximum Likelihood Estimation; MME = Moment Matching Estimation; LME = L-Moment Estimation; MDE = Minimum Distance Estimation AIC = Akaike information criterion; BIC = Bayesian information criterion; LL = Log-Likelihood value, K–S = Kolmogorov–Smirnov criterion; CVM = Cramér–von Mises criterion; A–D = Anderson–Darling criterion

L test results for lognormal distribution. In the following analysis, the parameter set that produces better goodness of fit test results, or small values of AIC, BIC and absolute log likelihood is selected for further analysis and comparison with other forms of distribution function.

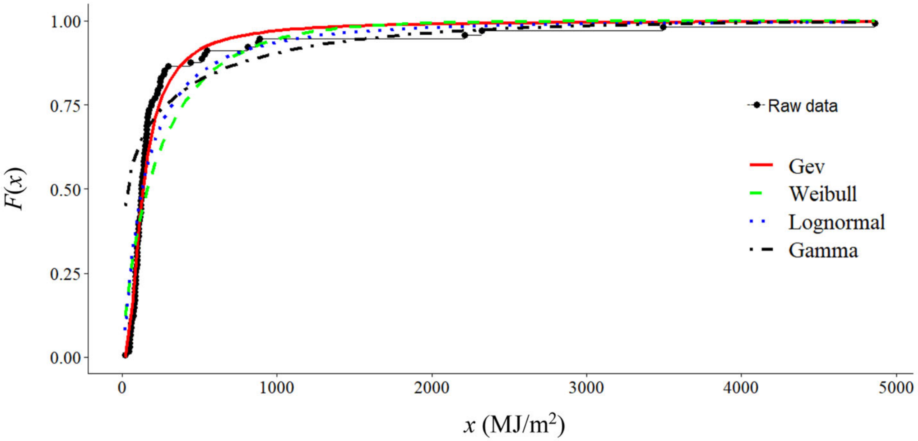
Although the two methods of fitting Gev produced slightly different parameter sets, the R library routines resulted in the same goodness of fit test outcomes. The distribution parameter set obtained from MLE method was selected for further analysis.

Apart from not satisfying selection Criteria (1), the Gumbel and normal distributions are shown to have the worst goodness of fit test results, and therefore, are excluded from further discussions.

The normalised histogram of fire load density data obtained from the total 85 rooms of the three surveyed schools is plotted in Fig. 1 together with fitted density distributions and cumulated distributions. The bin width for the histogram is 20 MJ/m^2. The frequency of the histogram is normalised such that:



(a) normalised histogram and probability density distribution functions



(b) cumulative distributions functions

Figure 1. The results of the survey distribution modelling.

$$f_i = \frac{F_i}{\Delta N} \tag{7}$$

where Δ is bin width, i is the bin index, F_i is the frequency in the ith bin and N is the size of the sample. The normalised frequency f_i satisfies:

$$\sum_{i=1}^{B} \Delta f_i = 1 \tag{8}$$

where B is the total number of bins (= 250 in this case). It is seen from Fig. 1a that the normalised frequency distribution contains a long tail, or heavily skewed towards high end of the range, which is attributed to the fire load density data of the libraries and storerooms (see Table 4) in the schools.

The plotted distributions in Fig. 1 are based on the MLE method which produces better estimates than other methods as indicated in Table 7. During the survey of the schools, no empty rooms were found. Therefore, a zero probability density value at $x = 0$ appears to be a valid assumption. All selected distribution functions, except Gev, yield $f(0) = 0$. For Gev, the domain starts at $x = \left(\mu - \frac{\sigma}{k}\right) = 12.87$ (MJ/m^2), i.e., $f(12.87) = 0$. All selected probability density distribution functions yield good agreement with each other at the high end of the domain for $x > 1000$ MJ/m^2. See Fig. 1a. Starting at x = 100 (MJ/m2), all the models tend to underestimate the cumulative probability in comparison to the experimental result (Fig. 1b). As x increases, the cumulative probability by Gev becomes exceeding that of the experimental value at around $x = 400$, the turning point for Weibull is approximately at $x = 1000$, for lognormal, at $x \approx 1200$ and for Gamma, at $x \approx 1500$ (MJ/m^2).

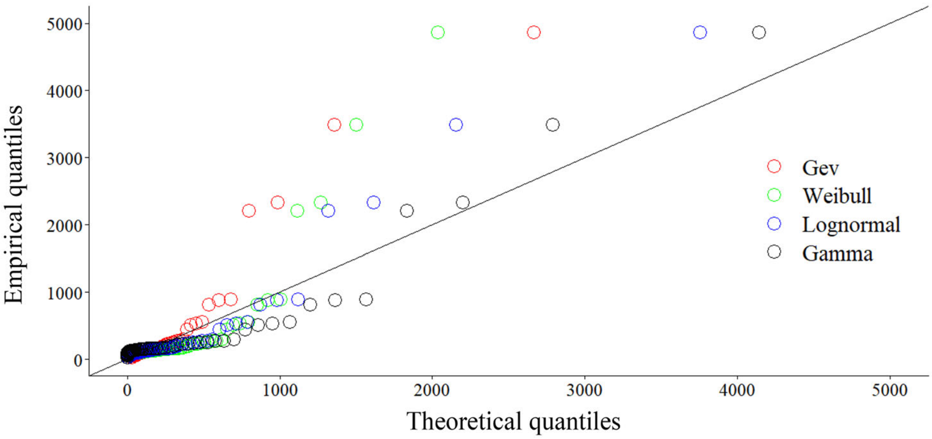
To visually demonstrate the quality of fit, the Q-Q and P-P plots are presented in Fig. 2. From Fig. 2b it is seen that the cumulative probabilities of the Gev closely match those of the empirical cumulative distribution. Data points representing the Gev distribution fall closely to the perfect line at lower end of the fire load density ($x < 500$ MJ/m^2); only at the high end of the range do the data points significantly deviate from the straight line. The Weibull distribution overestimates the fire load density of the empirical data for the same quantile and $x < 1000$ MJ/m^2 but gives an underestimate for $x > 1000$ MJ/m^2. The lognormal distribution displays a similar trend but less deviation from the straight line.

In order to give a more comprehensive comparison, all the selected distribution functions are ranked in Table 8 according to their goodness of fit test outcomes listed in Table 7.

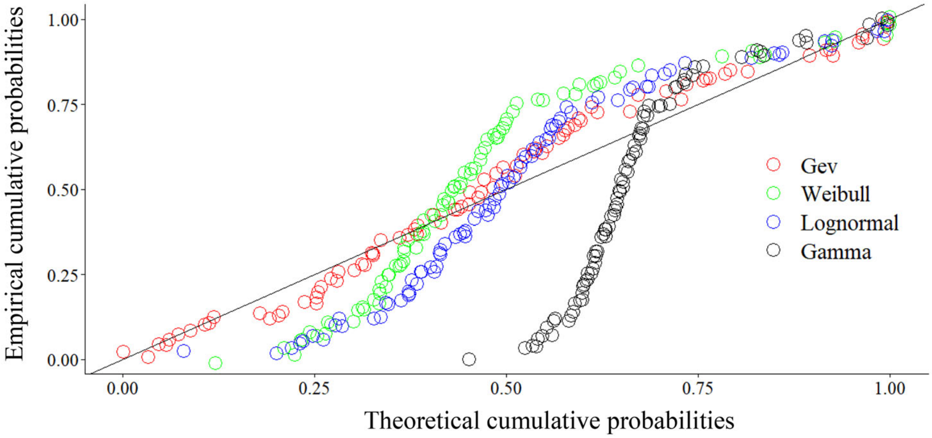
It is interesting to see from Table 8 that the AIC, BIC and log-likelihood tests provided the same rankings for all four density functions. Against the three goodness of fit criteria, Gev and lognormal distributions are ranked the first and second best, respectively, to fit the normalised histogram of the surveyed fire load data in the current study.

3.2.3. Other Considerations In this subsection, considerations are given to Criteria (3) as outlined in Subsection 3.2.1 to further compare the three candidature functions.

From a simplistic point of view, lognormal and Weibull distribution functions are preferred since both have two parameters, one less than Gev distribution function. The simplicity offers an advantage that the parameter values can be relatively easily calculated from the mean and standard deviation of the raw data. In the past literature, it was not often that the raw data of detailed fire load surveys were included in publications. The results are usually presented in terms of basic statistical parameters such as the mean and the standard deviation. Using density functions with fewer parameters, one could easily conduct a retrospective analysis to find a corresponding distribution parameter values from the published means



(a) Q-Q diagram



(b) P-P diagram

Figure 2. Evaluation of the regression modelling.

Table 8
Goodness of Fit Ranking

	Criteria		
Ranking	AIC	BIC	Log-likelihood
1	Gev	Gev	Gev
2	Lognormal	Lognormal	Lognormal
3	Weibull	Weibull	Weibull
4	Gamma	Gamma	Gamma

and standard deviations. In particular, there are straightforward correlations between the mean and standard deviations of lognormal distribution and the mean and standard deviation of the raw data [34, 35].

Gumbel and normal distribution functions were also evaluated in this study. The goodness of fit results indicated that they are ranked lowest among all selected distribution functions because of the mismatch of the domains. No explicit results of these two distributions are presented herein.

In fire safety engineering design process, certain percentile fire load values may be selected as input for design fires [1, 2]. To further compare Gev and lognormal distributions, we examine some given percentile values by these two distributions as listed in Table 9.

As we can see from Table 9, the differences between the values of mean and the three nominated percentiles by the two distributions are relatively small. In particular, the fire load density values by the lognormal distribution modelling at the 90th and 95th percentiles, which are nominated by the International Fire Engineering Guidelines [1], are slightly greater than the corresponding percentile values by the Gev distribution modelling. Greater fire load density values at a nominated percentile for design fire selection will result in more conservative or safer design of the fire safety systems. Only at even higher percentiles, such as the 98th, the lognormal distribution produces a lower fire load density value than the Gev distribution. However, the 98th percentile value is already a very conservative choice for engineering design.

Based on all criteria assessment, the lognormal distribution is deemed the most preferred probability density distribution of the fire load data obtained in the school buildings of the current study in Australia.

4. Discussion

4.1. Comparison with the Published Data from Other Countries

Hadjisophocleous and Chen [22] conducted fire load surveys within elementary and high schools located within Ottawa, Canada. Their study considered a total of sixty-seven (67) rooms and enclosures. The movable fire load density data by

Table 9
Comparison of the Mean and Percentile Fire Load Density Values (MJ/m²) by Gev and Lognormal Distributions

		Percentile		
Distribution	Mean	90th	95th	98th
Gev	240.1	430.2	667.6	1171.9
Lognormal	237.3	510.0	719.1	1058.8
Relative difference* δ (%)	− 1.18	16.98	7.43	− 10.14

*Relative difference is the percentage of the difference divided by the average, or $\delta = 200\frac{x_2 - x_1}{x_2 + x_1}$

Hadjisophocleous and Chen [22] is reproduced and compared with the data of the current study in Table 10. The mean fire load densities within Canadian computer rooms and libraries are generally deemed comparable with the current study, although it should be noted that the current study made no differentiation between primary or secondary IT rooms and libraries. The mean fire load density results for classrooms, science and art rooms of the Canadian schools are generally of a larger magnitude in comparison to the current study. Hadjisphocleous and Chen [22] observed that elementary classrooms comprised approximately twice the amount of fire load density in high school classrooms. This trend is comparable to the trend observed in the current study whereby primary school classrooms were found to comprise approximately 1.5 times the amount of the fire load density in the secondary school classrooms. There exist significant discrepancies in the results (particularly in the Max and the STD) for the elementary schools between the two studies as shown in Table 10. These discrepancies are attributable to the fact that that storerooms were not surveyed in the Canadian study as they were found to be closed. The high value of fire load density in storerooms (see Table 4) contributes significantly to the high Max and STD of the current study.

The design guide for structural fire safety prepared by Thomas [18] details fire load density data from various studies in multiple countries. The most comprehensive data set collated by Thomas was with reference to school buildings in Germany. The fire load density obtained by Thomas is reproduced in Table 11. Fire load density related to storerooms was noted to be significantly lower in comparison to the current study. Fire load density relating to libraries was noted to be

Table 10
Comparison of Moveable Fire Load Density in Different Room Types of School Building

	Moveable fire load density (MJ/m^2)							
	Hadjisophocleous and Chen [22]				Current study			
Surveyed rooms	Min	Max	Mean	STD	Min	Max	Mean	STD
Elementary schools								
Classrooms	174.4	483.3	303.9	79.5	19.0	297	149	57.0
Computer rooms	172.8	233.7	211.4	33.6	84.0	440	206	202
Libraries	357.1	684.6	545.8	157.8	213	886	551	322
All elementary school rooms	172.8	684.6	329.5	129.9	19.0	4860	473	939
High schools								
Classrooms	70.3	340.3	137.2	70.0	55.0	274	149	47.0
Computer rooms	136.6	348.2	201.0	71.9	84.0	440	206	202
Science rooms	269.9	461.8	336.0	63.8	42.0	163	69.0	41.0
Art rooms	368.3	595.9	490.7	93.5	61.0	149	100	28.0
Libraries	43.7	653.7	537.8	111.3	213	886	551	322
All high school rooms	70.3	653.7	265.1	155.9	42.0	886	138	172
All school rooms	70.3	684.6	–	–	19.0	4860	316	710

Table 11
Comparison of Moveable Fire Load Densities in Various Groups of School Rooms

	Moveable fire load density (MJ/m^2)			
	Thomas [18]		Current study	
Room type	Mean	90th percentile	Mean	90th percentile
Classrooms	115	165	149 (CL−P)*107 (CL−S)	229 (CL−P) 139 (CL−S)
Teacher rooms	375	720	–	–
Special rooms	190	290	–	–
Material rooms	705	1330	–	–
Lecture rooms	80	165	–	–
Admin rooms	450	760	–	–
Libraries	1510	2550	551	882
Storerooms	440	885	2330	4180
Others	190	465	297	583

*CL-P = Classroom primary; CL-S = Classroom secondary

approximately three (3) times the amount for libraries in the study presented above. Thomas's data does not differentiate between classroom types (i.e. primary or secondary) however the mean (i.e. 115 MJ/m^2) and 90th percentile (i.e. 165 MJ/m^2) fire load densities from Thomas's data were considered to be comparable to the mean (i.e. 107 MJ/m^2) and 90th percentile (i.e. 139 MJ/m^2) fire load densities for secondary classrooms in the current study.

4.2. Comparison of the Probabilistic Distribution Models by Others

The skewed histogram of fire load density is not unique to the current study. It was also found in surveys of a wide range of buildings, such as hotel buildings by Gao et al. [11], in commercial premises by Zalok et al. [10] and in school buildings by Hadjisophocleous and Chen [22]. It is not surprising to see from Table 1 that lognormal distribution is most commonly used in the statistical modelling to cope with the positively skewed fire load density data.

Thauvoye [15] compared the lognormal and Gumbel distributions for fire load in commercial building in France. No significant difference was found between the two distributions in respect to goodness of fit. However, the Gumbel distribution has a drawback because of its domain extends to negative territory.

The fire load density histograms obtained by Hadjisophocleous and Chen [22] from Canadian school buildings only displayed mildly skewed tail end and the range of variation was much smaller (see Table 10) most likely due to their relatively small sample size and absence of storeroom data which was noted to have a significant impact in the result of the current study. Unfortunately, the statistical modelling of the fire load density distributions was not found their study published in 2010.

4.3. Implications to Fire Safety Engineering Practice

The highly skewed distribution towards the right end or large fuel load density value means that the fuel load density is very sensitive to the percentile value at this end. In other words, a small change at the high end of percentile will result in a large variation in the corresponding fire load density value. For example, when the percentile value is increased from 90 to 95th, in Fig. 1b, the corresponding fire load density is almost increased by more than 68% (525 to 884 MJ/m^2) according to the surveyed data of overall fire load density distribution presented in Table 4 or by 38% (525 to 725 MJ/m^2) according to the fitted lognormal distribution. One should bear in mind of such high sensitivity in the selection of design fire load density.

The lower than surveyed fire load density values nominated in IFEG [1] at 90th and 95th percentiles (see Table 4) means that IFEG is less conservative. Should these percentiles be considered for design fire selection for schools, then more conservative fire load density values (or higher values) than that recommended in the International Fire Engineering Guidelines should be used in Australian context.

As discussed earlier, the high skewness of the distribution is ascribed to the data from storerooms in the current study. These data are true and realistic representation of the fire load in school buildings. Storerooms in school buildings are not necessarily designated rooms in terms of design and usage. Any room could potentially be used as a storeroom during the lifetime of a school building. On this basis, the impact of the storeroom data on the shape of PDF is real and should not be ignored or treated separately. If a designer wishes to either include or exclude the storerooms in the selection of design fire, adjustment can be made in the selection of the percentile value of the fire load density. This is the core of the performance-based probabilistic approach. So long it is justifiable, designers have the discretion to determine the design parameters.

One of the verification methods for performance-based fire engineering design is to use the deemed-to-satisfy provisions of building codes as a benchmark and then establish that the performance solutions have the equivalent risk profiles to that of the benchmark [27, 31–33]. In order to establish the risk profile of the benchmark, statistical characteristics of the buildings that satisfy the prescriptive codes are needed.

Apart from fire load density, ventilation factor and thermal properties of compartment lining materials are the other parameters that contribute to fire severity [1, 36]. From building regulatory point of view, these parameters are also random variables and require appropriate statistical descriptions. Studies in this area are, however, lacking in the literature and further research is warranted. Otherwise regardless of the accuracy or appropriateness of fire load density inputs, the equivalent fire severity calculations will be at risk of being erroneous.

5. Conclusions

This paper has presented the results of a field survey study on fire loads in schools within the Sydney metropolitan area. It has been revealed that the range of variation in fire load density in school building compartments is significantly wide. The histogram of the fire load density is found highly skewed towards the high value end. The results were modelled with a number of probability density distribution functions. A set of criteria was introduced for the selection of the distribution function. The statistical analysis determined that fire load density for all the rooms in the surveyed school buildings can be closely represented by generalised extreme value and lognormal distributions. Based on the considerations of range of domain, goodness of fit, robustness and versatility, it is recommended that lognormal is the preferred model to characterise the fire load density distribution.

The outcomes of the study have shown some similarities between fire load data collected from Australia and that from a number of other countries. The study also identified some issues in relation to data provided in commonly referenced documents such as IFEG. Discrepancies were found between early published data and the results of the current study. These discrepancies may be attributable to chronological change in the contents of the building of the same category and/or to the differences in geographic region/location.

Additionally, holistic fire load density values detailed in published documents do not account for subtle differences (e.g. school type and room use) which can have a profound impact on the outcome of fire safety engineering assessments. It has been found that while basic statistical characteristics show similarities globally, some other characteristics, particularly 80th, 90th and 95th percentiles, may differ from one country to the other. This outcome suggests that fire load selection for design fires [1] in fire safety engineering design and assessment of structural fire resistance should be better based on local data and a careful review of the unified approach in the International Fire Engineering Guidelines is warranted.

This study was limited to 3 schools in the Greater Sydney metropolitan area. It is not known whether the results represent the fire load distribution for typical Australian schools. More surveys in other states and cities would be necessary to consolidate and generalise the findings for guiding fire safety engineering design practice. Surveys of fire load for other types of occupancies and surveys of ventilation factors are also needed in order for engineers to have appropriate data to develop performance based design solutions.

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