Fire Load Survey and Statistical Analysis

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ABSTRACT

Fire load surveys in many building types are presented and analysed. They are based on two datasets which are studied in two separate chapters, after a brief presentation of the measurement method. The first dataset concerned fire loads in industrial and commercial buildings in Switzerland. ETH (Eidgenössische Technische Hoschule Zürich) and VKF (Swiss Fire Authority, Berne) inspected 95 companies in about 40 industrial sectors leading to 336 measures. A statistical analysis is made and the agreement between those data and two probability laws is studied. It is shown that lognormal law provides a better agreement than Gumbel law.

The second dataset concerns public buildings (such as shopping centers, hotels and hospitals) and offices in France for a total of 139 rooms. Those data were collected in the framework of "Projet National pour l'Ingénierie de la Sécurité Incendie" agreed by the French "Réseau Génie Civil & Urbain" (PNISI: National Project for Fire Safety Engineering). The same process as previously is applied: a chi-square test. Here, differences are not significant between Gumbel law and lognormal law. The explanation is related to the ratio of standard deviation over mean value which is much smaller for this dataset. It leads to equivalent distribution functions. The composition of fire load is also analyzed and reveals that wood material continues to be present in great proportion.

KEYWORDS: statistics, fire load density, Gumbel law, lognormal law

NOMENCLATURE LISTING

c_v	coefficient of variation	Greek	
f	probability density function	σ	parameter for lognormal law
F	cumulative distribution function	μ	parameter for Gumbel law
m	parameter for lognormal law	β	parameter for Gumbel law

INTRODUCTION

In case of fire, the amount of releasable energy is related to the mass of combustible materials. The fire duration depends on this fire load and on the heat release rate. This is related to the composition of the fire load and its exposed surface, the fresh air supply. Fire load density, which is directly linked to fire load, is a dimensioning parameter and many numerical models use it. It is thus necessary to have reliable statistical data. Such data can be found in the large amount of survey performed during the last decades [1], [2], [3], [4], [5] and [6].

In Switzerland, a risk analysis method exists for fire: the SIA 81 method [7]. It uses fire load densities measured in the sixties. Within the framework of an improvement of this method, a new series of measurement was performed in 2005 [8]. 95 industrial and commercial buildings located in 16 Swiss cantons and in Lichtenstein were investigated by ETH Zürich and VKF. An agreement between VKF/ETH and CTICM has been concluded to perform a statistical analysis of these data.

French data were collected within the framework of National Project for Fire Safety Engineering. This project is dedicated to improving the introduction of a performance-based approach in French regulations. It is based on the utilization of design fire scenarios in order to evaluate trial designs as far as the fulfillment of fire safety objectives is concerned. As the fire load density is an important parameter for fire design, an investigation was conducted and led to the collection of 70 measurements [9]. It concerns public

buildings (such as shopping centers, hotels and hospitals) and offices. They were performed by the Cergy-Pontoise University and Nancy Mines High-School in 2006-2007 [10], [11], [12] and [13].

MEASUREMENT METHOD

The methods used for the two datasets are very similar even if they were conducted independently. Four sorts of information were recorded for every room:

- General information (date, company name, room ID...)
- Geometrical parameters:
 - ❖ Width, length, height
 - Opening size
 - Wall material
- Fire load data including mass or volume, material, heat of combustion... A distinction is made between mobile and immobile (fixed) fire load. In the French survey process a further distinction is made between objects with a simple geometrical shape (desk, cupboard...) and those where characteristic dimensions are hard to estimate (chair...). For the first category, weight or volume is measured (the easiest is chosen) and for the latter the fire load is estimated by reference to a list of selected items representative of common products (wood chair, plastic chair...).

There are some differences between ETH/VKF and French protocols. The ETH/VKF protocol is described in detail in [8]. In the ETH/VKF survey prior to the visit, a first contact is established with the company to visit in order to identify what are the major fire loads and a literature search is carried out before the visit.

STATISTICAL ANALYSIS OF THE ETH INVESTIGATION

Global analysis

Here, the distinction between storage and production areas is made. Figure 1 shows the Cumulative Distribution Function (CDF) for the all 131 production areas. 95% of fire load densities are lower than 2500 MJ.m⁻². The mean value is 1080 MJ.m⁻² and the standard deviation 1920 MJ.m⁻² which leads to a coefficient of variation c_v of 1.78 (ratio standard deviation / mean).

The lognormal law (Table 1.) is a common law in many fields where asymmetric distributions are expected. Nevertheless, in structural engineering, the Gumbel distribution (Table 1.) is frequently adopted. In Eurocode 1 part 1-2 [14], fire load densities are also supposed to follow the Gumbel law. So, the agreement between these two laws and that dataset is tested via the least squares method. A more complete description of statistical tools used here is available in chapters on probability and statistics in the SFPE Handbook [15]. The best values for the parameters are the couples (m = 6.33; $\sigma = 1.13$) and ($\mu = 440$; $\beta = 530$). As shown on Fig. 1, the lognormal law gives better agreement (the curves are nearly merged).

Table 1. Lognormal and Gumbel	Table 1.	Lognormal	and	Gumbel	laws.
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Probability law	Lognormal	Gumbel (type I)		
Probability density function	$f(x) = 0 \qquad \forall x \le 0$ $f(x) = \frac{1}{\sigma\sqrt{2\pi}} \frac{1}{x} \exp\left(-\frac{(\ln(x) - m)^2}{2\sigma^2}\right) \forall x > 0$	$f(x) = \frac{1}{\beta} \exp\left(-\frac{x-\mu}{\beta}\right) \exp\left(-\exp\left(-\frac{x-\mu}{\beta}\right)\right)$ $\forall x \in R$		
Cumulative distribution function	$F(x) = \frac{1}{2} + \frac{1}{2} \operatorname{erf}\left(\frac{\ln(x) - m}{\sigma\sqrt{2}}\right) \qquad \forall x > 0$	$F(x) = \exp\left(-\exp\left(-\frac{x-\mu}{\beta}\right)\right) \qquad \forall x > 0$		

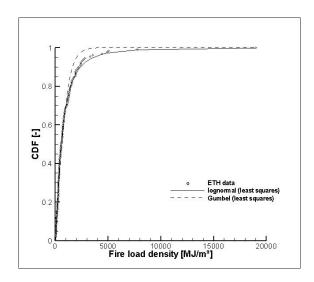


Fig. 1. Comparison experimental data – theoretical laws for production rooms

In this case, the Gumbel law is not able to describe the dataset. With this law, there is a non negligible probability of having negative fire load densities which is physically incorrect. This is particularly the case when the skewness of the PDF is high. As an example, Gumbel PDF are drawn for a coefficient of variation of 1.5 and of 0.5 on Fig. 2. As opposite, the lognormal law remains positive.

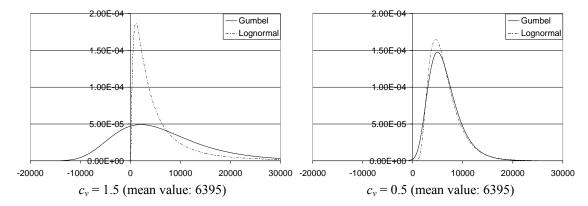


Fig. 2. Influence of coefficient of variation on the PDF shape.

For storage areas, fire load densities are mainly in the range [0 - 35000] MJ.m⁻² (95% of values) with a mean value of 11874 MJ.m⁻² and a standard deviation of 32774 MJ.m⁻² (c_v : 2.76). Fire load densities are greater in storage areas than in production areas (by a factor 10).

The coefficient of variation is really high and is accentuated by the maximum measured value (433710 MJ.m-2). This value was measured in a silo. The geometry of this kind of building is very different from other industrial and commercial buildings. Moreover, the construction provisions are specific regarding fire safety. If this value is omitted, the average would decrease to 9806 MJ.m-2 (-17 %) and the standard deviation to 14055 MJ.m-2 (twice smaller than before).

As previously, the adequacy between this sample and the two selected probability laws is tested. This leads to the following couples (m = 8.50; $\sigma = 1.30$) and ($\mu = 3890$; $\beta = 5270$) and graphs (Fig. 3). The Gumbel law gives poor results whereas the lognormal curve describes the dataset well. For fire load densities up to 13000 MJ.m⁻² there are nearly no differences; for greater fire load densities the lognormal law gives smaller values than those measured. It means that there is a higher probability to find high fire load densities with the lognormal law and this set of parameters: this option is safe.

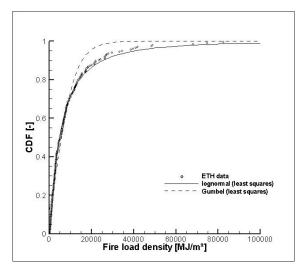


Fig. 3. Comparison experimental data – theoretical laws for storage rooms

It is common for storage areas to take into account the storage height. In this case, the fire load density is divided by the storage height. For this sample, the mean value is 3186 MJ.m⁻³ and the standard deviation 3367 MJ.m⁻³ leading to a coefficient c_v of 1.06. But even with this smaller coefficient of variation, the lognormal law remains the best way to describe the sample (Fig. 4). Its behavior is excellent up to 6150 MJ.m⁻³ (86% of values) and safe beyond.

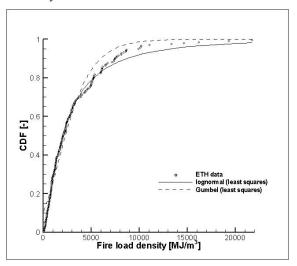


Fig. 4. Comparison experimental data – theoretical laws for storage rooms

Subset analysis

It is possible to divide the dataset into several subsets depending on the company activity. The following subsets are used:

- Chemical Industrial,
- Diverse goods,
- Wood processing,
- Cardboard / Paper processing,
- Plastics processing,
- Food processing,

- Metal processing,
- Textiles,
- Offices.

In order to keep at least 15 values in every subset, no distinction is made between storage and production area. Major characteristics for each subset are gathered in table 2. The analysis shows that the ratio mean value – standard deviation is always high and so that a lognormal is probably more adequate than a Gumbel law. Means values are distributed on a wide range (factor 10) but extreme values are related to subset with a limited number of samples. Parameters given by the least square method are reported in table 2 for every subset and the two probability laws.

	Number of samples Mean value MJ.m ⁻²	Mean	Standard		lognormal law		Gumbel law	
Sector		value [MJ.m ⁻²]	$\begin{array}{c c} \textbf{deviation} & c_{\nu} \\ [\textbf{MJ.m}^{-2}] & \end{array}$	c_v	m	σ	μ	β
Chemical industrial	21	13865	21860	1.58	8.11	1.97	2636	5919
Diverse goods	63	4712	7338	1.56	7.32	1.89	1301	2660
Wood processing	31	6235	8805	1.41	7.80	1.35	1811	2655
Paper processing	56	9880	16430	1.66	8.14	1.77	3064	6265
Plastics processing	41	5051	7865	1.56	7.60	1.27	1530	2040
Food processing	58	7945	12593	1.59	8.00	1.60	2641	4145
Metal processing	37	2461	3983	1.62	6.62	1.68	590	1175
Textiles	16	2609	4221	1.62	6.85	1.30	735	1069
Offices	12	1409	1854	1.32	6.33	1.14	429	546

A chi-square test is performed on each subset; results are displayed in table 3. Thus we can reject with a high probability (95% even 99%) the assumption of a Gumbel law to describe the following subsets: diverse goods, wood processing, paper processing, plastics processing, food processing and metal processing. For chemical industrial, textiles and offices, the assumption can not be rejected but the limited amount of data for these classes makes the analysis difficult. In conclusion, the lognormal law provides the best agreement with data as suggested.

Table 3. Chi-square test.

Sector	lognormal		Gumbel law		
Sector	U ^a	n ^b	U	n	
Chemical industrial	0.18	2	0.10	2	
Diverse goods	2.54	9	66.74	9	
Wood processing	4.37	4	11.58	4	
Paper processing	10.52	8	45.98	8	
Plastics processing	3.16	6	13.65	6	
Food processing	6.65	8	17.47	8	
Metal processing	0.61	5	38.66	5	
Textiles	0.08	2	0.26	2	
Offices	0.52	2	1.71	2	
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^aU: calculated criteria value

^bn: number of freedom degree

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STATISTICAL ANALYSIS OF THE PNISI (FRENCH) INVESTIGATION

Shopping centers

Twenty six stores were surveyed, 90% of fire load densities are in the range [0-910] MJ.m⁻². The mean value and the standard deviation are respectively 571 MJ.m⁻² and 372 MJ.m⁻² leading to a coefficient c_v of 0.65. The least squares method gives the couples (m = 6.12; $\sigma = 0.78$) and ($\mu = 370$; $\beta = 306$) as best parameters respectively for the lognormal and Gumbel law. As shown on Fig. 5, the agreement is slightly better with Gumbel law but the lognormal law can not be rejected with a chi-square test. This result is due to the fact that the coefficient of variation is low. The comparison with available data in the Fire Engineering Guidelines (F.E.G) [15] shows a good agreement with our sample whereas parameters chosen in the Eurocode for the Gumbel law lead to lower values for the 90% and 95% fractiles (Fig. 5).

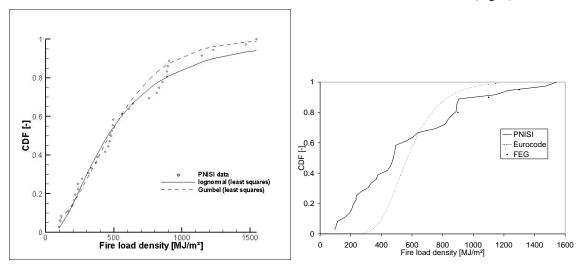


Fig. 5. Shopping centers: comparison with theoretical laws (left), comparison with others surveys (right)

The combustible materials were classified in one of the following categories: wood, textiles, paper, plastics and miscellaneous for other combustible objects. However, fire load is mainly composed of wood (44%) and textiles (34%) (Fig. 6). It reflects the fact that wood shelves are often used as a way to display goods whatever the type of store. Moreover, many stores are clothing stores so textiles represent an important category. As for the survey conducted by Carleton University and the National Research Council of Canada [5], wood/paper and textiles are the main combustible materials in clothing stores with respectively 44.5% and 48.1%.

Occupancy	Average	Fractile [MJ/m²]			
Occupancy	$[MJ/m^2]$	80%	90%	95%	
Hospital	230	350	440	520	
Hotel bedroom	310	400	460	510	
Offices	420	570	670	760	
Shops	600	900	1100	1300	

Table 4. Fire load densities extracted from [15].

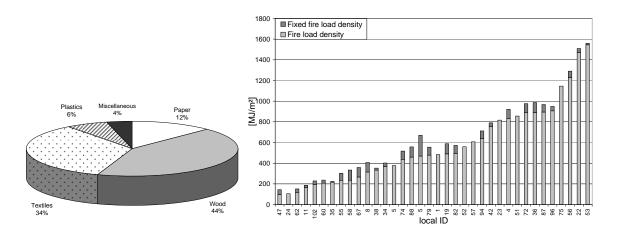


Fig. 6. Mean composition (%) for shopping centers (left), measured fire load densities (right)

For shopping centers (and also hotels, hospitals but not offices), the fire load induced by wall linings, floor, doors was measured, this is the *fixed* fire load density. Taking into account this part increases a little the mean value (622 MJ.m⁻²) but it does not modify the standard deviation. This fire load density is called as the *total* fire load density.

Hotels

Among the 22 surveyed rooms, there are 6 receptions, 6 laundries and 10 guest rooms. Their statistical characteristics are illustrated in table 5 but due to their limited sample size no comparison analysis with a Gumbel or a lognormal law is performed. Comparison with data in the F.E.G (table 4) or in the Eurocode is rather good but this result needs to be confirmed on a bigger sample (Fig. 7).

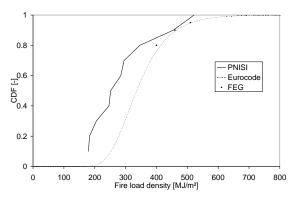


Fig. 7. Hotels: comparison with others surveys (right)

For reception rooms, the fire load density is between 120 and 400 MJ.m⁻² except for room number 6 with 1170 MJ.m⁻² (Fig. 8). This is due to the presence of a couch which represents 66% of the fire load. A bigger sample would certainly lead to the distinction of two categories:

- moderate fire load density for hotels where the reception room is a transit space,
- high fire load density for hotels where it is rather a waiting room typically in luxury hotels.

Table 5. Statistical characteristics for hotels.

	Fire load density [MJ.m ⁻²] Mean Standard deviation		Total fire load density [MJ.m ⁻²]		
			Mean	Standard deviation	
Reception	412	384	551	399	
Room	297	114	562	138	
Laundry	1279	763	1379	821	

The fixed fire load density is about 140 MJ.m⁻² representing thus 36% of the total fire load density for the category with moderate fire load density and 10 % for the category with high fire load density. Concerning the mean composition, the wood is present in high proportion (72%) in those areas, indeed desktops are often in wood (Fig. 8).

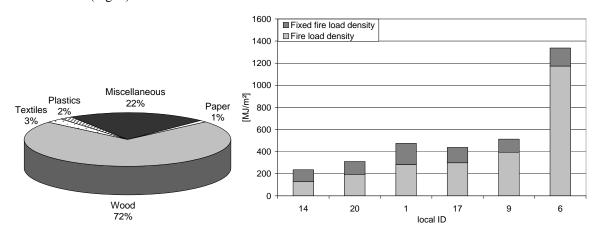


Fig. 8. Mean composition (%) for reception rooms (left), measured fire load densities (right)

For hotel guest rooms, the fire load density is really low (297 MJ.m⁻²) while the fixed fire load density is responsible for 48% of the total fire load density on average. This fact is due to the presence of wall linings (carpet, parquet) and wooden doors. Hotel rooms and hospital chambers have a particularity: people sleep inside so there is a bed of which the fire load may be high. As shown on figure 9, wood is always the main part of the fire load density (70%).

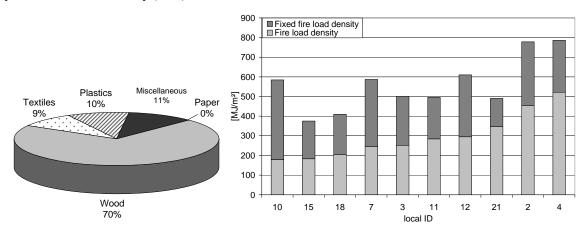


Fig. 9. Mean composition (%) for hotel guest rooms (left), measured fire load densities (right)

For laundries, two classes are present: low (below 800 MJ.m⁻²) and (above 1800 MJ.m⁻²) high fire load density. However, it is difficult to conclude on the origin of this distribution because many factors need to be taken into consideration: measurement time (was the linen always or already in rooms?), the way of storing (on clothes hanger or on pile), the number of present customer... Logically, textiles have an important part in the fire load with a mean value of 87%, the other part of fire load is made of wood often used for shelves (Fig. 10). In these two categories, the fixed fire load density is small (in the order of 100 MJ.m⁻²).

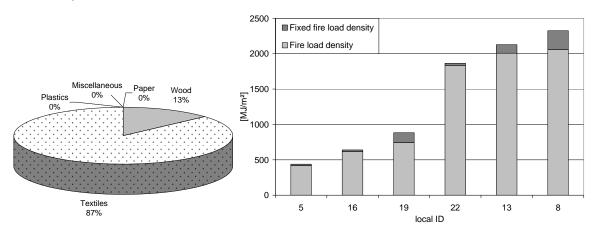


Fig. 10. Mean composition (%) for laundries (left), measured fire load densities (right)

Hospitals

Twenty rooms were surveyed in one hospital. Most of fire load densities were measured in the range [0-230] MJ.m⁻² for a mean value of 188 MJ.m⁻² and a standard deviation of 107 MJ.m⁻². The use of least squares method give the couple of values (m = 5.16; $\sigma = 0.48$) and ($\mu = 144$; $\beta = 78$) for the two probability laws (Fig. 11). As for shopping centers, a chi-square test can not reject one of these laws. Fire load densities are lower than FEG values and much lower than Eurocode values. Nevertheless, using Eurocode values would give a high level of safety for a place where evacuation is often problematic in case of fire and may lead to injuries.

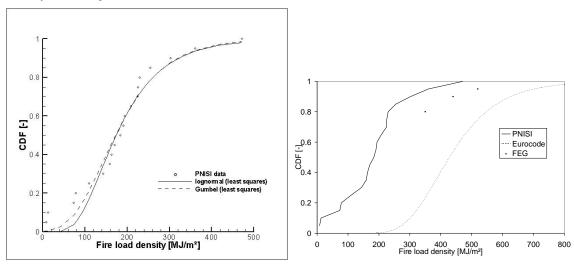


Fig. 11. Hospitals: comparison with theoretical laws (left), comparison with others surveys (right)

The behavior is similar to hotel guest rooms with a high fixed fire load density (mean value: 46% of total fire load density) even if it is lower in absolute value with a mean value: 158 MJ.m⁻² (Fig. 12). For the mean composition, wood is still the main material (70%).

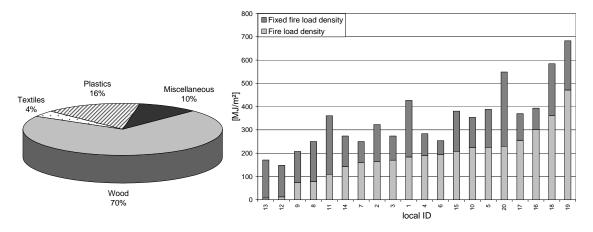


Fig. 12. Mean composition (%) for hospital (left), measured fire load densities (right)

Offices

The survey concerns 61 rooms in office buildings, including reading and meeting rooms. For this sample, the mean value and the standard deviation are respectively 657 MJ.m⁻² and 290 MJ.m⁻² resulting in a low dispersion ($c_v = 0.51$). Most of fire load densities are between 0 and 910 MJ.m⁻². As previously the dataset is approximated with a lognormal and a Gumbel law of which the parameters are fitted by the least squares method. It gives respectively (m = 6.23; $\sigma = 0.6$) and ($\mu = 423$; $\beta = 266$). Graphically, the agreement seems to be a little better with the Gumbel law but a chi-square test does not allow rejecting the lognormal law (Fig. 13).

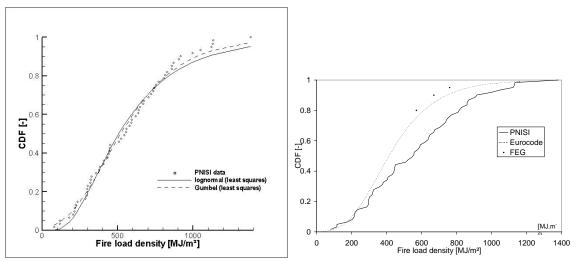


Fig. 13. Offices: comparison with theoretical laws (left), comparison with others surveys (right)

Fire load densities are higher than both the F.E.G and Eurocode values in the order of 35% - 40% (Fig. 13). Contrary to hospital rooms, values retained in Eurocode do not seem to be safe. Data collected by ETH contains also 9 offices (storage areas are excluded from the dataset) with a mean value of 516 MJ.m⁻². This is slightly lower (10%) than PNISI (French) data.

On average, cellulosic materials represent 81% of the fire load density with a few more paper than wood as expected for this kind of rooms (Fig. 14).

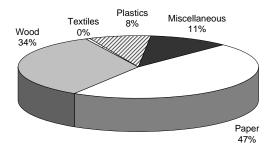


Fig. 14. Mean composition (%) for offices

CONCLUSION

In this paper, statistical results based on a survey in 475 rooms including hotel, hospital, shopping centers, offices and industrial buildings are presented. This work has been focused on the capability of two probability laws (lognormal and Gumbel) to describe accurately every type of occupancy. Whereas the datasets have high differences in term of mean value and standard deviation especially for industrial buildings, sets of parameters were found using a least squares method and a chi-square test was performed to check their validity. The lognormal gives always satisfactory results while Gumbel law can be used if the coefficient of variation is low (less than 1.0). Nevertheless the lognormal law gives a higher probability to have important fire load densities for our sets of parameters: this option is safe but may be conservative. The second result deals with the composition of the fire load. It appears that wood is in shopping areas, hotels, offices and hospitals very often the main material whereas plastics are present in small quantity. The analysis could be extended by increasing the number of data. This is an important point in a performance-based approach and an efficient way to detect a change in fire load distribution or their composition. Consequently, continuing the survey on fire load will provide useful information to be gathered in a national database.

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