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Industrial Accidents: are more Serious Events than Bhopal Possible?

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Major accidents unfortunately occur with a certain frequency in industry. Sometimes these accidents are of truly catastrophic proportions. There naturally come to mind events such as the leak and subsequent release of a toxic cloud of methyl isocyanate in the Indian city of Bhopal on 12 March 1984, resulting in 3787 fatalities (although some sources calculate the total as being up to 20.000, including ensuing fatalities over the years) . These occurrences are frequently categorised as being unpredictable and perhaps beyond human control (in Anglo-Saxon legal terminology, 'acts of God').
Quite the opposite, the aim of this paper is to demonstrate that catastrophic occurrences over the last one hundred years have conformed to a well-known statistical distribution and, as a consequence, were entirely foreseeable. Demonstrating this will open the way to the following issues:
1) Are events with consequences even exceeding those observed to date (for simplicity, referred to as trans-Bhopal events) possible?
2) Must the possibility of catastrophic events (of Bhopal and even trans-Bhopal category) be accepted with fatalistic resignation or, on the contrary, are there effective tools available to prevent such events?

1. Industrial accident information sources

The compilation of major industrial accidents by Mihailidou et al. (2012) has been utilised in this analysis as well as the United Nations Environment Program (UNEP) definition of major industrial accident. In accordance with this, an accident is deemed to be major if it causes at least: a) 25 fatalities; b) 125 injured, c) 10,000 evacuees; d) 10,000 persons deprived of water. Utilising these criteria, between 1917 and 2011 a total of three hundred and nineteen major accidents have been identified.

2. Heavy-tailed statistical distributions - very brief introduction to the potential distribution

Many empirical values are grouped around a central (or 'mean') value without there being significant proportions of elements very distant from it. In this manner, for example, in 2001 the mean height of males exceeding 15 years of age in Spain was 1.721 m. It is quite obvious that there are no adults with heights greater or lesser than this mean by a factor of 2 (less than 86 cm or over 344 cm!). These variables are satisfactorily described by means of statistical distributions in which the proportion which is very distant from the mean is insignificant (for example, the very well-known normal distribution) and which, consequently, can be adequately characterised by a mean and a standard deviation.
On the other hand there are other phenomena which show much greater variability, with values which extend across several orders of magnitude. It should be emphasised that these values, very distant from the mean, are not merely errors of observation or isolated phenomena ('outliers' in standard statistical terminology), but constitute an important part of the phenomenon and frequently point up its great underlying complexity. These variables require distribution functions where a large proportion is contained in the 'tail', known as heavy-tailed distributions. From among the foregoing, in recent years the potential law has been applied to the study of a series of phenomena, both natural and related with human activity. Some examples are (Clauset et al. 2009): a) the number of species in each mammalian genus; b) the intensity of gamma emission peaks in solar flares;

c) the population of cities of the United States of America; d) the gravity of terrorist attacks; e) the intensity of wars; f) the intensity of seismic movements.
The characteristic which most clearly distinguishes the potential distribution from more other more-common distributions, such as normal distribution, is its 'heavy tail'. That is to say that a non-trivial proportion exists at distant values, including of orders of magnitude, from the central values (mean, median). According to this distribution function, when the variable is multiplied by a given factor (2, for example), its frequency is divided by another constant factor (4, for example). The relationship between both factors determines the scale parameter, α. Given that this relationship is constant for any value of the function, it is said that it is scale-invariant. Or, in other words, that there is no qualitative difference between large- or small-scale events.
Clearly the distribution must have a lower threshold xmin, because the frequency would otherwise tend to infinity when the variable tends towards zero. Employing this terminology, the distribution density is as follows:

$$p(x) = \frac{\alpha - 1}{x_{\min}} \left(\frac{x}{x_{\min}} \right)^{-\alpha} \tag{1}$$

Integrating elementally, the following cumulative distribution function is obtained:

$$P(x) = \left(\frac{x}{x_{\min}} \right)^{1-\alpha} \tag{2}$$

3. Industrial accident distribution analysis

Following the inevitable (but minimal) mathematics, we can proceed to the real data. In this manner, Figure 1 shows (diamonds) the proportion of major industrial accidents analysed with N or more fatalities. The value selected for xmin is 20, that is to say solely those accidents with 20 or more fatalities have been included (a total of 85 cases in 94 years). The values of the mean (147) and the median (40) of the distribution are also shown in the figure (vertical lines).
As may be readily observed, the premises for the employment of potential distribution are very clearly complied with, since there is a proportion of 1% of values that exceed the mean by an order of magnitude. Returning to the height example, it would be as if 1% of the Spanish population had a height of 17.2 m or more!
A potential distribution (solid line) has been fitted to the values observed with parameters α=1.931 and σ=0.191. The goodness-of-fit has been checked by a Kolmogorov-Smirnov test.

4. Are catastrophic events (Bhopal category) truly unpredictable?

It is evident that if a phenomenon can be modelled by means of a distribution function, it is not totally unpredictable. To verify this assertion the fitting of the frequency with respect to the number of fatalities has been repeated, eliminating from the sample the ten most-catastrophic accidents, that is to say those with most fatalities (and which for simplicity are referred to in this paper as of 'Bhopal category'). The results obtained are shown in Figure 2.
In specific terms, the dashed line in the figure shows the fit which would have been obtained through discarding the ten Bhopal-category scenarios from the sample (also shown in the figure as triangles). The figure also retains the fitted straight line (continuous line) taking all scenarios into account.
As may be observed, the dashed line predicts the Bhopal-category events very well, although all of them are in the decade below the data employed in the fit. As a consequence, in view of these results, it cannot be stated that these events were unpredictable.

5. Are even more catastrophic events (trans-Bhopal category) possible?

The conclusion of the foregoing section naturally leads to questioning whether the possibility exists of even-more catastrophic events than those observed to date, referred to in this article as trans-Bhopal events. Figure 3 shows the extrapolation of the potential distribution to a proportion of 0.001. According to this figure, it is to be expected that one in every thousand major accidents will cause 30,000 or more fatalities.
Clearly, we must question if it is reasonable to extend the extrapolation. That is to say, whether a physical limit on the possible damage exists or whether a proportion is reached which is so low that it is only remotely probable that the scenario will arise in practice.

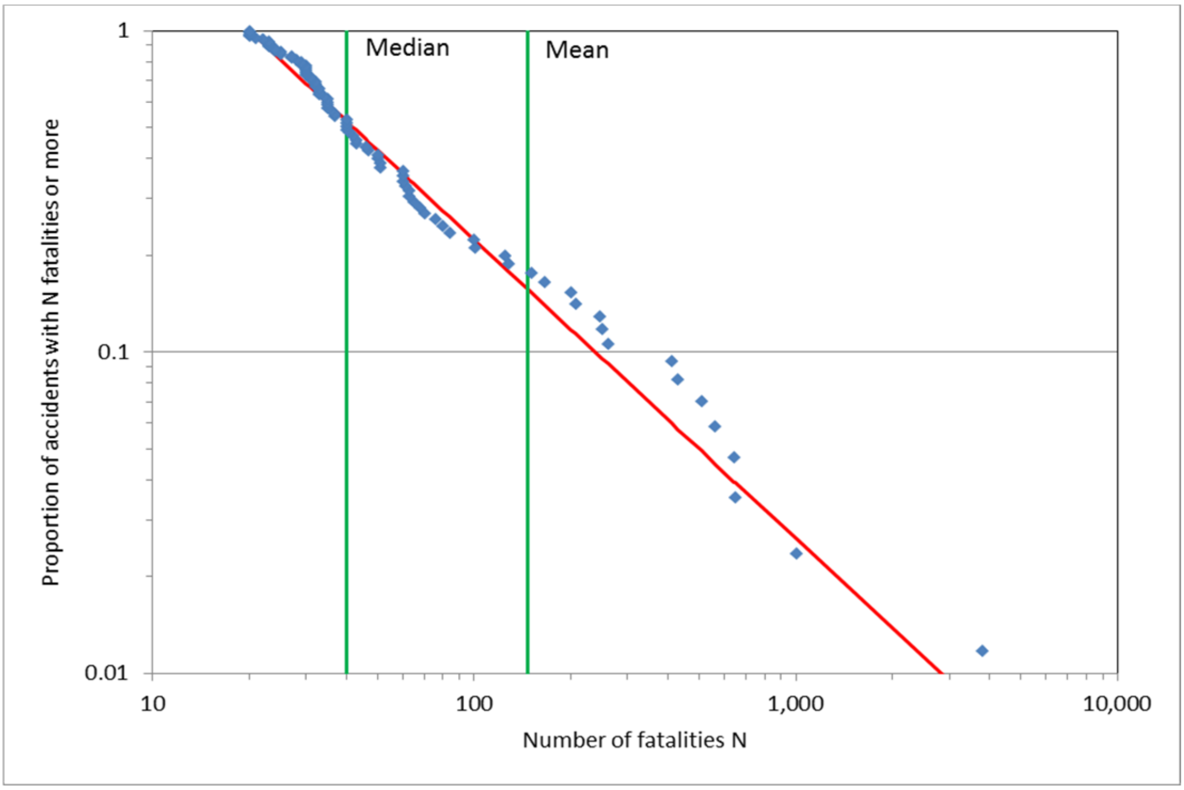

Figure 1. Cumulative distribution function (complementary) of the number of fatalities in major industrial accidents 1917-2011.

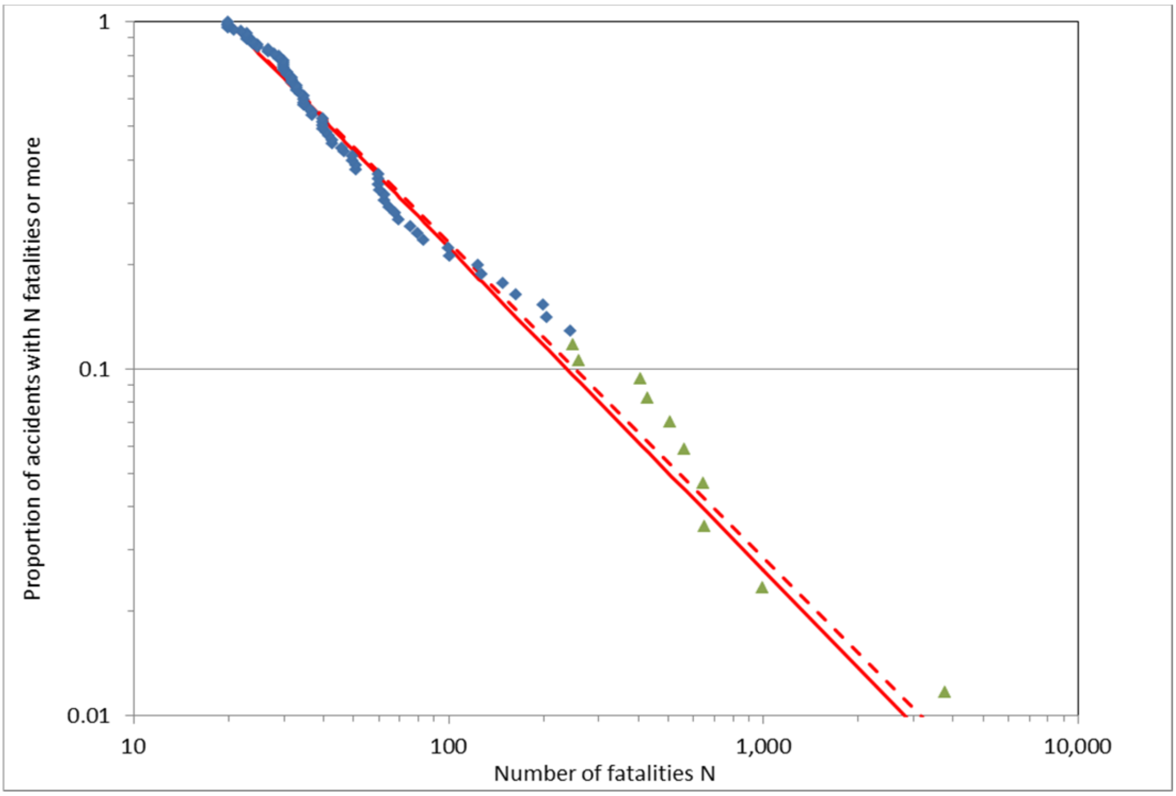

Figure 2. Cumulative distribution function (complementary) of the number of fatalities in major industrial accidents 1917-2011 (not including the ten most serious accidents).

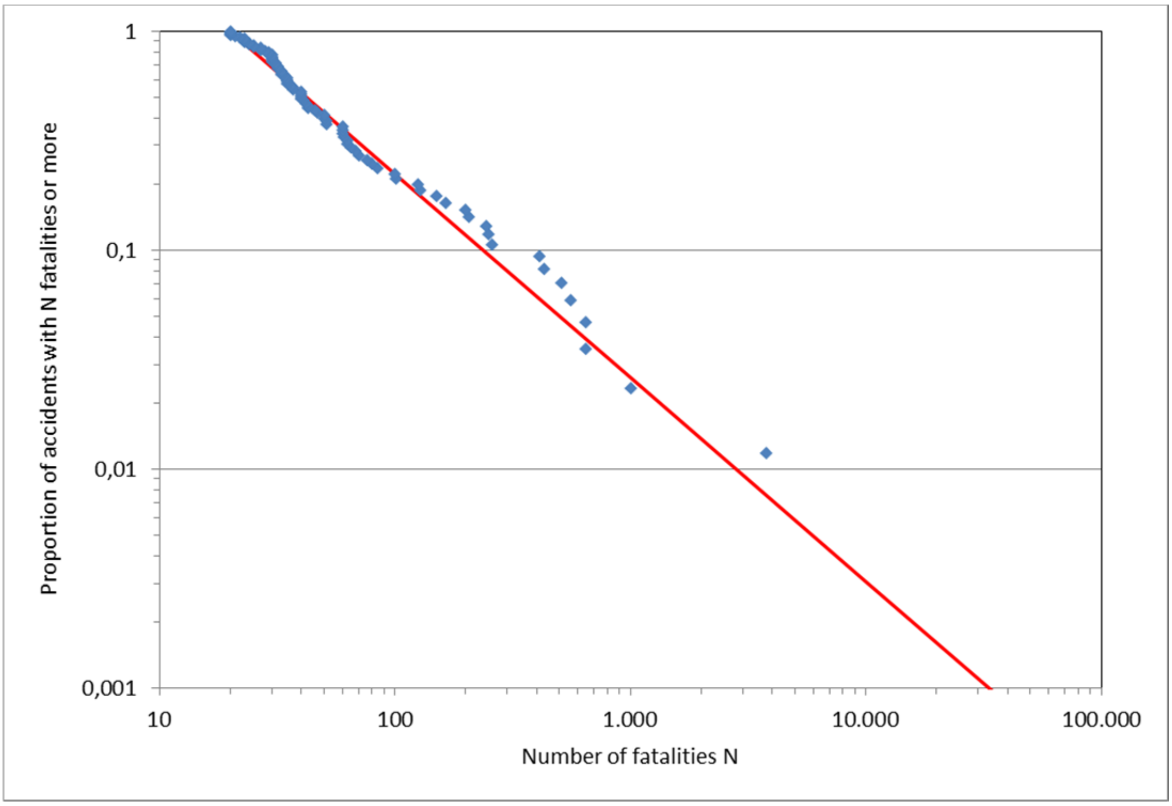

Figure 3. Cumulative distribution function (complementary) of the cost (millions of Euros at 2011 prices) in major industrial accidents 1917-2011 (extrapolation to a proportion of 0.001).

In terms of fatalities, over recent decades at least two phenomena have occurred leading to consider the possibility of scenarios with trans-Bhopal consequences. On the one hand, the progressive industrialisation of densely-populated regions, with the risks entailed from the proximity of large inhabited centres of population and potentially-dangerous industrial activities and, on the other, growing migration towards the same centres of population which are becoming authentic megalopolises. Furthermore, in recent years the development of bioengineering, chemical and nuclear industries have arisen as potential generators of catastrophic events.

Furthermore, it may be thought that the low proportion of trans-Bhopal accidents, taken together with the low frequency of major accidents, will make them unobservable in practice. It must be clarified at this point that, up to now, the time factor has not been included in the analysis. In effect, it has been restricted to studying the proportion of accidents as a function of magnitude, independently of the greater or lesser frequency with which they occur over time. In general terms, one major accident has occurred per year in the period considered, arising from which a trans-Bhopal scenario, with a proportion of 0.001, has a return period of one thousand years. It does not appear unreasonable to take it into account when compared with other phenomena of a natural origin (flood, inundation, earthquake, etc) with a lower or equal potential number of victims.

6. Are catastrophic events (trans-Bhopal category) acceptable?

In a pioneering article, Farmer (1967) established a criterion of acceptability of exposure to radionuclides leaking from nuclear installation which has also constituted the basis for acceptability criteria of societal risk in the chemical industry. In a very simplified manner, Farmer's criterion may be expressed as follows: 'if the consequences of event A are one order of magnitude greater than those of event B, then its probability must be lower at least by the same order of magnitude'.

This criterion is habitually represented by means of the Farmer curves, or F-N curves, with the number of fatalities N on the x axis and the cumulative frequency of accidents with N or more fatalities on the y axis. In a formal sense, the graphs employed previously have the same units, arising from which they may be considered as being Farmer curves for all industry globally. Nevertheless, differing from habitual practice, the graphs in this paper are not based on calculations or simulations but on the real cases observed.

Nevertheless, it is useful to compare the curves obtained empirically with Farmer's criterion. Consequently, Figure 4 shows the same graph as Figure 1, superimposing Farmer's criterion (dashed line).

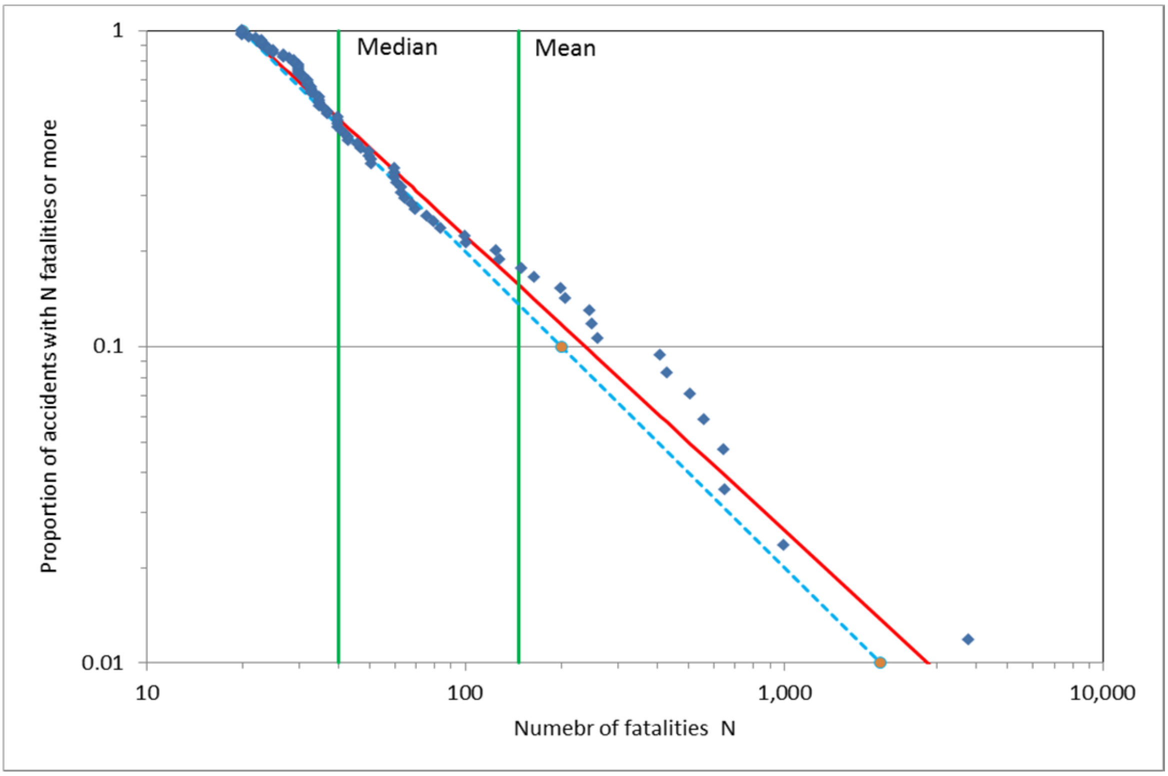

Figure 4. Cumulative distribution function (complementary) of the number of fatalities in major industrial accidents 1917-2011 compared with F.R. Farmer's risk acceptability criterion.

As may be observed, the fitted curve lies above Farmer's acceptability criterion, as do a good number of accidents with consequences exceeding 100 fatalities. Furthermore, it is observed that the gradient of the fitted curve is less steep than that of the Farmer curve, signifying that divergence increases with increase in the consequences of major accidents. Or, in other words, the frequency with which accidents with serious consequences (100 or more fatalities) are observed surpasses the habitually-accepted acceptability criteria, and it is foreseeable that it will be greater the greater the consequences considered.
On the other hand, in numerous (not to say in all) quantitative risk assessments (QRAs) carried out, whether in compliance with institutional or legal regulations (in general for land use planning), the results obtained always lie below the acceptability criteria. This induces the thought that factors exist which to date have not been taken into account in QRAs, leading to the calculated risk being lower than that observed in reality.

7. Is no defense possible in terms of trans-Bhopal category scenarios?

As has been demonstrated, the potential distribution permits the scales of variability of diverse phenomena to be explained. Nevertheless, a clear distinction must be made here between adverse phenomena of natural and human origin. In effect with respect to the former (e.g. earthquake intensity) the proportion of intensities observed to date macroscopically translates little- or poorly-understood physics and does not allow the prediction of phenomena of greater magnitude. On the other hand, in phenomena of human origin (as industrial accidents indubitably are), the correlations observed are the translation of a multitude of circumstances surrounding the accident scenarios. Among these the following are emphasised:
Design conditions.
Materials.
Construction, commissioning, operation, maintenance, management of change, inspection, ..., procedures.
Training of operating personnel.
Environment of industrial installations.
In short, inter alia, the process-safety conditions of installations. Consequently the distributions provided in this article reflect the predominant practices to date and should not be adopted without further thought and in a manner which may be qualified as fatalistic acceptance ('accidents will occur no matter what we do'). On the contrary, it is in our hands to improve the current practices adopted and, in this manner, modify the scale

factor of distributions and reduce both the frequency of accidents and the proportion of Bhopal and trans-Bhopal category scenarios.
In fact, we may influence accident scenarios in two ways. Firstly, by adopting better process safety practices, leading to a reduction in the frequency of occurrence of major accidents. Naturally, there is very extensive bibliography on this subject and to detail it would go greatly beyond its objective. It is sufficient to state that it may be summarised by the adoption of effective process safety management (PSM), including the creation of competence and a safety culture in the workforce.
Secondly, it may be questioned as to whether it is possible to influence the distribution of accident proportions. That is to say, whether measures can be adopted to reduce the proportion of accidents of Bhopal and trans-Bhopal categories or, what amounts to the same thing, to increase the value of the scale parameter, α. The answer is clearly in the affirmative. On the one hand, land-planning measures must prevent the proximity of built-up urban areas to dangerous industrial activities, in this manner reducing the maximum effect of a possible accident. On the other hand, it is possible to think of progressively more restrictive technological measures in respect of catastrophic-type scenarios. Thus, for example, a further order of magnitude of risk reduction is required for each order of magnitude of increase in the consequences in the habitual calibrations of the risk matrices or risk graphs employed when assigning safety integrity levels (SILs). For example, a calibration could be considered requiring two orders of magnitude of risk reduction for each order of magnitude of increase in the consequences, which would push α towards a value of 3.

8. Conclusions

This paper has established that the proportion of major accidents which have occurred in the last one hundred years follows a potential distribution. Similarly, it has demonstrated that scenarios with major consequences, here referred to as of Bophal category, have been foreseeable as a function of the proportions observed of scenarios with lesser outcomes. A logical consequence is that there exists the possibility, which must be taken into account, of the occurrence of scenarios with even more major consequences, referred to as of trans Bhopal category.
Furthermore, it has been established that the loss of human life associated with the accidents analysed clearly exceeds those which are acceptable when applying the classical risk acceptability criteria of F.R. Farmer. Given that in quantitative risk assessments the acceptability criteria are always satisfied, it may also be concluded that there is a factor which is not being taken into account in these assessments, leading to the results obtained being lower than the real risk.
Finally, and in a very brief manner, the measures available have been set out to limit the possibility of the occurrence of the aforementioned trans-Bhopal scenarios.

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