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Using the consequence - frequency matrix to reduce the risk: examples and teaching

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Abstract:

Consequences-frequency matrices (CFM) are diagrams with consequence and frequency classes on the axes. They permit to classify risks based on expert knowledge with limited quantitative data. In this paper, we propose to introduce uncertainty using Bayesian approach, which allow obtaining exceedance curves for frequency, for consequences and for risk. An example of such an approach is given with the case of a landslide.

INTRODUCTION

Risk systems are often complex and do not allow to develop a full numerical approach, since many aspects are not fully quantifiable. “Risk filtering, ranking and management” methodologies have been developed since the nineties along with the NASA space shuttle program (Haimes, 2008). To rank the risky events and scenarios, these methods used the so called “risk matrix” displaying frequency (λ) or probability versus consequences (Co), divided in classes for each axis. This also permits to rank the risk ($R \propto \lambda \times Co$) in classes. Such approach had been developed earlier in industry production sector (Gillett, 1985). These Consequences-frequency matrices (CFM) are diagrams with consequence and frequency axes respectively, which are divided into classes. The CFM are often used and presented in text books (e.g. Ale, 2009) as a tool for assessing and comparing different situations for objects at risks. Nowadays, several approaches of decision making are inspired by these methods and are applied in many administrations including EU for health problem (ECDC, 2011). CFM is also used in evaluating risks related to corporate risk management (TBCS, 2011), commercial acquisitions (DOD, 2006), natural risks (OFPP, 2013) and in insurances (ZHA, 2013). This approach also permits to visualize the effects and consequences of risk reduction measures (Figure 1) and to give a framework to understand risk assessment, which is very useful for teaching.
These methods aim at providing solutions for encountered problems of a specific situation by answering to the questions (Haimes, 2008): *What can go wrong? What are their consequences and likelihood?* It follows several steps (Krause et al., 1995; Haimes, 2008):

1. Scope definitions: what are the problems?
2. Creation of a group of experts concerned by each level of the analysed risky system
3. Hazard identification, i.e. identification of potential events and their scenarios

4. Hazard filtering and ranking in several sub-stages which implies to establish frequency (probability) and impact classes and their corresponding limits (in loop with point 5)
5. Risk management, including the quantification of the potential risk reduction, which necessitate the understanding of causes and effects
6. Finalization of decision making process
7. Refinement of the process with the feedback

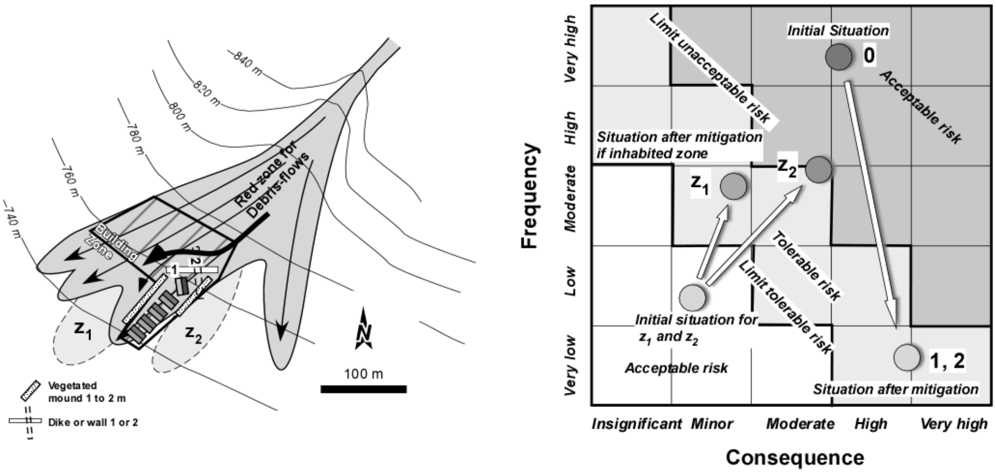

Figure 1: Example of potential building area in a high hazard area and illustration of the proposed solutions. CFM is used to represent the degree of risk. The scope of tolerable risk (light grey) is between the limits of tolerance and of acceptability (modified after Jaboyedoff et al., 2013).

However, these methods suffer from several weaknesses. First, the scales of risk level that are deduced from the CFM are often not consistent (Cox, 2008). For instance, if they are not well designed, a point at the corner of a class can belong to 3 different risk classes. Secondly, the uncertainties are often not assessed.

Some attempts have been performed to introduce uncertainty in the input data by using fuzzy logic for technical system (Krause et al., 1995): the classes are fuzzified by applying a membership function to the classes of frequencies and impacts.

In the present paper, we try to develop a method using CFM by developing the point 4 of the above mentioned list, with an example of landslide from the point 3 to 5. The basis of this method is to introduce Bayesian approach for the belonging classes, i.e. likelihood based on triangular distribution, using the prior probability given by experts. Then, the probabilities of an event to belong to a class of risk are calculated giving probability for each matrix element.

METHOD

The belonging to a class and its uncertainty

When experts give their opinions about the belonging to a class of events, which might for example be named “very low, low, medium, high, very high” and refers to the intensities, (or frequencies) and impacts (or consequences), uncertainties are involved. As it is proposed by the fuzzy logic framework (Zadeh, 1975), this is not unique and can also have a probability of belonging to other classes, which means that when an expert attributes an event to a class it implies also a “membership” to other neighbouring classes. Instead of using the fuzzy logic terminology as “membership”, it is preferred to use the likelihood $P(C_j|CE_i)$ of the attribution to a class CE_i by an expert to be distributed to neighbouring classes C_j.

The estimation of the uncertainty can be, for example, empirically decided by a group of experts, or an expert can give his definition of belonging to a class. This can be a way to introduce the uncertainty, but this not the one chosen here.

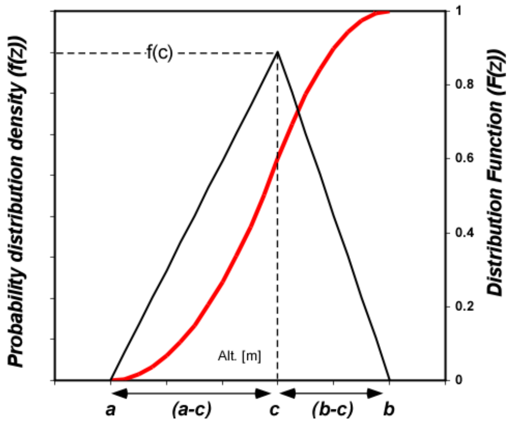

Figure 2: parameter defining triangular distributions.

Formally, if a class has a lower limit l_j and upper limit l_{j+1} and if the distribution of the weights from a class chosen by an expert CE_i to the others using a scale of value x is given by $f(x)dx$, then the likelihood or weight to belong effectively to the class C_j is given by:

$$P\left(C_j \middle| CE_i\right) = \int_{l_j}^{l_{j+1}} f(x)dx \qquad [1]$$

The function $f(x)$ can be of any type, and chosen in different ways by determining the variance, the mean, etc. Here, we will use the triangular distribution (Kotz and van Drop, 2004; Haimes, 2008) (Figure 2):

$$f(x) = \begin{cases} 0 \quad for \quad x < a \\ \dfrac{2(x-a)}{(c-a)(b-a)} \quad for \quad a \le x \le c \\ \dfrac{2(b-x)}{(b-c)(b-a)} \quad for \quad c < x \le b \\ 0 \quad for \quad x > b \end{cases} \qquad F(x) = \begin{cases} 0 \quad for \quad x < a \\ \dfrac{(x-a)^2}{(c-a)(b-a)} \quad for \quad a \le x \le c \\ 1 - \dfrac{(b-x)^2}{(b-c)(b-a)} \quad for \quad c < x \le b \\ 1 \quad for \quad x > b \end{cases} \qquad [2]$$

Where $F(x)$ is the repartition function of $f(x)$ ($F(x) = \int f(x)dx$), and the domain $[a, b]$ corresponds to non-zero $f(x)$ and c is the x value of the maximum of $f(x)$.

Classes definitions

The triangular density distribution is often used for expert knowledge (Vose, 2008). It presents the advantage to ask expert simple questions in order to define the distribution:

- What do you consider as the lower possible value (a) for an event (frequency, intensity, impacts, etc…), classified in the class C_j?
- What do you consider as the upper possible value (b) for an event (frequency, intensity, damage, etc…), classified in the class C_j?

Here, we will consider that the maximum off $f(x)$, i.e. $f(c)$ is located at the central value of the class considered by the expert as the most probable, but other choices can be used.

The expert assessment for a specific event

In the global procedure for all matrix approaches (Haimes, 2008), all the possible events (Ev) have to be listed. Each Ev corresponds to a process that can lead to different scenarios for consequence and frequency.

The class and their associated distribution definitions are independent of the events. An expert will have its own interpretation of a potential event Ev that leads to several scenarios of impact and frequency independently. In that case, he must give, for each scenario, a weight to the corresponding class, i.e. for each class correspond a scenario (or more) for consequence corresponds, and this is also applicable for frequencies scenarios. Therefore, all couples of frequency or probability (p)/consequences (Co) related to an event Ev (p, Co) must be distributed following the potential scenarios. For instance, as proposed by Vengeon et al. (2001), the frequency can be set first by an array of probability – delay or more generally relative classes of probability. Then, the probability must be normalized to 1 and distributed among the respective belonging to the others classes, i.e. $P(CE_i)$ the expert weight distribution for one event (prior probability) (Figure 3a). This can be performed also for the impact. By following this logic, using the Bayesian theory, the probabilities $P(C_i)$ of a frequency or an impact in the class C_i are given by:

$$\begin{bmatrix} P(C_1|CE_1) & \cdots & P(C_1|CE_n) \\ \vdots & \iddots & \vdots \\ P(C_n|CE_1) & \cdots & P(C_n|CE_n) \end{bmatrix} \begin{bmatrix} P(CE_1) \\ \vdots \\ P(CE_n) \end{bmatrix} = \begin{bmatrix} P(C_1) \\ \vdots \\ P(C_n) \end{bmatrix} \qquad [3]$$

By introducing values for the limits, it is then possible to provide exceedance curves for consequence or return period (Figure 3b).

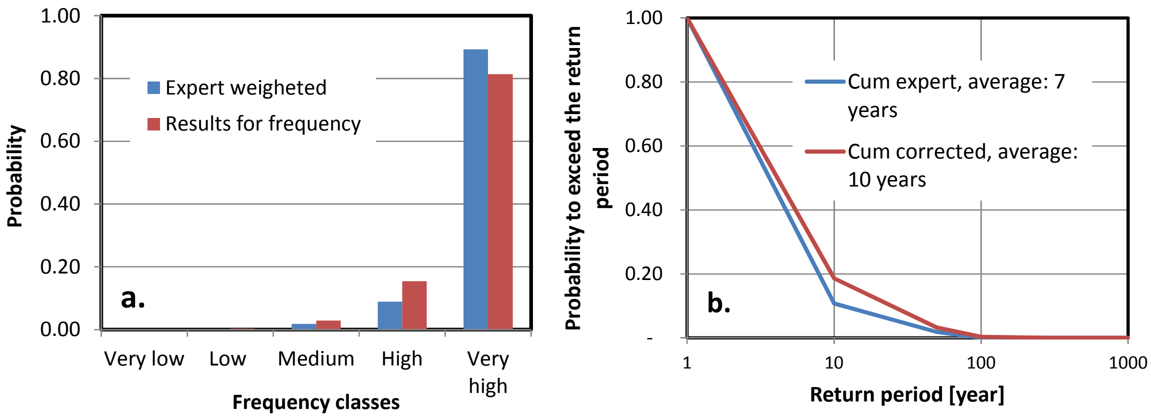

Figure 3: a. histogram of the probabilities P(CE) (blue) and P(E) (red). b. resulting curve of exceedance using the class limit (see in example for the limits).

The matrix

The different classes for probabilities and consequences can be multiplied to get a matrix of probability of each element (Figure 4), where each element of the risk matrix corresponds to a scenario of on event. This allows to obtain an exceedance curve of risk level that is attributed to each element. In the present case, we use the multiplication of the class value 1 to 5 with 5 being the highest.

As each element of the CFM possess a probability, using the scale of values for the class limits, the average risk can be calculated, as well as a curve of exceedance.

THE EXAMPLE OF A PARTICULAR UNSTABLE MASS OF PONT BOURQUIN LANDSLIDE

Landslide settings

Pont Bourquin Landslide (PBL) is located in the Swiss Prealps, close to Les Diablerets, Switzerland (Jaboyedoff et al., 2009). First evidences of recent gravitational deformation can be observed on aerial photos of the end of the Sixties. This activity gradually developed until 2004. The first large slope displacements happened in 2006, when movements up to 80 cm occurred on the head scarp. Subsequently, a mudflow reached the road just below the landslide on 5th of July 2007 and another flow destroyed the forest at the toe of the slide in

August 2010. For this second event, we were able to demonstrate the drop of surface shear wave seismic velocity at a depth of 9-11 m a few days before the collapse (Mainsant et al. 2012a). Afterwards, remedial works were carried out, including a trunk-framed box at the toe of the instability and gullies on the mass body to evacuate surface waters. However, the landslide body is still moving, with velocities similar to the former ones.

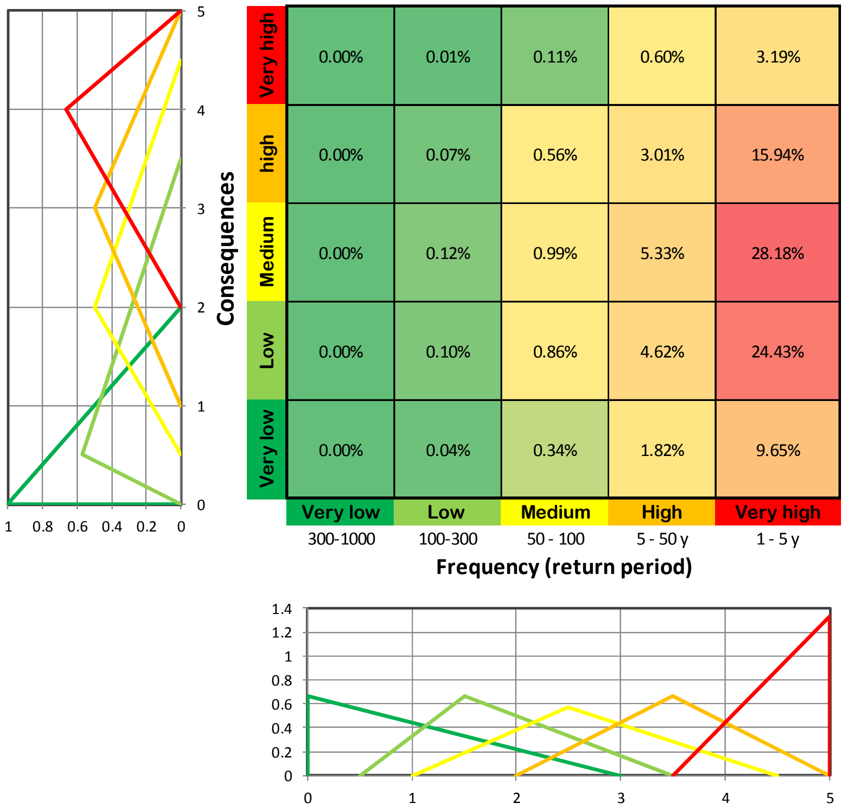

Figure 4: Example of matrix showing the proximity of each element of the matrix and the distribution function used to calculate the likelihood $P(C_j|CE_i)$ of both axes.

Nowadays, the landslide is still active and three zones are particularly threatening. In the present example, we will assess the risk for one of these potential source areas. It is an approximatively 5000 m^3 material that is detached on the north-eastern part of the landslide. The displacement is observable by visual inspection of the back scarp, sudden reactivation failure of this compartment and a fast propagation toward the road is expected. We will not mention a detailed description of the situation as it is not the goal of this paper. Therefore, we will simply present an example illustrating the general framework of the method.

The classes and scales

To create the limits of classes for the frequencies or return periods we use a modified version of the Swiss danger matrix (Lateltin, 1997): Very low (300-1000 years), Low (100-300 years), Medium (50-100 years), High (5-50 years) and Very high (1-5 years). A 1 year lower limit is used because a return period of zero would give an infinite frequency.

The classes of consequences have been designed depending on the considered scenario. We used 5 million CHF as the worst case scenario, which corresponds, according to the willingness-to-pay value generally used in Switzerland, to the death of one person (Figure 6). Each class is one order of magnitude different from its neighbours.

Setting the prior probabilities

Prior probabilities have been set using equation [1] and the triangular distributions shown in figure 4. For very low frequencies, looking at the likelihood function in figure 4 below the matrix, the error of attribution can be quite high towards the higher frequencies, while in a less extent, it is also the case for the very high frequencies towards the lower (Figure 4). For the intermediate classes, they are distributed nearly symmetrically over neighbouring classes.

The classes of consequences are defined by a decision tree as it is done in health disease prevention (ECDC, 2011). This starts by looking at if the landslide sudden reactivation failure will reach to the road or not, considering up to the possibility of killing one person in a vehicle. Please note that not all impacts have been taken into account here.

Figure 5: location of the unstable zone on the landslide and the national road that can be affected.

Results

First, we can see in figure 3 that the use of prior probability to correct expert assessment implies that the average return period changes from 7 to 10 years. The curve of exceedance shows that the corrected probability to exceed 10 years is around 20%, whereas it is 11% for the original value. Using the exceedance of the consequences, the values are more distributed for the corrected values than for the original one (Figure 7). This is clear from the average value of corrected costs (99'000.- CHF) which is double from the original one (41'000.- CHF). The probability to be above 500'000.- CHF for the corrected value is of 4% and zero for the non-corrected one.

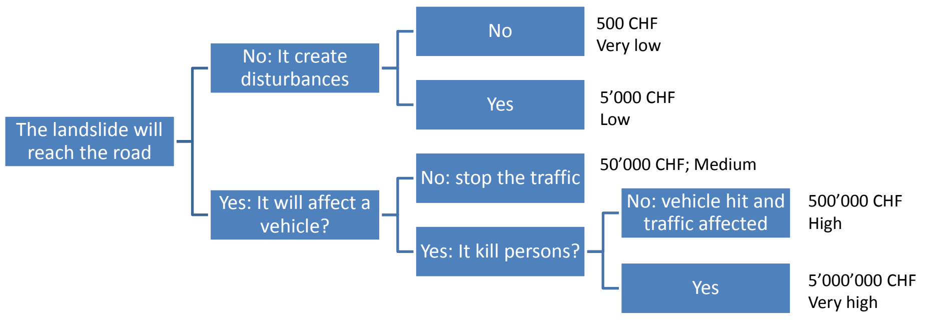

Figure 6: decision tree to deduce the consequences levels.

Now looking at the matrix results (Figure 4), we can extract the curve of exceedance for the risk level divided in five classes from 1 to 25 (5 × 5) in 5 equal classes (Figure 8). This clearly shows that there is 20% of chance to be in the very high risk class and less than 20% to be below medium risk. It is also possible to obtain the average risk, which is around 107'000 CHF/year.

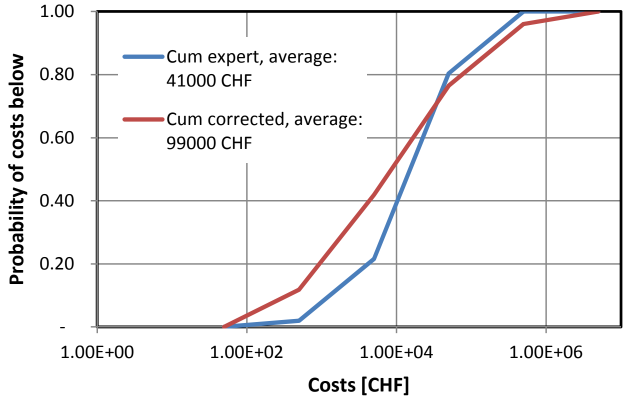

Figure 7: curve of exceedance using the limit of the classes for both corrected and uncorrected probabilities.

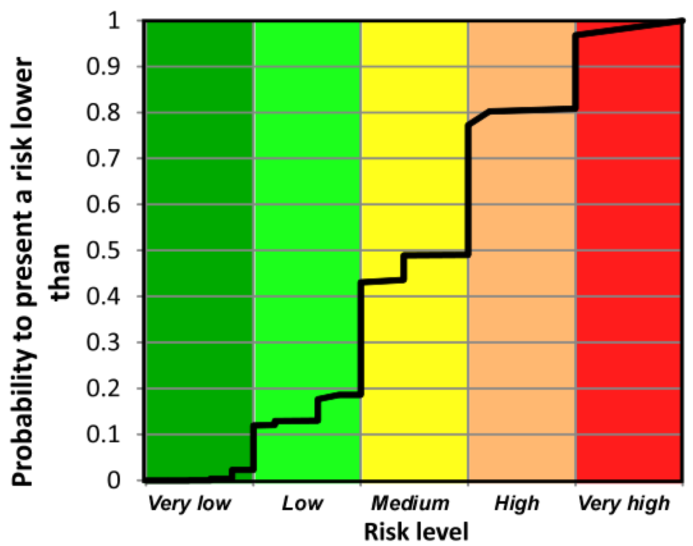

Figure 8: curve of exceedance for risk levels.

DISCUSSION AND CONCLUSION

The presented method is still in development; however, it already shows some interesting results. It allows to extend the domain of hazard and consequences that are often not considered by experts. In addition, it does not only give one result, but also gives exceedance curves. The fact that the experts must give two times their opinions, first for the likelihood, and second for the prior probability (weight for each class) is a way to introduce uncertainty, which is often lacking in the risk matrix approach. The use of Bayesian approach is also easier than fuzzy logic. Their results when compared to the results obtained from a more classical risk analysis have the same order of magnitude (Limousin, 2013), which give 278'000.- CHF / year for the 3 unstable masses. As a consequence, we think that this method must be tested on other sites. Nevertheless, there are several remaining problems:

- The discretization of the value by class which are not equal in width raises the problem of non-linearity and singular points at the limits. This has to be further explored, especially using function like power law or exponential.
- The way to calculate the risk and its distribution
- The extension of the classes to infinite and to zero is a problem. Until now, the sum of CFM probability matrix is equal to one, however, for instance, event with longer return period can be considered, but their weight has to be well assessed.

It is clear from the above results and figure 1 that this method provides also a good way to visualize the risk reduction, by changing the scenario and consequence weights, and it will keep the uncertainty which is not usually the case. In addition we experienced in courses that the use of risk matrix are a good way to promote collective work in a class and to address several different types of risks.
We think that the present method improves some of the weaknesses of the matrix approach, and which will give an excellent background for courses.

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