Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p27653-cd

Development of a risk assessment platform for lifeline networks

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The risk assessment of lifelines is an extreme complicated approach which needs to get simplified using basic probabilistic concepts to maintain its due accuracy along with providing it with due applicability. A platform is suggested in this paper to grant present requirements of risk managements and to make a reliable basis for future improvements and advancements.

Keywords: Lifeline, Vulnerability, Fragility

1. Introduction

Lifeline and infrastructure networks are supposed to be the blood vessels of human society. They form the main structure of civil life and sustainability of societies. There are lifelines, which constitute the basis of support of other networks. Power and communication networks may have such a role within a country.

The shortage of such a critical network can affect other infrastructures, leading to eventual disasters and crisis that can trigger secondary consequences within the country, like blackouts within power network or chaos due to missing of communication elements etc... Hazards which are prone to affect the lifelines functions are supposed to be:

Earthquakes, atmospheric turbulence, atmospheric overheating, icing, human errors, vandalism, sabotage and terrorism, local and global overloads, new fashion power supply abrupt change, …

Providing a global database and data gathering system for global hazards and their effects on lifelines seems to be very difficult due to their wideness and complexity, but it can be facilitated, regarding the conceptual image of probabilistic characteristics of the hazard occurrence. Many platforms like Hazus (FEMA ,1999) and Syner-G (Kaynia A.M., 2013) have been devised in the past for risk management of urban areas within the US, Europe, etc... The present attempt is to introduce a platform to model the vulnerability characteristics of lifelines in a new fashion regarding the scarcity and complexity of lifelines events information.

2. Main idea

Probabilistic assessment of infrastructures against hazards cannot be explicitly based on statistical data of actual effects of events, due to the scarcity of data and their conceptual deviation from the actual purpose of data gathering.

For instance when a storm occurs and some power network lines or substations fail, there are distortions in data according to what they have been supposed to reveal. The data description of the event is divulging such an information: A storm with the velocity of v (which is not accurate) caused a substation to fail to deliver power. Such a data although being an evidence, doesn't provide the exact velocity related to the failure of every damaged component of the power system. This distortion along with the scarcity of data make it impossible to provide the appropriate likelihood function for the velocity of failure as a basis to calculate the probability of failure within the network. Such a problem exists for all lifelines and for all kind of hazards, which make the lifelines probabilistic assessment a complicated job.

The complexity of lifeline systems and their equipment and system interdependency push the governmental authorities toward subjective data concept being raised out of the experts' opinions and judgements rather than the exact data recorded in the past.

The basis of data providing in global infrastructure probability engineering are evidences rather than exact data. This should be treated using evidence and inference concepts. According to these theories, no exact and explicit data but evidences exist to support the probabilistic assessment (Dempster, A.D., 2007).

3. Probabilistic inference methods

The foundation of probabilistic inference is to use the previous data or basic opinions of experts as believes or prior probabilities. A likelihood implied by new events usually plays the role of a new believe source which is in essence an extreme perception out of few data, although it is the way of probabilistic inference in the past (Dempster, A.D., 2007, Sentz, K., 2002). For instance, a single experience of failure in an infrastructure makes the social judgement tending toward abrupt increase of risk management budget and a single experience of non-failure behaviour may calm down the tendency toward more serious risk management. This approach is inevitable due to general lack of suitable data. According to Bayesian inference method any new event data would participate in improvement of believes (with an epistemic error) out of using a poor likelihood as a new belief, challenging old believes (Bernardo, J.M., Smith, A.F.M., 2000). The amount of such an error would be reduced due to new data aftermath of subsequent events.

4. Theoretical basis

It is known that the occurrence of all kinds of hazards can be supposed as a Bernoulli process. Each event may be identified with its return period. A big amount of database within power and other networks are related to short return period events (SRPE) which are in access through daily and periodical function report within networks. Rare events are scarce in nature but they can be provided or predicted subjectively according to experts' judgements or objective PDF. Imprecise probabilistic inference which is one of the bases of AI can be used to improve the preliminary database regarding the eventual rare type event like strong earthquakes. Actually, in the process of risk management the problem of rare events like earthquakes and tornados are a matter of disaster management essentially.

To get to a global (and not necessarily total) solution for lifelines risk problem one has to identify a global hazard probabilistic distribution (likelihood) identification. The occurrence of events in any point of a network is not complicated to identify. They can be based on accessible data of hazards without sophistication on identification of the nature of the hazards. The key point of such a problem is that the hazard occurrence without specific identification can be supposed as a Bernoulli process and the distribution of all hazards can be assumed as Poisson, like what is popular for seismic hazard. Even the vulnerability of lifelines can be assumed as Bernoulli process and a Poisson distribution can be supposed to be fitted on it. eq(1) (Fig 1)(Ang, A.H-S., Tang, W.H., 1975)

$$P_f = e^{\frac{-t}{T}} \tag{1}$$

Where :

P_f= Probability of network failure

t= Lifetime of the network

T= Return period of the network failure

The trace of the eq (1) is shown in fig (1).

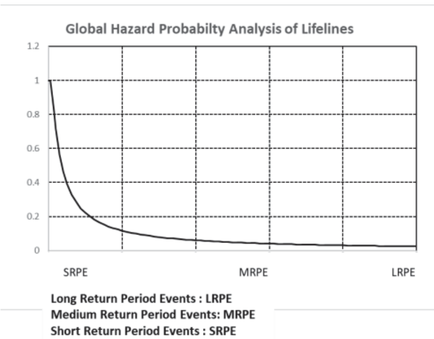


Figure (1): A general scheme of probabilistic risk in lifeline networks (Poisson trend)

The trend shown in figure (1) can be used for vulnerability analysis of lifeline networks. According to the concept of this proposal, the imprecise probabilistic assessment is done with a help of subjective expert opinion and with the further aid of AI and remote sensing tools for data improvement. As an example for the above-mentioned methodology, we can have a table describing the damages to the network, according to periodical reports (Table 1).

Table (1): Example of loss due to hazards within the power network in a region

Loss	15-20	10-15	5-10	1-5	0.5-1
	M$	M$	M$	M$	M$
Events in 20 Yrs	1	3	4	7	10
Return Period (Yrs)	20	6.7	5	2.9	2
Yearly Probabillity of exceedance (Poisson)	5%	14%	18%	29%	39%

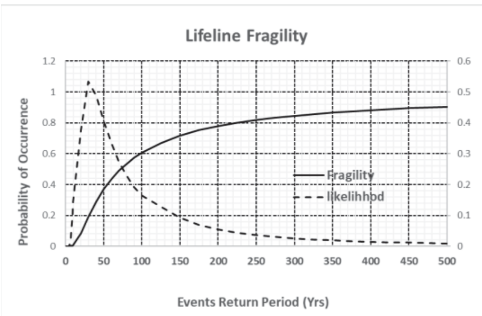
The above table can be provided for any extent of power or other networks territory. The above table shows that in a typical part of a network the probability to have more than 15-20 million USD of loss in a year is about 5% but there is a probability of about 39% to have a loss of about 0.5-1 USD. These types of data are useful to manage the budgeting of networks to withstand accidents and losses. It is shown here that in the case of global view to networks it is essential to model losses and not necessarily the hazards. In this case the fragility curves are of less importance in comparison to specific fields like seismic risk assessment of networks.

This perspective can give more practical understanding of networks and lifeline risk analysis specifically when armed with AI which is a tool to gather and process the loss data within the network.

According to above-mentioned concept a general relationship for fragility of lifelines can be developed. The general trend of lifeline fragility-vulnerability curve is shown in figure (2). It can be seen that a change of variable from event intensity to event return period has made a situation to provide a global vulnerability curve, which is known as a manipulated Poisson Distribution function as in eq (2).

$$P_f = 1 - e^{\frac{-t}{T}} \qquad (2)$$

This function as traced in fig (2) is the probability of no exceedance of events .



Figure(2): Vulnerability curve of lifeline networks (Poisson trend)

With a basic subjective matrix, explaining the influences of lifelines on different socio economic and environmental features within the society a practical vulnerability image of the lifelines can be founded subjectively. In table (2) the effect of different lifelines on various social factors and vis versa is shown. The quantities are subjective and can be suggested by a variety of experts or normal persons and manipulated to reach to a consistent and reliable basis.

Table (2): Subjective effect of lifelines on social factors

Subjective Effect of lifelines on Social factors							
Lifeline Networks	Essentiality	Criticality	Vulnerability	Environmental Effect	Ecnomical Effect	Social Effect	Total Effect
Power Network	1	1	1	1	1	1	1.000
Gas Network	0.8	0.8	1	0.8	1	1	0.512
Communication Network	0.8	0.8	1	0.6	1	1	0.384
Health Network	0.8	0.8	0.8	0.6	1	0.6	0.184
Safety Network	0.8	0.8	0.8	0.6	1	1	0.307
Education Network	0.7	0.5	0.6	0.6	0.5	0.8	0.050
Higher Education	0.6	0.5	0.6	0.6	0.5	0.8	0.043
Transportation Network	0.5	0.6	0.6	0.6	1	1	0.108
Water Network	1	0.8	0.6	0.8	1	1	0.384
Sewage Network	0.8	0.6	0.6	1	0.5	0.5	0.072

The interdependency of various lifelines can be modelled subjectively through a matrix called here "Interdependency Matrix". Each member I_{ij} of the matrix is to evaluate the effect of damage in lifeline j on lifeline i (table 3).

Table(3): Subjective damage effect of lifelines interdependency

	Interdependncy of Lifelines										
	Power Network	Gas Network	Communication Network	Health Network	Safety Network	Education Network	Higher Education Network	Transportation Network	Water Network	Sewage Network	Total
Power Network	1	0.2	0.1	0.2	0.3	0	0	0.2	0.2	0	2.2
Gas Network	0.3	1	0.2	0.2	0.3	0	0	0.2	0.2	0	2.4
Communication Network	0.6	0	1	0.2	0.3	0	0	0.2	0.2	0	2.5
Health Network	0.6	0.1	0.4	1	0.4	0	0.3	0.2	0.4	0	3.4
Safety Network	0.6	0	0.4	0.2	1	0	0	0.4	0.2	0	2.8
Education Network	0	0.1	0.2	0.2	0.2	1	0	0.2	0.2	0	2.1
Higher Education Network	0	0.2	0.2	0.2	0.2	0	1	0.2	0.2	0	2.2
Transportation Network	0.4	0.1	0.2	0	0.4	0	0	1	0	0	2.1
Water Network	0.3	0	0.2	0.2	0.4	0	0	0.2	1	0	2.3
Sewage Network	0.2	0	0.2	0.2	0.1	0	0	0	0	1	1.7

Effect of damage in communication network on safety network

Total effect of damage in all networks on safety network

With the suggestion of a relationship between the lifeline vulnerability mentioned as a percentage of lifeline value and the return period a general view of the financial vulnerability can be provided. For an example, the following relationship is proposed for a part of lifeline subjected to events. The relationship can have variation for different lifelines, which is related to the experiences within various lifelines.

$$V = 0.000002\, T^2 \qquad (3)$$

In table (3) the vulnerability of lifelines is shown for some return periods.

Table (3): Vulnerability of lifelines according to eq (3)

Return Period (yrs)	10	50	500
Vulnerability	0.0002	0.005	0.5

In this table it can be seen that the vulnerability of part of a network under an event with a return period of 500 years is equal to 50% of the network. According to table (3) this is considered for 1% of the total network.

The vulnerability function is related to the part of the lifeline under consideration. For instance the vulnerability function is smaller for a part of lifeline network in comparison with the whole lifeline network. The equation (3) can be assumed within a small town for a typical lifeline.

After the above-mentioned concepts and relationships and according to differences between lifelines in their effect on social aspects (table 2) and regarding the damage effect of interdependency between various lifelines (table 3) in addition to the vulnerability expectation of events with various return periods (eq 3) the expected vulnerability in lifelines can be modelled through eq (4).

$$V_i = V.I_I.I_p.I_s.I_d \quad (4)$$

In which:

V_i: Expected vulnerability of lifeline i expressed as a part of total network value

V: Vulnerability based on return period expressed as part of the total network

I_I: Importance factor (table 4)

I_p: Participation index (table 4)

I_s: Index of effect on social and environmental factors (table 2)

I_d: Index of interdependency of lifelines (table 3)

The expected vulnerability of different lifelines (eq 4) is shown in table (4). According to results of table (4), a trace of the vulnerability curve for different lifelines is shown in figure (3).

Table(4): Expected vulnerability of lifelines

Vulnerability (part of lifelene value)							
Lifeline	Importance Factor	part of network	Return Period (Yrs)				
			10	50	100	200	500
Power Network	1	0.01	0.000002	0.00005	0.0002	0.0008	0.005
Gas Network	1	0.01	0.00000128	0.000032	0.000128	0.000512	0.0032
Communication	1	0.01	0.00000128	0.000032	0.000128	0.000512	0.0032
Health Network	1	0.01	0.000001024	0.0000256	0.0001024	0.0004096	0.00256
Safety Network	1	0.01	0.000001024	0.0000256	0.0001024	0.0004096	0.00256
Education Network	1.5	0.01	0.00000063	0.00001575	0.000063	0.000252	0.001575
Higher Education	1.5	0.01	0.00000054	0.0000135	0.000054	0.000216	0.00135
Transportation	1	0.01	0.00000036	0.000009	0.000036	0.000144	0.0009
Water Network	1	0.01	0.00000096	0.000024	0.000096	0.000384	0.0024
Sewage Network	1	0.01	0.000000576	0.0000144	0.0000576	0.0002304	0.00144

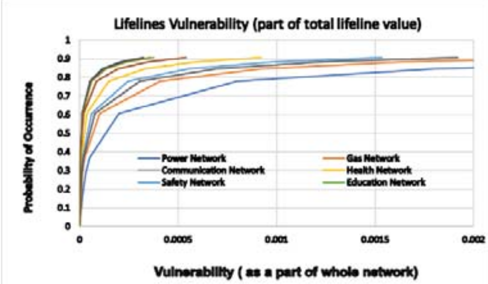


Figure (3): Vulnerability curve of lifeline networks

4. Results

As it is explained in the previous section, a subjective method of assignment of vulnerability indices has been proposed and implemented using the judgement of a single exemplary expert for an exemplary country.

According to curves of figure (3) if an event with a likely damage cost of 0.0005 of the total power network occurs, its likelihood to invoke such a damage is around 0.7 and its return period is around 16 yrs. according to eq (1). For a lifetime of 50 yrs assumed for the network.

The calculation can be repeated for some other experts and the results can be combined using the logic tree method based on the total probability theory concept, to get to a more reliable basis for management decisions.

5. Summary and Conclusion

An approach has been introduced for vulnerability analysis of lifelines using Poisson distribution function versus return periods. Events in this research have been assumed to be the damage of systems and not the natural and human events leading to damage. Such an approach will turn the modified Poisson distribution as represented in this paper, into a vulnerability function (fig 2).

A relationship between vulnerability as part of total network assets value and the return period has been proposed in eq (3) and in the table (3). It has been quantified to make a sense of the relationship. It seems logical to have 50% of the lifeline to be destroyed in an event of 500 years of return period. This can be challenged for further research objectives.

A subjective method of assignment of factors affecting the vulnerability is proposed which can be used with the aid of expert opinions based on total probability concept.

In the case of occurrence of failure within a lifeline network challenging the vulnerability curves proposed in this work, a likelihood curve concerning lower or upper lifetime should be used to modify the belief PDF. A simple method of inference is as shown in equation (5).

$$Bel_{pos}=L().\ Bel_{pri} \qquad (5)$$

Where:

Bel_{pos}: posterior belief PDF after modification

Bel_{pri}: prior belief PDF before modification

L(): a PDF (Likelihood) according to new experience of events

The implementation of the method is subject of further studies and papers in the future.

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