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On the Use of Fuzzy Logic Assessment for High Consequence Implementation Risk Analysis

Stan Spray, Arlin Cooper, and Rebecca Bennett
Sandia National Laboratories

Abstract

"High consequence" operations are systems, structures, and/or strategies for which it is crucial to provide assured protection against some potential catastrophe or catastrophes. The word "catastrophe" implies a significant loss of a resource (e.g., money, lives, health, environment, national security, etc.). The implementation of operations that are to be as catastrophe-free as possible must incorporate a very high level of protection. Unfortunately, real world limitations on available resources, mainly money and time, preclude absolute protection. For this reason, conventional "risk analysis" focuses on "cost-effective" protection, demonstrating through analysis that the benefits of any protective measures chosen outweigh their cost. This is a "crisp" one-parameter (usually monetary) comparison.

A major problem with this approach, especially for high consequence operations, is that it may not be possible to accurately determine quantitative "costs," and furthermore, the costs may not be accurately quantifiable. Similarly, it may not be possible to accurately determine or to quantify the benefits of protection in high consequence operations.

These weaknesses are addressed in this paper by introducing multiple parameters instead of a single monetary measure both for costs of implementing protective measures and their benefits. In addition, a fuzzy-algebra comparison based on fuzzy number theory is introduced as a tool in providing cost/benefit tradeoff depiction, with the incorporation of measures of the uncertainty that necessarily exists in the input information. The result allows a more informative comparison to be made through use of fuzzy results, especially at the extreme bounds of the uncertainty.

Problem Overview

Increasingly, the public is demanding tighter accountability of system performance as it impacts operational safety, environmental consequence, and health considerations. Realizing that no system is perfectly risk-free, the designer makes a subjective decision as to the level of risk that will be accepted basing the decision upon a quantitative comparison of the 'benefits' of the system to the 'costs' of the system. For high-consequence operations where the risk of failure can produce catastrophic results and where the required safety measures significantly impact design considerations, the identification and quantification of risk is crucial. Typically, classical probabilistic risk analysis is the basis for quantifying the benefits and costs. Unfortunately, this approach has its weaknesses since it:

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- 'one-dimensionalizes' all risks by quantifying the risks in terms of a single probability, with the tendency being to minimize or ignore the uncertainty bounds associated with the number
- incorporates statistical characteristics (if done at all) even when there may be insufficient statistical data
- tends to negate the significance of those events which have been assigned a very low probability of occurrence even though such events may be crucial to high-consequence operations
- tends to ignore non-quantifiable parameters such as the effects of damage to an organization's reputation, the threat of prosecution or liability, the long-range effects of environmental damage, the user-convenience and the user-acceptance of system features, and employee morale.

The approach is further weakened by the normalization of all risks in terms of a one-dimensional representation, financial cost.

Another possible approach would incorporate fuzzy logic in assessing degrees of risk. This approach can be multi-dimensional by permitting the simultaneous consideration of risk parameters along with their uncertainties and by accommodating the effects of subjective parameters as they also affect risk considerations. Such an approach may highlight specific system weakness otherwise not considered through a classical or 'crisp' risk analysis approach, especially at the extreme bounds of the uncertainty. Of course, for high-consequence operations, identification, quantification, and combination of these risks may be particularly critical. The purpose of this paper is to introduce a multi-dimensional analysis approach which uses fuzzy logic to represent the risk implications of a system, including the financial and non-financial costs associated with the implementation of protective measures, as well as the inherent benefits of the system. The focus of this approach will be directed towards high-consequence operations.

High Consequence Operations

Operations for which safety is crucial can be called "high-consequence" operations. Systems which encompass obvious high-consequence operations include the air-traffic control network, the manned space-flight program, and the nuclear weapons transportation system. However, as the complexity of any operation, system, or design increases, the potential for it, too, being classified as "high-consequence" increases. The transition occurs when the safety-related risks corresponding to the system complexity reach a certain threshold. This threshold is reached sooner when the interaction between the system and Nature's forces is highly sensitive, or generally, when the interactions between the human and the system increases. The threshold level can usually be raised through technology.

Many choices that affect safety must typically be made in high-consequence operations. Ideally, these choices are made in the design phase of the system resulting in intentional system constraints. It is these constraints which minimize high-consequence risks and generally discourage, for example, the construction of million-story skyscrapers or aircraft 1000 times larger than currently built. For these two examples, the benefits are simply overwhelmed by such risks as the potential great loss-of-life should a fire occur, or in the case of the skyscraper, should a severe earthquake be experienced. Other system characteristics, such as complicated operational logistics required to facilitate the entry and exit of large populations, would pose other risks. The decisions required in order to evaluated the acceptability of a high-consequence operation are fundamentally made through a cost-benefit tradeoff. This means that ideally the system attributes (which are attained as a result of the design parameters) are maximized and the implementation costs, operating costs, and potential losses are minimized. The result is a cost-effective system.

Even though optimized benefit-cost analyses does result in certain types of risk reduction, there are some operations that simply cannot be redefined or redesigned so that they fall below the high-consequence threshold. The manned space-flight program is a good example of an operation which is unavoidably high-consequence. As with all high-consequence operations, the permissible level of risk has been driven to infinitesimal degree greatly affecting the final benefit-cost analysis.

Risk Analysis Basics

In order to evaluate the reliability, performance, or effectiveness of a system, the system parameters are modeled through a mathematical representation. Importantly, a degree of simplification is introduced in the modeling process due to the fact that not all parameters may be incorporated, aspects of time-effects may not be represented, and insufficient data may prevent accurate representation of parameter performance. Therefore, modeling, by definition, introduces a degree of error into the analysis, which in certain circumstances may unduly bias the results.

A benefit-cost analysis is a mathematical representation and comparison of the potential 'investment gains' and the 'investment losses' associated with an operation. This modeling tool incorporates the identification and quantification of risk. To reduce the possibility of model omissions or of undue bias, a risk analysis process can be defined [Ref. 1]. The steps of such a process include the following [Ref. 1]:

1. Identify the system assets and assign a value to each asset
2. Identify the threats to the system
3. Identify the vulnerabilities of the system
4. Estimate the risks, i.e., the probability of each vulnerability
5. Calculate the annual loss expectancy (ALE) for each vulnerability
6. Identify potential protective measures
7. Estimate the ALE reductions for each vulnerability due to each protective measure
8. Select cost-effective protective measures
9. Respond to experience by modifying protective measures, by recovering from disasters, and, if appropriate, by prosecuting transgressors.

Whereas classical, or 'crisp,' risk analysis methods have typically been used in modeling to quantify risk, another analysis method incorporating fuzzy logic to assess degrees of risk may provide a way to represent and manipulate the nonstatistical uncertainty inherent to certain high-consequence operations. Fuzzy logic is an appropriate analytical approach when dealing with high-consequence operations specifically because it permits the evaluation of accentuated risks which are typically outside the realm of common system performance considerations and which are often poorly quantified, if quantifiable at all. Fuzzy set theory permits the simultaneous consideration of combinations of risks without the requirement that these risks be normalized in terms of 'dollar' value.

The Multiple Parameter Concept

A risk analysis that is based only on monetary cost can be represented using a single parameter (cost) as a function of threat level. For example, fire destruction loss could be determined for an operation from fire department statistics for similar operations (Figure 1). There is significant uncertainty associated with this function.

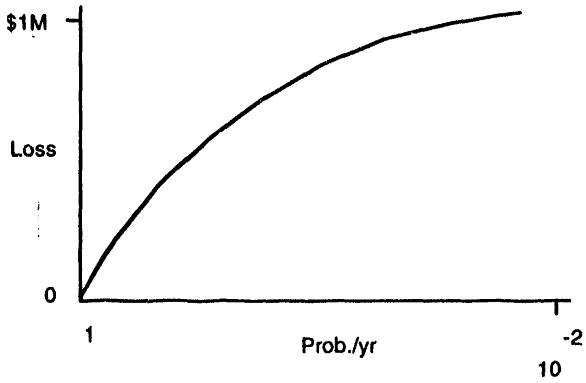

Figure 1. Fire Loss Statistics for an Example Operation

The concern over such a situation would be based on both probability and cost. A "high consequence" operation would be one for which cost was very high at a "credible" probability. Assume a single point on the abscissa, 0.01, as the threat (e.g., to meet a safety requirement). The cost ($1M) could potentially be reduced to an acceptable level (hypothetical cost savings) by introducing protective measures. This assumes that annualized savings due to the protective measures could also be determined (Figure 2).

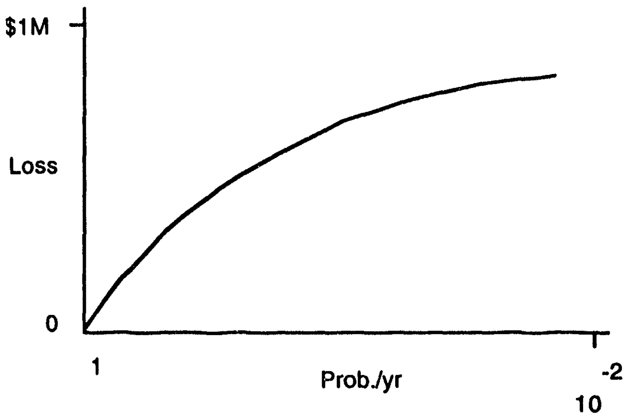

Figure 2. Cost Curve with Protective Measures

Cost-effectiveness is then determined by comparing the expected savings against the projected cost. For the example, the deduced values are shown in Figure 3:

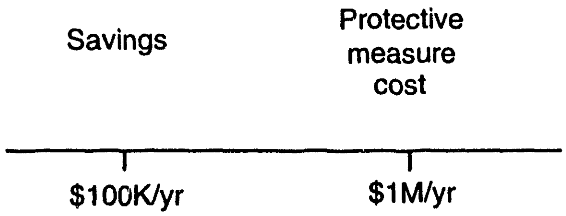

Figure 3. Comparison of Benefit and Cost of Example

The "crisp" result indicated is that the protective measures to meet the requirement are not cost-effective (they costs more than they save). The uncertainty issue will be addressed subsequently.

Introducing factors other than monetary cost adds parameters to quantitative comparisons. The aggregate of parameters may be only weakly comparable. In effect, there can be multiple ordinates for various types of losses, all depending on a single abscissa (e.g., annual loss frequency). For illustration, we will add another loss parameter: employee morale, where the percentage is used to indicate morale loss (0 for none to 100 for complete).

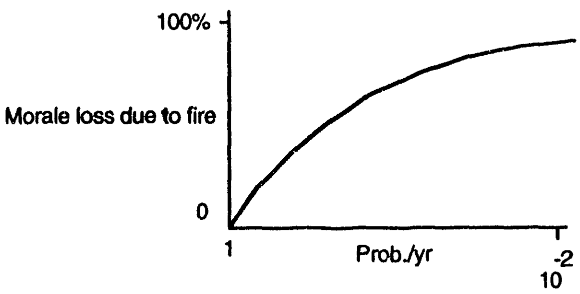

Figure 4. Employee Morale Loss Projection

The total loss would then be the sum of the two losses (monetary and morale) and the total savings due to the protective measures would also be summed. Adding dissimilar loss factors requires some normalization standard, introducing additional uncertainty. Here, a monetary standard will be arbitrarily chosen. The difficulty of measuring morale monetarily is highlighted by this process. The results are shown on the figure below.

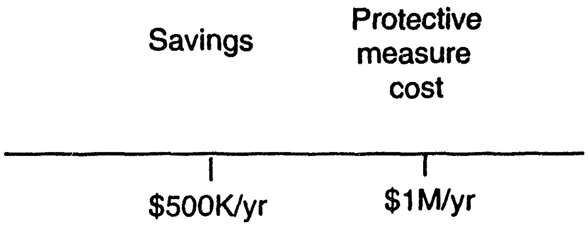

Figure 5. Cost-Benefit Comparison with Protective Measures

The result shows more savings than were initially identified, but the crisp result still indicates that the protective measures are not cost effective. However, if there is an overlap of the cumulative uncertainties, the measure of cost-effectiveness is uncertain, not crisp, and this variability is generally greatest in high consequence operations.

Fuzzy-Algebra Depiction of Uncertainty

The uncertainties indicated above could be described mathematically, using probability distributions. However, in the example there is no basis for such precise description. Furthermore, assuming common probability distributions suppresses the extremes of the uncertainty. Fuzzy number descriptions are better matched to the available information. The apparent precision of the fuzzy mathematics does not imply certainty, but rather makes mathematical operations involving uncertainty factors more systematic and instructive. In particular, the extremes of the fuzzy numbers are not suppressed.

A fuzzy number is a convex and normal fuzzy set [Ref. 2]. A triangular fuzzy number (TFN) has linear membership ranging from the most likely value to the upper and lower bounds. Using TFNs to represent the uncertainty displayed in Figs. 1-5 results in the TFNs shown in Figure 6.

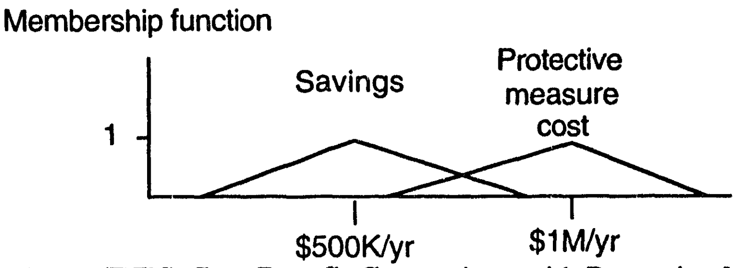

Figure 6. Fuzzy (TFN) Cost-Benefit Comparison with Protective Measures

The cost-benefit comparison for TFNs is performed by subtracting cost from benefit (the difference of two TFNs). The result is shown in Figure 7.

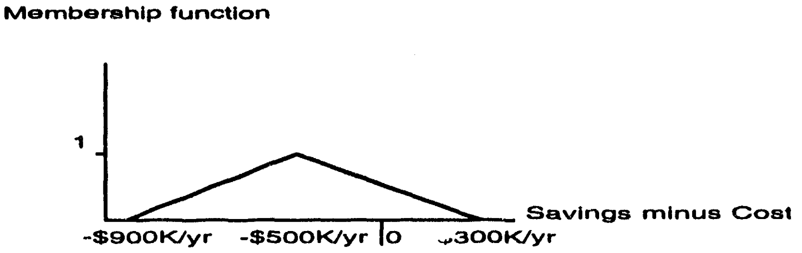

Figure 7. Fuzzy TFN Representation of Savings minus Cost

The results of this example show that the benefit of the protective measures could outweigh the cost, although the general expectation is that they do not. This is in sharp contrast to the crisp analysis, which does not emphasize the uncertainty as well. Fuzzy mathematics also differs from probabilistic analysis in that the extremes of the uncertainty are not suppressed.

Conclusions

The technique outlined in this paper provides an informative way of handling multiple parameters and uncertainty. It forces one to think carefully about the combined costs of a variety of parameters that may be difficult to quantify, especially monetarily. It also displays analytically the uncertainty involved, without suppressing the extremes of the uncertainty. Probabilistic modeling information that may not be well known need not be assumed. This is especially important for high consequence operations.

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