Economy-Based Countermeasure Decisions

A tutorial for SH&E professionals

By Clark Kilgore and P.L. Clemens

WHEN A HAZARD IS FOUND that poses risk to a particular asset within a system, the level of risk can be calculated. A countermeasure is proposed to reduce this risk to a lower level that is also calculable. The cost of adopting the countermeasure is known; it includes implementing, maintaining, operating and, ultimately, decommissioning the countermeasure in addition to initial outlay.

Practical questions now arise. Is there an economic advantage to be gained? Will the reduction in risk warrant the cost of adopting the countermeasure? Should a more effective or a less costly countermeasure be sought? Should several less costly options be implemented instead of a single expensive one? Should the status quo be maintained?

Defining Risk Quantitatively

To decide the merit of adopting a countermeasure, before and after levels of risk must be determined. Many texts define risk as the simple mathematical product of the severity of the harm the hazard may produce through a loss event (S) and the probability that the loss event will occur (P) (Stephenson, 1991). Thus risk (R) is shown as this simple relationship:

Equation 1: $R = S \times P$

It should be noted that there are no universally recognized symbols for these terms; the terms and symbols in this article are those adopted by the authors for classroom use.

To assess risk quantitatively, one must express its severity and probability components quantitatively and perform this multiplication. Numerical values must be assigned to the severity level of the harm that may be caused by the hazard and to the level of probability that this harm will occur. Because probability is dimensionless, the dimensional units in which risk is expressed will be those conveyed by the severity term. Also, because probability must apply to a specific interval of time or to a particular operating cycle, trial, mission or group of these, the value of risk found will apply only to that same interval, cycle, trial, mission or group.

These concepts may be more readily grasped if expressed visually. Figure 1 presents a plot of severity (S) value as a function of loss probability for various values of risk. Logarithmic scales have been chosen for the axes in this case in order to encompass greater numerical spans than can be shown using linear scales. The diagonal lines that appear are isorisk contours (i.e., contours along which risk, the product of severity and probability, has a constant value). Thus, the value of risk represented by point A [$(10^{-5} \times 10^{6}) = 10$] is equal to the risk value expressed by Point B [$(10^{-2} \times 10^{3}) = 10$]. For the point shown as Q, risk is evaluated as the product of 3×10^{4} (the loss severity value) and 2×10^{-5} (the probability value), giving a risk value of 6×10^{-1}.

Evaluating Severity

Of the two components of risk, severity is usually quantified with greater ease. In many cases, the cost of recovery from a posited loss event can be estimated and taken to represent severity. By convention in risk assessment, the severity component is often taken as the worst-possible level of harm that may be produced by the hazard (Leveson, 1995). This is also often called the worst-credible level to distinguish it from the worst-conceivable level, the latter being a level that can be imagined but is patently unreasonable to consider.

For many hazards, harmful outcomes will be more likely at lower levels of severity than the worst-credible case. However, the products of multiplying these lower levels of severity and their accompanying increased probabilities will be more or less constant for an array of outcomes. They will, therefore, represent much the same value of risk. The practice of assessing risk for the worst-credible outcome is further supported on the argument that the result will customarily be pessimistic. Exceptions

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to this generality arise and should be guarded against (Clemens, 1999).

Evaluating Probability

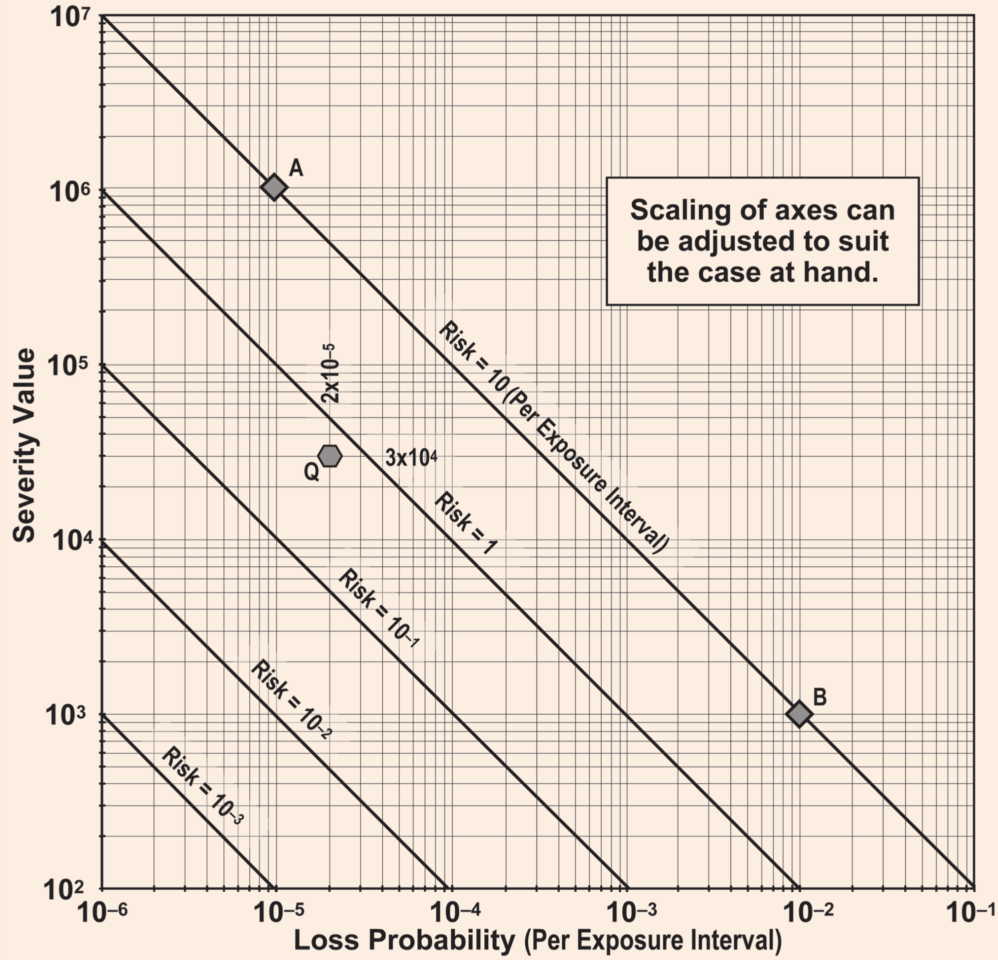
The value of probability to be applied in assessing risk must represent the likelihood of experiencing a loss outcome at the same level of harm for which severity is evaluated, customarily the worst-credible level. The probability value must apply to the specific duration for which risk is to be assessed.

According to Browning (1980), probability is “the mathematical likelihood of [a loss event] in a specified interval of time, or in the course of a particular operational cycle, or trial or mission.” The value of risk assessed using this expression of probability then applies to that same specified interval of exposure and only to that interval.

For example, suppose that one is assessing the risk of a computer hard drive crashing. Probability will be based on the characteristics of the equipment, service and environmental stresses, and some specified number of operating hours. The hard drive crash risk evaluation will apply to this same number of operating hours. Severity in this case can be assumed to be the overall cost of replacing the hard drive; some may wish, with good reason, to include the worth of lost data as a component of severity.

Figure 1

Loss Values for Various Loss Probabilities



Strategies to evaluate probability include:

•Use experience-based data for the same or similar phenomena.

•Use published tables. These usually express failure rate (λ) from which failure probability (P_F) can be calculated. The relationship between the two is discussed shortly. Ebey and Clemens (1996) present an assortment of failure rate data sources.

•Estimate the probability based on engineering judgment. Applying heuristic judgment in probabilistic risk assessment is unavoidable—judgment must be used if only in selecting an analytical model. Ebey and Clemens (1996) provide guidance for estimating failure probabilities.

Dealing with Dimensional Distinctions

Needs for quantitative risk assessments fall predominantly into two broad categories. Handling of the probability component of risk differs between one-time loss events and recurring loss events.

One-Time Loss Events

In one-time cases, the analyst needs to know the probability of a loss event occurring at a particular level of severity during a specified period. The number of occurrences that might arise is not of interest. Either of two factors might lead to this need:

•Concern is for a high-severity potential outcome (i.e., an extreme perceived severity component of risk).

•The nature of the hazard or of the hazard ensemble (a collection of hazards that can lead to a particular loss event) precludes recurrences.

The probability of the crash of a specific aircraft while on a particular flight is an example of a one-time event, as are the probability of destruction of a rare painting by fire or the probability that an individual might succumb to a fatal disease during a selected decade of life. Irrecoverability or irreparability characterizes these cases.

The relationship between λ and mean time to failure (MTTF) is important. [Mean time between failures (MTBF) will occupy the same role in the case of repeated loss events.] From MTTF, λ is found as follows (Raheja, 1991):

Abstract: *In controlling a risk, the chief concern is the availability of countermeasures and their effectiveness. While countermeasure cost is of concern, decisions to adopt a given intervention are often based only on informally reckoned economic considerations. A more exact evaluation of the economic worth of adopting a given countermeasure can often be derived with relative ease if based on the fundamental mathematical definition of risk. Doing so helps to guide countermeasure selection.*

Equation 2: $\lambda = 1/MTTF$

Notice that λ acquires the dimensions of rate or frequency (e.g., the reciprocal of units of time, of operational cycles, trials, missions). This expression appears in the Poisson distribution (Raheja, 1991) for the limiting case of a stochastic system experiencing *no* loss event occurrences:

Equation 3: $\Re = \varepsilon^{-\lambda T}$

$\Re$ = reliability (the probability of no loss events over the interval T)
ε = the Naperian base, 2.718+
λ = failure rate
T = exposure interval (period for which probability is to be evaluated; units are those used to express MTTF).

It follows that the probability of some (i.e., one or more) loss events (P_F) must be:

Equation 4: $P_F = 1 - \Re = 1 - \varepsilon^{-\lambda T}$

It can be shown that if the exposure interval is brief compared to MTTF, then as a useful approximation:

Equation 5: $P_F = 1 - \varepsilon^{-\lambda T} \cong \lambda T$

This approximation yields small errors—less than 11% for values of T less than 0.2 MTTF. The errors produce, in any case, only pessimistic results (i.e., values for P_F that are higher than those arrived at using the complete expression). From Equation 1 and Equation 5, risk now becomes:

Equation 6: $R = S(1 - \varepsilon^{-\lambda T})$

Using Equation 5, Equation 6 can now be approximated as:

Equation 7: $R \cong S(\lambda T)$

Loss Rate

Loss rate is a valid loss exposure [a hazard] will present, for the loss event T, a characteristic loss rate R_T, equal to the severity multiplied by the frequency:

$R_T = S_T \times F$

where R_T = loss rate
S_T = loss severity (the sum of all the costs attributable to one occurrence of the loss event T).
F = loss frequency. Loss will occur at a frequency set by the probability P_T, which is a fraction between 0 and 1, where 0 represents intrinsic impossibility and 1 represents absolute certainty.

In this context, F represents true frequency of occurrence rather than classical probability. Thus, it is possible for the value of F to exceed unity. This would not be the case were it to represent probability (P_T) which is further defined by Browning (1980) as "the mathematical likelihood of [a loss event] in a specified interval of time, or in the course of a particular operational cycle, trial or mission."

λ = failure rate
P_F = failure probability of occurring in period T

***Note.** Adapted from* The Loss Rate Concept in Safety Engineering, *by R.L. Browning, 1980, New York: Marcel Dekker.*

Repeated Loss Events

This category encompasses those instances in which a hazard or hazard ensemble threatens to produce repeated loss events. The concern is for cumulative risk over a specified period. For example, a particular motor vehicle may suffer a number of flat tires over its lifetime of use; it is then the likely accumulated total loss over a specified period during the duration of ownership that is of interest.

The total count (N) of loss events to be expected from a hazard over a specified period (T) must now be used rather than the probability of one or more events, as had been the case. In addition, it is total expected loss (L_E) that is to be evaluated rather than classical risk. Thus, following from the form of Equation 1:

Equation 8: $L_E = SN$
where $N \cong \lambda T$
Thus, $L_E \cong S\lambda T$

It should be noted that this and many of the equations that follow are shown as approximations. They approximate the Poisson distribution model for cases in which T < MTTF; they are often called "rare event" approximations.

Evaluating Countermeasure Worth

The One-Time Loss Event

Consider that a particular hazard poses one-time risk at some level (R_1) and that a countermeasure is contemplated that will reduce this risk to a new level (R_2) by lowering either severity, probability or both. Then the reduction in risk (ΔR) may be expressed as:

Equation 9: $\Delta R = R_1 - R_2 = (S_1 P_{F1}) - (S_2 P_{F2})$

Repeated Loss Events

With repeated loss events, total expected loss (L_E) from Equation 9, replaces risk (R) in Equation 10. The result is:

Equation 10: $\Delta L_E = L_{E1} - L_{E2} = [(S_1\lambda_1) - (S_2\lambda_2)]T$
ΔL_E is the reduction in loss.

Examples

A One-Time Loss Event: Transporting Art

An insurer is asked to evaluate the risk of transporting an irreplaceable art treasure across the continent. The item's value is $13 million (which becomes the S term in Equation 6). It will cost $2,600 to ship the item 2,900 miles (which becomes the T term in Equation 6). In shipments of this kind, the threat of total loss of cargo through a highway accident is estimated at ~3.3×10^{-8} per transport mile; this becomes λ in Equation 6. Thus, using Equation 6 to evaluate risk:

$$R = 13 \times 10^6 (1 - \varepsilon^{-(3.3 \times 10^{-8})(2.9 \times 10^3)}) = \$1,244$$

This is the dollar value for the risk of loss of the art treasure as a consequence of a highway accident in the course of the trip.

To reduce risk, shipment by air is considered as a countermeasure (time in transit has been considered inconsequential, whether by truck or by air). However, the shipping cost is now $8,400, an increase of $5,800. The probability of loss of cargo by

Table 1

Blending Machine Performance

Item	Relevant data	Symbol
Current vane break rate (now) (experience-based)	0.008/production day	λ_1
Vane replacement cost (average, including cleanup, product loss and downtime)	$1,288	$S_1 = S_2$
Countermeasure cost (torque limiter) (including installation)	$8,360/machine	CC
Countermeasure maintenance cost	$205/year/machine	m
Anticipated vane break rate (new) (estimated, with torque limiter)	0.003/production day	λ_2
Anticipated operating duration	8 years (2,000 production days)	T
Interest rate assumed	10% or 0.10	i

Note. *The terms and symbols in this article are those adopted by the authors for classroom use.*

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this mode of transportation, based on the insurer's database, is ~1.2×10^{-8} per transport mile. Again using Equation 6:

$$R = 13 \times 10^6 (1 - \varepsilon^{-(1.2 \times 10^{-8})(2.9 \times 10^3)}) = \$452.39$$

Air shipment as a countermeasure affords a risk reduction of $1,244 - $452.39 = $791.61. This is insufficient to offset the $5,800 increase for air shipment. Shipment by truck remains the favored transportation mode if economy is to be the sole determinant. Much the same result would have been obtained by substituting the approximation offered as Equation 7 into Equation 10 and recognizing that $S_1 = S_2$ and $T_1 = T_2$:

$$\Delta R = R_1 - R_2 \cong ST(\lambda_1 - \lambda_2)$$

$$\Delta R \cong (13 \times 10^6)(2.9 \times 10^3)(3.3 \times 10^{-8} - 1.2 \times 10^{-8}) = \$791.70$$

Repeated Loss Event: A Rocket Propellant Blender

A facility manufacturing solid propellant rocket motors uses a group of blending machines to formulate and combine propellant and oxidizer materials before casting. A partially congealed mass of propellant material sometimes develops within a blender, a phenomenon called "clodding." Blender mixing vanes encounter these clods, causing them to break away from their supporting arms. The sundered vanes then become embedded in the propellant slurry.

Recovery from a vane break is costly—it interrupts production, and requires cleanup and equipment replacement. Cleanup activities can also expose personnel to the propellant material. A torque-limiting coupling with a slip detector and an alarm feature is proposed as a countermeasure against the probability of vane breakage. The alarm prompts shutdown when a torque set point is exceeded. The clod can then be removed with a minimum of downtime and product loss.

The data in Table 1 characterize the performance of each blending machine in the group and indicate the anticipated outcome of adopting the countermeasure. The question becomes: Would a reduction in expected loss warrant adopting the torque limiter as a countermeasure? By performing a basic benefit-cost ratio analysis on the proposed countermeasure and comparing it to the status quo, a degree of desirability can be determined. Given management is of the mindset to make changes, and it has the needed capital to implement them, the option that presents the greatest benefit/cost ratio is deemed the appropriate choice. Should the benefit derived be small, management may opt to wait or look for others areas in which to invest the available funds.

In this example, it is assumed that the process in question will produce a certain benefit regardless of the number of vanes broken. By reducing the probability of breakage, an added benefit can be achieved. Therefore, the calculations only examine the cost factor associated with each option. The option that results in the lowest cost would yield the largest benefit/cost ratio holding the benefit equal for each option.

An annual maintenance cost will be incurred for both options (countermeasure or status quo). This cost is $205/year and is denoted by the variable *m.* To account for the monetary expenditures accurately, one must assume an interest rate—in this example, 10%. Since no specific benefits are defined in the problem, it is assumed that both options yield the same benefit. Therefore, a comparison of the costs associated with each option is used as the deciding factor. Any reduction in cost would be considered an increase in the benefit of the operation.

Option 1: Status Quo

- Rate of vane breakage = 0.008/production day.
- Life of operation = 2,000 days.
- Expected number of vanes broken over life of operation = (0.008 vanes/production day)(2,000 production days) = 16 vanes.

Present Value

Present value is the value of money discounted to account for the time value of money and other factors such as investment risk. Present value of money is always less than the corresponding future value. This type of calculation is often used when comparing cash flows of like items.

•Cost to replace a broken vane = $1,288/vane.

•Cost to replace broken vanes over the life of operations = (16 expected vanes broken) ($1,288/vane replacement) = $20,608.

•Maintenance cost over life of operation = (8 years) ($205/year) = $1,640.

•Total annual cost for Option 1, C_1 = Cost of replacement per year + annual maintenance costs = $20,608/8 + 205 = $2,781.

Using a present value (PV) calculation at time 0 to determine the present value of the annual costs, the true value of dollars spent can be determined.

$$PV = (1 + i)^n - 1/i(1 + i)^n$$

$$PV = (1 + 0.1)^8 - 1/0.1(1 + 0.1)^8 = 5.33$$

Now, using the annual cost of $2,781 and the PV factor of 5.33, the present value of the cost adjusted for interest is 5.33($2,781) = $14,822.73

Option 2: Implement the Countermeasure

•Cost of countermeasure = $8,360.

•Rate of vane breakage = 0.003/production day.

•Life of operation = 2,000 days.

•Expected number of vanes broken over life of operation = (0.003 vanes/production day)(2,000 production days) = 6 vanes.

•Cost of vane replacement = $1,288/vane.

•Cost to replace broken vanes over the life of operations = (6 expected vanes broken)($1,288/vane replacement) = $7,728.

•Maintenance cost over life of operation = (8 years)($205/year) = $1,640.

•Total annual cost for Option 2, C_2 = Cost of replacement per year + annual maintenance costs = $7,728/8 + $205 = $1,171. Again, using the PV factor derived earlier with the new annual cost, a new present value is determined: 5.33($1,171) = $6,241.43.

Combining the initial cost of the countermeasure with the adjusted annual cost, the true cost of the countermeasure is: $8,360 + $6,241.43 = $14,602.43. Net annual savings is $2,781 - $1,171 = $1,610. (Net annual savings is the benefit derived by subtracting the annual cost of countermeasure options from annual cost of status quo.)

So, for option 1 (status quo), the cost is $14,822.73 over the life cycle; for option 2 (countermeasure), the cost is $14,602.43 over the life cycle.

Payback Period Determination

The payback period (the duration of operation over which the saving in cost owing to the reduction in risk exactly equals the cost of adopting the countermeasure) can be found by determining how many years of saving $1,610 it will take to equal the total cost of implementing the countermeasure:

•Total cost = $14,602.43.

•Payback = $14,602.43/$1,610 = 9.07 years.

Although the countermeasure reduces the replacement cost of a broken vane by $1,610/year, the initial cost of implementation ($8,360) makes this option undesirable. Also, the payback period exceeds the expected life of the operation. If the cost of the countermeasure was to be reduced or an increase in benefit was achieved, the countermeasure should be reevaluated.

Conclusion

Often, selecting a countermeasure to control a risk is based on intuitive perception rather than on applying risk management principles found in the practice of system safety. In many cases, applying those principles is not a complicated process. A rational selection from among competing countermeasures can be based simply on the basis of the relative cost and effectiveness of the feasible candidates.

As a simple test of effectiveness, the cost of adopting a countermeasure should be offset by the reduction in risk that is realized. The residual risk that remains after adopting the countermeasure must be acceptably low, and applicable codes and standards must be satisfied. Beyond that, accepting residual risk is a prerogative reserved to management. When matters of safety and health are at risk, the process becomes more complex and falls beyond the scope of the treatment intended here. ■

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