

Integrating Value Engineering and Probabilistic Risk Assessment: A Synergistic Approach to Value Improvement

Mark W. Dejmek - Fluor Daniel, Inc.
Kimberly A. Ford - Fluor Daniel Inc.



Mr. Dejmek is a graduate of the University of Illinois at Urbana/Champaign, where he earned bachelors degrees in both Chemistry and Chemical Engineering. Upon graduation he went to work for Technica Inc. (now DNV Technica), a consulting firm which specializes in the area of Process Safety/Reliability Analysis. There, Mark was primarily involved in conducting Quantitative Risk Assessments (QRAs) for clients in the petroleum, chemical, and petrochemical industries. Mark is currently employed by Fluor Daniel, in Houston, Texas, where he is a member of the Process Safety and Reliability Group. At Fluor Daniel, Mark has conducted numerous probabilistic risk and reliability studies, to support design projects and also for enhancement of existing facilities.



Ms. Ford is a Chemical Engineering graduate of Michigan State University. Upon graduation, Kim accepted a position with 3M, in St. Paul, Minnesota. Following two years of working as a Manufacturing Engineer in various plants in 3M's North American operations, she went to work for Technica Inc. There she specialized in HAZOP and other qualitative process safety studies. Kim is currently a member of the Process Safety and Reliability Group of Fluor Daniel's office in Houston, Texas. While at Fluor Daniel, she has continued to develop her expertise in qualitative process hazards analysis techniques. Kim is also a trained Value Engineering Workshop facilitator and responsible for the development of the VE program in the Fluor Daniel's Houston Office.

ABSTRACT

Probabilistic Risk/Reliability Analysis (PRA) is often used as a value-added service with the aim of optimizing system design. The methods of PRA are highly compatible with Value Engineering (VE). Probabilistic methods can be used to analyze the results of a VE study to choose between alternative options identified by the VE team. Furthermore, since system safety and system reliability are measures of functionality (and hence directly related to value), the quantification of these factors can provide the VE team with added insight and direction. In the end, the use of VE and PRA in combination can produce results above and beyond those associated with either individual method.

INTRODUCTION

As is well known, Value Engineering (VE) considers both cost and functionality. However, whereas capital cost reductions resulting from VE recommendations

are often easily quantifiable, a similar quantification of functionality can sometimes be difficult, particularly when issues of system safety or system reliability are involved. Fortunately, there exists the discipline of Probabilistic Risk/Reliability Analysis (PRA), which has been used extensively in the nuclear and chemical process industries. Through the application of probabilistic methods, the risk analyst can develop objective measures of system performance. These results can be of great benefit to the VE team, in that the true impact of an idea being considered can be determined.

BASIC PROBABILITY CONCEPTS

The definition of *probability* is fairly intuitive, but actually several meanings exist, and the distinctions are of some practical importance. Three useful definitions are¹:

Equal Likelihood - If a situation has n equally likely and mutually exclusive outcomes and if n_A of these outcomes are event A , then the probability, $P(A)$, of event A is:

$$P(A) = \frac{n_A}{n}$$

This probability can be calculated *a priori* and without doing experiments. A good example is the toss of an unbiased die, which has six equally likely outcomes. The probability of throwing any individual number is 1/6.

Relative Frequency - If an experiment is performed n times and if event A occurs on n_A of these occasions, then the probability, $P(A)$, of event A is:

$$P(A) = \lim_{n \rightarrow \infty} \frac{n_A}{n}$$

This definition of probability is the most widely used in engineering. In particular, it is this definition which is implied in the estimation of failure probability from field failure data.

Personal Probability - This definition relates probability to a degree of belief. It is a numerical measure of the belief which a person has that an event will occur. A good example of this is a weatherman's claim of, "70% chance of rain tomorrow." Personal probability is sometimes referred to as Bayesian probability.

Regardless of which definition is implied, a probability is a dimensionless number between 0 and 1. Related to probability is *frequency*, which is a measure of how often an event occurs over time. A frequency can be greater than 1 and must have units of time^{-1} . Examples of frequencies are: 6.4×10^{-4} per year, 3.1 per million hours, 3 per day.

The inverse of frequency is *recurrence period*, which indicates the expected length of time before a failure. Thus, an event with a frequency of 1.0×10^{-2} /year would be expected to occur approximately once every 100 years. Thus, for this event, the recurrence period, or *Mean Time Between Failures (MTBF)* is 100 years. Noteworthy is the fact that a high MTBF is indicative of high reliability.

A more general term is *likelihood*, which is often used to speak of probability or frequency interchangeably.

BASIC PROBABILITY RELATIONS

Consider an event A , which has a probability of occurrence P_A . The event that A does *not* occur, $\sim A$, has a probability of $P_{\sim A}$ as given below:

$$P_{\sim A} = 1 - P_A$$

This relation is simply a consequence of the fact that events A and $\sim A$ are *mutually exclusive*, i.e., both cannot occur simultaneously, and they are *exhaustive*, i.e., they represent the entire range of possible outcomes and so their probabilities sum to 1 (i.e., 100%).

Thus, if event A represents system success, then event $\sim A$ represents system failure and:

$$P_{\text{failure}} = 1 - P_{\text{success}}$$

For any two *independent* events A and B , with probabilities P_A and P_B respectively, the probability that A and B both occur is the *intersection* of sets A and B as given below:

$$P_{A \text{ and } B} = P(A \cap B) = P_A \times P_B$$

For any number of *independent* events A, B, \dots, N with probabilities P_A, P_B, \dots, P_N respectively, the probability of all events occurring simultaneously is:

$$P_{\text{all}} = P\left(\bigcap_{i=A}^N P_i\right) = P_A \times P_B \times \dots \times P_N$$

Thus, for any number of independent *necessary events*, i.e., events which are required to satisfy a secondary condition, the probability of the secondary condition is calculated by multiplying the probabilities of the necessary events.

For the same two events A and B , the probability that at least one of them occurs is the *union* of sets A and B and is given as follows:

$$P_{A \text{ or } B} = P(A \cup B) = P_A + P_B - (P_A \times P_B)$$

The product $P_A \times P_B$ is subtracted to avoid "double-counting" the intersection. For small values of P_A and P_B , this product is negligibly small and the union can be calculated simply as the sum of P_A and P_B .

For independent events A through N , the probability of at least one occurring is given as follows:

$$P_{\geq 1} = P\left(\bigcup_{i=1}^N P_i\right) = P_A + P_B + \dots + P_N - (P_A \times P_B) - (P_A \times P_C) - \dots - (P_{N-1} \times P_N) + (P_A \times P_B \times P_C) + (P_A \times P_B \times P_D) + \dots + (P_{N-2} \times P_{N-1} \times P_N) + \dots + (-1)^{n-1} (P_A \times P_B \times \dots \times P_N)$$

Very often the probabilities considered are small enough that the higher order terms can be neglected and the above equation reduces to:

$$P_{\geq 1} = P\left(\bigcup_{i=1}^N P_i\right) = P_A + P_B + \dots + P_N$$

Thus, for any number independent *sufficient events*, i.e., those events where only one is required to satisfy a secondary condition, the probability of the secondary condition can be calculated by adding the probabilities of the sufficient events (given that the probabilities involved are small).

RISK AND RELIABILITY ANALYSIS

Risk, by definition, is a measure of loss expressed in terms of both the likelihood and magnitude of the expected damage. Accordingly, risk analysis involves three steps: (1) hazard identification; (2) consequence analysis; (3) frequency analysis. After identifying an "undesired" event, the risk analyst then seeks to quantify the potential consequences of that event and the associated likelihood of these consequences being realized.

Reliability may be formally defined as the probability that a system or component fulfills its intended function without fail for a specified mission time, under specific operating conditions. The reliability analyst seeks to quantify this probability through the application of a number of formal methods.

Risk and reliability are related to one another and, indeed, a number of the same techniques are used in both risk analysis and reliability analysis. In both disciplines, the events of concern tend to be equipment failures. The chief difference is that risk analysis tends to focus on failures that can lead to human injury, whereas reliability analysis primarily concerns itself with events that lead to lost production and hence lost revenue. Thus, while risk analysis and reliability analysis are often treated as separate disciplines, they

have much in common and can also be referred to as a single entity, viz., probabilistic risk/reliability analysis (PRA).

PRA INPUT

PRA generally involves the creation of some type of *system model* which seeks to mimic the behavior of the actual system by incorporating appropriate logic related to system parameters and inter-relationships. To this end, the input required by the PRA analyst is twofold: (1) information which defines the *system logic*, the behavior and interactions of the various system components; and (2) data required to quantify the system model. Information required to define the system logic can generally be provided by the design engineer or other individuals familiar with the system. Quantitative data on equipment failures are available in the form of generic data bases or can be generated from site-specific operating data. Sources of equipment failure data have been discussed elsewhere in the literature².

PRA RESULTS

In general, the results of a PRA come in three forms: (1) a quantitative evaluation of overall system performance (e.g., safety, reliability) and an evaluation of its adequacy; (2) a criticality listing, which ranks the various subsystems and components in terms of their importance with regard to overall system performance; (3) a comparison of various suggestions for reducing risk or improving reliability.

This first result is often seen as the most important. Examples of system performance measures include projections of statistical injuries per year for a risk analysis and expected number of system outages for a reliability analysis. These results can often be compared against target criteria (e.g., corporate standards) to determine if any improvement in system functionality is required.

No less important is the criticality ranking which can be produced by a PRA. For each component in a system, a quantitative measure of its impact on overall system performance relative to other components is produced. This is particularly important in risk/reliability studies, where the *Pareto Principle* generally holds true. The Pareto Principle, or 80/20 rule, is a guideline which states that 20% of the components in a system are responsible for 80% of the system problems. For this reason, it is known as, "the rule of the important few versus the unimportant

many.” By identifying and focusing on the relatively few important failures, it is possible to target enhancement efforts to where the greatest return on investment can be achieved.

The last important product of a PRA is the ability to objectively compare different alternatives for improving the system, through the execution of sensitivity studies. Since the system model acts as a “virtual system,” it is possible to make alterations to specific system parameters with the aim of examining what the effect will be on overall system performance. For example, it is possible to evaluate what effect a risk mitigation measure (e.g., the installation of a gas detection system) will have on the total risk associated with a system.

Each of these results can be of great utility to the Value Engineer at various stages in the VE process.

USING PRA IN A VE STUDY

PRA can be applied at various points during the VE process in order to support different purposes. PRA may serve as the initiator for a VE workshop by identifying where and how VE can be most effective. The most natural integration of PRA in the VE process is during the Evaluation Phase. In considering the numerous ideas that are generated, the team will be able to apply these tools to estimate their impact on functionality. A third application of PRA in conjunction with VE, is to use PRA to measure the overall impact of a VE workshop.

PRA AS A PRECURSOR

Risk and reliability analyses performed prior to a VE workshop provide information related to system criticality which can be used by the team to focus their efforts. The PRA study results will include a list of subsystems critical to achieving the required system performance. This list serves the VE team by identifying: (1) non-critical areas that present a great opportunity for cost reduction; or (2) critical areas that require focused creative effort in order to meet the functional requirements of the project.

The list of critical items can serve as the basis for a VE workshop with the objective of improving system reliability or safety. The VE methodology will provide a framework for developing creative ideas for enhanced functionality. Traditional solutions to these problems (e.g., from a Hazard and Operability Study) typically include redundancy or additional safety systems. The

solutions from a VE workshop would more likely focus on process simplification and hazard elimination. Both types of solutions improve functionality; however, those from the VE workshop may also reduce capital cost, while the traditional solutions tend to increase it.

CASE STUDY #1

This difference was recently observed on a project where a risk analysis had indicated that one of the key safety systems for a tank that was to be installed was the vapor recovery and transfer system. It was critical that the vapors were collected and safely transferred to the incinerator. The system design utilized a blower to pull the vapors from the tank and transfer them to the incinerator. It was also possible for the blower to pull air into the system, creating an explosive environment. Because of this, a nitrogen purge would be required. A safety study, HAZOP (Hazard and Operability Study), was conducted. In this study, a multi-disciplinary team developed safeguards involving multiple oxygen analyzers and safety shutdowns. Subsequently this project was considered in a VE workshop. The results from this workshop developed a transfer system based upon a nitrogen eductor. This system provided the inerting and the motive force simultaneously, thus eliminating the potential for transferring a combustible mixture to the incinerator. This simplified approach maintained all of the required functionality while reducing the capital and maintenance costs.

Systems that do not appear on the list of critical items resulting from the PRA may represent areas of opportunity for cost reduction. Because these areas are not critical to system safety or reliability, it is possible to eliminate over-design and to develop cost reduction ideas through value analysis. The PRA results also indicate that in these areas improvements in reliability or safety are not going to influence the overall reliability or safety of the entire project. Accordingly, these types of ideas should not be given a great deal of consideration.

PRA IN THE EVALUATION PHASE

The use of PRA during the Evaluation Phase is also very effective. During the Evaluation Phase the VE team is judging the ideas generated during the creative Speculation Phase. The team is to judge and select ideas based upon qualitative and quantitative criteria.

At the beginning of the Evaluation Phase, the team may develop a list of criteria to be used for selecting ideas for further consideration. Alternatively, in some

cases, the project may have a set of criteria for project success that are to be used by the VE team. In either case, the following items are typically included in the list for a project in the chemical process industries:

- Safety
- Reliability
- Capital Cost
- Operating Cost

On a qualitative basis, it is possible to evaluate an idea using all of these criteria based upon engineering judgment. Typically, the members of a VE team would not have sufficient knowledge of the system reliability and risk models to make such judgments. Therefore, including the risk analyst who is familiar with these models in these decisions will improve the results of this phase.

As the evaluation moves on to the quantitative comparison, the team is challenged to choose between capital costs that are quite easy to determine and life cycle costs that can be quite complicated. Given this challenge and the desire to reduce capital investment, the short term capital savings is often chosen even when it does not represent the greatest value to the project. In some cases, therefore, it is important to use quantitative criteria such as reliability and risk, in addition to the capital and operating costs. During the VE workshop, a risk analyst who is familiar with the project will be able to provide quantitative estimates of the impact on risk and reliability just as the estimator does for cost. He will also be able to help the team in developing the proposals for a given idea by providing specifications for its eventual success (e.g., "Yes, if ...")³.

CASE STUDY #2

For off-shore oil and gas production projects, reliability is usually the most important measure of project success. Therefore, in evaluating the ideas in a VE workshop, it is critical to determine the impact of specific ideas on the overall system reliability. This was true during a recent workshop that had the objective of optimizing the functionality to be provided on each of two platforms being designed. At the beginning the study, two identical platforms were planned. However, it was believed that one of the platforms could be simplified by utilizing the systems on the other platform. By creating a stronger relationship between the two platforms, the overall

system reliability became more greatly dependent upon the reliability of the systems on the larger platform.

During the qualitative portion of the Evaluation Phase, the reliability engineer provided input regarding the relationship between the system under discussion and the ability of the system to deliver at the required rates. This allowed the team to eliminate ideas that were expected to have a significant negative impact on the overall system reliability. After the screening, the functionality of each of the platforms was defined. Then the reliability model was utilized to optimize the final configuration and to ensure an acceptable system functionality. In the end, the cost of the second platform was reduced by nearly 50% with no reduction in overall system functionality.

PRA AS A MEASURE OF VE IMPACT

The PRA method which is probably most relevant to evaluating the impact of proposed changes resulting from a VE workshop is reliability modeling. Specifically, reliability simulation, which involves the development of a detailed system model, can be of great benefit. These computer tools can be used to simulate many years of plant operation, including the operating expenses, maintenance expenses, and lost production due to outages. From this simulation, an estimate of the life cycle cost can be developed.

The development of a reliability simulation model for a particular plant can be quite complex, requiring many weeks of effort from a reliability analyst. This large effort makes the use of this most sophisticated tool difficult during the confines of the VE workshop; however, it can be very useful when applied after the completion of the study.

This approach can be used in conjunction with Value Engineering in two useful ways: (1) to measure the impact of proposed modifications on system functionality; and (2) to measure the impact of proposed modifications on Life Cycle Cost associated with the system.

Within a VE workshop, the impact of the various proposed ideas is often considered on an individual basis. This approach is appropriate for supporting the team's effort to screen the ideas in order to eliminate those with the least potential for success. However, following the workshop, it is frequently desirable to understand the total impact on system functionality of all of the ideas being proposed by the VE team. PRA tools, such as reliability simulation and fault tree

analysis, can be used to measure the total effect on system reliability or system safety. This type of evaluation will ensure that sufficient functionality will be maintained after implementation of all of the recommended modifications.

Another application of reliability simulation is the estimation of life cycle cost. By developing system models which represent the configuration both before and after VE, the life cycle cost reductions associated with the effort can be estimated. An analysis of this type will ensure that the most beneficial selections were made and that the trade-off between capital cost and operating/maintenance costs has been appropriately addressed.

VE AND PRA SYNERGY

As the previous discussion and case histories demonstrate, the separate disciplines of VE and PRA complement each other quite nicely. Indeed, the use of both PRA and VE in tandem can produce results of greater accuracy and utility than those associated with either individual method. In addition to improvement in the final product of a study, the adept use of tools from both disciplines can actually reduce the time and effort required by the study team. An awareness of the various tools which exist, regardless of the discipline in which they originated, can be of great benefit in any problem-solving endeavor.

BENEFITS TO PRA

Historically, risk analysis has most often been done with the aim of enhancing system safety, often through the implementation of safety systems which result in an increase in capital cost to the project. The use of risk analysis in conjunction with Value Engineering highlights another important application of risk analysis: to identify opportunities for cost reduction which do not appreciably impact the level of safety associated with the system. This is an important and practical application of risk analysis which is often overlooked. Using PRA to focus only on enhancement measures can lead to "gold-plating" in design. This is a criticism of PRA often levied by managers who, although they may still place a high priority on system safety, must also keep in mind the issue of project cost. By applying PRA also as a tool to eliminate unnecessary over-design, the risk analyst will provide additional application of his services and will see his discipline more widely embraced.

Another difficulty with which the PRA analyst has often contended is the appropriate and useful application of the results of a study. PRA results can be complex and, in some cases, difficult to understand for those unfamiliar with the discipline. Moreover, a past criticism of PRA is that the results produced can sometimes be difficult to use in a practical sense. The use of PRA in conjunction with VE addresses this issue in that it provides a further outlet for the use of PRA results. Thus, the overall performance measures, criticality rankings, and sensitivity analyses, which have traditionally been used to develop and modify operating and maintenance strategies, can also be applied to the more universal goal of overall value improvement.

BENEFITS TO VE

All Value Engineers learn the fundamental equation:

$$Value = \frac{Functionality}{Cost}$$

While costs can often be quantitatively estimated quite easily by the VE team, the assessment of functionality is generally based on qualitative judgment. This can have the effect of turning the VE workshop into a cost-cutting effort, rather than a true value improving exercise. The benefits of quantification are evident and, fortunately, the tools for accomplishing this have already been developed and are being utilized by risk/reliability engineers.

Safety and reliability are important measures of functionality and, hence, are directly related to value. Accordingly, it is beneficial to develop an accurate estimate of safety and reliability to be used within the context of the VE study. This will allow the team to better evaluate two types of ideas: (1) those where the reduction in functionality is too great to support the cost savings; (2) ideas with large improvements in functionality but low cost impact. In summary, the use of PRA allows the team to treat functionality and cost in a similar manner, thereby providing a true measure of value.

Another challenge for the VE team is to select the functions that present the greatest opportunity for improvement, and hence, are selected for consideration in the Speculation Phase. Typically, this is accomplished by adding the cost dimension to the FAST diagram. However, this can be supplemented by the use of the criticality rankings produced by a PRA

