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Using Cost of Quality Approaches to Improve Commercial Space Transportation Safety

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Abstract

Safety must be tied to the profitability of a launch vehicle company in order for safety to become an essential part of that company's culture. Corporations have begun to realize the importance of safety to productivity and profitability, but few uniform methods exist for analyzing the economics of safety. Methods do exist for analyzing the cost of poor quality, and a commercial launch vehicle operator could adapt these methods to help identify the cost benefits of safety improvements. This paper describes a safety cost analysis model based on quality cost management approaches. The paper also provides examples showing how cost analysis models might be used to help prioritize safety improvement efforts while improving the corporate bottom line.

Introduction

There are a number of reasons why senior business executives, including executives in companies that build and operate commercial space launch vehicles, institute safety processes and commit to maintaining a safe environment. Most executives try to create an environment that promotes safety because they feel they have a moral and ethical obligation to employees, their families, and the public. Managers also understand that they must comply with the law, so they certainly follow safety regulations to avoid legal consequences. However, the reality is that in most cases a company's priority is return on investment. The success or failure of a company is measured by its profitability and its productivity. Therefore, safety must be more than just a social responsibility – safety must also benefit the bottom line to be an integral and long-lasting part of a commercial organization's culture. As stated by Jerome Lederer, aviation safety pioneer,

> *"Of the major incentives to improve safety, by far the most compelling is that of economics. The moral incentive, which is most evident following an accident, is more intense, but is relatively short-lived."*

Although senior company officials may intuitively understand the importance of safety to the bottom line, demonstrating quantifiable financial return can be difficult for safety-related investments. There has not been a uniform approach to identifying and analyzing the safety costs in order to determine the return on safety investments. Also, companies often do not collect data to show how a safety improvement program can improve the company's financial position. Compounding this problem is the fact that safety-related professionals seldom use business models or speak in business terms. Safety professionals often speak in terms of "things" (failures, hazards, etc.) while managers often use the language of "dollars" (costs, financial performance, etc.). Without a compelling financial incentive, and without a common language between safety professionals and senior management, business leaders may find it difficult to invest in safety above a level needed for compliance or to meet ethical obligations. The result is that the safety functions of an organization can become reactive and compliance-oriented (ref. 1).

The commercial space transportation industry may be able to use analytical approaches to characterize potential cost savings from safety improvements. Quality management approaches have been developed to identify and characterize costs of poor quality, and cost models have been developed to show the financial benefits of quality improvements. This paper discusses the relationship between quality and safety and shows how those quality management principles and cost models can be adapted to analyze safety costs. This paper also describes a safety cost analysis approach that can be used in the commercial space transportation industry to help characterize and prioritize safety improvement efforts. The paper provides hypothetical examples of how safety cost models can be used to make the financial case for safety in launch vehicle organizations.

Relationship Between Safety and Quality

To understand the relationship between safety and quality, one can start by examining the common themes of some of the most prominent experts in the quality field such as W. Edwards Deming, Armand Feigenbaum, or Joseph Juran. By taking the statements of these quality experts and replacing the word "quality" with the word "safety," one achieves statements of the commitment necessary for effective quality (or safety) management. Examples of such statements include the following (ref. 2):

- Quality [safety] improvement is a never-ending process
- Top management commitment, knowledge, and active participation is essential to achieve quality [safety]
- Management is responsible for articulating a company quality [safety] philosophy, company quality [safety] goals, and measurable quality [safety] objectives
- Quality [safety] is an organization-wide process, and all employees in the organization need to be active participants
- A common language and set of procedures are important to communicate and support the quality [safety] effort
- A process must be established to identify the most critical quality [safety] problems, determine their causes, and find solutions

In addition, quality assurance and engineering activities can be linked to safety engineering efforts. Quality assurance includes all the planned or systematic actions necessary to provide adequate confidence that a product or service will satisfy a customer's needs. Quality assurance includes activities such as inspections, audits, data collection and evaluation, testing for quality attributes, statistical sampling, metrology, and so on. These quality assurance activities assist in determining that objectives and requirements, including those related to safety, have been identified, evaluated, tracked, and resolved.

While a link between quality and safety exists, it is important to note that quality is not necessarily safety. Safety is freedom from harm, while quality is the totality of features and characteristics of a product or service that allow that product or service to satisfy a customer's needs. Quality includes such dimensions as performance, reliability, durability, serviceability, aesthetics, or other factors that affect a customer's perception of the product or service. Therefore, a product may contain many of the dimensions of a high-quality product and still not be safe. An automobile for example may be a high quality product according to the factors described above and still might not protect its occupants in an accident.

Although quality is not safety, quality engineering and management techniques can and do help improve safety, and these techniques can be used as a starting point in looking for ways to improve the bottom line through safety improvements. One commonly used quality management technique is the cost of quality model.

Cost of Quality Model

Philip Crosby argued in his book *Quality Is Free*, "Doing things right the first time adds nothing to the cost of a product or service. Doing things wrong is what costs money." (ref. 3). Crosby describes a "cost of quality" model consisting of four categories to make his case. These categories, described as follows, may be used to analyze the costs of poor quality:

Prevention Costs. Prevention costs are the cost of all activities taken to prevent defects in products and services. Examples of such activities include design reviews, drawing checking, planning, specification review, and training.

Appraisal Costs. Appraisal costs are the costs associated with measuring, evaluating, or auditing products or services to assure conformance with requirements and standards. Examples include the cost of incoming and source inspections, testing of purchased material, product audits, and the calibration of equipment.

Internal Failure Costs. Internal failure costs are those costs that occur prior to delivery or shipment of the product, or the furnishing of the service, to the customer. Examples are the costs of scrap, rework, and retesting.

External Failure Costs. External failure costs are those costs that occur after delivery or shipment of the product, or after furnishing of the service, to the customer. Examples are customer complaints, customer returns, and product recalls. Some external costs, are fairly easily measured (for example, customer returns); these are known as direct costs. Other costs, known as indirect costs, are less obvious, hard to measure, and often delayed (for example, loss of reputation).

All these costs can be added together to determine the total cost of quality. The goal of modeling the cost of quality is not to obtain absolute financial performance measures but rather to facilitate quality improvement efforts that will lead to operating cost reductions. Note that the term "cost of quality," although widely used, is somewhat of a misnomer. Improving quality is, according to Crosby and others, never costly; therefore, a better term may be "cost of poor quality." However, "cost of quality" will be applied here given its wide use.

The cost of quality can be analyzed in terms of two general areas of cost: proactive activities (prevention and appraisal costs) and reactive costs and results (internal and external failure costs). The classic model of quality costs, illustrated in figure 1, shows that as prevention and appraisal activities are increased failure costs decrease until some optimum in total quality costs is reached. It should be noted that in most cases this optimum is never achieved, and most organizations remain on the left side of the curve (ref. 4).

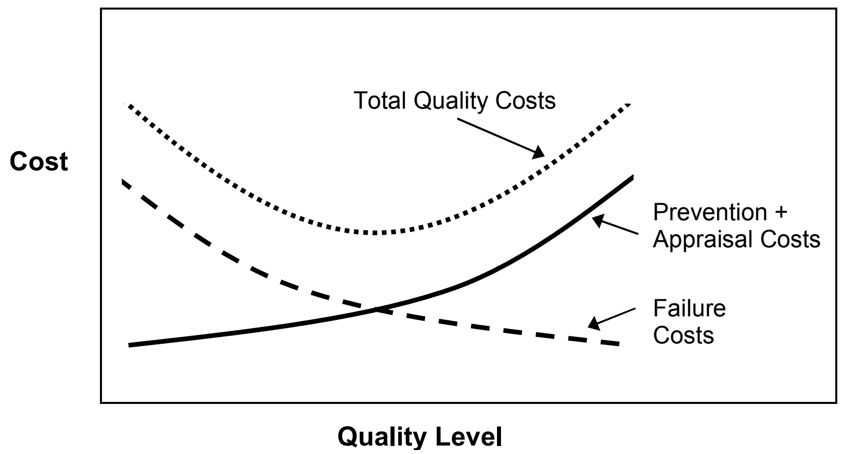

Figure 1 – Classic Model of Optimum Quality Costs

Since its introduction, the cost of quality model has gained wide acceptance as a tool for managing the cost of production, and application of cost of quality approaches has led to many successes (refs. 5-7). Management can use the cost of quality model to facilitate quality improvement activities that ultimately improve the company's bottom line. When implemented, the cost of quality model can help identify weaknesses in company's overall approach to quality (too much scrap and rework, insufficient testing, not enough training) as well as strengths. Process changes can be described using monetary measures in order to justify such changes to management (ref. 4).

Application of Cost of Quality Model to Safety

Behm, et al. (ref. 1) took advantage of the analogy between quality and safety and used the cost of quality model as a basis for building a business case for safety; their study showed how such a model could be used for companies managing ergonomics programs. Researchers and practitioners have applied similar models to the construction industry in order to understand the true costs of safety activities (refs. 8, 9). Stroup and Greene (ref. 10) identified categories of risks and costs for aircraft that can also be used in developing a business case for safety.

A safety cost model could be developed for the commercial space transportation industry by using similar items from the cost of quality model discussed above and including new items unique to safety and the industry. Each item in the following list is not necessarily applicable to all launch vehicle operators; therefore, an operator should determine the applicability of each item to its operation. In addition, an operator may identify items not on this list that are important to its operation.

Prevention Costs

- Design safety planning: System Safety Program Plan, Software Development Plan, etc.
- Safety reviews: Preliminary Design Review, Critical Design Review, Test Readiness Review, Flight Readiness Review, supplier safety reviews, etc.
- Design safety support: Preliminary Hazard Analysis, Failure Modes and Effects Analysis, Fault Tree Analysis, standards development, flight safety analyses, maintainability studies, software usability studies
- Safety reporting
- Safety training
- Procedures development
- Mishap planning
- Configuration management and control tools and meetings
- Internal safety standards development
- Fire and medical crews on hand during flight

Appraisal Costs

- Safety audits
- Safety inspections
- Verification analysis and testing
- Test equipment for safety verification
- Equipment calibration and upkeep
- Supplier qualification
- External certifications

Internal Failure Costs

- Design corrective actions
- Rework due to design changes
- Scrap due to design changes
- Supplier corrective actions
- Rework of supplier rejects
- Scrap of supplier rejects
- Troubleshooting of anomalies and failures of safety-critical systems during verification or rehearsal
- Rework and repair due to anomalies and failures of safety-critical systems during verification or rehearsal
- Reinspection and retest costs after anomalies and failures of safety-critical systems during verification or rehearsal
- Delay costs due to verification failures

External Failure Costs

Direct Costs

- Troubleshooting of anomalies and failures of safety-critical systems during flight
- Rework and repair due to anomalies and failures of safety-critical systems during flight
- Reinspection and retest costs after anomalies and failures of safety-critical systems during flight
- Damages for accident or incidents not covered by insurance (such as accident investigation and clean-up)
- Penalties and fines
- Insurance deductibles

Indirect Costs

- Business losses due to damage to the reputation of the organization

- Loss of staff productivity
- Loss of equipment use
- Liability costs

It is important for a launch operator to keep its own safety cost analysis program simple and practical in order for it to be effective. The safety cost model is a management tool, not a detailed financial reporting system, and as such serves to supplement existing systems. The cost model need not include every cost, but rather should focus on those items of most importance to the company. Determining which items are important is an iterative process, and the model should be updated as more knowledge is gained. As the effort becomes more mature the operator can develop more sophisticated models and use this data to help determine financial measures such as rates of return on investments, net present value on future investments, and so on.

Example: Analyzing and Reducing Internal Failure Costs

The public safety record of the commercial launch vehicle industry is exceptional. In over 170 commercial launches licensed by the FAA Office of Commercial Space Transportation to date not a single member of the public has been injured. There have of course been anomalies and failures in flight, and the FAA has issued fines for safety violations, but to date the external failure costs have been relatively small in the commercial space launch industry as whole.

Although external failure costs to date have been minimal, the commercial space transportation industry is well aware of the potential for significant financial losses, including bankruptcy of individual corporations or collapse of the segments of the industry, which could result should an accident cause injury to a member of the public. Therefore, the industry must continue to look for cost-effective strategies to prevent external failures, specifically those costs resulting from accidents. One such approach to reducing external failures is to reduce internal failures and associated costs. The industry has not been immune to internal failures, in part because of the technical difficulties of implementing technologies used in commercial launch vehicles. In addition to increasing the cost of production, these internal failures are often precursors to external failures, and studies have shown that reduction of these internal failures can prevent accidents (ref. 11). Therefore, the industry should focus on reducing internal failures as a proactive approach to not only reducing costs but also to reducing the possibility of mission loss or public safety impacts. These internal failure costs could be identified through the cost of safety model and then reduced through the application of preventive strategies as described above.

The following is an example of how a hypothetical launch vehicle operator might analyze trends in preventive, appraisal, and internal failure costs. Table 1 shows the sample prevention costs for four fiscal quarters (Q1, Q2, etc.). Appraisal and internal failure costs could be developed in a similar manner. Often the launch vehicle operator will initially focus its analysis and safety cost improvement efforts on reducing internal failures; therefore, external failure costs may not be analyzed until the program has reached maturity.

Table 1 – Hypothetical Prevention Costs

Prevention Cost Item	**Q1 Costs**	**Q2 Costs**	**Q3 Costs**	**Q4 Costs**
Design safety planning	1000	1100	1100	1000
Safety reviews	0	2000	0	2000
Design safety support	1000	3000	4000	4000
Safety reporting	500	500	500	500
Safety training	2000	2000	2000	4000
Mishap planning	500	0	0	500
Configuration management	2000	300	300	300
Internal safety standards development	300	300	0	0
Fire and medical crews	0	0	0	0
Subtotal – Prevention	*7300*	*9200*	*7900*	*12300*

Figure 2 plots the subtotals for each of the safety cost categories to illustrate cost trends. In this case as the prevention and appraisal costs increase, the internal failure costs decrease, which is typical of a quality cost improvement program (ref. 4). In addition, prevention costs are typically a small percentage of the total costs; therefore, increases in prevention costs could potentially lead to large reductions in failure costs.

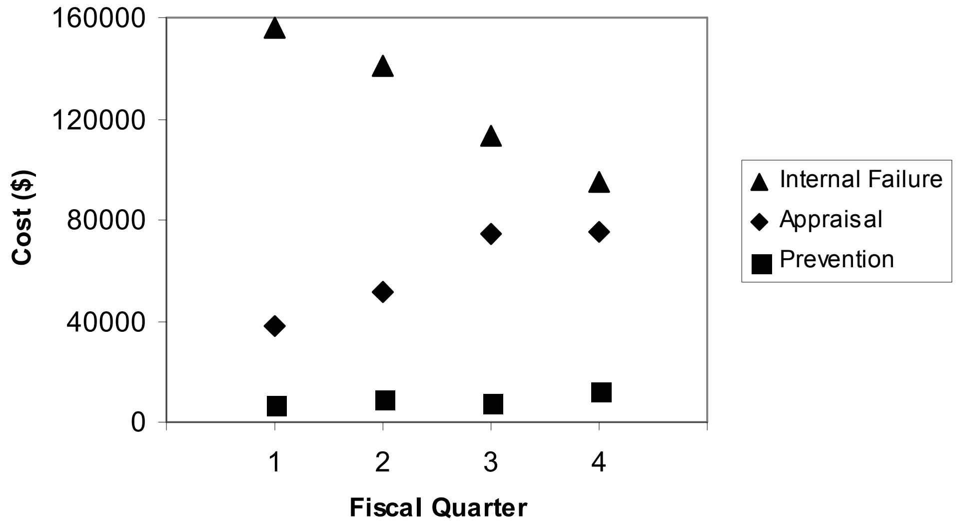

Figure 2 – Trend Analysis of Hypothetical Safety Costs

In returning to the analogy between quality and safety, the strategy for reducing quality costs is the following (ref. 4):

1. Take a direct attack on failure costs in an attempt to drive them down as low as possible
2. Commit to and invest in corrective and prevention activities to bring about improvement
3. Evaluate appraisal costs as results are achieved (are appraisal costs sufficient to reduce the failure cost risks, or are the appraisal costs sufficient considering performance improvements?)
4. Continuously evaluate and redirect prevention efforts to gain further improvement

This quality cost reduction strategy is based on the premise that for each failure there is a root cause, causes are always preventable, and prevention is always cheaper. This is also the strategy that should be taken in improving safety and reducing safety failure costs. Safety failure costs can be measured and then reduced through analysis of data, determination of root cause, and instituting corrective and preventive actions. Therefore, it is important as part of a failure cost reduction effort for the launch vehicle operator to institute an anomaly reporting and corrective action system as part of its overall cost reduction approach. Without such an anomaly reporting system the obvious cost problems may be evident, but some of the hidden, and ultimately most expensive, costs may remain unaddressed.

Example: Uncertainty and Sensitivity Analyses

Although the cost of safety model can be fairly straightforward to develop, obtaining good data can be difficult. Some data may not be well defined, while other data may be highly variable. In these cases, because of the uncertainty of the input values, single point estimates of the costs may not be appropriate or may be misleading. A launch vehicle operator could analyze the best and worst cases to bound the costs. However, while the best-case/worst-case analysis approach gives the ultimate range of outcomes, it does not provide an estimate of how likely the results are (and usually the best and worst cases are highly unlikely). In addition, the results of a best-case or worst-case analysis are usually too optimistic or too pessimistic, and therefore misleading. A more appropriate approach to analyzing cost uncertainty is to use Monte Carlo simulation to quantitatively determine the range and likelihood of costs.

Monte Carlo simulation is a common approach used in cost analysis to assess financial risk (refs. 12, 13). In Monte Carlo simulation a cost model is repeatedly evaluated. Each individual evaluation (or "trial") uses different values for the cost model's input parameters. Selection of the input values is made randomly from probability distributions identified for each input parameter. The output for each trial is collected, and all outputs are collected to create a probability distribution for the simulation. This output probability distribution represents the range and likelihood of the costs. More information on Monte Carlo simulation can be found in Environmental Protection Agency's *Guiding Principles for Monte Carlo Analysis* (ref. 14).

Often the cost analyst creates the Monte Carlo simulation inputs using triangular probability distributions based on available data or expert opinion. A triangular distribution describes the situation where one knows the minimum, the most likely value, and the maximum for an input. For example, based on historical data an operator may know that the minimum value for rework of supplier rejects is $5000, the most likely value is $8000, and maximum value is $11000. These values would yield the triangular probability distribution shown in figure 3. Using this approach an operator could develop triangular distributions for each input to the safety cost model, and place those inputs into a spreadsheet.

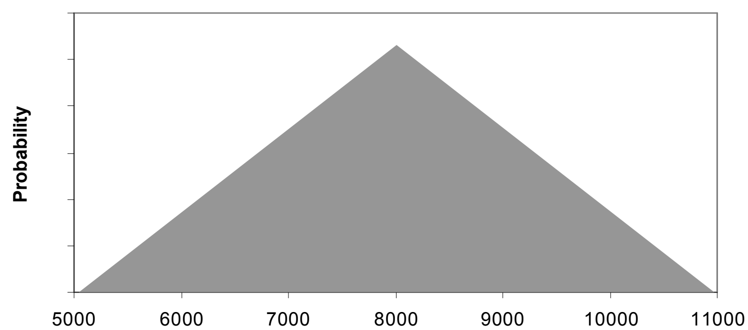

Figure 3 – Triangular distribution for rework of supplier rejects

Software tools are available that allow the operator to run the simulation within a computer spreadsheet. A launch vehicle operator could run its Monte Carlo simulation with these tools using the triangular distributions for the inputs and the total cost of safety as an output. In this hypothetical example it will be assumed that the operator runs 5000 trials of the model. The output of the simulation is shown in figure 4. The simulation results show the minimum total safety costs to be approximately $132,000 while the maximum total safety costs are approximately $209,000. The results also show that there is an 80 percent certainty that the values will lie between $154,651 and $179,654. Therefore, as can be seen by the figure, the operator can describe both the range and the likelihood of the safety costs using this model and Monte Carlo simulation. The operator can also obtain other statistical parameters such as the average value and the standard deviation of the data using this analysis.

A key goal of any cost-benefit analysis is to understand the inputs that most affect the total cost. By determining the sensitivity of the total cost to each input a launch vehicle operator can prioritize efforts to improve safety. This sensitivity is determined by the model itself and the magnitude and uncertainty of the inputs. Figure 5 shows a sensitivity chart generated from the Monte Carlo simulation. For this hypothetical example, supplier qualification costs have the most influence on the total costs, followed by rework due to design changes, and then scrap of supplier rejects. Therefore, these are the areas that an operator should address first. For example, an operator could examine the supplier qualification program to determine if enough time is being spent on developing procedures or planning tests, and whether improvements in these areas could help reduce the qualification costs. A launch vehicle operator could also examine in depth the factors that are leading to rework (what specific safety design changes are leading to rework, and what processes or procedures need to be improved to reduce these costs). In addition, an operator could examine the supplier rejects (what components are failing safety verification tests, and what are the root causes of those failures) and try to reduce those costs. Note that in many of these cases the measures taken to reduce the overall cost lead to improvements in product quality because many of the safety improvements are also quality improvements (improved procedures, less scrap, less rework, more efficient qualification, etc.).

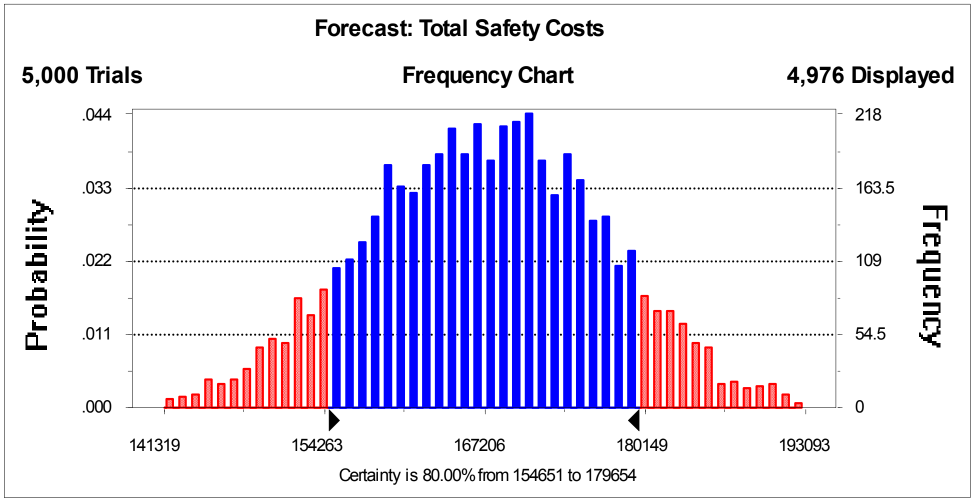

Figure 4 – Monte Carlo Simulation Output, Total Safety Costs

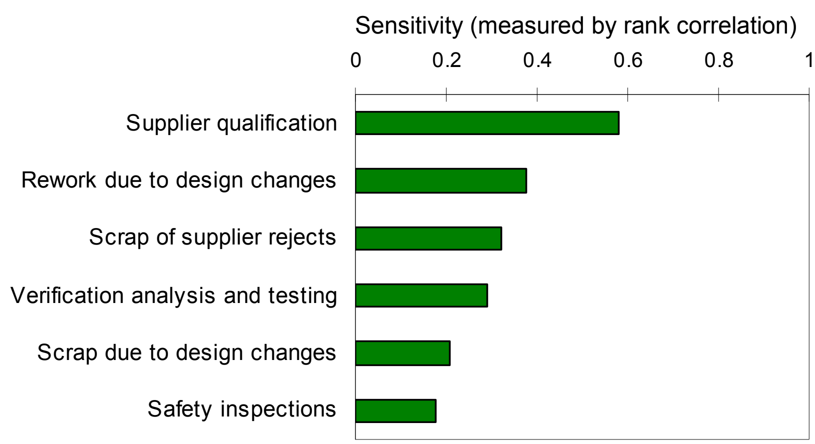

Figure 5 – Sensitivity Chart Resulting from Monte Carlo Simulation of Total Safety Costs

<u>Lessons Learned from Cost of Quality Implementation Efforts</u>

Implementing a safety cost analysis program can be a difficult task in some organizations. Lessons learned from implementing cost of quality programs can be instructive to those trying to implement a safety cost analysis program.

As described in reference 15, individuals implementing a safety cost analysis program should have at least a basic knowledge of accounting principles, safety principles, and quality engineering and management. Knowledge of accounting principles helps gain credibility with management. Knowledge of safety and quality principles are needed to assure that the efforts integrate in the larger safety and quality improvement efforts. Those implementing a safety cost analysis effort must keep the larger safety effort in mind because it is safety systems, not cost of safety models, which improve safety and reduce costs.

Several authors have identified potential obstacles in implementing cost of quality programs (refs. 15, 16). Leaders of safety cost analysis efforts should keep these roadblocks in mind when developing their own programs:

- Management may not understand the principles of quality costing, and therefore may not support work in this area because they may not see the value of the effort.
- Management may not understand quality (or safety) principles, and therefore may not want to expend additional resources to improve these areas.
- The business may be profitable, and therefore it may be difficult to convince management that improvement is needed.
- The existing accounting system may not readily allow tracking of quality costs.
- Because the quality cost analysis system is usually not entirely compatible with existing accounting systems, a separate system (needing its own administrative resources) is often required.
- Quality and safety efforts are often not budgeted and therefore most of the work in these areas is reactive rather than proactive.
- Those implementing the program may spend too much time trying to determine whether a given cost should fall under prevention or appraisal costs. Therefore, these individuals may waste time that could be spent on the overall objective of finding those costs that are driven by internal and external failures and eliminating the cause of those costs.
- The quality cost analysis effort may fail without participation and support from multiple functions within the company, including the accounting department and the company controller.
- Initial quality cost estimates are likely to be low, in part because of a failure to recognize hidden or delayed costs.

Success in cost of quality efforts has been achieved in a number of organizations through a variety of strategies, including the following (ref. 17):

- Forming cross-functional teams to identify cost issues
- Initially selecting only a few key processes to evaluate
- Implementing pilot programs to test the concepts and approaches for identifying and reducing costs
- Using standard root cause analysis techniques (Fishbone diagrams, brainstorming, etc.) to help identify the fundamental reasons for cost and quality problems
- Keeping the initial cost analysis efforts simple and understandable
- Using trend analyses to analyze costs over time
- Ranking problems by failure dollars to identify those worth the effort
- Tracking and reporting the progress on implementing corrective actions

Leaders of safety cost analysis efforts should take advantage of these and other lessons learned to effectively implement their own safety cost analysis program.

Summary

This paper has described a safety cost analysis model based on effective quality management practices. This model can be used to show how safety improvements help a company's bottom line. Safety improvements can help improve a commercial launch vehicle operator's financial position in large part because most of the safety improvements will likely also lead to quality and reliability improvements. Safety cost analysis efforts can highlight the most significant areas for improvement, and can help track those improvements using quantifiable measures. Safety cost analyses can help justify and steer investments to preventive actions, which are the most effective approaches to reducing the risk of launch vehicle accidents. Such cost analyses are necessary to assure that safety improvement processes become an integral part of the commercial launch vehicle operator's culture.

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Biography

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