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Failure Mode And Effects Analysis As A Mechanism For Assessing The Cost Consequence Of A Failure

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Failure Mode and Effects Analysis as a Mechanism for Assessing the Cost Consequence of a Failure

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ABSTRACT

This study investigated the possibility of including the cost consequence of a failure in the *a priori* risk assessment methodology known as Failure Modes and Effects Analysis (FMEA). This entailed developing a model of the standard costs that are incurred when an electronic control module in an automotive application fails in service. These costs were related to the DFMEA ranking of the level of severity of the failure mode and the probability of its occurrence. A series of Monte Carlo simulations were conducted to establish the average costs expected for each level of severity at each level of occurrence. The results were aggregated using fuzzy utility sets into a 9 point ordinal scale of cost consequence. The criterion validity of this scale was assessed with warranty cost data derived from a case study. It was found that the model slightly underestimated the warranty costs that accrued, but the fit could be improved with adjustments dictated by actual usage conditions.

The problems with the risk prioritization system of FMEA, referred to as RPN, were discussed and citations of literature on possible corrections to this system were presented. An attempt was made to compare the tendency of RPN to produce Pareto Optimality violations with a parallel system of risk prioritization involving cost. It was found that the "Cost Priority Number" had a lower likelihood of producing optimality violations than did RPN. However, this is not heralded as a major advantage as "CPN" is not put forth as a method of prioritizing financial risks inherent in a design or process.

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INTRODUCTION

Overview

This chapter seeks to outline the conditions that prompted the research questions. Against this background, the research proposal can be judged for suitability. The structure of the ranking system used in Failure Modes and Effects Analysis (FMEA) is presented along with several observations on the problems with this approach to risk prioritization. A discussion of the importance of the cost consequences of failures underscores the proposition that the value of the analysis can be enhanced with the inclusion of a cost dimension. The chapter concludes with the problem statement, research questions, and statement of need that define this research and a brief introduction to the methodology that will be used to assess the hypotheses derived from the research questions.

Background

Failure mode and effects analysis is intended to identify areas of potential risk in a design or manufacturing process (hereafter referred to as the process) and to do this early in the product development cycle. A cross functional team examines every component in the design or process and determines (a) what might possibly go wrong with the components in service, (b) what effect each of these failures would have on a customer, and (c) what mechanism(s) could lead to the onset of the failed conditions.[1] For each of the ways the product or process could fail—known as failure modes—the team catalogs the controls that are in place to prevent or detect the cause of the failure. Each failure mode is ranked based on (a) the severity of the effect, (b) the anticipated frequency of occurrence, and (c) the ability to detect the problem in the developmental context.[2] This exercise allows the team to assess the level of risk that each potential failure mode presents. An overall ordering of the failure modes, based on this risk characterization, allows prioritization of the actions to be taken in response to the potential failure modes. This is necessary because time and resource constraints make it impossible to address all of the problems before product launch. As Kmenta and Ishii have put it "All problems are not equal…companies should give the most attention to the potentially severe and frequent failures" (2001, p.12.1-2).

Failure mode and effects analysis was developed by the US military in 1949 and published in the US Armed Forces Military Procedure *MIL-P-1629* (Lotfi, 2015; Wang, 2011). The National Aeronautics and Space Administration (NASA) employed FMEA on a number of programs in the 1960s, both manned (Apollo and Skylab) and unmanned (Viking, Voyager, Magellan, and Galileo). The civil aviation industry and the Society for Automotive Engineers (SAE) jointly published an FMEA manual, *ARP926*, in 1967 (Evco Nordic A/S, n.d.). Ford Motor Company began using FMEA in the 1970s as a response to problems with the *Pinto*—a

[1]Everything outside of the system defined by the product or process is considered ideal or irrelevant for the purpose of the FMEA. Inputs are not considered to be potential causes of a failure mode. So, for example, supplied components and processing equipment are assumed to meet design requirements.

[2] In a DFMEA, consideration is limited to detections that are part of the design process; in a PFMEA detection is limited to manufacturing concerns in the manufacturing process.

vehicle design that could catch fire in rear end collision events (Carlson, 2014). This was followed by the wide spread use of FMEA in the automobile industry in the U.S.

FMEA as an Assessment of Risk in the Auto Industry

In the automotive industry in North America and Europe, FMEA is required. Every supplier must submit an FMEA, done on both the product design (referred to as a Design FMEA or DFMEA) and the manufacturing process (termed a Process FMEA or PFMEA), as part of their demonstration of launch readiness. Approval to begin production can be withheld if this is not done.[3] The Ford Motor Company, General Motors Corporation, and Chrysler Corporation (now known as Chrysler Group, a subsidiary of Fiat Chrysler Automobiles), in a cooperative effort, produced an FMEA manual. This manual, published by the Automotive Industry Action Group (AIAG) in 1993, is the sine qua non for FMEA development in the auto industry. The AIAG FMEA manual provides the format, definitions, and procedure that the industry has accepted as the standard. The AIAG FMEA manual is a very well structured guide that is easy to use and rather straightforward in the explanations provided for each aspect of the FMEA. The AIAG manual is largely permissive in its approach giving generous latitude to the user to develop strategies that work for their needs (e.g., ranking criterion and the layout of the FMEA report).

[3] The rule states that production cannot start until the FMEAs are completed. But, in fact, the start of production is not in jeopardy…the ability to collect payment for the product being supplied is. Furthermore, money cannot be recovered for expenditures made in preparation of product launch (e.g.,, tooling costs) until approval is obtained. Maria Beck Anderson (2012) considers this paradigm—FMEA as a requirement of the OEM —"very dangerous". In her view, this reduces FMEA to a "check the box" task. As a consequence, "…the benefits of performing the FMEA will be reduced and often the increased customer satisfaction will not compensate the cost of performing the FMEA" (p.9).

FMEA is a conceptual analysis. It is often undertaken before much is known about the field performance of the product or process being reviewed. This is a consequence of the fact that FMEA is done early in the development cycle. Hatty and Owens (1994) observe that responding to a defect is 100 times more expensive after launch than if the problem had been addressed in the product design phase. Production problems are 10 times more costly after launch then if addressed during the process design phase. Arunajadai, Uder, Stone, and Turner (2004) state "Research has shown that nearly 80% of the costs and problems associated with product design are created during product development, and cost and quality are essentially designed into products during the conceptual design stage" (p.511). FMEA, done early, allows potential problems to be anticipated and corrective and preventative actions (CAPA) to those problems to be put in place before the design leaves the CAD modeling space.

AIAG submits that conducting a failure mode and effects analysis of the product design or process can lead to improvements by:

- Assessing the design against functional requirements, manufacturability, serviceability, reliability, safety, recycling requirements, and alternative designs.[4]
- Conceiving the potential problems a design could face and how this would be felt by the customer.
- Compelling the consideration of the causes of the potential problems.

[4] Selvan, Jegadheesan, Varthanan, and Senthilkumar (2013) have used FMEA to evaluate competing designs of sand cast molds.

- Understanding the inherent risks in a design before the design work is completed and judging each risk in terms of the risk level (criticality).[5, 6]

- Directing the thought process of the design responsible team to conceive of design solutions that lead to an amelioration of the risk level of the design or process.

- Establishing a record of the evaluation process that can guide future developments.

Both design and process FMEAs are work products of a due diligence activity intended to further the understanding of the risks inherent in a development. The documents are required by the Original Equipment Manufacturer (OEM) to (a) understand the failures that the product they are being supplied could experience, and (b) assess the quality of the actions the supplier has taken to protect them from any deleterious consequences of product failure. Because they explore areas of potential product failure, FMEAs are considered material to product liability litigation.

Throughout the time it has been in use, Failure Mode and Effects Analysis has acquitted itself masterfully at what Bluvband, Grabov, and Nakar (2004) call "The main FMEA objective….the identification of ways in which a product, process, or service fail to meet critical customer requirements" (p. 1). But two distinct shortcomings have been identified in the literature:

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[5] Segismundo and Miguel (2008) use FMEA to anticipate the impact potential failure modes have on the project schedule and to determine the level of testing to plan for.

[6] NASA uses FMEA to identify "single point" failures—instances where a single mechanism, without the aid or supplement of any other event, can cause the failure mode (Harkins,1999).

1. The system used to prioritize risk relates the dimensions of the risk assessment in a way that is not defensible mathematically and is ineffective at resolving fine distinctions between risks having equal ranking.

2. The system does not consider the cost implications of the potential failure conditions it identifies.

Risk Ranking.

Severity.

Once a failure mode for an item or process step has been identified and the effect it will have on a customer is understood, the question can be asked "How bad is this?"; "On a scale of one to ten, what would I rank this, in terms of 'pain level' or 'grievousness'?". The answer one gives to this question is known as the severity ranking of the effect.[7] Severity, in an FMEA, is based on a 10 point ordinal scale of values that allows the team to indicate the relative seriousness of the effect of a failure mode on an end user. Where there are multiple effects given for a failure mode, the severity ranking is found by considering the most serious effect.

Occurrence.

The occurrence rank expresses "the likelihood that a specific cause/mechanism will occur resulting in the failure mode within the design life" (AIAG, 2008, p.45). It is, therefore, an index of probability and AIAG attempts to make occurrence an interval scale ranking. As an example, the ranking guideline for the DFMEA suggests a rank of '5' be assigned to an effect that occurs

[7] Shebl, Franklin, and Barber (2012) reviewed the validity—Face, Content, Criterion, and Construct—of FMEA used in healthcare. They found that there was a tendency to overestimate severity of the effect of failure. This underscores the need to continually monitor product reliability and modify the FMEA as required (see Lotfi, 2015).

with a frequency of 1 in 2000; an occurrence rank of '6' would indicate a frequency of occurrence of 1 in 500; and so forth (see Table 2). In addition to this measure of incidents per *n* opportunities, the ranking guideline for occurrence offers a "word description" of likelihood.[8] The word descriptions provide five subjective terms that can be used to describe occurrence: "Very Low", "Low", "Moderate", High", and "Very High". If statistical data are available on the frequency of occurrence of the failure mode (through testing or based on the field performance of a similar item or process step), its use is preferred. If not, "a subjective assessment can be made by using the word descriptions" (AIAG, 2008, p.92).[9]

Detection.

Detection, in a DFMEA, is the rank associated with the best means of detection that are part of the design process. In a PFMEA, it is the ability of the process controls to find a failure mode so as to keep if from advancing any further in the process. While severity and occurrence are intended to view the condition from the customer's perspective, detection is not. Detection is an index of how well the supplier's system (design and testing, or process controls) can pick up the condition. Where there are multiple detection controls that could react to the condition, the lowest detection ranking is used to reflect the detection of that item or process step. Although effective detection would *either* detect the failure mode *or* the causal mechanism that could lead to failure, AIAG does not embrace this view. AIAG asks the team to assume the failure has

[8] All of the ranking scales provide a word description that guides the team in establishing the ranking level. Occurrence alone offers a quantifiable means of scaling along with the word description.

[9] It is important to note that the presence of numerical limits does not eliminate the subjective nature of the ranking process. Wall (2011) cites research that shows that subject matter experts tend to overweight the importance of probabilities ranging between 0.05 and 0.4 and under weight events with probabilities of occurrence between 0.4 and 0.9. At the same time, probabilities between 0.0 and 0.5 are taken to be essentially the same as $p = 0$ and probabilities between 0.92 and 0.99 are considered to be $p = 1$.

already developed and to rate detection on how well the failure mode can be sensed. If occurrence ranking is low, it should not be assumed that detection will be low. Detection ranking requires the assumption that the failure mode has occurred, regardless of how unlikely that occurrence may be.

The three dimensions by which FMEA establishes the level the risk of a failure mode—Severity, Occurrence, and Detection—are all set up on a 10 point ordinal ranking scale. For each, the degree of risk to the end user increases as the ranking score increases from 1 to 10. However to achieve this, the logic behind the rank scoring of the three areas of consideration differs. As Occurrence ranking increases, the likelihood of the event increases. An increase in Severity represents increasing seriousness of the consequence of a failure. However when detection ranking increases, the success of the detection effort *decreases* (Sofyalioglu, & Ozturk, 2012). The rationale here is that the risk that defective material will get to the customer is inversely related to the ability to detect the problem and remove the defective material from the product stream.[10]

The subjective nature of the ranking system frequently leads participants in the FMEA development to differ in their evaluation of a dimension of risk for a given failure mode. Andersen (2012) points out that such differences tend to be resolved in one of two ways: either (a) the rankings of the team are averaged together to form a consensus value, or (b) the ranking proposed by the team member at the highest pay grade or possessed of the most forceful

[10] Note that, for both Occurrence and Detection, a ranking score of 1 means the condition cannot exist. A ranking of 1 for occurrence means that the failure is eliminated through preventative controls (the fact that the word description calls it *very low* likelihood notwithstanding). A ranking of 1 for detection means that "Discrepant parts cannot be made because item [sic] has been error-proofed by process/product design" (AIAG, 2008, p.100) though it could be argued that error-proofing is not a detection.

personality is used.[11] In either case, there is an unfortunate loss of precision in the characterization of risk.

RPN.

The precepts of continuous improvement would require all items on the FMEA be subjected to an improvement activity (e.g., PDCA) in an unending effort to make the product less prone to failure. But the reality is that improvements can only be tackled as time and money allow. As AIAG puts it "Due to inherent limitations on resources, time, technology, and other factors, [the team] must choose…to prioritize [their] efforts" (AIAG, 2008, p.57). Indeed, Kmenta and Ishii (2001) maintain that the purpose of an FMEA is "to prioritize failures in accordance to their risk" (p.12.1-20). The Risk Priority Number (RPN) is a metric intended to facilitate that process. The Risk Priority Number is the product of the rank score for Severity × Occurrence × Detection. This is computed for each item or process step and, with this number, each item in the FMEA can be ordered based on level of risk—the higher the RPN, the higher the level of risk and the greater the urgency in addressing that risk. AIAG does not offer an evaluation criterion for RPN. It is up to the team to determine which RPN numbers are taken to be critical concerns and which can be seen as "'acceptable' risk" (AIAG, 2008, pp.59 & 105).[12,13] As changes are made to the controls that address an area of risk, the ranking will

[11] Dong (2007) recognized the need to deal with varied subjective assessments in reaching a consensus ranking value. He used Fuzzy Utility Theory to more effectively reconcile those differences.

[12] It is important to note that AIAG, while indicating that RPN is available to assist with risk prioritization, says that it should not be construed as a measure of relative risk. Nor should it be seen as obviating the need for continuous improvement. AIAG further states that the assessment of "'acceptable risk'…should be based on an analysis of severity, occurrence, and detection and not through the application of RPN thresholds" (AIAG, 2008, pp.59 & 105).

[13] Arunajadai et al. (2004) point out that "…there has not yet been a universal decision as to what constitutes an acceptable risk" (p.521), a fact that is leveraged in product liability litigation.

change. The FMEA form provides four columns at the extreme right hand side for (a) severity, (b) occurrence, (c) detection, and (d) RPN to capture the value of these rankings after a modification of the design or process has been accomplished.

Concerns with RPN.

AIAG recognizes an inherent danger in establishing an RPN or a combination of ranking values as a "threshold" above which actions MUST be taken: It could result in the team "gaming" the ranking process so as to achieve scores that are below the threshold and will not compel any action. Other writers submit that RPN itself is a flawed index.

Relating the indices.

RPN is intended to roll-up the information contained in three separate indices into a single overall representation of risk. However, there is no rationale for relating the ranking criterion together multiplicatively (Liu, Bian, Lin, Dong, and Xu, 2011). None of the dimensions of risk increase in scale as a function of the other dimensions. For example, a failure mode does not become more severe as the likelihood of occurrence increases or the ability to detect it decreases. Furthermore, the ranking scales are ordinal and multiplying three ordinal numbers together to form the RPN is mathematically untenable and results in a meaningless number (Bradley & Guerrero, 2011; Kmenta &Ishii, 2001; Shebl, Franklin, & Barber, 2012, Wheeler, 2011). The operation treats qualitative designations as if they were derived from a cardinal scale and had quantitative value. Moreover, Franceschini and Galetto (2001) have observed that "the definition of the RPN on a formally wider scale than that of the three component indexes…generates a fictitious increase of its resolution" (p.2994).

The intervals of the three ordinal scales represent subjectively determined differences in magnitude and are not identical. For example, when detection ranking is compared with occurrence ranking, it is clear that one is based on a linear progression of value while the other is non-linear (Liu et al., 2011; Pillay & Wang, 2003; Segismundo & Miguel, 2008).[14] An increase in a ranking level on one scale is not equivalent in terms of the degree of difference it represents to the same level of increase in rank on either of the other scales (Shebl et al., 2012).

These problems and inconsistencies notwithstanding, one of the most frequently criticized aspects of the risk ranking process is that all three dimensions of risk are considered to be of equal importance (Pillay & Wang, 2001). This creates the problems with Pareto optimality discussed below.

The RPN scale.

There are 10 levels of severity rating, 10 levels or occurrence, and 10 levels of detection. This makes for the possibility of 1000 different characterizations of a failure mode. But the multiplication of the ranking values does not produce 1000 unique numerical products. In fact, only 120 distinct numbers can be developed. This means that 88% of the range is empty. The RPN values of 60, 72, and 120 can be formed from 24 different combinations of Severity, Occurrence, and Detection scores while a value of 1000 can only be formed by a single combination of multiplicands. This is graphically represented in figure 1.

According Shebl et al. (2012) “the first four RPN values [cover] 0.4% of the scale, while the last four values cover 20% of the scale. No number having a prime factor greater than 10 can

[14] When the occurrence ranking values are plotted against the incidents per 1000 vehicles that each value represents, the best fit regression line has the equation $Y = 4E\text{-}06 \times X^{7.3866}$ ($R^2 = 0.9966$). This describes a power function relationship between the independent variable and the dependent variable.

be formed. Thus the numbers 11, 22, 33, or even 990, which are multiples of 11 cannot be formed and are excluded. 1000 is the largest number, but 990 is the second largest followed by 810, 729, and 720." (p. 5).

The distribution of RPN values is skewed towards the high end of the scale. It has a mean of 166 and a median of 105. With 1000 unique numerical values from 1 to 1000, a mean of 500.5 would be expected with a median of 500.5.

Liu, et al. (2011) also note that small changes in one of the three multiplicands will influence the RPN differently depending on the partial product of the other two values. As an example, increasing severity by one point will lead to a 100 point increase in RPN if occurrence is 10 and detection is 10 but will only bring about a change of 16 points if occurrence and detection are both set at 4.

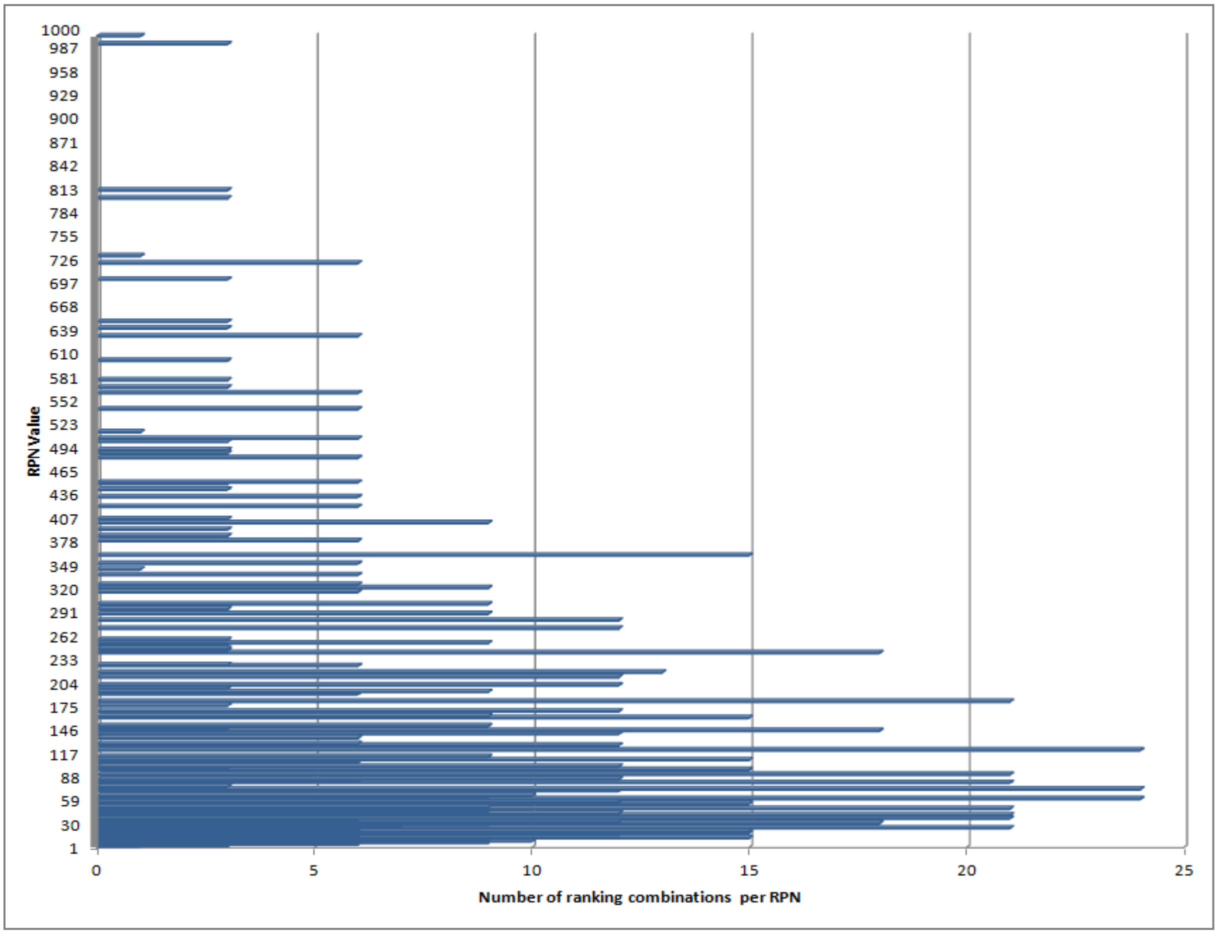

Figure 1. Bar chart showing the distribution of ranking values that form the RPN scale.

The problem of Risk Prioritization.

The multiplicity of ranking combinations that produce the same RPN value make it very difficult to order the results of an FMEA analysis in terms of priority. The relative importance of the S, O, and D dimensions of risk has not been established and RPN is developed assuming the three factors have the same importance. The problem this creates is illustrated by D.J. Wheeler (2001) in an article entitled *Problems with Risk Priority Numbers: Avoiding More Numerical Jabberwocky*. Wheeler noted that 15 ranking combinations could produce an RPN of 360—a value that is higher than 862 other ranking combinations. Having the same value for RPN each of these 15 conditions would require equal consideration as regards priority of the concern. Wheeler looked at two of those conditions:

1. Severity = 10 (Hazardous); Occurrence = 9 (Very High); and Detection = 4 (Moderately high)—RPN: 360

2. Severity = 4 (Very Low); Occurrence = 9 (Very High); and Detection = 10 (Impossible to detect)—RPN: 360

He observes the following:

> According to the auto industry *FMEA Manual*, [condition 1] involves a hazardous failure mode that would affect the safe operation of the vehicle and that would occur without warning. This problem would have a very high incidence of occurrence, affecting approximately one vehicle in three. And this problem would have a moderately high chance of being detected during the design phase and eliminated from the vehicle before production. In the same way [condition 2]…corresponds to a failure mode that would affect fit and finish. This failure mode would affect approximately one vehicle in three and cannot be detected in the design phase. Does it seem reasonable…that the two problems…should be equivalent? Is a hazardous problem affecting one vehicle in three that might be caught before production of equal importance with an appearance problem affecting one vehicle in three that cannot be caught at the design phase? (p. 3)

This is the problem of Pareto Optimality. Pareto optimality describes a state in which it is impossible to improve the condition of one factor in a set without worsening the condition of some other factor in that set. (Petrie, Webster, and Cutosky, 1995). In the context of FMEA, Pareto Optimality means that "higher criteria scores cannot lead to lower importance scores and a lower ranking" (Bradley and Guerrero, 2011, p.747). If $O_n \geq O_m$, $S_n \geq S_m$, and $D_n \geq D_m$, then the importance (O_m, S_m, D_m) cannot be greater than the importance ascribed to (O_n, S_n, D_n) (from Bradley and Guerrero, 2011). But tying the three ranking factors together in RPN means that an increase in either O_m, S_m, or D_m will cause RPN_m to equal or exceed RPN_n bringing about a diminution in the relative importance of (O_n, S_n, D_n) and a loss of the Pareto optimal state. This, in turn, would result in resources being allocated to ameliorate a less important risk condition at the expense of a more important risk condition.

Many believe severity should be weighted higher than any other dimension in considering the relative risk of two or more failure modes (Teng and Ho, 1996). Others replace a consideration of severity with a measure of cost consequence (e.g., Dong, 2007). This point of departure notwithstanding, there is general agreement regarding the need to resolve Pareto optimality problems in FMEA and avoid situations in which "a high risk failure mode [goes] unnoticed" (Belu, Khassawnew, and Al Ali, 2013, p.69).

Cost Consequences of Failure

The cost associated with ensuring good quality product is made, or poor quality product is found, fixed, or scrapped is referred to as the "Cost of Quality" (CoQ). It is widely recognized as a cost driver with the potential to significantly affect profitability.[15] CoQ can range from 15 - 40% of total costs (Albright & Roth, 1992; Brust & Gryna, 2002; Harry & Schroeder, 2000; Plunkett & Dale, 1988; Archambeau, 2004; Waje & Patil, 2012). Improving quality and

[15] Brown (1978), using regression to related failure cost to profit margin, found that for every dollar reduction in failure cost, profit increased by $5.46 (from Krishnamoorthi, 1986).

conformance to requirements therefore lowers the costs of goods sold.[16,17] Harrington (1987) offers the opinion that "…a typical company can save more money by halving poor quality than by doubling sales" (Harrington , 1987, cited by Weheba & Elshennawy, 2004).

The Concept of Cost of Quality.

Cost of Quality is the term that is given to any cost that would *not* have been incurred if the quality of the product was perfect (Chiadamrong, 2003). Schiffauerova and Thomson (2006) put it this way:

> CoQ is usually understood as the sum of conformance plus non-conformance costs, where cost of conformance is the price paid for prevention of poor quality (for example, inspection and quality appraisal) and cost of non-conformance is the cost of poor quality caused by product and service failure (for example rework and returns) (p.1).

Armand Feigenbaum (1956) considered the cost of conformance to consist of appraisal costs (the costs of test, measurement, and inspection intended to find nonconformities or deleterious trending in the process), and prevention costs (the cost of designing out the causes of nonconformities in the product or process). His model for cost of quality had three tangible cost elements: Prevention, Appraisal, and Failure. The cost of failure experienced when non-conforming product is manufactured can be parsed into external and internal costs. This is recognition that non-conforming product found at the OEM's manufacturing facility or the end user would have a set of costs different from that of non-conforming product found in-house.

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[16] The reduction in cost that accompanies an increase in quality makes more income available for adding content to the product. This, in turn, increases the quality of the design and leads to increased sales. This phenomenon has been called the "Deming Chain Reaction" (Neave, 1990).

[17] Brust and Gryna (2002) assert that, on a macroeconomic level, a reduction in the cost of quality makes more salable product available for the same amount of resource input which raises GDP.

External failure costs include part replacement, expedited shipping costs, service calls, and often, compensation payments to the OEM. Internal failure costs include, but are not limited to, scrap and rework…and these costs can be substantial. In a study by Chopra and Garg (2011), an Indian textile company with cost of quality per sales intake at 9.93 attributed 64% of those costs to internal failures.

Juran and others recognized that there are also intangible costs that trace to quality problems. It has been asserted that these intangible costs amount to at least 10-15% of production costs (Chiadamrong, 2003). Dobrin and Stanciuc (2013) maintain that the intangible or "hidden" costs of quality are the *largest* contributors to total CoQ.[18] This view point is supported by the work of Omar and Murgan discussed below. Kume (1985) expressed the belief that loss of market share is a larger economic consequence of poor quality than are failure costs. Giakatis, Enkawa, & Washitani (2001) and Han & Lee (2002) believe hidden quality costs are more than three times that of visible costs (from Yang, 2008).

Tangible costs.

Several costs are associated with the failure of a product in the field. Principle among these are the costs of fixing or replacing the product. The cost of either of these responses includes one or more of the following:

[18] Dobrin and Stanciuk (2013) demonstrated that hidden costs could be modeled using the Taguchi loss function. This would mean that hidden costs go up as the square of the distance from target quality.

- The cost of the replacement parts.[19]

- The cost of the technician's time to analyze the problem and affect the repairs.[20]

- Shipping costs:

    — Standard shipping if a parts depot or service center is being stocked.

    — Expedited shipping if the response is time critical or involves a part that is not stocked.

- Transportation and accommodation costs of sending specialists to the field site if a repair facility is not in place or support is needed for the repair process.

- Unique costs:

    — Short manufacturing runs to make the replacement parts, if not in stock

    — Failure analysis (FA) costs

    — A "Life time buy" of components that are at the end of their life at a supplier but must be available for service builds of replacement product.

    — Inventory costs for replacement parts and/or components to make the replacement parts.

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[19] Zimwara, Mugawagwa, Maringa, Mnkandla, Mugwagwa, and Ngwarati (2013) examined a casting company with CoQ at 6.6% of sales. External failure costs constituted 19% of the costs of poor quality. This represents 1.3% of sales revenue. Warranty replacement accounted for 63% of those costs.

[20] Guinot, Evans, and Badar (n.d.) showed that two single aspects of the tangible cost of quality, replacement cost of a unit required to respond to a warranty claim and failure analysis of a customer return, can change a Present Worth projection from positive to negative under certain conditions.

— Containment of stock that needs to be inspected or replaced with corrected material.

— Compensation to the OEM for downtime or yard holds that result from a failure to supply usable product in the required quantities to keep production running.[21]

— Disposal of unusable material.

Supply chain management costs.

Yim (2014) investigated the impact of "Latent defect – Undependable product – eXternal failures" (LUX) on sourcing decisions. He defines a latent defect as "a flaw or weakness [in a component] that could not be discovered by reasonable inspection prior to sale" (p.341) and he asserts that companies often respond to latent defects by reconfiguring their supply chain. In the 1990s, a popular sport utility vehicle sold by Ford recorded an inordinate number of rollover accidents. Latent defects with the tires supplied by Firestone for use on these vehicles were felt to contribute to these accidents. Ford had to recall 13 million tires and wade through legal action that took up to eight years to resolve (Chiles, 2001). Yim notes that Ford Motor Corporation ended a relationship with Firestone that traced back to the founding of the company as a response to this issue.

Many other examples can be found of companies establishing dual sources of supply of the same component in order to militate against issues with LUX or unreliable supply. Either desourcing or establishing multiple sources of supply introduce added costs to a program. In the

[21] A significant quality "spill" in the automotive industry can get very expensive very quickly. The containment, inspection, and replacement costs are only a part of the costs that can accrue. Original Equipment Manufacturers (OEMs) run up huge costs if a production line goes down. If a line down or a yard hold is the result of a quality problem with a critical component, the supplier of that component will be required to compensate the OEM for the costs of the lost production or delayed shipment.

former case, bringing an inexperienced replacement supplier to a point where the former supplier had been vis-à-vis capacity and quality is to bring sunken start-up costs back into the cash flow. In the latter case, increases in piece price due to reduction in volume and the consequent effect on economies of scale are incurred. Multiple sourcing also carries an intangible cost: The loss of relationship with a favored supplier—a concept advocated by W. Edwards Deming (1982) as a way to incentivize increased investment in quality improvement efforts by the supplier.

Warranty costs.

Warranty obligations require that the supplier cover all of the costs that result from a verifiable failure of the product they supply for a stipulated period of time. The supplier and the OEM's warranty specialists meet to review product performance each year. The number of claims that must be paid by the supplier is identified and the supplier reimburses the OEM for the cost of responding to these issues.[22] The costs include, but are not limited to, the cost of the replacement unit (assessed at the price that must be paid for the unit at the OEM's service parts division which carries a mark-up of 3 to 5 times the price the supplier is paid by the OEM), and the cost of the dealer service action.[23]

[22] Only a few of the claims (typically 5% or less) are returned to the supplier for failure analysis. Characterization of the claims is done on the basis of the dealers' report of the service actions. The claims are tossed into one of five "buckets" indicating that the problem traces to: (a) the OEM's assembly plant, (b) the dealership, (c) an adjacent component, (d) the supplier (due to their assembly process, the product design, or a component on that product), or (e) No Trouble Found. The supplier is on the hook for any claim that falls into the last two buckets. One North American OEM just charges the supplier for 50% of the cost of everything over 0.15 C/1000 regardless of the cause of the claim.

[23] This author knows of instances in which the OEM has added the cost of the loaner vehicles provided to their customers during the service event.

Increasingly, warranty settlements include paying for a portion of the cost of product that was replaced in a service campaign but, upon testing was found to be acceptable for use. That is, testing of the returned product found no functional irregularities. This "No Trouble Found" (NTF) condition results from any of three situations: (a) a repair technician has replaced a functioning component in the course of working through a trouble shooting sequence (i.e.,"Replace component 'A'…if the problem is not corrected, replace component 'B'"…and so on until the source of the problem is reached), (b) the problem with the product is caused by a problem with the system to which it is a part, or (c) the trouble is an intermittent condition—testing just happened to be done when the condition was not active and the product appeared fully operational.

In some products or systems, the number of returns in the "No Trouble Found" category is larger than the number of returns binned to any other category. OEMs tend to assume that the large number of returns that are called NTF are either intermittent conditions that just haven't been analyzed fully or are the result of disingenuous reporting to avoid warranty payments. In the automotive industry, some OEMs are demanding additional testing of NTF returns to ensure that they are not, in fact, intermittent in occurrence. An increasing number of OEMs are demanding that suppliers share in the cost of NTF returns – up to 50% in some cases (The OEM takes the position that they had to pay to replace the parts…the supplier should share that pain). This makes NTF returns doubly expensive: the cost of additional testing is added to the cost sharing required for NTF returns.

Omar and Murgan (2014) conducted a simulation using a model of the costs of quality (following Chiadamrong, 2003). This model looked at three aspects of the costs imposed by poor quality: (a) Production invisible costs (the costs of material, labor, machine utilization, material handling, and technical services required to replace or repair a quality problem), (b) visible quality costs (the cost categories of Prevention, Appraisal and Failure), and (c) opportunity costs (discussed below). Their simulation assumed a 1% defect rate and accounted for Type I and Type II errors. They found that at a 1% defect rate, the costs of the defects would break down as shown in Figure 2: 15% of the costs would be recognized as falling into one of the standard PAF categories (details of this are shown in figure 2b). But there would be substantial "invisible" production costs associated with repairing or replacing the defective product in the CoQ subcategory of "Failure". These costs are rarely recognized as additional costs and are placed under standard operational expenditures in cost accounting.

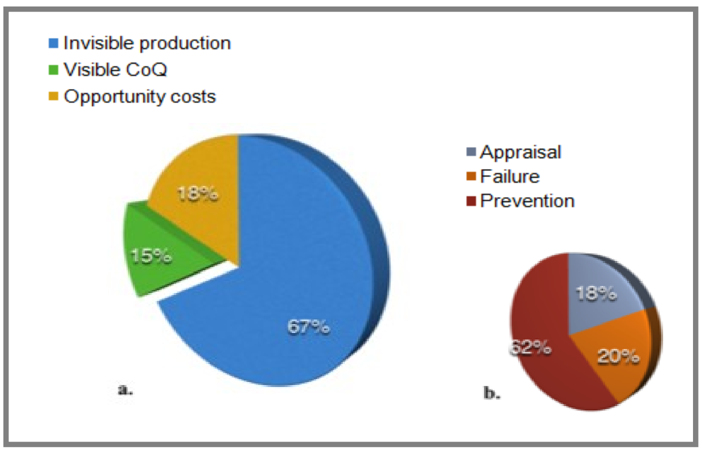

Figure 2. The breakdown of the cost resulting from defects. Figure 2a shows the main categories of the cost breakdown: visible CoQ, invisible production, and opportunity costs. Figure 2b breaks down the CoQ costs into the sub categories of prevention, appraisal and failure costs. (from Omar and Murgan, 2014).

Intangibles of CoQ.

Pricing constraints.

Freiesleben (2004) submits that, given customers that are "rational decision makers", the awareness of quality concerns with a firm's product will affect their willingness to pay regular price for that product. As he puts it:

> In the presence of quality problems, the probability customers receive good and fully usable products is lower than 100%. The expected utility from the use of a randomly chosen product is equally reduced. A customer cannot be sure whether a purchase will yield full value…expected net utility is lower than the full utility the customer would be able to derive from a surely flawless product. The customer might be lucky to pick a good product, but he or she might also be unlucky and have a negative net utility. (p.50)

The sense of risk of a negative net utility from buying a product of questionable quality, if not addressed, can lead to loss of business. One means of addressing this is to reduce the price of the product. The lower price compensates for the risk a customer takes in purchasing a product that may fail. This is what Freiesleben calls paying a "risk premium".

Paying the risk premium, in and of itself reduces a firm's profitability. But it comes alongside the increased costs being paid for materials needed to make up for rejects and returns, and the increased costs associated with warranty expenses. Furthermore, as Freiesleben points out, a company that operates with high CoQ experiences constraints on their ability to respond to market pressures with further price reductions or to protect against material cost volatility with price increases.

Opportunity costs.

Intangible costs resulting from poor quality include opportunity costs. Sandoval-Chavez and Beruvides (1998) recognize three components to opportunities costs: underutilization of installed capacity, inadequate material handling, and poor delivery of services (cited by Schiffauerova and Thomson, 2006). The first two of these categories, underutilized capacity and inadequate material handling, are termed process inefficiencies by Omar and Murgan (2014) and include the costs of added set-up, additional waiting and idle time, and additions to inventory costs that are imposed by responding to poor quality. In their simulation they found these costs constitute 40% of the opportunity costs while poor delivery of services made up the rest.

Another frequently cited opportunity cost is the loss of customers as a consequence of an experience with, or report of poor product quality. Received wisdom has it that, a failure to satisfy a customer puts at risk that customer's repeat business and the business of everyone they interact with socially. Mark Foucher, with *Cadillac* customer relations, said of this tendency "Satisfied customers tell eight to ten others. Dissatisfied customers tell 16 to 20 others. Twenty-five percent of the dissatisfied customers tell as many as 40 other people" (from Kmenta and Ishii, 2001, p.12.1-1). Ball (2006) states that, "…it's usually less expensive to maintain existing customers than to acquire new ones" (p.36).[24] Reichheld and Sasser (1990) assert that, if companies could retain 5% more of their customers, they could increase profits by almost 100% (from Schiffauerova and Thomson, 2006).

This concern is not limited to producers of short lived commodities that frequently need to be replaced. It is even seen in "one and done" markets like housing. Zbranek (2000) notes that most builders make only one sale per family and do not see the value in "going the extra mile" to provide a quality product to win repeat business. Rosenfeld (2009) illustrates the fallacy in this viewpoint:

> An unsatisfied customer, naturally, will not buy again from the same company; but in addition, he/she will share the frustrations with many others, thus deterring more

[24] Ball notes that an exception to this is found "... in commodity-driven businesses where purchase transactions are sourced at the time of need based primarily on price and to a lesser extent on availability" (Ball, 2006,p.36).

> potential customers as well. It is said that a satisfied homebuyer brings at least another one to the same company, while an unsatisfied homebuyer deters at least one. Thus, the aggregated damage is the loss of, at least, two potential customers for each serious case of external failure." (p.114)

Rosenfeld observes that, in Israel, the cost to a construction firm of correcting quality issues after commissioning averages 20,000 New Israeli Shekels ($5,949). If the profit from a home sale is put at 60,000 NIS ($17,546), the cost of a quality issue—repair cost plus the loss of a future client–comes to 80,000 NIS ($23,395). Viewed in this way, the cost of poor quality is four times the cost of the re-work action alone.

Waje and Patil (2012) maintain that, to the cost of the rectification of a quality issue, one must often add a "Nuisance cost". This recognizes that the customer is often inconvenienced during the process of having quality issues fixed, and this comes at a cost. They estimate that when one considers time value, based on the individuals wage per unit time, nuisance costs can amount to 0.66% additional cost paid by the consumer for poor product quality. Freiesleben (2004) points out that, even where a warranty is offered to assuage a consumer's concern regarding risk exposure, it is a less than satisfactory response to poor quality, in part, because of nuisance costs. A customer that must get poor quality product repaired or replaced under warranty is experiencing inconvenience and the nuisance costs are not remunerated by the producer.

Snieska, Daunoriene, and Zekeviciene (2013) submit that the loss of customer goodwill and brand damage are costs that must be considered alongside the actual loss of the customer's business. In the long run, the loss of reputation and image can weaken the commitment of current customers and repel future business. Further, it has even been argued that diminished image can affect the morale of workers and translate to losses in productivity (Neave, 1990).

Snieska, et al. treat customer goodwill as a function of the importance of the operational requirement times the difference between the organization and the competition's performance against that requirement. This is given by the expression I_i x R_i where I_i is the importance of the requirement and R_i is the factor for the relative success in satisfying that requirement. Brand damage is represented by the following expression (from Damodaran, 2001):

$$\text{Brand value} = [(V/S_b) - (V/S_g)] \times Sales \qquad (1)$$

Where V is the market value of the company, S_b is the sales value of the brand, and S_g is the value of the sales of the company's main products. In a pilot study of a Lithuanian medical supply company, hidden cost—loss of goodwill plus brand damage—was shown to amount to 28% of the sales for the period of the study.

Despite the value that a cost of quality determination provides in understanding cash flow and quality standing, studies have found that few companies are using CoQ data at all (Baatz, 1992; Gupta & Campbell, 1995; Rasamanie & Kanapathy, 2011; Sower, Quarles, & Broussard, 2002; Viger & Anandarajan, 1999; Yang, 2008).[25, 26] Pursglove and Dale (1996) suggest three reasons for the low use of CoQ: (a) a lack of understanding of the concept and principles of CoQ,

[25] Baatz (1992) found that only 5 of the 22 finalists for the 1991 Malcolm Baldrige Award even measured cost of quality let alone used it in a meaningful way (Sower et al., 2002).

[26] Not all authors believe that tracking quality costs is important. Dobrin and Stanciuc (2013) observe that W.E.Deming felt that "cost analysis for quality is a misguided waste of time and measuring quality costs to seek optimum defect levels is evidence of failure to understand the problem". P.Crosby felt that measuring quality costs was important only "for the development of 'quality' thinking within an organization" (p. 1479)

(b) a lack of data, and (c) a lack of interest on the part of managers in quality costs. To this list, Rodchua (2006) and Rasamanie & Kanapathy (2011) add a lack of cooperation between disparate departments involved in the process. Johnson and Kaplan (1987) note that quality costs are often placed into overhead and are not binned in useful categories for analysis. "Today's management accounting information system…is too late, too aggregated, and too distorted to be relevant for managers' planning and control decisions" (from Sower and Quarles, 2006, p.6). Brust and Gryna (2002) observe that "…organizations mistakenly measure only total output (acceptable and non-acceptable), they are camouflaging quality problems. Clearly, the pertinent output measure is product that is usable by the customers" (p.66). But as Kume (1985) points out, "The goal of business management is to increase profit, not reduce cost. A cost increase will not be a managerial problem as long as the company obtains more profit to offset the additional cost" (p.15).

The cost of quality is a significant index but it is difficult to measure and little used. The need to rectify this is glaring and the FMEA is an ideal instrument for accomplishing this. The aspects of FMEA that lend to a cost of quality analysis include the following:

1. It provides a detailed breakdown of how a product or process can fail. This allows cost of quality data to be directed to potential quality issues with surgical precision.
    a. The severity of the failure and the probability of occurrence translate to how much a failure can be expected to cost and how often the cost is incurred.
    b. The detection associated with the failure measures the ability to catch the problem before the product ships. Detected in-house, the resulting costs are

internal failure costs; a failure to detect and contain the concern results in external failure costs (Plunkett and Dale, 1988).

c. FMEA identifies the design or process controls that are appropriate for the failure mode. This allows appraisal and prevention costs to be associated with each failure mode.

2. The FMEA ranking paradigm provides engineers with a simple means of establishing the magnitude of each of the dimensions of a potential failure. An ordinal ranking scale, if extended to a consideration of the cost dimension, removes difficulty from the assessment of the cost consequence of a failure.

Problem Statement

The problem for this study was to (a) develop a means of capturing costs associated with failures as characterized in a Failure Mode and Effects Analysis, and (b) include the cost of quality implications of the failures in the analysis in a way that lends itself to the ordering of relative risk of each of the failure modes in the FMEA.

Research Questions

1. Can cost of quality considerations be included in the a priori assessment of risk done with FMEA?

2. Can a Cost index be added to the elements of an FMEA risk assessment that is consistent with the established risk ranking methodology and does not require arcane computational techniques to manage?

3. When costs of field failures are considered in the FMEA analysis, does the susceptibility to Pareto Optimality concerns become unreasonably high in comparison to that already seen with RPN?

Related Hypotheses

The first research question recognizes that much of what constitutes the cost of quality impact of a failure mode is unknown at the concept phase of a program. The extent of a "spill", the customer's reaction (warranty claim or tortious redress), the resources that must be expended to understand the issue, and contain /correct it once understood are all case specific and can only be appreciated after the event. Further, certain aspects of cost of quality may not be measured and, indeed, may not be measureable in a way that allows the association of an action to a specific antecedent (e.g., the degree of loss of customer loyalty that traces to the failure of a particular component in service). This concern is reflected in Hypothesis 1:

Hypothesis 1.

H_{01}: $CoQ_{\text{expected}} = CoQ_{\text{observed}}$

There is no difference between the cost consequence of failures as projected from a failure mode and effects analysis (CoQ_{expected}) and the costs that accrue if the failure mode is actually observed (CoQ_{observed})

H_{a1}: $CoQ_{\text{expected}} \neq CoQ_{\text{observed}}$

Cost of Quality cannot be modeled in a fashion that is able to associate the costs of failure modes, based on the permutation of elements of the FMEA characterization process, to actual costs as determined from historical case data.

One of the more attractive aspects of the FMEA methodology as a means of characterizing risk is the simplicity of the ranking process. A Subject Matter Expert (SME) is presented a simple 10 point scale for rating risk that is easy to understand and use. Hypothesis 2 addresses the ability to develop a similar ranking for the cost consequence of failure:

Hypothesis 2.

H_{02}: $Scale_{SOD} = Scale_{CoQ}$

An ordinal scale for the cost consequence of quality can be developed that is equivalent to that already used for Severity, Occurrence, and Detection.

H_{a2}: $Scale_{SOD} \neq Scale_{CoQ}$

A consideration of the cost consequence of a failure does not lend itself to the FMEA ranking methodology as it requires elaborate, product specific computations that (a) can only be developed in a post hoc analysis of cost of quality, and (b) defies a simple ordinal listing.

When one uses RPN as a prioritization scheme, one must accept the risk that Pareto Optimality could be violated in the development of the RPN ranking values. Many authors have expressed concern about this, and Arrow and Raynaud (1986) have gone so far as to state that it is axiomatic that any alternative to RPN must perform better than RPN in this regard.

Certain dimensions of the cost consequence of a failure are directly related to the severity of a failure mode effect. For example, litigation, yard holds, recalls, etc. are not costs that attend a low severity failure mode such as one ranked as an “annoyance”. It is therefore unlikely that a severity ranking in the safety/legal region of a cost based risk priority matrix would be superseded in the prioritization by a ranking value from the annoyance region. But, given a high occurrence of a an event in the more costly return/no buy region, could the addition of cost cause the entry to rise above a higher severity failure mode in terms of risk priority? This problem will be explored by testing Hypothesis 3.

Hypothesis 3.

H_{03}: $POV_{\text{RPN}} = POV_{\text{CPN}}$

The potential for Pareto Optimality violations (*POV*) of ordered risk ranking in an FMEA is not affected by the introduction of cost of quality in the risk consideration.

H_{a3} : $POV_{\text{RPN}} \neq POV_{\text{CPN}}$

The potential for Pareto Optimality violations is not the same for CPN compared to RPN.

Statement of Need

FMEA offers a means of anticipating problems with a design or a process allowing mitigations to be put in place to reduce the probability of the problems occurring or increase the ability to detect the problem conditions should they develop. It was designed to focus consideration on areas of user safety and compliance with government regulations. It has proven effectiveness and value in this capacity. However, the methodology has been plagued with problems in the prioritization of the failure modes using the Risk Priority Number. Further, the methodology is limited. Risk assessments in business are almost universally based on financial considerations. But the financial dimensions of a failure mode are not considered by FMEA.

There is a need to maximize the value of the FMEA as a risk assessment tool by including an assessment of the cost of each of the failure modes. At present, there is no index that allows an FMEA development team to establish cost consequences of a failure. So there is a need to relate the characterization of risk with its potential cost and to develop a scaling instrument to allow the incorporation of cost consequence into an FMEA.

Statement of Assumptions

The following assumptions were applied to this study:

1. All FMEA are developed for automotive applications in compliance with the AIAG *Failure Mode and Effects Manual, 4th edition*.

2. Ranking of entries on the FMEA are established with the best engineering judgment available at the time, supported, where possible, by tests, simulations, and / or field performance data of prototypes or similar designs.

3. FMEA ranking values of severity of the failure modes used in the validation which follow represent initial assessments and have not been updated to reflect lessons learned on the product or process.

4. All DFMEA are developed for electronic modules designed for in-vehicle locations.

    — The products are intended to operate in conditions that range from -40° C to 85° C at humidity levels up to 65% RH.

    — The modules are able to operate in full spectrum of vibration (sprung) established for U.S. road conditions for passenger vehicle applications.

— The modules are able to operate under these conditions for 15 years and 200,000 miles.

5. All PFMEA address production processes that meet the requirements of the automotive industry:

   — Ppk $\geq$ 1.67

   — TAKT times based on annual volumes in excess of 60,000 units.

6. All cost assumptions in the study are based on nominal costs of quality values, and industry standard manufacturing cost structures that apply to the North American automobile market and are given in USD.

7. Inputs to the design or process are assumed to be free of defect or deviation from design intent. Therefore, where a component defect has caused a field failure in a case being used in the criterion validation of the study, the cause of the failure will be taken to be either (a) inadequacies in the design and development effort, or (b) a manufacturing concern. That is, if the component fails in service, it will be assumed that it was the victim of a sub-optimal circuit design, or improper material selection; or it was damaged in the plant. Ranking values taken to represent the case will therefore be taken from mechanisms describing failure modes of that type.

Statement of Limitations

Cost data used in the simulations will be derived from (a) government and academic surveys, analyses, and estimates of the manufacturing cost structure for the industry, and (b) nominal costs for various quality issues experienced by Tier 2 automotive electronics supplier. As such, they lack the specificity that would be possible with actual cost data.

The sample size and the type of the failure modes used to validate the model are constrained by the number and type of product or process elements which have had demonstrable performance concerns over the past three years, with cost data available to the author. Thus the power of the validation will be greatly limited and the validation itself will be considered a screening assessment.

Statement of Methodology

A cost model will be developed that captures the cost of quality elements for various failure conditions. The model will be subjected to sensitivity analysis (Monte Carlo simulations) to assess how the costs are affected by changes in FMEA ranking. These data will be used to establish a ranking scale for costs. Fuzzy logic techniques will be used to convert the resultant cost ranges to a ranking scale.

Validation will use failure data obtained from a case study. The root cause of these failures will be used to identify which elements of the FMEA apply. The rank scoring of those elements will be used to determine the cost consequence ranking that the original assessment would have assigned if such a ranking option were available. The actual external failure costs will be compared to the expected costs based on the original FMEA ranking.

Definition of Terms

Appraisal costs: "The costs associated with measuring, evaluating or auditing products or services to assure conformance to quality standards and performance requirements" (ASQ, 1999).

C**ause of a failure mode**: "an indication of how the failure could occur, and is described in terms of something that can be corrected or can be controlled" (AIAG, 2008, p.91). "Causes are the circumstances that induce or activate a failure mechanism" (p. 41).

Cost Priority Number: A term for the risk priority ranking that results from multiplying Severity × Occurrence × Cost consequence of a failure. This index has been developed for the purpose of this study to allow a comparison of CoQ projected for a failure mode with the RPN for that failure mode.

Cost of Quality (CoQ): "The cost of NOT creating a quality product or service…any cost that would not have been expended if quality were perfect contributes to the cost of quality." (ASQ, 1999). "The cost incurred in ensuring quality, together with the loss incurred when quality is not achieved" (Yang, 2008). Armand Feigenbaum (1956) felt that the total cost of quality was comprised of the expenses brought on in responding to failures on the one hand, and the expense of any inspection or detection activities (appraisal costs) and/or the cost of the efforts to prevent the failures from occurring on the other. Phillip Crosby (1979) simply divided CoQ into the cost of good quality (CoGQ) (i.e., all costs expended in the attempt to conform to requirements) and the cost of poor quality (CoPQ) (i.e., the cost of associated with any failure to conform to requirements).

Customer: The recipient of the product or processing operation. AIAG submits that there are four customers to be considered in an FMEA:

— The End User defined as "the person or organization that will utilize the product" (AIAG, 2008, p.11).

— The Original Equipment Manufacturer's assembly plant. The personnel that touch the supplier's product and require it to meet the needs of the system to which it is installed.

— Tier 1 sub-assembly or processing entities.

— Regulators: "government agencies that define requirements and monitor compliance to safety and environmental specifications which can impact the product or process" (AIAG, 2008, p.11).

To this list, a fifth will be proposed:

"The Next Operation As Customer" (NOAC). This signifies that, whoever receives the product or operational output - whether paying for it or simply moving it to the next operation in the process, must be recognized as the customer.

As much as possible, this paper will limit the use of the term customer to "end user" or to generic references. When referring to the organization that purchases material from the supplier, the term "OEM" or "manufacturing facility" will be used.

Detection: "The rank associated with the best detection control listed in the Current Design Control, Detection [identified for that failure mode]" (AIAG, 2008, p.53).

Failure cost: All costs that result when a product or service does not function as required by the customer.

- **Internal failure costs**: Costs resulting from a product or service that does not meet specifications when assessed before the product or service is provided to the customer.

- **External failure costs**: Costs associated with product or service that failed for the customer upon receipt or in use.

Failure mechanism: "the physical, chemical, electrical, thermal, or other process that results in the failure mode" (AIAG, 2008, p.39).

Failure mode: The way or manner in which a product or process could fail to meet design intent or process requirements (AIAG, 2008, p.12).

Fuzzy logic: A method of managing vagueness in a language dependent system of distinctions. This requires translation (fuzzification) of the language based values into a fuzzy set and evaluating them based on the rules of membership for the set. The resultant is found by translating back to the original "crisp" set (de-fuzzification).

Linguistic variable: "A variable whose values are expressed in natural or artificial languages…useful for providing approximate characterization in [an] uncertain environment" (Zhang and Chu, 2011, p.208).

Occurrence: "the likelihood that a specific cause/mechanism will occur resulting in the failure mode with the design life": (AIAG, 2008, p.45).

Pareto boundary: The limit at which a collection of values in a selection set are Pareto optimal.

Pareto Optimality: A condition in which an improvement in one aspect of a value in the set will cause one or more other values in the set to fall below the boundary of acceptability. (see Petrie, Webster, and Cutosky, 1995).

Potential Failure Effect: The consequence or result of a failure mode as perceived by the customer.

Prevention costs: "The costs of all activities specifically designed to prevent poor quality in products or services" (ASQ, 1999).

Ranking: Assigning a position on a scale that establishes the relative order of the item under consideration with respect to a set of qualitative criterion for the characteristic being assessed.

Risk Priority Number (RPN): The product of the ranking values of Severity, Occurrence, and Detection established for a failure mode. The RPN values for all of the failure modes in an analysis are intended to allow the team to order the failure modes based on the risk each represents.

Severity: "the value associated with the most serious effect for a given failure mode" (AIAG, 2008, p.37).

Validity: An assessment of the accuracy of an instrument in measuring the phenomenon it is intended to measure. Four types of validity are often tested:

— Face validity: The relevance of the instrument.

— Content validity: The extent that the results produced by the instrument include the domain it was intended to measure.

— Criterion validity: The extent that the method correlates with other measures of the same phenomenon.

— Construct validity: The extent the measurements from the instrument are consistent with theoretical concepts and previously developed measurements. (from Shebl, Franklin and Barber, 2012).

Warranty: "A contractual agreement that requires the manufacturer to rectify a failed item, either through repair or replacement, should failure not be attributed to reckless use, and should it occur during a period specified by the warranty" (Singpurwall and Wilson, 1993, as cited in Rai and Sigh, 2009, p.15). Rai and Singh (2009) point out that, in addition to functioning as indemnification against failure for the purchaser, warranty also serves as a promotional tool for the manufacturer. "…buyers often view products with longer warranty coverage to be more robust and reliable [than products with lesser warranty coverage]" (p.17). The warranty coverage shown on the sticker may prove a feature that clinches a sale in the showroom if it exceeds that offered on a competitor's product.

Summary

In this chapter, the ranking system used to prioritize risk in an FMEA was reviewed and the concerns that relate to this system were presented. The absence of a cost dimension was noted and the concept of cost associated with quality problems was discussed. The need for improved ranking and the need to add a cost consideration to the analysis was stated and the problems that must be addressed to meet these needs were delineated. Finally a high level outline of the methodology that will be used in an attempt to answer the research question was presented.

CHAPTER 2

REVIEW OF LITERATURE

Overview

This chapter presents a survey of pertinent literature. It examines three conceptual areas: (a) the models that have been developed to represent the costs of quality, (b) the ways in which FMEA has been used to understand costs associated with failures, and (c) the various methods that have been developed to address the problems with risk prioritization in the traditional approach to FMEA.

Cost of Quality Models

It has long been held that field failures, though regrettable, might need to be accepted at some level. The economic feasibility of better products, so called "gold plated and bullet proof designs", has limits. Juran (1962) suggested that the cost of field failures could be reduced by increased expenditures on appraisal and prevention efforts undertaken to assure that product quality is acceptable.[27] But it was felt that there was an optimal point beyond which the money

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[27] The Hubble telescope is an example of enormous field failure costs being amassed in spite of a successful appraisal effort that found the problem before product launch. The results of the appraisal test by a null corrector were discounted in favor of contradictory information from a more sophisticated instrument that happened to be improperly assembled (Dunar and Warring, 1999).

spent in the failure reduction effort would come to exceed the money saved by the reduced cost of the failures.[28]

This "classic" view of cost of quality (CoQ) has recently been challenged. It is now held that failure costs can be driven down to near zero.

> New technology has reduced inherent failure rates of materials and products, while robotics and other forms of automation have reduced human error during production, and automated inspection and testing have reduced human error of appraisal. These developments have resulted in an ability to achieve perfection at finite costs (Campanella, 1999, p.9).

This new view of the relationship of quality costs is referred to as the "Par Value" model of CoQ. It posits that the improved effectiveness of prevention and appraisal actions means that the reduction in failure costs from the breakeven point to a point near zero no longer requires unreasonable increases in expenditures in CoGQ.[29]

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[28] The relationship between the cost of prevention plus appraisal efforts and the cost of failures was shown graphically by Gryna (1988). The cost per good unit of production was laid out along the ordinate scale and the level of defectives, decreasing outwardly, on the abscissa. This graph showed that increasing the expenditure on appraisal plus prevention corresponded to a decrease in the cost of failures until the defective level reached around 25%. This was the point at which Total CoQ was optimal (i.e., at its lowest point). Beyond this point, an asymptotic increase in the cost of prevention plus appraisal was required in order to drive field failures any lower. Subscribing to this view, Veen (1974) observed that, given the ever increasing demands for higher quality, it may be advisable to "operate to the right of the minimum cost…In this way, an organization is always one step ahead of developments and can think about tomorrow's problems instead of having to devote all its energy to today's problems" (Plunkett and Dale, 1988,p.1724).

[29] Gryna's graph of this condition showed the optimal level of total CoQ lying to the right of the point of intersection of CoGQ and CoPQ. Greater efficiencies of CoGQ meant lower costs were required in this area to bring CoPQ to near zero…the optimal point of Total CoQ. Burgess (1996) conducted simulations that led him to conclude that, in certain time constrained conditions, the classical model applies. But as the time horizon lengthens, the par value model is a better fit. (cited by Schiffauerova and Thomson, 2006).

Clark (1998) felt that there was an inverse relationship between the total cost of quality and the quality level of the organization. He asserted that the cost of poor quality runs at around 1percent of gross sales for companies that have achieved a “Six Sigma” level of operational maturity, 15 to 25 percent of sales for companies operating at the four sigma level, and 25 to 40 percent of sales for companies at three sigma (from Archambeau, 2004). Moreover, companies with immature quality systems spend the largest amounts responding to internal and external failures. Cokins (2006) estimates that failure costs at the start of a quality management program range between 65 to 70% of the total CoQ. Appraisal costs are between 20 and 25% of total CoQ and prevention costs are around 5%. An increased level of maturity would see more funds being directed towards appraisal activities and on internal failures while external failure costs declined. At the highest level of maturity, most of the CoQ expenditures would go to prevention activities. Relatively little would be spent on either internal or external failures (Beecroft, 2001; Crosby, 1979; Evans & Lindsay, 1996; Montgomery, 1996; Mitra, 1998; Sower, Savoie, & Renick, 1999; Yasin, Czuchry, Dorsch, & Small, 1999) (cited by Sower et al., 2002). Support for this notion is provided by the work of Sower, Quarles, and Broussard (2002). In a survey of 129 companies that assess cost of quality, they found that a significant negative correlation does exist between quality system maturity (as determined by the ANSI/ISO/ASQ Q9004-2000 maturity level classification system) and the amount of money expended on external failure costs.

Krishnamoorthi (1986) gathered data on prevention, appraisal, and failure cost from 23 companies representing different industries and with quality management systems at different levels of maturity. He related percent of expenditure for internal and external failures to (a) percentage of the expenditure made for appraisal, and (b) percentage of expenditure made for prevention. Polynomial regression gave the following equations relating these costs:

$$E = (5.9 \div P) + (298 \div A) \qquad (2)$$

$$I = (121 \div P) + 0.213A \qquad (3)$$

Where:

E = percentage of external failure costs

I = percentage of internal failure costs

P = percentage of prevention costs

A = percentage of appraisal costs.

R^2 for Equation 2 was .63 and that for equation 3 was .80. While Krishnamoorthi acknowledges his sample was limited in size and lacked specificity, he notes that both equations support the idea of an inverse relationship between prevention and appraisal expenditures and the costs of poor quality.

Weheba and Elshennawy (2004) argue that, the par value model of CoQ notwithstanding, failure costs will never diminish to zero. The CoQ curves relate process expenditures to total failure cost assuming perfect design quality. External failure costs—customer service, warranty actions, etc—are often a function of design considerations that are outside of process control. A perfectly manufactured design may not meet customer expectations. Further, it is subject to usage conditions that it may not have been made to withstand, and reliability and durability of the product are functions of material selection, system integration, component layout, etc. which are design decisions and not processing activities. Brust and Gryna (2002) state that "…for moderately complex to complex goods, 30% of field problems are due to manufacturing defects, 40% to design and 30% to usage conditions" (p.66)

Kume (1985) feels that the CoQ models presented above are conceptually correct but require qualification. He states "failure cost and prevention and appraisal should be considered separately. Failure costs represents waste; they are genuine losses, because they would not be expended if quality were perfect [while] Prevention and Appraisal costs…are spent to reduce failure cost" (p.17). He maintains that if expenditures on prevention and appraisal are not effective in this regard they would also be waste and should be categorized as failure costs. But properly designed appraisal and prevention activities are worth striving for. LNS Research (Cambridge, MA) determined that investments made in CoGQ "are more than offset by the reductions in poor quality" (Bangert, 2012, p.36). Gary Cokins of Analytics-Base Performance Management, LLC has asserted that, even if the expenditure in prevention and appraisal does no more than equal the saving from a reduction in poor quality, it is worthwhile. The company may be out the same amount of money, but by keeping poor quality product out of the hands of the customer, hidden costs have been avoided (Bangert, 2012).

Phillip Crosby (1979) broke the cost of quality down into two components: The cost of conformity and the cost of non-conformity. The former includes all costs that are accrued in an effort to ensure that products conform to requirements. The latter is, of course the cost of failing to produce conforming product. This characterization is accepted by Cokins (2006), Dobrin & Stanciuc (2013), Thoday (1976), and the British Standards Institute in BS 6143 (1981) (Plunkett and Dale, 1988). The cost of non-conformity is recognized as consisting of internal and external cost components, a distinction that Hesford and Dale (1991) heartily endorse. They feel that the aggregation of internal and external failure into a single failure cost bucket can result in some external failure costs being hidden. Should this occur, appropriate corrective action cannot be taken (Schiffauerova and Thomson, 2006). Dobrin and Stanciuc submit that the cost of non-conformity—what they call the cost of poor quality (CoPQ)—must embrace hidden costs as well as the tangible internal and external cost elements. They used Taguchi loss function to model customer dissatisfaction as a function of time spent waiting in a queue for service.

The American Society of Quality (ASQ) maintains that the cost of quality can be broken into four categories: internal failure, external failure costs, appraisal costs, and prevention costs (ASQ, n.d.). This characterization of CoQ enjoys broad acceptance (cf. Shiffauerova and Thomson, 2006).[30]

Godfrey and Pasewark (1988) proposed a model for CoQ comprised of (a) the cost of defect control, (b) the cost of failure, and (c) the cost of lost sales (cited by Sower, Quarles, and Broussard, 2002). Sower, et al. (2002) maintain that this model, if de-constructed, is equivalent to the ASQ model. Defect control embraces the cost of appraisal and prevention, while failure costs equal the sum of internal and external failure costs. Sower et al. submit that the category of lost sales−defined as "the cost of current and future sales that will be lost if defective units are received by customers" (p.3)—is an element of external failure cost in the ASQ model. While this is possible—ASQ defines external costs in quite general terms that do not *exclude* intangible cost consequences—it is somewhat presumptuous. Shepard (1998) observed a general tendency to base failure costs on "costing variances". Such a basis for cost accounting would tend to

[30] According to Schiffauerova and Thomson (2006), United Technologies Corporation, Essex Telecommunication Products Division employed the P-A-F model to measure CoQ. After five years, investments made in "P" and "A" resulted in a 26% improvement in productivity brought on by reductions in failure costs.

merge specific tangible cost elements…and to be entirely insensitive to intangible elements (cited by Sower et al., 2002). Thus, external cost accounting, whatever ASQ intends it to be, would likely not capture lost sales due to poor quality.

Yang (2008) proposes a model that consists of Prevention, Appraisal, Internal failure, External failure and Hidden costs. This latter category is broken into "Extra resultant costs" and "Estimated hidden costs". Extra resultant costs consist of the extra costs associated with a response to an internal failure—lost operational time, rework labor, extra materials required for replacing scrapped product—all of which are measurable. But there are hidden costs that are difficult to measure (e.g., lost sales due to poor quality). Although these costs must be estimated, they are real and Yang believes they should be included in CoQ assessments.

Xerox developed a CoQ model made up the cost of Prevention, Appraisal, Failure (internal and external), "exceeding requirements" (costs resulting from providing information or service that was not required by the customer), and the cost of lost opportunity.[31]

Weheba and Elshennawy (2004) represented the cost of conformance with equation 4.

$$E(RC)_L = E(C_M) + E(C_i) + E(C_d) \quad (4)$$

Where $E(RC)_L$ is the average or expected level of conformance (reactive cost) per unit time. This represents the cost incurred by maintaining stable operations at the existing level of conformance. It is made up of the cost of monitoring the state of operation, $E(C_M)$, the cost of inspecting production units, $E(C_i)$, and the cost of deviating from performance targets, $E(C_d)$. A

[31] Shiffauerova and Thomson (2006) claim that Xerox was the first company to use opportunity costs in CoQ determination. They further claim that, using this model, Rank Xerox in England achieved and 83% reduction in CoQ. In the U.S., the Marketing Group of Xerox used the model to reduce CoQ by $54 million.

second equation, representing the cost of introducing planned changes to the process to improve the level of conformance, was supplied. That equation considers the cost of evaluating the process change, and an estimate of process set-up time and time required to evaluate the effect of the change. To this is added a factor to account for uncertainty and the possibility that further testing will be required. The sum of these factors is adjusted by a “realization factor” to capture the probability that the changes will lead to the anticipated improvement. These two equations, taken together, provide an instrument to evaluate the economics of quality improvement.

Omar and Murgan (2014) built a model, based on work done by Chiadamrong (2003), which is given in equation 5.

$$E(C_{COQ}) = E(C_{PIQC}) + E(C_{VQC}) + E(C_{OC}) \quad (5)$$

Where:

$E(C_{COQ})$ is the expected cost of quality.

$E(C_{PIQC})$ is the expected production invisible quality costs. This is developed by summing the cost of material, machining costs, labor costs, and material handling costs associated with replacing failed product, together with any failure analysis and repair costs that apply.

$E(C_{VQC})$ is the expected visible quality costs. This captures prevention costs, appraisal costs, and failure costs.

$E(C_{OC})$ is the expected opportunity costs. This is comprised of the cost of set-up, the cost of idle production, inventory costs, the cost of waiting, and external failure costs.

It is interesting to note that the simulations conducted by Omar and Murgan, using this model, support the theory of some (e.g., Porter & Rayner, 1992 and Plunkett & Dale, 1987—cited by Snieska, Daunoriene & Zekeviciene, 2013) that (a) prevention costs contribute the greatest amount of the visible quality costs, and (b) as prevention expenditures increase, appraisal and failure costs will decrease. Further, their simulations showed that direct labor, while frequently targeted in cost cutting efforts, only contributes 3% to the expected total cost of quality.[32]

FMEA adapted to CoQ determination

Rhee and Ishii (2003) adapted FMEA to the determination of the cost consequence of potential failure modes, an approach they termed Life Cost-based FMEA. They observed the following:

In Life Cost-based FMEA, risk is assessed on the basis of the cost of the failure(s). Expected cost is represented by equation 6.

$$\text{Expected failure cost} = \sum_{i=1}^{n} p_i c_i \tag{6}$$

Where p is the frequency of occurrence, c is the cost associated with the failure, and n is the total number of components in the system. Failure cost is a function of severity and probability of occurrence.

[32] David Anderson has stated that efforts to reduce labor cost by shipping jobs to low cost countries "is legendary for *raising* [emphasis added] quality costs" (Bangert, 2012, p.36). Guinot and Ulmer (2014) showed that the relative economic advantage of transferring jobs to low cost countries could be offset by the cost of responding to one quality spill that required containment and corrective response of relatively short duration.

Failure cost is composed of labor cost, material cost, and opportunity cost. Labor can be broken into detection activities, and repair work, while opportunity costs consist of delay (non-value added activities such as set-up, shipping, waiting for results, and formulating responses), and recovery time (time to re-set the system to its original operating state).

Labor cost = occurrence × [detection time × labor rate × no. of operators] + [repair time × labor rate × no. of operators] + [delay × labor rate × no. of operators]

Material cost = occurrence × cost of the part(s)

Opportunity cost = down time × hourly opportunity cost

Down time = [detection time + repair time + delay time] = (1 - availability) × operation time

Failure frequency = Downtime ÷ Mean Time to Repair

Detection affects cost. If detection of the failure mode occurs in-house, costs are less than if the failure evades detection and is found by the customer. Furthermore, failure costs increase as the time between the origin of the failure and its detection increases (Rhee and Spencer, 2009). In recognition of the importance of detection in this regard, Ben Daya and Rauf (1993) developed a weighting system that gave detection the highest value in an RPN calculation (Sofyalioğlu and Öztürk, 2012).

Niezgoda and Johnson (2007) model total project risk in terms of cost of implementation by adding the initial cost of the project, which they represent as C_0, to equation 6. Niezgoda and Johnson propose that the risk assessment begin with an initial FMEA. From this, RPN is calculated in the usual fashion to guide the prioritization of risk mitigation actions. But the initial FMEA process is followed by an “extended FMEA” that moves the consideration of risk into the cost-based realm. Occurrence ranking provides the measure of probability for the cost equation. The factor c_i, which represents the cost of the failure mode, is taken from a ranking table. The values on this table are developed by establishing a percentage of the project cost for each severity (consequence) rank. Thus, a severity rank of 10 would assign a cost factor of 100% of the project costs to the failure mode. A severity rank of 8 would have a cost factor of 75% of the project costs…and so on.

Hassan, Dayarian, Siadat, and Dantan (2008) also represent the cost of a failure as the probability of occurrence times the cost of the response to the failure effect. But they use the FMEA Occurrence rank times the Detection rank to represent probability of the event occurring. This, then, makes the risk determination specifically pertain to internal failure (i.e., failure modes detected within the processing realm).

Wang (2011) proposes basing the consideration of severity on the cost impact of the effect of a failure. Cost, in this scheme, is the sum of rework, reprocessing, scrap, waste disposal, labor, opportunity cost, and inventory holding costs that are incurred as a result of the failure. The cost amount is used to rank the failure mode effect on a 10 point scale. RPN is found by multiplying this rank by the rank for occurrence and detection of the failure mode.

Gilchrist (1993) focused on the cost implications of failures that escaped the manufacturer's facility. Occurrence is multiplied by the probability of *not* detecting the failure (essentially, 1-D where D is the detection rank) and this partial product is multiplied by the cost of an external failure in order to derive the RPN. Gilchrist recognized two categories of external failures: either the customer detects the problem and warranty replacement costs result or the faulty condition is not detected and failure occurs in service. In this latter case, it is assumed that an accident occurs and litigation and settlement expenses form a part of the cost of failure (from von Ahsen, 2008). von Ahsen (2008) expands on this idea and has cost embrace repair, replacement, decreased profits, loss of potential business, etc. as they apply. Moreover, von Ahsen recognizes the fact that, the better the detection, the higher the probability that the failure will be found before shipping and external failure costs are accrued. She, therefore calculates RPN as shown in equation 7.

$$RPN_c = (O) \times \{(Đ/O) \times E[C_e]\} + \{(D/O) \times E[C_i]\} + \{\bar{O} \times (D/\bar{O}) \times E[C_c]\} \qquad (7)$$

Where:

RPN_c = risk priority number based on cost

C_e = cost of externally detected failures

C_i = cost of internally detected failures

C_c = cost of false positive inspection results

$Đ/O$ = the conditional probability of not detecting a fault before delivery

D/O = the conditional probability of detecting a fault before delivery

$D/\bar{O}$ = the conditional probability of detecting the fault, given it has not occurred.

Shafiee and Dinmohammadi (2014) developed a modified FMEA to evaluate the comparative risk of repairing wind turbine systems based on cost of repairing failed equipment. Occurrence was determined as the ratio of the instances of failure for a given failure mode over a set period of time, to all failures over that period. In place of severity, the authors used a cost index. This consisted of the sum of all the costs that were incurred when a wind turbine failed and needed to be serviced: the cost of the replacement parts, the cost of equipping the maintenance crew and transporting them to the site, the cost of the labor required for the service action, and the cost of lost production experienced during the downtime. Detection was the ratio of the number of failures to the number of failures plus the number of instances a failure was avoided because it was effectively detected. Thus, *D* is an index of failure to detect. Occurrence × Cost × Failure to detect gives the risk rank—termed the cost priority number (CPN)—as a continuous scale (in Euros). The authors note that the CPN requires field failure data and, as a consequence, a traditional FMEA risk assessment is recommended for instances where these data are lacking. Traditional FMEA was found to produce results that were very close to those of the cost consequence of failure method in terms of the identification of potential failure modes of concern.

Dong (2007) asserts that the "the ultimate goal of FMEA is to reduce the cost due to failure, the cost due to failure modes should be the objective for decision making" (p.960). To this end, he established the index for expected cost shown in equation 8.

$$E(C) = C_{fm} p_{fm} (1 - p_d) \tag{8}$$

Where:

$E(C)$ is the expected cost due to the failure mode

C_{fm} is the costs found to result from the failure mode

p_{fm} is the probability of the failure mode occurring

p_d is the probability that the failure will be detected

Cost clearly is related to the probability of occurrence and the probability that it will escape detection—both values that can be derived from the FMEA. Dong also submits that C_{fm}

is directly proportional to severity—the higher the severity ranking, the more costly is the failure mode effect. This cost relationship is established subjectively (based on engineering judgment and experience) by the team developing the FMEA. Dong converts the ranking scores for cost, occurrence, and detection into what he terms "utility values". Cost is converted by taking the ranking and dividing by the highest cost value (the amount established for S = 10); the utility value of occurrence is -1/log *p*. The risk priority index is the cube root of the product of the utility values for cost, occurrence, and detection established for each failure mode. Prioritization of the cost-based risks is accomplished using fuzzy logic. A triangular membership function is established based on RPI scoring for all the engineers on the team, fuzzified by setting the min and max values at zero and the average at 1. Defuzzification uses either the centroid method or the Center of Maximum method of Hellendorn and Thomas, (1993). The fuzzy membership function, used to rank utility values, frees the prioritization process from the problems seen with the traditional RPN approach.

Abdelgawad and Fayek (2010) developed a severity ranking system that set the level of severity based on scope/quality impact, time impact, and cost impact. A five point linguistic definition of severity (termed "impact") was developed ranging from low (no noticeable scope change, quality degradation not noticeable; insignificant schedule slippage; and cost impact < 1% of project cost) to Very high (scope or quality does not meet expectation; service date delay ≥ 10% of project duration; and cost impact ≥ 10% of project cost).

Braaksma, Meesters, Klingberg, and Hicks (2012) set severity equal to the ratio of the cost of preventative maintenance to the cost of failure in FMEA done on production equipment. If maintenance cost is high compared to the cost of failure, severity is high. This made the index of greater value to maintenance teams.

Harpster (2005) set up three zones of financial risk based on severity. A severity rank of 1 to 3 describes a problem that customers tend to accept. They become inured to the level of annoyance resulting from the flaw in appearance or the noise level.[33] Harpster calls this "the conditioned response zone" and believes that this represents little financial concern to the supplier. Severity rankings of 4 to 8 describe a zone he calls "return/no buy". Problems in this zone will send customers to the dealership to get the parts replaced. It does not matter whether the ranking was based on a loss of primary function (S = 8) or a reduction in comfort/convenience (S = 5), it will be attended by a warranty claim and a disgruntled customer. If a severity of 9 or 10 is awarded to a potential failure mode, the zone of "safety/legal" is entered. "[In this zone,] someone gets injured or a governmental regulation is violated [and] the company is exposed to the greatest level of financial risk" (Harpster, 2005,p.3). While Harpster does not place dollar figures to any of the zones, his system does serve to bracket the levels of cost consequence (see table 3).

Alternative Methods of Risk Prioritization in FMEA

Liu, Liu, and Liu (2013), in a review of the literature published in the period 1992 to 2012 on methods to address the shortcomings of FMEA, found that the vast majority of this work focused on improving the criticality analysis. Among the alternatives methods that received attention, 39% (29 of 75) employed fuzzy rule based systems to develop risk priority. Another 13% used fuzzy sets in conjunction with other techniques (e.g.,, Grey Relational Theory, Analytical Hierarchy Process, etc.). Multi-criteria Decision Making (MCDM) was the

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[33] It can be assumed that some of these customers did not seek warranty repairs because they were unwilling to pay the nuisance cost that Waje and Patil (2012) identified for a problem of such little importance.

second most frequently explored alternative technique. Much effort was also devoted to establishing relative importance between the three dimensions of risk – severity, occurrence, and detection.

Arrow and Raynaud (1986) suggest several "Axioms" that they feel should be satisfied by any ranking system that pretends to replace RPN for risk prioritization (cited in Bradley and Guerrero, 2011). Four of these axioms are given here:

Axiom 1: Pareto optimality should be maintained

Axiom 2: Transitivity must be achieved. That is, if $RPN\,(O_n,S_n,D_n) > (O_m,S_m,D_m)$ and $(O_m,S_m,D_m) > (O_k,S_k,D_k)$, then (O_n,S_n,D_n) must be greater than (O_k,S_k,D_k).

Axiom 3: Independence of irrelevant alternatives is required. That is, if $(O_n,S_n,D_n) > (O_k,S_k,D_k)$ for some failure modes m, k, $(1\ldots.N)$, then the relative ranking of m and k should remain undisturbed when an additional failure mode is introduced.

Axiom 4: The system should be easily understood by decision makers (from Bradley and Guerrero, 2011).

This list of axioms will be used to assess the alternatives considered for use in assessing risk rank.

Multi-criteria Decision Making.

Franceschini and Galetto (2001) employed the Multi-Expert – Multiple Criteria Decision Making (ME-MCDM) method of Yager (1993) to compare and order the qualitative scales used in FMEA. The methodology essentially establishes membership in a fuzzy set through the membership function given in equation 9:

$$RPC(a_i) = \text{Min} [\text{Max} \{\text{Neg} (I(g_j), g_j(a_i)\}] \quad (9)$$

Where:

$RPC(a_i)$ is the Risk Priority Code for the failure mode a_i

$I(g_j)$ is the importance associated with the evaluation criterion g_j

Neg ($I(g_j)$) is the negation of the importance assigned to the decision making criterion. The negation of the *j*th value of an *n* point ordinal scale, Neg (L^*_j), is given as $L_{(n-i)+1}$. So, for example, an importance value of 8 on a 10 point scale would, when negated, gives (10 - 8) + 1 = 3.

The authors illustrate the use of this method by comparing the FMEA ranking of a failure mode with S = 6, O = 6, and D = 3—all based on a 10 point scale—having an RPN of 108. Applying equation 9, we see

$$RPC(a_1) = \text{Min} [\text{Max} \{\text{Neg} (L^*_{10}), L_6\}, \text{Max} \{\text{Neg} (L^*_{10}), L_6\}, \text{Max} \{\text{Neg} (L^*_{10}), L_3\}] = \text{Min} [\text{Max} \{L_1, L_6\}, \text{Max} \{L_1, L_6\}, \text{Max} \{L_1, L_3\}] = \text{Min} [L_6, L_6, L_3] = L_3$$

Where L^*_j is the importance criterion and L_i is the rank.

In this way, all failure modes are assigned an RPC and the RPCs can be ordered from highest to lowest to provide a ranking of risk. This membership function does not require treating the qualitative S, O, and D ranks as if they were quantitative values. The rankings of each failure mode can, therefore, be evaluated against each other with "no need to use numeric values and force undue precision on the design team experts" (Franceschini and Galetto, 2001, p.2997). Moreover, the team is able to adjust the importance criterion of any of the scales to "weight" the dimensions of the risk assessment as required. If, for example, the team wished to weight severity higher than occurrence and reduce the influence of detection to the lowest possible level, they can assign the 10 point occurrence scale an importance of, say, L*5 and detection L*1. This would result in the following *RPC* determination:

$$RPC(a_1) = \text{Min}\ [\text{Max}\ \{\text{Neg}\ (L^*_{10}), L_6\}, \text{Max}\ \{\text{Neg}\ (L^*_5), L_6\}, \text{Max}\ \{\text{Neg}\ (L^*_1), L_3\}] = \text{Min}\ [\text{Max}\ \{L_1, L_6\}, \text{Max}\ \{L_6, L_6\}, \text{Max}\ \{L_{10}, L_3\}] = \text{Min}\ [L_{6,} L_{6,} L_{10}] = L_6$$

The *RPC* for a_1 would go from $L3$ to $L6$. It would gain in priority ranking reflective of the dimension of risk that the team felt was more important. A failure mode with S = 4, O = 3, and D = 9—also having an RPN of 108 (designate this a_2)—would no longer be able to claim equal importance in spite of a lesser severity level.[34] The adjusted importance ranking in the example above would give a_2 an *RPC* of $L4$ and place it below a_1 in terms of importance.

Yate's method of treating comparisons between ordinal scales, and the multi-criteria ranking application of Franceschini and Galetto, "[adhere] to the rules of measurement theory" (Bradley and Guerrero, 2011, p.748). This approach satisfies the axioms of Pareto optimality, transitivity, and independence of irrelevant alternatives. Further, Andersen (2012) notes that converting the ranking values from numbers to levels (L1, L2, etc.) makes it less likely to misinterpret the rankings as interval values. However, Bradley and Guerrero (2011) point out that the ranking system does not effectively "reflect positive association with higher scores" (p.750).

[34] Teng and Ho (1996) would endorse this weighting practice. They maintain that "no matter how small the probability is for a critical failure mode (with a catastrophic effect), this failure mode should still be on the top of the list of items to be removed [through mitigation]" (p. 18).

Equation 9 is intended to favor the risk dimension for which the highest level of importance is ascribed. Selvan, Jegadheesan, Varthanan, and Senthilkumar (2013) were interest in selecting the risk level that would have had the *lowest* RPN. They felt that this approach would speed up correction activities by directing efforts to the least significant issue first. This dictated reversing certain elements of the ME-MCDM function, as shown equation 10.

$$RPC(a_i) = \text{Max}\ [\text{Min}\ \{\text{Neg}\ (I(g_j), g_j(a_i)\}] \quad (10)$$

Fuzzy Rule-based Systems.

Fuzzy logic was developed by Zadeh in 1965 as a means of treating imprecise or subjective evaluations. The theory of fuzzy sets expresses imprecision quantitatively by introducing characteristic membership functions that can assume values between 0 and 1 corresponding to degrees of membership from ‘not a member’ through to ‘full member’ (Hopgood, 2012, p.71).

Expert assessment of risk is subjective and the language based ranking system of the FMEA lacks definitive value intervals. This is a problem that is not rectified by shoe-horning the linguistic evaluation into a 10 point ordinal scale. Fuzzy logic is a tool that is ideally suited for treating problems like this. Many researchers have used fuzzy sets to address one or more aspects of FMEA development (Abdelgawad & Fayek, 2010; Liu et al, 2011; Pillay & Wang, 2003; Sofyalioğlu & Öztürk, 2012; Zhang and Chu, 2011). Liu et al. (2011) mention that, among the qualities that fuzzy sets bring to FMEA is the ability to cope with additional risk factors, such as an index of cost consequence.

Other approaches.

Clustering analysis.

Arunajadai et al. (2004) tested 41 electromechanical consumer products[35] to assess the failure modes exhibited by the products, based on component function. They found: (a) a Pareto like relationship existed between failure modes and the failures observed: 40% of the failure modes produced 92% of the failures; (b) only 42 of 180 identified functions experienced failure in testing and; (c) there did not seem to be a relationship between component count and failures that represented new failure modes. Based on these results, Arunajadai and his associates attempted to identify the "critical few" failure modes that the design team should focus effort on to bring about large reduction in failure occurrence. To do this, they used clustering analysis (K means method) to determine which failure modes associated with particular functions. Of the 32 failure modes in the exercise, 9 clusters were formed. These clusters were grouped into one of three categories based on occurrence: Type I clusters contained failure modes that tended to occur alone; Type II clusters had failure modes that were found together with other failure modes; Type III failure modes had low frequency of occurrence. From this, the design team could target their mitigation activities to those failure modes that produce the most failures and get the greatest "bang for the buck".

[35] The selection of products included an air purifier, a palm sander, a hand vacuum cleaner, a coffee maker, a hair dryer, an engraver a floor jack, a grinder, a jigsaw, a leaf blower, a popcorn popper, a toaster and a water purifier.

Ranking by SOD code.

Wheeler (2011) proposed a system of ranking that was free of the mathematical distortions of RPN. In this system, Severity, Occurrence, and Detection would be ranked in the time honored fashion but, instead of using 10 point ordinal scales, Wheeler proposed the use of 5 point scales. The ranking of the failure modes based on risk level would be done using a 3 digit code formed by the rank score assigned to Severity, placed next to the score assigned to Occurrence, and ending with the rank score for Detection. For example, if S = 5, O = 4, and D = 2, the SOD code would be '542'.

> An SOD code based on rankings of 1 through 5 will result in 125 values for 125 situations. When these SOD codes are placed in descending numerical order, they will prioritize the situations first by severity, second by occurrence within each level of severity, and lastly by detectability within each combination of severity and occurrence. (Wheeler, 2011, p.6).

AIAG, in the 4th edition of their FMEA manual, has recognized the SOD code ranking system as an acceptable alternative to RPN.

Alternative uses of detection in risk ranking.

Kmenta and Ishii (2001) feel that the detection index does not accurately measure the contribution of detection to overall risk.[36] They propose using only the dimension of Severity and Occurrence to establish risk rank. This system would have three levels each for S and O—High, Medium, and Low (corresponding to rank scores of 9, 3, and 1). High severity in

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[36] This position stands in contrast to that of Ben Daya and Rauf (1993) mentioned previously.

conjunction with high occurrence would give an SO rank of *highest*; high severity and medium occurrence would give an SO rank of *high* (as would high occurrence and medium severity); and so on for all nine combinations of S and O rankings.[37]

This is intuitively satisfying in that it aligns well with other approaches that consider risk to be a function of the consequence of an outcome and the likelihood of its occurrence. AIAG has a similar SO methodology for risk assessment that is considered to be an acceptable alternative to RPN.

A different view of the value of detection is maintained by Koberstein (2008). He established a ranking scale for detection that relates the rank value to the probability of detecting the failure mode.[38] By multiplying the complement of this probability times the ppm value established for the failure mode (the occurrence rank), one gets the ppm of the failures that are not detected in plant and get to the customer. This is the failure rate (λ_n) for that failure mode. Koberstein determines these values for each of the *n* failure modes identified for the product. The total failure rate for the product, then, is given by

$$\lambda_{product} = 1 - [(1-\lambda_1)\,(1-\lambda_2)\,(1-\lambda_3)\ldots\,(1-\lambda_n)] \tag{11}$$

Khanmohammadi, Rezaei, Jassbi, and Tadayon (2012) developed a detection ranking scale based on signal detection theory. The premise of this theory is that four states exist in a detection system: stimulus present, response is absent (Miss); stimulus present, response follows

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[37] The ranking combination of Low severity and Low occurrence is not given a subjective priority value and any combination of Medium and Low rank scoring results in the assessment "As time permits". This means, of course, that the need for action is not dismissed but the urgency can be related to expediency.

[38] The relationship between rank score (x) and probability of detection (y) is given by $y = 0.9007x^{0.049}$ ($R^2 = 0.9891$)

(Hit); stimulus absent, response absent (Correct rejection); and stimulus absent; response occurs (False alarm). The scale was formed using fuzzy inference that considered the performance of the sensor and the response of the operator to the alarm from the system. Sensor response was modeled using Bayesian probability and the operator's response recognized human reliability factors (Hacker, 1998 as cited by Khanmohammadi et al, 2012). Defuzzification provided the ordinal detection scale values.

Spatial mapping of RPN scores.

Krippner and Koberstein (2009) developed a 3D array with the ranking scale for S, O, and D as the axes. The RPN values for a failure mode would establish a location in this 3D space. "Trigger scores" were developed—combinations of S, O, and D scores at or above which a response is dictated—and these scores demarcate the boundaries of regions given in Table 1. If an RPN is located within one of the regions, certain actions are dictated. Figure 3a shows the "Risk Cube" with the lower boundary for the RED region. Figure 3b shows the upper boundary of the GREEN region. Figure 3c shows the boundary that describes a region in which a special characteristic must be assigned to the part or function that has an RPN that lands within it.

Table 1.

The criterion for establishing the boundaries in the Risk Cube (Krippner & Koberstein,2009) and the action that must be taken if an RPN is located in that region.

Region:	Rule:	Response:
RED	S = 9 or 10; O > 1; D = any value S = 5,6,7, or 8; O > 3; D = any value S = 1,2,3, or 4; O > 5; D > 5	Action is mandatory
YELLOW	RPN is located between RED region and GREEN region	Use discretion
GREEN	S = 9 or 10; O = 1; D = 1 S = 5, 6, 7, or 8; O = 1; D < 5 S = 1, 2, 3, or 4; O ≤ 3; D < 5	No action required
BLUE	S = 9 of 10; O > 1; D > 1	Assign "Critical" Characteristic
PINK	S = 7 or 8; O > 4; D > 1	Assign "Significant" Characteristic

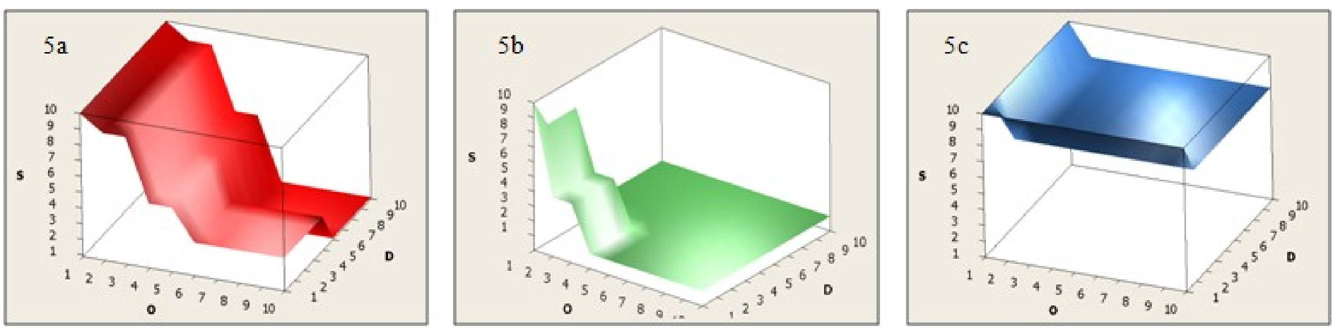

Figure 3. The figures illustrate the Risk Cube with (a) the lower boundary of the RED region, (b) the upper boundary of the GREEN region and (c) the lower boundary of the BLUE region (Krippner & Koberstein, 2009 - Reproduced by permission).

Honda Motors has the rankings for severity, occurrence, and detection determined along the lines established by AIAG and RPN is the product of the three rank scores. But Honda has established a means of prioritizing that departs from AIAG by establishing threshold scores. If the RPN value is between 1 and 26, action on the issue is given a *C* rank: Low priority, "Implement measures where time and resources allow". If the RPN falls between 27 and 129, it is ranked a *B* concern: Moderate priority, "Monitor the occurrence and implement measures accordingly". RPN scores between 130 and 425 are *A* ranked concerns: High priority, "Must implement measures". Above 426 and the concern is *S* level: Top priority "immediate measures required" (Honda, 2012, p.5).

Summary

This chapter provided an overview of the work reported on modeling the cost of quality. With few exceptions, these models recognize the basic division of CoQ originally proposed by Feigenbaum (1956): Internal and External failure costs, costs of appraisal and cost of prevention. Several models attempt to capture intangible or hidden costs of quality, and while there is no single means of representing such intangible costs as loss of customer loyalty and brand damage, few researchers deny their importance.

Attempts to use FMEA to assess the cost consequence of failure recognize that FMEA provides a characterization of the seriousness of a failure effect and the probability that that effect will be realized. These two factors alone find frequent use as a way to assign cost to the failure mode. Detection is frequently used to identify the likelihood that a quality concern will leave the manufacturing facility and, in so doing, lead to costs associated with external failures.

Finally, the problems with risk prioritization have been met with numerous inventive methods to either correct for the defects of RPN (e.g., fuzzy rule based compensations) or depart from the RPN system altogether (e.g., SOD ranking).

CHAPTER 3

METHODOLOGY

Overview

This chapter describes the approach that will be used to pursue answers to the research questions. It begins by discussing the model that associates costs to different levels of failure based on the severity and occurrence ranking assigned to the failure mode effect in the FMEA. The means of representing the aspects of cost of quality identified by Omar and Murgan—production invisible costs, visible quality costs, and opportunity costs—are introduced. An overview of the simulation that will be used to explore the relationship between severity, occurrence and cost consequence is provided. The chapter concludes with a description of the means by which criterion validity and violations of Pareto Optimality will be assessed.

The research questions that will be explored are:

1. Can cost of quality considerations be included in the a priori assessment of risk done with FMEA?

2. Can a Cost index be added to the elements of an FMEA risk assessment that is consistent with the established risk ranking methodology and does not require arcane computational techniques to manage?

3. When costs of field failures are considered in the FMEA analysis, does the susceptibility to Pareto Optimality concerns become unreasonably high in comparison to that already seen with RPN?

Assessment of the Cost Consequences of Failure Modes using FMEA

Modeling Cost of External Failure. [39]

The dimensions of the risk characterization of an FMEA assessment will be related to the cost that can be expected should the failure mode be experienced. Severity and occurrence rankings will establish (a) the costliness, and (b) the extent of each failure. Characterization of the costs associated with each severity ranking will follow Harpster (2005).

For this analysis, the cost structure of an electronic control module purchased by a North American automobile manufacturer will be used. The product is essentially a computer, mounted inside the vehicle passenger compartment that controls a system function in the vehicle. It monitors the vehicle operating conditions and manages the response of the system it controls as conditions require. Figure 4 is a diagram of a control module and the vehicle interfaces involved in controlling the occupant safety systems.

The module consists of a printed circuit board with components attached (either soldered or pressed onto the PCB); a housing and cover; and a connector to allow the module to mate, via a wire harness, to the vehicle communication system. The study will be based on an occupant safety system control module that would be considered "mid-line" in terms of the features that it

[39] It is recognized that internal failure costs can be easily included in a model of this kind. Detection rankings can be used to ascribe a probability to the quality concern being found in-house. The severity ranking of the PFMEA can be used to determine the location and the nature of the concern. Cost figures can be assigned accordingly. The addition of internal failure costs is planned for a follow-up to this study.

offers (i.e., not all of the airbags shown in figure 4 are configured and no roll rate sensing or inertial measurement functions are available in the module). An annual volume for the vehicle line of 164,000 units per year will be assumed and all costs will be annualized. These modules are considered non-repairable.

Production Invisible Quality Costs.

As with previous studies, every instance of external failure will require that a replacement unit be supplied to the customer. Omar and Murgan (2014), with their model element $E(C_{PIQC})$, captured cost of material, machining costs, labor cost, material handling cost, and failure repair cost that result from replacing a field failure. The model to be used for this study will use BOM cost, labor cost per unit, and overhead per unit—factors that the business plan associates with the manufacturing costs of the product—to cover these "hidden" costs.[40] Two advantages follow: (a) these factors are easily obtained by an FMEA team and are among the costs that are carefully tracked and considered accurate, and (b) such things as preventative maintenance, engineering support, costs associated with appraisal, inventory carrying costs, and material handling are captured in the overhead element of the product costs.

[40] Banker, Potter, and Schroeder (1995) looked at the cost profile of 32 U.S. manufacturing plants in the area of electronics (n = 15), machinery (8), and automotive components (9). They found that 65.2% of the costs incurred by electronics plants went to direct materials, 8.4% to direct labor, and 26.4% to overhead (fixed + variable). These figures differ somewhat from those found by Marks (2008) in his study of manufacturing costs. He determined material costs to be 72.8% of mfg costs, direct labor constituted 8%, and overhead was 19.3%. This study will more closely follow Marks with direct materials at 76.6%, and overhead at 19.3%.

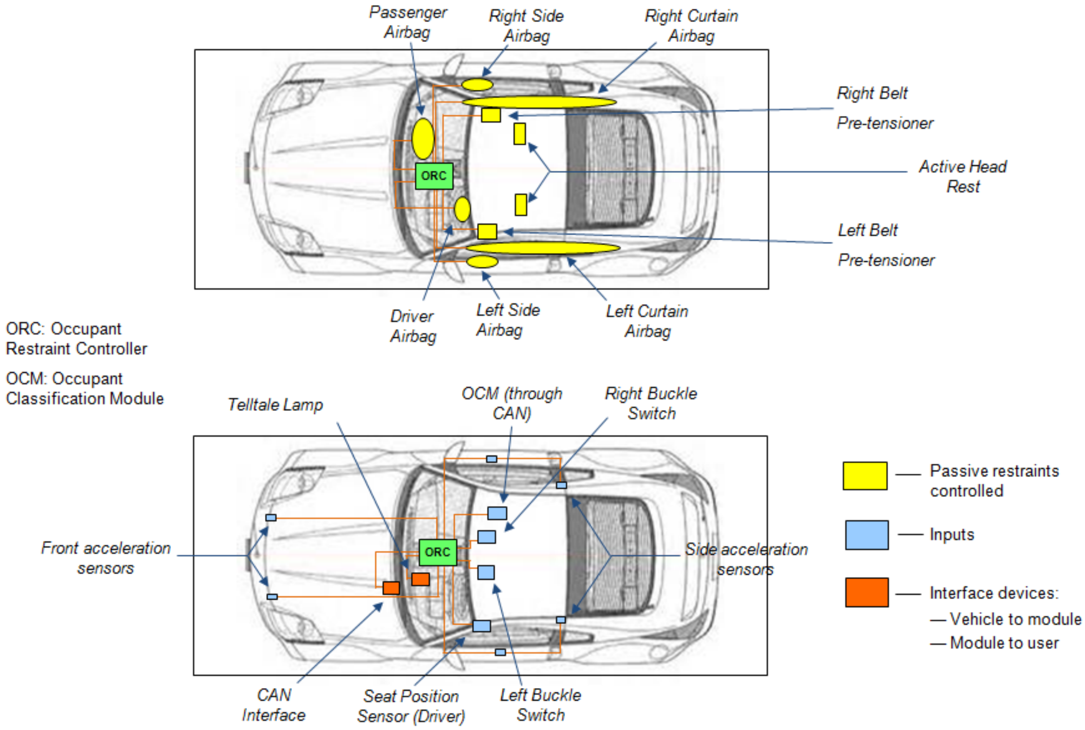

Figure 4. The electronic module used to control the safety systems in a typical vehicle. The module is located under the instrument panel in the console area of the passenger compartment. This module monitors acceleration changes and directs the deployment of the airbags and seatbelt pretensioners in a crash event.

Visible Quality Costs.

$E(C_{VQC})$ in this study is represented by (a) sorting and inspection efforts undertaken to "contain" a problem found in the field, (b) the cost of failure analysis of returned product, and (c) the penalty assessed by the OEM for the non-conforming product. This latter cost takes two forms: (a) the fee that is charged when a zero km issue is found to be the fault of the supplier (referred to as a Non-Conforming Ticket charge), and (b) warranty assessments.

An electronics module manufacturing process has in-line and end-of-line automated inspection operations which constitute the bulk of the proactive appraisal costs.[41] The capital recovery and operating expenses of this equipment are amortized into the price of each unit of sale and, therefore, are considered to be captured by the module costs in the model. A response to a field issue may only require that this equipment be reprogrammed, at nominal cost, to add or enhance detection capability. These reactive appraisal costs are negligible and the appraisal portion of the visible quality costs will therefore be limited to the cost of containment, sorting, and inspection identified above. Reactive prevention costs—like product redesign or reprogramming—are problem specific. The model will make no attempt to represent these costs. But it is recognized that an average cost could be developed for a basket of prevention responses and this could be used to represent the prevention costs of quality in the model.

At every severity level, a certain number of failures will be found before the vehicles ever make it out of the vehicle assembly plant. These are referred to a "zero mileage" or "zero kilometer" returns. Zero km returns incur additional appraisal costs. The OEMs have paid for working product and they demand that any product that is not working at the assembly plant undergo analysis to allow the problem to be understood and contained. Thus, every zero kilometer return requires that a technician devote time to the analysis of the return. The case study will assume that each zero kilometer return will require up to 5 hrs to analyze at the labor rate used in the standard assumption (equivalent to a non-union wage for the occupation, at a

[41] A distinction is herein being made between appraisal and prevention costs that are already in place ahead of any field issue and those that are put in place in response to the issue. The former will be termed proactive costs, and the latter reactive costs. Note that reactive costs, used in this way, differs from the meaning ascribed to the term by Weheba and Elshennawy (2004).

manufacturing site in the South-central United States).[42] This value will be allowed to vary randomly between 1 and 5 hours per analysis.

Any quality concern that could affect multiple days of production or multiple lots of product will require containment. This is a process of sequestering all suspect product at the OEM's assembly facility, in transit, and in the supplier's WIP and warehouse. The model will assume that there will be one quality incident per period in the Return / No buy and Safety / Legal regions of severity that will require containment. The containment, sort, and inspection action will be assumed to run over a period of 2 to 5 days (allowed to vary randomly) and will require a sort company to assign 3 inspectors working 10 hrs per day at minimum wage.[43]

In addition to the cost of this failure analysis, every issue occurring in the OEM's plant triggers a billing to the supplier for the non-conformance. The "ticket" that is sent along with the returned goods describes the issue and gives a breakdown of the costs that must be reimbursed for the annoyance the issue caused. This study will assign ticket charges that align with those typical of the industry: A minimum of 6 hrs of "administrative effort" on the OEM's part to process the tickets at an hourly rate of $44. This is to say, every ticket means at least a $264 charge to the supplier. To this fee, are added charges for "excess handling", "remove/replace" and return of the NC part. For the purpose of this study, every zero km return will require

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[42] The labor costs used in this study are based on the mean wage for Electrical and Electronic Equipment Assemblers (occupation code 51-2022), as put forth in the Bureau of Labor Statistics publication *May 2014 National Industry-Specific Occupational Employment and Wage Estimates* -- $32,070 per year. *Salary.com* projects the benefits and contributions (Social Security, 401K, disability, healthcare, and vacation pay--assuming no bonus and no pension) for this annual income to be $14,666. This brings the total annual compensation to $46,736. Given 50 weeks of scheduled work at 40 hrs per week, hourly cost of labor becomes $23.38.

[43] An OEM that operates a union shop is compelled by the union to require the supplier to use unionized labor for the sorting activity. This would of course require a higher wage per hour of service. However, the model will use minimum wage as it is closer to the median wage rate of union and non-union OEM plants taken together.

payment to the OEM of $533— 3 hrs for remove/replace and 3 hrs for excess handling, and standard administration charges.[44]

The hypothetical supplier used in this study has set aside a portion of the sales returns to cover warranty costs. This is referred to as a warranty accrual and, in this hypothetical scenario, is set at 0.3% of sales revenue.[45] The warranty accrual provision anticipates the expenditures for cost of quality for the product. Warranty costs up to this amount are covered by the allotment. But when warranty costs are in excess of the accrual, gross margin is consumed beyond the amount the supplier was prepared to relinquish for CoPQ. The accrual, then, is a way to gage $E(C_{VQC})$—any visible quality costs above the accrual value exceed the "target" for CoQ.

The model assigns 1.9% of the sales price for every actual warranty claim. This is the amount that *Warranty Week* reported to be the average claim payment made by automotive part suppliers in 2013. If a quality issue is severe enough to lead to litigation, a factor of 0.57% of sales will be charged for every incident. This factor reflects the legal cost paid by U.S. Fortune 200 companies in 2008 (Duke Law School, 2010).

Opportunity Costs.

Opportunity costs, $E(C_{OC})$, are difficult to characterize and capture. In a sense, opportunity costs can be partially represented by debiting ROS by the gross margin of each part

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[44] Based on a review of several recent NC tickets from a North American OEM, this assumption is conservative.

[45] *Warranty Week* (n.d.) reported warranty accruals among all US automotive part suppliers ranged from 0.95% of sales in 2007 to 0.58% of sales in 2015. The best-in-class automotive electronic parts supplier had accruals set at 0.3% of sales in 2008—the latest survey of this segment. From this, 0.3% was taken as an accrual value that (a) is realistic for the segment, and (b) would require the minimal amount of margin to be surrendered to cover CoPQ .

× the number of parts replaced due to a quality concern in the field.[46] The line time devoted to building these replacement parts is time in which saleable product could be built, but is not. The replacement part displaces a saleable part. It therefore not only represents unrecovered cost, it is also a unit of lost profit. Thus, opportunity costs will be accounted for in the model by moving the gross margin for every non-conforming part into the cost column of the ledger.[47, 48]

No attempt will be made to include the very real but nebulous costs associated with lost business, brand damage, etc. While these are considered substantial opportunity costs, they are not immediately felt and they are not clearly associated with a particular quality incident. Further, an FMEA team would quickly come to see that the FMEA cost projections which included the cost of lost business would over estimate the "actual" affects that standard indices provide. It would not take long before the projections would be dismissed as failing face and criterion validity tests.

Sensitivity Analysis: Cost consequence vs. Severity and Occurrence levels.

Monte Carlo simulations will be run at each of the three severity levels, Conditioned response, Return / No buy, and Safety / Legal, with the cost profile appropriate to the severity

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[46] *CSIMarket.com* places the gross margin for the "Electronics Instruments and Control Modules" industry for Q1, 2015 at 26.88%. The price of a control module with mid-line features in volumes of around 200K will be taken to be 38.50 USD. Given the manufacturing cost structure used here, gross margin for this study becomes 19.0% [(price – mfg cost)/price].

[47] As mentioned above, Rhee and Ishee set opportunity costs equal to down time × an hourly opportunity cost figure. This hourly opportunity cost figure is presumably defined by the user and that definition varies from user to user. Rhee and Spencer (2009) even note that some users take the entire cost of the facility and line equipment, amortized over the operating life, as the value of this hourly opportunity cost.

[48] Managed in this way, $E(C_{PIQC}) + E(C_{OC})$ is simply the sales price of each piece of product that is built as a replacement of a field failure. The cost of goods sold represents invisible costs of replacing the product and the profit lost on the sale of the replacement part is the opportunity cost. If validated, this would hand the FMEA teams a very easily captured measurement of cost.

level and claims varying with Occurrence ranking. For each occurrence rank, the C/1000 value[49] assigned to that rank in table 2 will be used to establish the number of claims associated with that 'O' ranking. The growth in claims that will be realized as the occurrence ranking is moved upward is appreciable. Figure 5 relates the occurrence rank to the nominal C/1000 value AIAG assigns to it. The curve describes a power function relationship between the independent variable and the dependent variable. ($Y = 4\text{E-}06\ X^{7.3866}$; $R^2 = 0.9966$).

Table 2.

The incidents per vehicle associated with each occurrence ranking level (Reprinted from Potential Failure Mode and Effects Analysis (FMEA), 4th Edition 2008 Manual with permission of FCA, Ford and GM Supplier Quality Requirements Task Force.).

Likelihood of Failure	Occurrence of Cause - PFMEA (Incidents per items/vehicles)			P_{pk}	Rank.
Very High	≥ 1 in 10	≥ 100/1000	≥100000 ppm	< 0.55	10
	1 in 20	50/1000	50000 ppm	≥ 0.55	9
High	1 in 50	20/1000	20000 ppm	≥ 0.78	8
	1 in 100	10/1000	10000 ppm	≥ 0.78	7
Moderate	1 in 500	2 /1000	2000 ppm	≥ 1.00	6
	1 in 2000	0.5/1000	500 ppm	≥ 1.20	5
	1 in 10000	0.1/1000	100 ppm	≥ 1.30	4
Low	1 in 100000	0.01/1000	10 ppm	≥ 1.47	3
	≤1 in 1000000	≤0.001/1000	1 ppm	≥ 1.67	2
Very Low	Failure is eliminated through preventive control				1

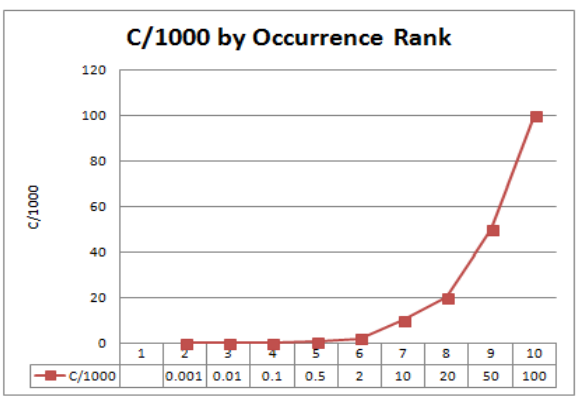

Figure 5. Occurrence rank scores graphed against the c/1000 (conditions per 1000 vehicles) value they represent.

49 C/1000 — "conditions per 1000 vehicles"—groups all quality concerns that lead to a warranty claim (i.e., the "conditions") into an index of supplier quality. The annual claims can be found by multiplying the C/1000 value by the number of vehicles for the year and dividing by 1000.

The C/1000 value used in the simulation will be the value established for the occurrence ranking selected for the run. It will follow a triangular function with the min and max set at the point half way between the C/1000 for the selected occurrence value and C/1000 value for the next lowest and next highest occurrence ranks respectively. The most likely value will be the C/1000 value assigned to the selected occurrence rank score.

Table 3.

The AIAG severity ranking showing the grouping suggested by Harpster (Ranking table reprinted from Potential Failure Mode and Effects Analysis (FMEA), 4th Edition 2008 Manual with permission of FCA, Ford and GM Supplier Quality Requirements Task Force.).

Severity					
Effect	**Severity of Effect on Product (Customer Effect)**	**Effect**	**Severity of Effect on Process (Manufacturing / Assembly Effect)**	**Rank.**	
Failure to Meet Safety and/or Regulatory Requirements Hazardous with warning	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.	**Failure to Meet Safety and/or Regulatory Requirements Hazardous with warning**	May endanger operator (machine or assembly) without warning.	10	Safety / Legal
	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.		May endanger operator (machine or assembly) with warning.	9	
Loss or Degradation of Primary Function	Loss of primary function (vehicle inoperable, does not affect saft vehicle operation).	**Major Disruption**	100% of product may have to be scrapped. Line shutdown or stop ship.	8	Return / No buy
	Degradation of primary function (vehicle operable, but at reduced level of performances).	**Significant Disruption**	A portion of the production run may have to be scrapped. Deviation from primary process including decreased line speed or added manpower	7	
Loss or Degradation of Secondary Function	Loss of secondary function (vehicle operable, but comfort/ convenience functions inoperable).	**Moderate Disruption**	100% of production run may have to be reworked off line and accepted.	6	
	Degradation of secondary function (vehicle operable, but comfort/convenience functions at reduced level of performance).		A portion of the production run may have to be reworked off line and accepted.	5	
Annoyance	Appearance of Audible Noise, vehicle operable, item does not conform and noticed by most customers (>75%).	**Moderate Disruption**	100% of production run may have to be reworked in station before it is processed.	4	
	Appearance of Audible Noise, vehicle operable, item does not conform and noticed by many customers (>50%).		A portion of the production run may have to be reworked in-station before it is processed.	3	Conditioned response zone
	Appearance of Audible Noise, vehicle operable, item does not conform and noticed by discriminating customers (<25%).	**Minor Disruption**	Slight inconvenience to process, operation or operator.	2	
No effect	No discernible effect.	**No effect**	No discernible effect.	1	

Based on the zero kilometer return data for a similar electronic module, the number of zero kilometer returns that are managed by the manufacturer each year has averaged 25. In the simulation, zero km returns will be allowed to vary randomly between 1 and 30.

While the exact costs of a given failure cannot be completely anticipated, the simulation will assume that failure modes having severity of 9 and 10 will bring Litigation costs. It is reasonable to suppose that, if the occurrence of such high severity failure modes exceeds a certain level, a NHTSA mandated recall can result. NHTSA requires that 75% of the replacement stock must be built up before a recall can be initiated. This will require a cost provision for bank builds, material order costs, transport costs, etc. A scenario involving a recall is being considered but will not be included in the data that is subjected to validation.

For severity rankings that fall in the conditioned response area, the full number of incidents for a given occurrence do not show up as warranty claims. Rai and Singh (2009) refer to these types of failures as "soft failures". They would agree with Harpster that, for soft failure modes, the vehicle owner is either unaware of the problem or they consider it no more than a nuisance that is not worth seeking service to correct. But, in early life, a new car owner is highly sensitive to any flaw or imperfection. Every effort is placed into maintaining the "show room" quality of the vehicle and, with full warranty coverage, no financial downside is perceived. Rai and Singh suggest that, in the first few months after a vehicle purchase, it is not unusual to see up to 9% of all service activity on a vehicle line during the warranty coverage period. In this study, all simulations done for the conditioned response scenario will allow a slightly more conservative value of 7% of the claims to impact CoQ.[50]

Each Monte Carlo simulation will run 5,000 iterations (sample size of 50 – standard random sampling) with the cost consequence determined for each condition of severity at each

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[50] The module is located under the console or instrument panel. It is covered by an interior trim feature and out of view of the end user. Minor issues with form and fit are simply not visible to the user. Functional problems will telegraph their presence by lighting a warning lamp on the instrument cluster. The lamp is a Bernoulli system—it is either on or off. No information on the type of problem that led to the "lamp on" condition is provided, but the owner's manual requires the user to seek immediate service action. Consequently, the user cannot take a casual view to any quality issue – cosmetic or functional…and issues in the conditioned response regions will not involve functional considerations. The conditioned response regions will be included in the simulation but the development of the scale for cost consequence of an airbag control module will only consider the severity categories of Return/No buy and Safety/Legal.

occurrence rank. The results of this will provide a CoQ value (reported as percent of sales) for every combination of severity and occurrence.

Cost Consequence Scale Development

The Monte Carlo simulation will produce a set of distributions of the costs that can be expected for every severity level (in the grouping of Safety/Legal, Return/No Buy, and Conditional Response) at every level of occurrence. Using fuzzy set techniques, a membership function will assign locations on a 10 point ordinal scale to these costs based on their measure of central tendency. A matrix will be developed from this that relates the severity rank value on one axis to the occurrence rank value on another. The cost scale values will form the field of the Cartesian space allowing an FMEA team to determine the cost rank given the severity and occurrence ranks that have been assigned to the failure mode.

Evaluation of the Ranking Matrix for the Cost Consequence of Failure

Criterion validity.

The development of a ranking scale for the cost consequence of quality issues requires validation. More specifically, the criterion validity of the instrument must be assessed. Shuttleworth (2009) defines criterion validity as a process of calibrating the instrument against a known standard. To do this, field performance data from a case study of an electronic module manufacturer will be reviewed. Where a significant quality incident is found, the cost of quality data will be gathered on the failure. In most instances, these data are limited to warranty and zero mileage costs, but those costs would be inclusive of fees and penalties (e.g., NTF cost sharing, line stop charges, etc.). Where it is known that containment or a field response (e.g., software reflash at the OEM's facility) was undertaken, the costs of those campaigns will be included in the total costs.

The component that caused the field failure will be identified. The FMEA entry for the circuit or component will be reviewed and the severity and occurrence values assigned to the failure mode will be used to determine the cost consequence ranking that would have been established for that failure mode. The cost as percentage of sales for that cost ranking will be compared to the actual costs for the field issue using a Chi square test of association and Fisher's exact test of 2 proportions to determine whether the samples differ significantly. As this is essentially a comparison of a test instrument value against an actual condition, it is being presented as a Bias assessment.

Usability.

A formal analysis of construct validity is not planned. The ability to establish a scale that is akin to the current ranking scales used in FMEA in terms of construction and use will be the factor that will lead to the assessment of usability. As mentioned above, a matrix or table will be developed for the cost consequence of a failure mode as a function of severity and occurrence rank scoring. It is expected that this will not present any issues as regards ease of use. It requires no head scratching, discussion, or supposition to award a cost rank to a failure mode. The cost consequence ranking will simply require a look-up action.

Pareto Optimality Assessment

The Cost scale developed above will be used to associate an ordinal indicator of cost consequence to every combination of severity and occurrence. When this is completed, it will be possible to develop a risk priority scale which, like RPN, is the product of three ordinal dimensions of risk—Severity × Occurrence × Cost. These "cost priority numbers" (CPN) for the severity values that lie in the "Return -No Buy" region will be compared to the values in the "Safety/Legal" region using a pairwise difference test. This test will allow the difference between every combination of CPN from those two regions of the risk ranking scale to be determined. A Sign test will establish the breakdown of instances where the CPN of the higher severity region is above, equal, or below the CPN of the lower severity region. This will be compared to results obtained from a similar treatment of RPN using a Chi Square test of association. The Chi Square test of the Sign test output will show (a) whether the difference *within* each scheme shows a greater number of lower severity priority scores above those of the higher severity scores (i.e., more opportunities for optimality violations), and (b) whether there is a significant difference *between* the RPN and the CPN sign test values.

Note: The assessment of the relative opportunity for Pareto optimality violation using CPN is considered a theoretical exercise at best. The ME-MCDM technique of Franceschini and Galetto (2001) offers a means of weighting the risk prioritization scales to favor whichever dimension that is seen as important to the FMEA team. This makes any issues of Pareto optimality with an RPN-like prioritization scheme immaterial. Furthermore, an important assumption behind the development of a cost index for FMEA is that it will reveal circumstances where a potential failure mode that has a severity that is low enough to be disregarded as a concern brings about a cost consequence that is large and warrants action. If the seriousness of the effect of a failure mode on a customer is not enough to get anyone's attention, the "cha-ching" of the cash register will.

Summary

A summary of the methodology is provided in Table 4.

Table 4.

A chart summarizing the Methodology for this research.

Summary of Methodology	
Research Question 1	Can cost of quality considerations be included in the a priori assessment of risk done with FMEA?
Hypothesis 1.	Cost of Quality cannot be modeled in a fashion that is able to associate the costs of failure modes, based on the permutation of elements of the FMEA characterization process, that significantly correlates to actual costs as determined from historical case data
Method of Analysis.	1. Establish the components of cost that are typically associated with each level of severity ranking at each occurrence level. 2. Run Monte Carlo simulations for each permutation of severity and occurrence with each of the cost factors allowed to vary as appropriate to that factor. 3. Using Fuzzy set associations, relate the results of the simulation in a ten point ordinal scale. 4. Develop a look-up matrix that allows the cost of failure rank to be determined for each combination of severity and occurrence. 5. From a case study of actual field failures, gather the costs of the failure, as percent of sales, for several examples. 6. Find the FMEA rankings that were assigned to each of the failure modes selected in step 5 from the original FMEA developed for the product. 7. Compare the costs that would be expected based on this original ranking with the costs that actually resulted from the failure mode in the field to determine if a significant difference between expected costs and actual costs exists.
Means of testing the hypothesis.	Chi square test of association and Fisher's Exact Test of 2 proportions
Research Question 2	Can a cost index be developed that is consistent with the established risk ranking methodology used in FMEA?
Hypothesis 2.	A consideration of the cost consequence of a failure does not lend itself to the FMEA ranking methodology as it requires elaborate, product specific computations that (a) can only be developed in a post hoc analysis of cost of quality, and (b) defies a simple ordinal listing.
Method of Analysis.	Subjective analysis
Means of testing the hypothesis.	Inspect the results of research question 1. The feasibility of a cost scale will be evident by the success at achieving steps 1 through 4 of the method of analysis.
Research Question 3	When costs of field failures are considered in the FMEA analysis, does the susceptibility to Pareto Optimality concerns become unreasonably high compared to RPN?
Hypothesis 3.	Pareto Optimality of ordered risk ranking in an FMEA is not altered by the introduction of cost of quality in the risk consideration.
Method of Analysis.	1. Conduct pairwise difference test of the priority scores of the Return/No buy region and the Safety/Legal region of (a) CPN and (b) RPN priority schemes. 2. Subject the difference values from 1(a) and 1(b) to a Sign test to obtain the number of pairs in each scheme which had lower severity scores above/below/equal to higher severity scores. 3. Determine whether between and within results from 2 are significant using a Chi square test of association of the sign test values.
Means of testing the hypothesis.	Chi square test of the results of a sign test of the pairwise difference between RPN vs. CPN

CHAPTER 4

RESULTS

Overview

This chapter discusses the method of analysis and means of testing employed to assess each of the hypotheses developed above. The first section presents the structure and outcome of the Monte Carlo simulations. These simulations provided the model of the cost consequence of failure with conditions that characterize varying combinations of severity and occurrence. This produced a distribution of cost of quality values for each of the three levels of severity at each of nine levels of occurrence. Using fuzzy set associations, the average CoQ value for each of the simulation outcomes for the Return / No buy and Safety / Legal regions were combined to form an ordinal scale of cost ranking. Using this scale, a look-up matrix was developed that provided a cost ranking for each combination of severity and occurrence. The criterion validity of this system was assessed using some actual cost figures derived from a case study.

Multiplying the cost consequence values by the corresponding severity and occurrence values, produced a risk priority ranking scale that corresponded to the risk priority number system used in FMEA. The chapter concludes with an examination of the susceptibility of this CPN system to Pareto optimality violations relative to that experienced by the RPN system.

Establishing Cost Consequence Ranking

Monte Carlo simulations

Using the CoQ parameters described above, Monte Carlo simulations were set-up to establish the cost consequences of failures at the three severity levels (a) Conditioned Response, (b) Return / No buy, and (c) Safety / Legal. At each severity level, the occurrence value advanced from O=2 through to O=10. For severity rankings in the Return / No buy and the Safety / Legal portions of the chart, every claim invoked replacement costs, sorting costs, and warranty fees. Every zero km return led to an NCT charge and the assessment of failure analysis (FA) costs. For severity rankings in the Safety / Legal zone, legal fees were also included. The Conditioned Response values differed in that no sorting was performed and only 7% of the failed product was replaced.

9 simulations were run for each of the three severity levels—one run for each of the Occurrence rankings from 2 to 10. The simulation allowed the frequency values to vary about the most likely value, established by the conditions per thousand vehicles appropriate for the ranking level, following a triangular distribution. Each Monte Carlo run consisted of 5000 iterations (here termed periods) using a Latin Hypercube sampling method with a sample size of 500 and an alpha value of 0.05.

The c/1000 values generated in the simulation were converted into claims using equation 12. The number of claims was multiplied by the sales price of a module and this, in turn, was multiplied by 0.019 to establish the warranty component of $E(C_{VQC})$ for the period.

$$\text{Claims/yr} = \text{conditions per one thousand vehicles x (annual sales volume} \div 1000) \qquad (12)$$

The number of zero kilometer returns for the period was randomly generated (with values ranging from 1 to 30). This number was used to compute failure analysis costs according to equation 13. Zero km returns were also used to establish the NCT charges ($533 × the number of returns).

$$\text{FA costs} = \text{zero km returns} \times \text{hours spent in analysis} \times \text{hourly labor rate} \qquad (13)$$

Containment costs, as mentioned above, were set at the cost of three inspectors working 10 hours per day times the number of days assigned to the sort (randomly generated with values ranging from 2 to 5 days). The simulation assigned only one sort for the period.

Module replacement costs were represented by the number of claims plus zero km returns times the per unit costs of manufacturing, corrected for scrap. Opportunity costs were obtained by multiplying the number of returns by the gross margin per module. Finally, a factor representing the annual legal fees—0.0057 × annual sales—was added to the costs of any period for which the severity rank fell in the ranking level of Safety / Legal. The rolled up costs were converted into percent of sales using the volume assumption for the period.

The cost of quality as a percentage of sales, determined in this way for each of 5000 periods, was averaged together to establish the cost consequence for the combination of severity level and occurrence for the run. Table 5 gives the results of this CoQ determination. Figure 6 shows the relationship between these values graphically. From this figure it can be seen that the amount set aside to cover warranty costs (the “accrual”) was exceeded at all occurrence levels of the failure modes in the Safety / Legal range (S=9 and S=10). In the Return / No buy severity region, costs exceeded accruals at the point where the frequency of occurrence reached 2 conditions per 1000 vehicles (O=6). Even severity rankings in the Condition Response region saw costs exceed accruals at O=8 and above.

Table 5.

The average cost of quality, as a percentage of sales, for each of three severity levels at nine levels of occurrence ranging from O=2 to O=10.

	CoQ (%sales)		
	Conditioned Response	Return / No buy	Safety / Legal
2	0.053	0.068	0.6375
3	0.132	0.142	0.712
4	0.157	0.18	0.75
5	0.161	0.235	0.806
6	0.177	0.481	1.05
7	0.23	1.23	1.8
8	0.323	2.55	3.12
9	0.537	5.59	6.16
10	0.933	11.26	11.83

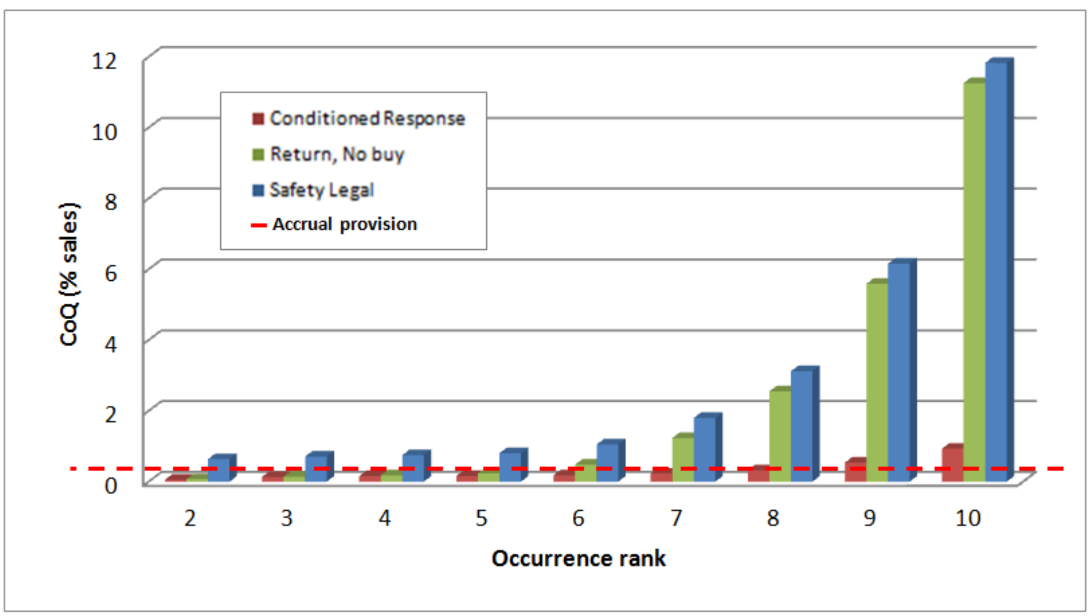

Figure 6. A bar graph showing the CoQ values obtained at each occurrence level in the severity categories of Conditioned Response, Return / No buy, and Safety / Legal. The red dotted line is set a 0.3% of sales. This is the amount that was set aside to cover warranty costs at the start of the program.

Cost Consequence Scale development

Fuzzy Utility.

The cost levels that were determined for the Return / No buy and the Safety / Legal severity regions were developed into a single 10 point ordinal scale of cost consequence following Dong (2007). In his work, Dong established a Risk Priority Index using "fuzzy" sets based on the subjective estimation of cost as a function of severity, made by five engineers. Membership in a utility set was established for each collection of estimations using equation 14.

$$U_{ij} = C_{ij} \div C_{10j} \tag{14}$$

Where:

U_{ij} = the utility value assigned to the estimate *i* of engineer *j*

C_{ij} = the *i*th cost estimate

and C_{10j} = the highest value for the cost driver under consideration

In this way, an ordering of cost estimates was achieved with each level being a proportion of the highest cost level, set at 1.

Dong then arranged each engineer's utility values in a triangular membership function with the base of the triangle (membership grade = 0) set at the minimum and maximum utility scores for that engineer, and the apex (membership grade = 1) set at the value determined from equation 15.

$$\sum_{j=1}^{n} U_j / n \tag{15}$$

Once arrayed in this fashion, defuzzification was done to determine the Risk Priority index to assign to the evaluation. For this, Dong used the Center of Maximum technique developed by Hellendoorn and Thomas (1993) (from Dong, 2007). This technique assigns the crisp value for the set as the average of the minimum value and the maximum value in the fuzzy set.

Using this methodology, fuzzy utility sets were developed for the cost consequence values for the Return / no buy and Safety / Legal severity regions. Table 6 gives these fuzzy set values along with the Center of Maximum values for each pair of entries at each occurrence level. Crisp values were obtained by multiplying the Center of Maximum value at each level by the average value of C_{10} for the two sets.

Table 6.

Results of the fuzzy utility set development using cost consequence data.

Fuzzified costs		De-fuzzified	
Return	Legal	CoMax	Crisp CoQ
0.006	0.054	0.030	**0.35**
0.013	0.060	0.036	**0.42**
0.016	0.063	0.040	**0.46**
0.021	0.068	0.045	**0.51**
0.043	0.089	0.066	**0.76**
0.109	0.152	0.131	**1.51**
0.226	0.264	0.245	**2.83**
0.496	0.521	0.509	**5.87**
1.000	1.000	1.000	**11.54**

Average C_{10} = 11.54

Note. The fuzzy utility values of the costs determined for the Return / no buy ("Return") and the Safety / Legal ("Legal") regions are given in the box on the left. The Center of Maximum values ("CoMax") for each pair and the Crisp CoQ values, in % of Sales, derived from these are shown on the right.

Cost Consequence Matrix.

Figure 7 shows these crisp CoQ values against the values obtained from the Monte Carlo simulation at each occurrence rank. These Crisp CoQ entries were assigned ranking values 2 through 10— from lowest cost to highest— and became the scale of cost consequence for use in FMEA development. Figure 8 shows the polynomial regression of cost, as percent of sales, on CoQ ranking score.

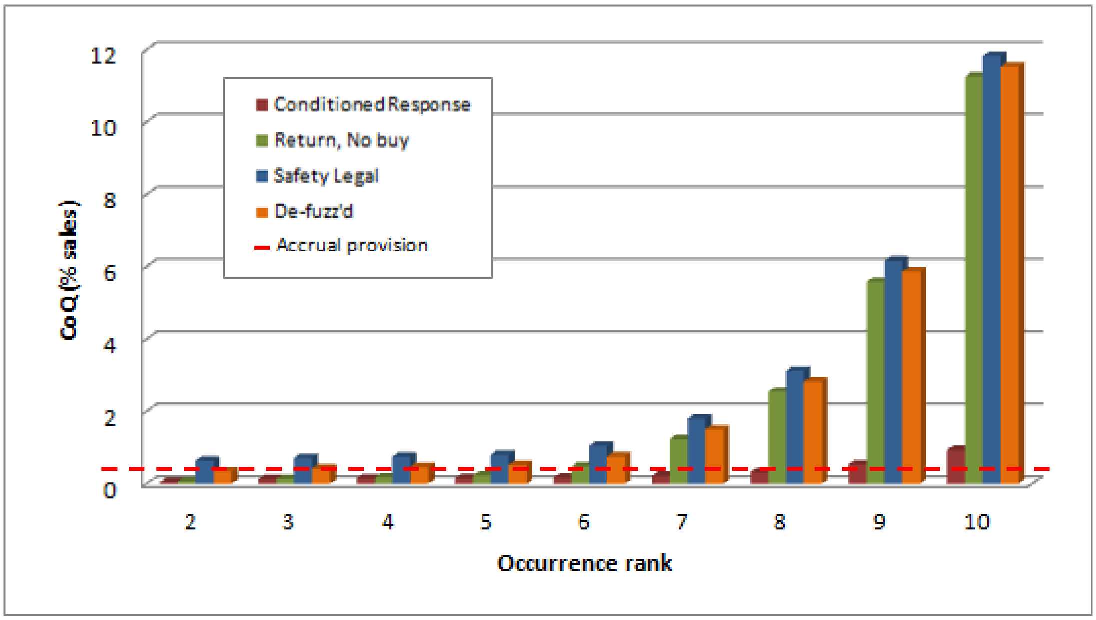

Figure 7. The bar chart shown in figure 6 with the crisp values of the cost consequence of failure at each level of occurrence added (orange bars). The chart shows the fuzzy sets produced values that track closely with the costs found for Return / No buy and Safety / Legal.

A matrix or look-up table was developed that allows a user to determine the cost consequence rank score that is appropriate for any given combination of Severity and Occurrence rank scores. This matrix is given in table 7. Figure 9 maps the relationship between Severity, Occurrence, and cost consequence as a wire diagram in a 3D space.

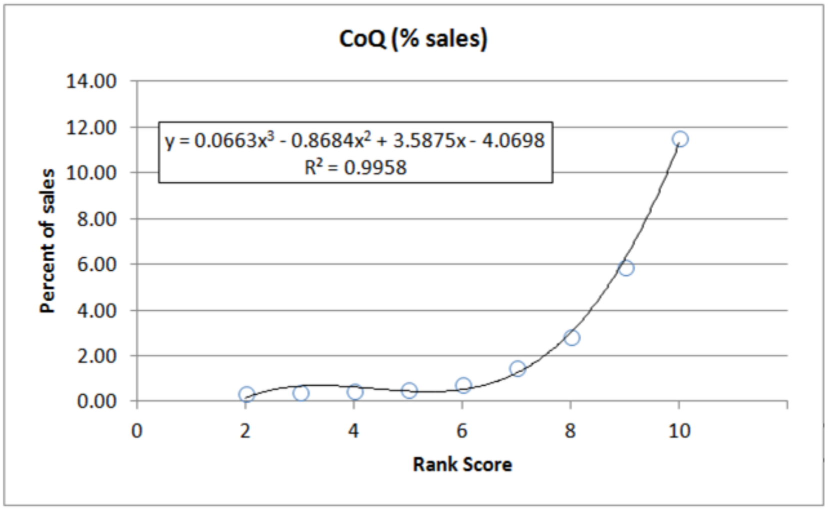

Figure 8. The values for cost consequence plotted against the rank score assigned to each value are shown. The equation of a polynomial regression of these points is given in the box above and to the right of the curve.

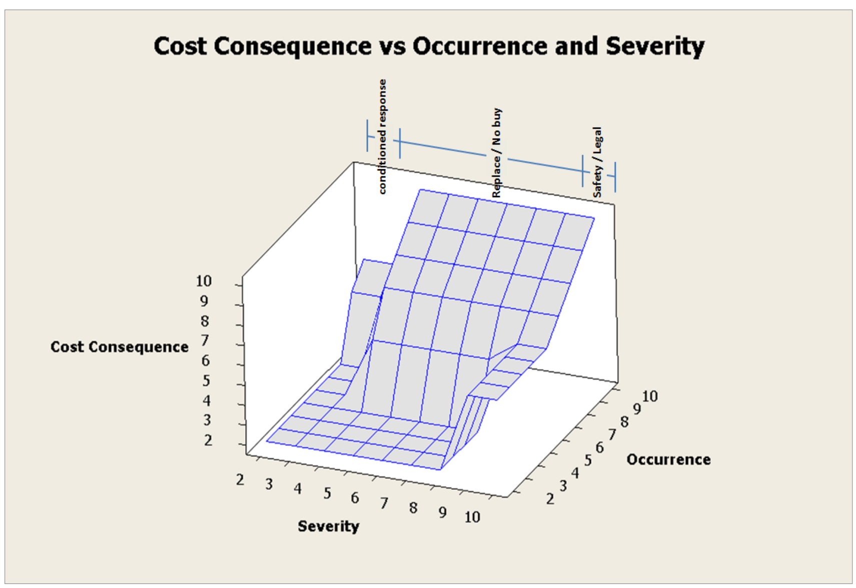

Figure 9. Wire frame diagram of the cost consequence that related to various combinations of Severity and Occurrence ranking scores.

Table 7.

The look-up table of cost consequence rank scores.

Severity \ Occurrence	2	3	4	5	6	7	8	9	10
2	2	2	2	2	2	2	2	5	6
3	2	2	2	2	2	2	2	5	6
4	2	2	2	2	5	7	8	9	10
5	2	2	2	2	5	7	8	9	10
6	2	2	2	2	5	7	8	9	10
7	2	2	2	2	5	7	8	9	10
8	2	2	2	2	5	7	8	9	10
9	6	6	6	6	6	7	8	9	10
10	6	6	6	6	6	7	8	9	10

Note. This table can be used to determine the cost consequence ranking score to associate with a given combination of Severity and Occurrence scores when developing an FMEA.

Criterion Validity of the Model of Cost Consequence of a Failure Mode

A Case Study

Warranty data was obtained for a field issue involving a failure of a component on an electronic module. This module was similar to the hypothetical product developed for the CoQ model described above. Three years of data on this issue showed that the component was failing in service (fusing open) at a frequency that roughly fit an occurrence ranking of '4' (i.e., C/1000 = 0.099).[51] The warranty settlement arrived at between the supplier and the OEM for this product established that portion of the costs incurred in responding to the field issues that was to be assumed by the supplier. Those costs covered the cost of replacing the original modules and the

[51] The ranking for occurrence of this issue will be based on actual incident data. This will allow the actual costs to be assessed assuming the occurrence ranking was based on a knowledge of the physics of failure and conditions of use that aligned with what, in fact, transpired. Each year will be evaluated discretely as the model assumes a one year window of service life.

labor costs for the replacement operation. For year 1, the total remittance paid by the supplier amounted to 0.037% of the sales of the modules. For year 2, the costs came to 0.065% of sales and in year 3, the figure was 0.060%.

Comparison of the Model to the Actual Costs

The DFMEA ranking of the severity of an open at the circuit that carried this component was '7'. The look-up table for the cost consequence of a failure mode of this severity with occurrence ranked at '4' gives the value of '2'. The "Crisp" value assigned to a cost consequence ranking of '2', 0.35% of sales, is an order of magnitude greater than the actual annual expenditures for the cost of external quality from the case study. This is not unexpected as the model includes cost considerations other than warranty expenditures alone.

To better understand the effectiveness of the model, an "apples to apples" comparison was made between the actual warranty costs from the case study and the replacement and warranty costs taken alone from the cost consequence model of the Return / No buy region at occurrence of '4'. This gave a cost of poor quality value of 0.0203% of sales. A Chi Square test of association comparing each of the three years of actual settlement payments to the predicted value of the model showed that no significant difference existed between the outcome percentages ($p = 0.276$ at $\alpha = 0.05$). This is shown in figure 10.

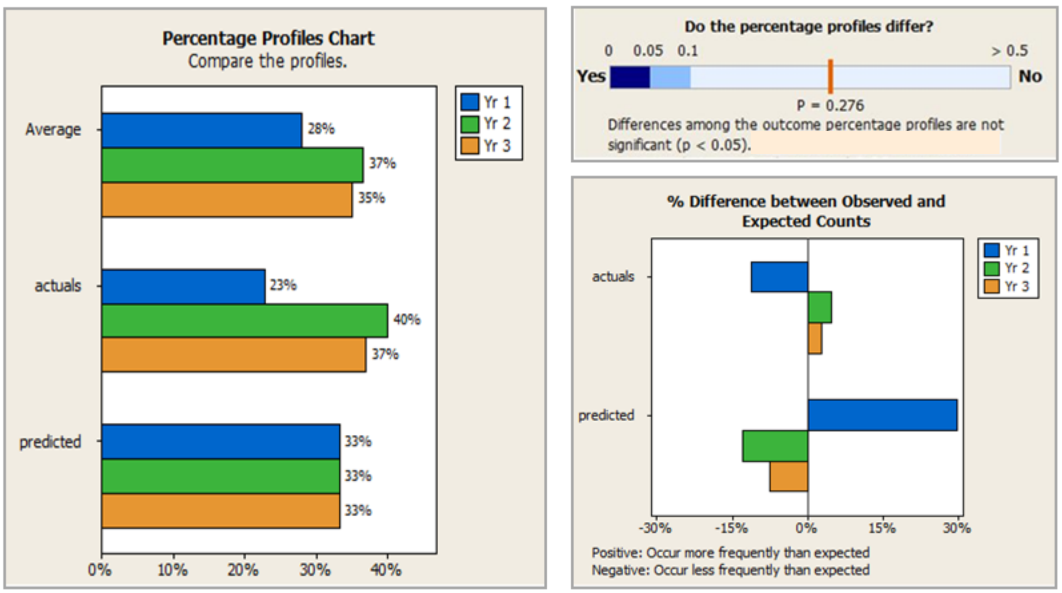

Figure 10. A Chi Square test of association comparing the 3 years of actual warranty payments for a failure mode of S = 7 and the values the model assigns for replacement costs and warranty.

Fisher's exact test of two proportions was performed on the actual values vs. the Monte Carlo run of the Return / No buy region at Occurrence of '4' using only the warranty and replacement aspects of the model.[52, 53] The test determined the difference between the proportion for the average actual costs minus the proportion for the warranty only costs of Return / No buy at O = 4 was 0.034 with the 95% CI at (0.026 to 0.042). This showed the proportions to be

[52] *Minitab* states "Fisher's exact test is accurate for all sample sizes, but can only be calculated when the null hypothesis states that the population proportions are equal" (*Minitab* "Help" for 2 Proportion testing, n.d.).

[53] *Minitab* required the proportions to be presented as integers for events per trial. This required coding of the data—CoQ as % of sales values were converted to units of cost per 3000 units of sales (100 modules selling at $30 dollars per module).

significantly different with the actual costs higher than the warranty only model values (p = 0.000 at $\alpha = 0.05$).

Pareto Optimality: RPN vs. Cost Consequence

General Relationship of RPN and CPN

A difference test was performed between the RPN scores of a traditional prioritization of risk and the scores that result when severity, occurrence, and cost consequence are combined multiplicatively. This test subtracts all CPN values from each of the RPN scores in a pairwise manner. A positive difference indicates that the RPN score (the minuend) was greater than the CPN score to which it was related (the subtrahend) and a negative value would indicated the opposite condition with respect to relative magnitude.

Figure 11 shows a histogram of the pairwise difference values that resulted from the difference test performed on all RPN vs. all CPN. If the zero sum condition existed between RPN and CPN, this histogram would be symmetrical with the median at zero. However, the histogram in figure 11 is skewed left (Skewness = -0.33). A sign test set the median value for these differences at 2.00. 7300 values were equal to the median; 319,890 were below the median; and 328,910 were above the median. The difference values were significantly higher than the median ($p = 0.000$ at $\alpha = 0.05$).

A Mann-Whitney test of rank scoring compared the positive difference values to the absolute value of the negative difference values. This test showed that the median of the two scoring systems, when corrected for ties, were significantly different ($p = 0.0000$ at $\alpha = 0.05$). While there are more instances of RPN exceeding CPN (328,910 as compared to 319,891), the median difference in the rank scores is greater for CPN (220 as compared to 132). This is represented in figure 12.

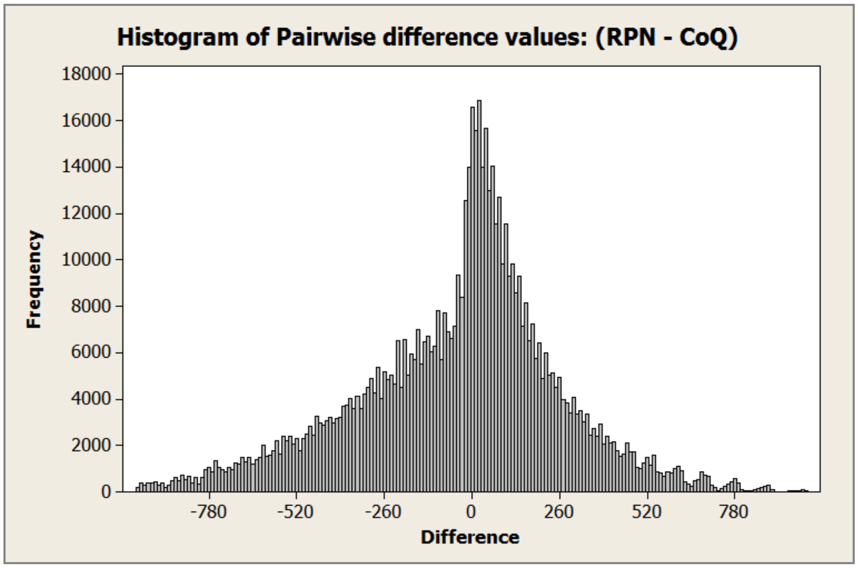

Figure 11. Histogram of the pairwise difference values obtained by subtracting all CoQ values from all RPN values.

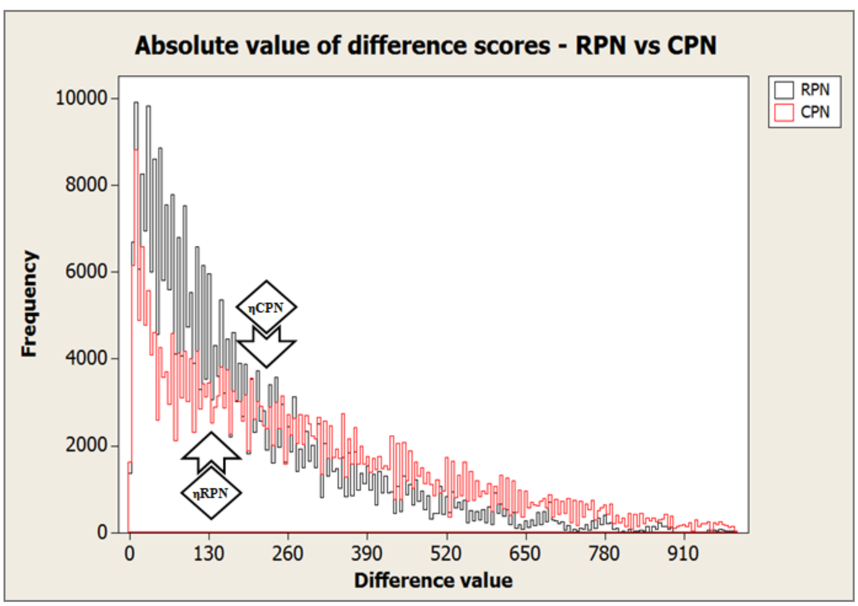

Figure 12. Histogram of the absolute difference scores between RPN and CPN. The location of the median (η) for both CPN and RPN are indicated with arrows.

POV: Within and Between Comparison of RPN and CPN

The pairwise difference values within each scale–Return / no buy vs. Safety / Legal–were obtained. Every Return / no buy value that is larger than a paired Safety / Legal value is a potential optimality violation. It represents an instance in which a lower severity failure mode would displace a failure mode with higher severity in importance by virtue of the fact that it presented a higher risk prioritization score. Comparing the number of such opportunities produced by RPN to that of CPN would allow a judgment to be made as to the scale that is more susceptible to this problem.

A sign test of these difference values for RPN showed the median difference was -88. 880 values were equal to the median; 52,584 values were below the median; and 27,356 exceeded the median. In comparison, the CPN scores for Return / No buy vs. Safety / Legal had a median difference value of -184. 400 of the difference values equaled the median; 58,870 fell below the median; and 21,550 of the values were above the median. A comparison of the frequency distribution of the pairwise differences of RPN and CPN can be found in figure 13. This histogram and the sign test values suggest that the difference test scores are lower for CPN than the scores obtained from the RPN scale. A Mann – Whitney test shows a significant difference in the median rank values of the two distributions with CPN, having a median rank at -184, lying below RPN with a median rank of -88 ($p = 0.000$ at $\alpha = 0.05$). The median score for the difference is lower (more negative) for the CPN compared to the RPN scale and there are fewer difference values that are higher than the median value in the CPN scale. The Chi square test of association (table 8 and the supporting charts in figure 14) shows this relationship to be significant ($\alpha = 0.05$).

The test of association shows that the difference scores (Return – SL) for CPN had significantly more values below the expected value than did RPN.   CPN had fewer values equal to the expected median difference value than did RPN. Nonetheless, CPN still had a smaller number of values above the expected value than did RPN.

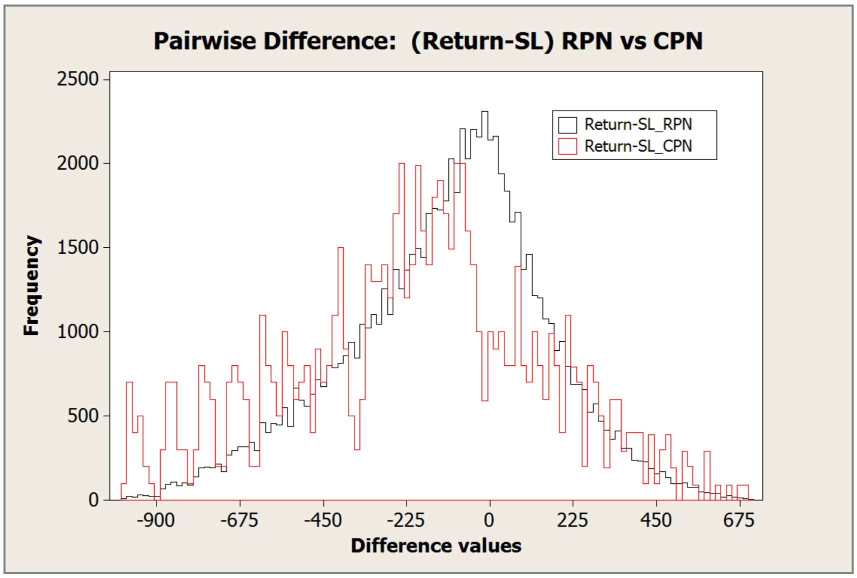

Figure 13. A histogram of the difference scores for the RPN in the Return / no buy (return) region vs. the RPN in the Safety / Legal (SL) region overlays the histogram for the differences scores for CPN (shown in red).

Table 8.

Chi square array: Observed vs. Expected values of the sign test of differences when Safety / Legal priority values are subtracted from the corresponding Return / no buy values for the scales RPN and CPN.

Observed and Expected Counts

	RPN		CPN	
	Obs	Exp	Obs	Exp
Below	52584	55727	58870	55727
Equal	880	640	400	640
Above	27356	24453	21550	24453
Total	80820		80820	

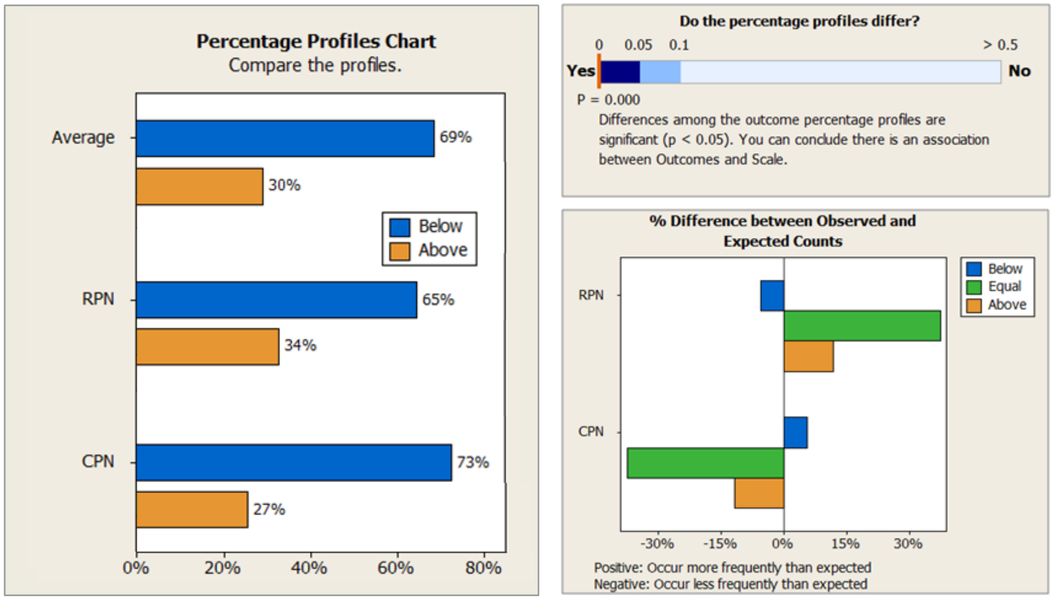

Figure 14. Chi square test of association comparing the pairwise difference values – "Return / no buy" minus "Safety / Legal" - for the RPN scale compared with those values for CPN. The Percentage Profiles Chart compares the profile for each scale to the average profile. The % Difference Chart gives the percent difference between observed and expected counts for each scale

A Mann-Whitney test found the median for the absolute value of the difference scores for "Return / no buy" minus "Safety / Legal" for CPN to be significantly different from the median value of RPN ($p = 0.0000$ at $\alpha = 0.05$). The median rank of the absolute value of the pairwise difference scores for RPN (172) was less than that of CPN (252) suggesting that the amount of the difference in CPN ranking in Return / no buy and Safety / Legal ranking tends to be larger than the difference found in RPN ranks. The graph of the absolute value of the pairwise difference scores of CPN and RPN is given in figure 15.

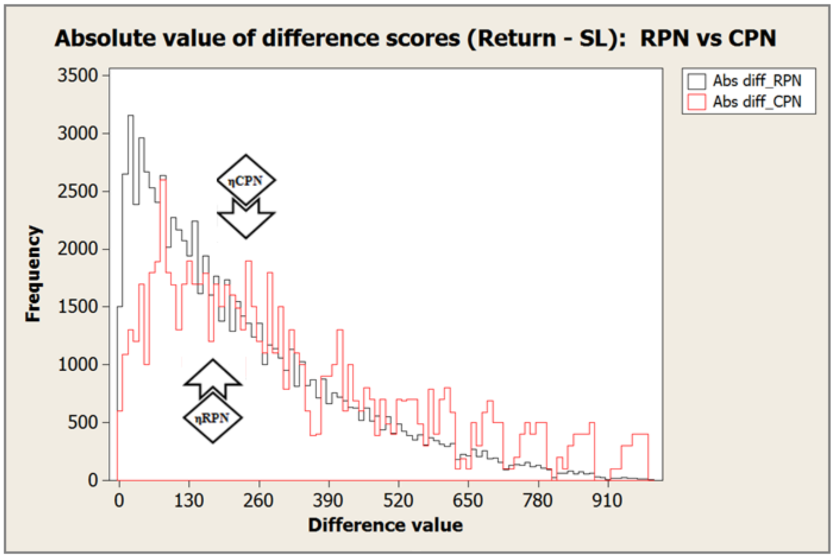

Figure 15. The histogram of the absolute value of the difference scores for "Return / No buy" - "Safety / Legal" is given for RPN (black line) and CPN (red line). The median rank value determined by Mann-Whitney is shown with arrows.

Summary

This chapter described the approach used to establish the cost of quality values, given as percent of sales, which would attend failures having effects that fall into each of three regions of severity at frequencies established by each of the levels of occurrence. When the cost consequence ranking of an actual field failure was compared to the costs that were actually incurred for that failure, it was found that the model tended to overestimate those costs. When those aspects of the model that more closely conformed to the actual costs indices were used in the comparison, the model was found to slightly underestimate the actual costs.

The relative susceptibility of CPN to Pareto optimality violations was found to be slightly lower than for RPN. The Chi square test of association conducted on the sign test values from a pairwise difference test of the Return / No buy regions compared to the Safety / Legal region of the two scales showed that CPN had significantly fewer instances of observed values above expected values than did RPN.

CHAPTER 5

DISCUSSION, CONCLUSION, AND RECOMMENDATIONS

Overview

This chapter begins with an examination of the hypotheses formed around each of the research questions in light of the results obtained from the research exercise. From this, a conclusion is presented that attempts to distill the findings into a final assessment of the problem. Finally, recommendations of activities that could be pursued to follow-up on this work are offered.

Hypothesis 1: Modeling Cost Consequences of failure modes with FMEA

This research effort presumes that the cost consequence of a failure could be estimated based on the values of severity and occurrence assigned to the failure mode effect when the DFMEA is developed. This would add to the understanding of the risk inherent in the design and it would be available to the team at a very early point in the development. If the cost consequence is considered to be serious, mitigation actions could be undertaken to reduce the probability that the effect would be realized.

In an effort to establish such a predictive capability, the cost consequence model was developed. To paraphrase George E.P. Box (1987), this model is wrong…but it may be useful.

To assess the degree of confidence one should place in its usability, a small sample of actual warranty data was obtained and used as the basis of a test of criterion validity. If the cost consequence model has merit, the cost values expected for the failure mode, as determined from the severity and occurrence ranking values of the DFMEA, should not be significantly different from those that actually attend a failure of that type in service.

The data concerned a component that had been rated Severity of ‘7’ and it demonstrated a failure rate that aligned with the AIAG Occurrence rank of ‘4’. The cost consequence for such a risk characterization would have been ‘2’— CoQ = 0.35% of sales. A comparison of this value to the actual cost consequence for the three years of the case study found the projected value to be significantly higher than the actual values. However, the projected value embraces costs that are not represented in the actual data. These data strictly dealt with the module replacement costs.

To evaluate the effectiveness of the model in projecting these actual costs, the values that were obtained for module replacement and warranty costs alone were extracted from the Monte Carlo run on the Return / No buy region at occurrence of ‘4’. These data were compared to the actual warranty values using a Chi Square test of association and this comparison showed that the model and the actual values are not significantly different at $\alpha = 0.05$. However, Fisher’s exact test of two proportions indicated that there was a significant difference between the two values with the model values falling below the actual warranty values. This latter test is taken to be a better reflection of the relative relationship between the two values as it is less susceptible to problems brought on by the small size of the sample of actual costs.

External CoQ is only one dimension of the cost consequence of a failure...and warranty payments are only one aspect of external failure costs. Unfortunately, no other costs could be obtained in this case study. This limitation is compounded by the problems associated with the small sample size. These facts notwithstanding, the results of the assessment require the rejection of the null hypothesis. The alternative hypothesis H_{a1}, which states that $CoQ_{\text{expected}} \neq CoQ_{\text{observed}}$, must be accepted.

Note that with slight adjustments, the model's warranty plus replacement costs can be brought into better alignment with the actual costs. By simply multiplying the replacement cost parameter by 2.25 and adding a factor for service labor (3 hrs × the labor rate used in the model),[54] p for Fisher's exact test approaches unity. The effect size of the original model [warranty + (1× replacement cost)] compared to the actual warranty values had a Cohen's d of 2.27 (25.01% overlap of the distributions). This is shown in figure 16. With the aforesaid adjustments, Cohen's d goes to 0.008 (96.01% overlap). Such an adjustment can be made as required to "calibrate" the model to a specific OEM warranty scheme and increase the criterion validity of the model.

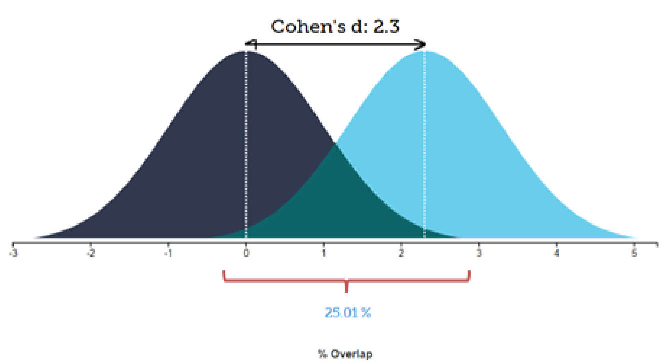

Figure 16. The effect size of the original model [warranty + (1x replacement costs)] compared to the average value of the actual warranty payments is shown. This has a Cohen's *d* of 2.27 (25.01% overlap). (Representation from Magnussen, n.d.).

[54] Three hours is the time allowance that has been established by the OEM in the case study for replacing this product. This figure was used to assess the labor costs portion of the actual warranty charges. The wage rate used here is the rate established above for non-union labor.

The $E(C_{VQC})$ factor of the model did not take into account the keystone pricing that the supplier had to accept in their warrant settlements with the OEM in the case study. Neither did the model attempt to estimate the cost of the service labor for the replacement. Yet using only the 1.9% of sales adjustment for warranty costs added to 1× replacement costs, the model still tracks well with the case study warranty remittance. The screening done here suggests that the model undershoots this one area of cost, but not by much. It therefore could be argued that the model returns a conservative estimate of the costs of quality and may, indeed, be useful in providing an engineering team with a reasonable gage of the minimum cost impact of a failure.

Hypothesis 2: Development of an Ordinal Scale of the Cost of a Failure Mode

Using fuzzy set methods, the cost estimates for each of the regions of severity at each occurrence level established with Monte Carlo simulations were developed into an ordinal scale that is similar to that currently used for ranking the dimensions of risk in an FMEA. Only the severity and occurrence rankings from 2 to 10 were used as AIAG considers a severity rank of '1' to indicate "No discernible effect" and an occurrence rank of '1' to indicate that the condition will not surface as a concern due to preventative measures. As a consequence the CoQ scale only spans a 9 point range from 2 to 10. However, the scale is similar in construction and use to the existing FMEA ranking scales. Furthermore, because it is based on occurrence, the line of best fit for the cost vs. rank score follows a high order polynomial regression line, similar to that of occurrence ranking.

There is no reason to reject the null hypothesis H_{02} : $Scale_{\text{SOD}} = Scale_{\text{CoQ}}$. The scale of cost consequence is equivalent in structure and function to ordinal ranking scales used for the other dimensions of risk assessed in an FMEA exercise.

Hypothesis 3: Potential for Optimality Violations

The pairwise difference test comparing all ranking combinations formed from ranking values 2 through 10 for each dimension of risk showed that there was a significant difference between the prioritization scales referred to as RPN and CPN. The sign test performed on the values of a comparison of these scales showed that a significantly higher number of values lie above the median. Since the signs of the difference test indicate which scale had a higher rank score at a given point in the sample space, the results showed the minuend—RPN—produced larger priority scores. But this first assessment (here termed the "General Relationship") matched the entire ranking scale, including the Conditioned response portion of the scale. This brought in values that caused the CPN scale to be skewed towards the low prioritization scores. In fact, the Mann-Whitney test of the absolute value of the difference scores showed that, even though more of the RPN scores were higher than the corresponding CPN scores, where CPN was higher, it was significantly higher than RPN.

In the "within comparison", the difference values were developed by subtracting the Safety / Legal scores from the Return / no buy score within a ranking scale. Comparing the results obtained for RPN and CPN in this test provides the evidence upon which H_3 can be adjudicated—every instance in which a positive difference value occurs represents a potential Pareto violation and the ranking scale with the greater amount of positive difference values would be the more susceptible scale.

The difference test showed that RPN had more Return / no buy values that were larger than the corresponding Safety / Legal values than did the CPN scale. The sign test showed a higher (less negative) median for RPN. The Chi square test of association showed the observed positive values exceed the expected value by an amount that was significantly greater for RPN than the amount found for CPN. From this it can be concluded that there are more opportunities for Pareto optimality violations (POV) using the RPN scale than there are in using the CPN scale. Based on this, it is felt that there is insufficient support for H_{03} and the alternative hypothesis, H_{a3} : $POV_{RPN} \neq POV_{CPN}$, is accepted.

Note the following:

— Cost consequence is intended to elevate failure modes that would normally be considered no more than a moderate concern to the attention of the team if the combination of severity and occurrence suggests the potential cost of a failure is high. Its development was inspired by concerns that FMEA tends to overlook failure modes that end up costing the company significant amounts of money if the failure occurs. Therefore, users are challenged to view cost as the dimension of risk with which to judge Pareto optimality violations, rather than severity.

— While CPN can be employed as a risk prioritization scale, it is subject to the same kinds of problems found with RPN. As a consequence, if it is to be used in this capacity it must be weighted or modified using one of the techniques currently being developed to correct for issues with RPN [e.g., The ME-MCDM technique of Franceschini and Galetto (2001)].

Summary and Conclusion

Using FMEA to develop an understanding of the seriousness and the likelihood of a failure of a product or process is well established. Identifying the costs of such a failure adds a new dimension to this understanding. This study attempted to develop a model that relates basic costs to failures based on the severity and occurrence ranking of the DFMEA. An initial attempt to assess the criterion validity of the model indicates that adjustments might need to be made to certain elements to more closely match actual costs. The null hypothesis which stated that the cost consequences projected by the CoQ ranking system would not be different from actual costs was, therefore, rejected.

The susceptibility of a RPN prioritization system to Pareto optimality violations was found to be greater than that of a similar system based on CPN. This requires a rejection of the null hypothesis that stated that no significant difference would exist in this area.

With sufficient field data, "calibrations" to the CoQ model can be made. Yet even if the model can only claim to be close to the actual costs, it still would have value in alerting a team to areas where they could experience unwanted expense should a failure occur. It might not be necessary to reduce the bias between the model and actual costs down to the penny in order for cost consequence to be beneficial in this regard. But whether the system is accepted as is or modified to reduce bias, it was found to be both intuitive (not requiring extensive training to use or understand) and to be as easy to use as the current risk ranking system. In fact, it can be argued that arriving at a cost consequence rank score using the CoQ matrix is easier than for any dimension of risk ranking that is currently a part of an FMEA exercise. The values of cost derive from the rankings given for severity and occurrence...no evaluation or decision making is required. It is, therefore, completely free of subjective influence.

Recommendations

The model used in this study could be refined as follows:

- Replace the general cost estimates based on industry standards, survey data, and best guess that are used in the model with cost data that is specific to the product under review–Deriving such data from the case study was not possible as it is highly sensitive and could not be used without endangering confidentiality. The model should be calibrated to the specific business case if it is to be maximally effective.[55]

- Develop a warranty assessment index that has general applicability. There is much variability in the ways each OEM determines (a) that portion of the returns that the supplier must cover, (b) the amount that must be paid for module replacement, and (c) how the dealership labor is charged. If a correlation can be made between the different OEMs (and between one warranty review and the next for any given OEM), then the model can replace the average warranty cost index (here 1.9% of sales) with a more precise means of representing warranty costs.

- Opportunity costs are herein dealt with by the loss of the gross margin. This is not entirely satisfying as the opportunity costs are widely regarded as being larger in impact than this is able to show. However, this author believes that any arcane computation of opportunity cost will be difficult to justify to the engineering team that is seeking a simple, but realistic index of cost consequence. Future research should be directed at attempting to identify meaningful consequences of CoQ that impact opportunity.

[55] It is clear that the model lends itself to the development of a tool in which each of the parameters can be tuned by the user. Specific cost structures and risk scenarios can thus be "programmed" in to the tool to improve the fit of the cost consequence estimates.

Future research should attempt to do the following:

- Gather a larger sample of field failures in a case study and attempt to derive a more complete assessment of the costs for each of the field issues. The validation done in this study was greatly constrained by the lack of field data. A full understanding of the effectiveness of the cost projection will require more and better data on field failures.

- Develop other product cost characterizations and expand the usability of the system beyond just electronic modules for automotive applications.

- Evaluate the current management of the costs associated with poor quality. Determine (a) how completely the costs drivers are understood and monitored and (b) how the accounting systems that are not "activity based" book the various components of CoPQ.

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APPENDIX A: SYMBOLS AND ABBREVIATIONS

The symbols and acronyms used in this paper are listed here along with their intended meaning. The symbols are grouped under the name of the author that introduced the symbols and they are arranged according to the order in which they appear in the paper.

Symbols

From Guinot (2015): Hypotheses formed from Question 1 through 3

$CoQ_{expected}$: The cost of quality anticipated for the failure mode based on the value of Cost Consequence of Failure determined from the DFMEA rankings for Severity and Occurrence for that failure mode.

$CoQ_{observed}$: The cost of quality that results from the actual occurrence of the failure mode.

POV_{RPN} : The potential for Pareto Optimality violations inherent in the RPN prioritization scheme

POV_{CPN} : The potential for Pareto Optimality violations inherent in a hypothetical CPN prioritization scheme

$Scale_{SOD}$: The ordinal ranking scale developed for ranking the dimensions of risk in an FMEA

$Scale_{CoQ}$: An ordinal ranking scale that represents the cost consequences of a failure mode

From Snieska, Daunoriene, and Zekeviciene (2013): the loss of customer goodwill and brand damage

I_i : importance of the specification requirement

R_i : the factor for the relative success in satisfying that requirement.

V : the market value of the company,

S_b : the sales value of the brand

S_g : the value of the sales of the company's main products

From Weheba and Elshennawy (2004) : the cost of conformance

$E(RC)_L$: average or expected level of conformance (reactive cost) per unit time

$E(C_M)$: the cost of inspecting production units

$E(C_i)$: the cost of deviating from performance targets

$E(C_d)$: the cost of introducing planned changes to the process to improve the level of conformance

From Omar and Murgan (2014) : Expected cost of quality

$E(C_{COQ})$: the expected cost of quality

$E(C_{PIQC})$: the expected production invisible quality costs

$E(C_{VQC})$: the expected visible quality costs

$E(C_{OC})$: the expected opportunity costs

From von Ahsen (2008) : Cost of quality

RPN_c : risk priority number based on cost

C_e : cost of externally detected failures

C_i : cost of internally detected failures

C_c : cost of false positive inspection results

Đ/O : the conditional probability of not detecting a fault before delivery

D/O : the conditional probability of detecting a fault before delivery

$D/\bar{O}$: the conditional probability of detecting the fault, given it has not occurred.

From Dong (2007) : Cost due to failure

$E(C)$: the expected cost due to the failure mode

C_{fm} : the costs found to result from the failure mode

p_{fm} : the probability of the failure mode occurring

p_d : the probability that the failure will be detected

U_{ij} : the utility value assigned to the estimate i of engineer j

C_{ij} : the ith cost estimate

C_{10j} : the highest value for the cost driver under consideration

From Franceschini and Galetto (2001): Multi-Expert – Multiple Criteria Decision Making technique used for prioritization based on cost estimates

$RPC(a_i)$: the Risk Priority Code for the failure mode a_i

$I(g_j)$: the importance associated with the evaluation criterion g_j

Neg ($I(g_j)$) : the negation of the importance assigned to the decision making criterion

From Guinot (2015): Model of the cost consequence of a failure

See Appendix B

Acronyms

AIAG: Automotive Industry Action Group

ASQ: American Society of Quality

C/1000 : Conditions per 1000 vehicles

CAPA: Corrective and Preventative Actions

CoGQ: Cost of good quality

CoPQ: Cost of poor quality

CoQ: Cost of Quality

CPN: Cost Priority Number

DFMEA: Design Failure Modes and Effects Analysis

FA: Failure Analysis

FMEA: Failure Modes and Effects Analysis

LUX: Latent defect–Undependable product – eXternal failures

MCDM: Multi-criteria Decision Making

ME-MCDM : Multi-Expert – Multiple Criteria Decision Making

NCT: Non-conforming Ticket

NHTSA: National Highway Traffic Safety Administration

NIS: New Israeli Shekels

NOAC: Next Operation As Customer

NTF: No Trouble Found

OEM: Original Equipment Manufacturer

PCB: Printed Circuit Board

PDCA: Plan, Do, Check, Act

PFMEA: Process Failure Modes and Effects Analysis

Ppk: Process capability determined from the standard deviation of the sample being studied

RPN: Risk Priority Number

TAKT: A German word for musical meter. It defines the rate at which production operation must proceed in order to meet the capacity demands of the customer.

USD: U.S. dollars

APPENDIX B: MODEL RELATING FMEA RANKING TO THE COST CONSEQUENCE OF A FAILURE

Production Invisible Quality Costs:

$E(C_{PIQC}) = (BOM + Labor_{unit} + Overhead_{unit} + Scrap) \times (Q_{0\,km} + Q_{field})$

Visible Quality Costs:

$E(C_{VQC}) = [Q_{0\,km} \times (FA + NCT)] + Sort + (Q_{field} \times Warranty) + Legal$

Opportunity Costs:

$E(C_{OC}) = (Q_{0\,km} + Q_{field}) \times Gross\ Margin$

Cost Consequence:

CoQ (% sales) = $[\{E(C_{PIQC}) + E(C_{VQC}) + E(C_{OC})\} \div (Price \times Vol_{period})] \times 100$

Where:

BOM = The material cost per unit of production.

$Labor_{unit}$ = Labor cost per unit of production.

$Overhead_{unit}$ = Overhead cost per unit of production.

$Scrap$ = The std scrap allowance for a production run

$Q_{0\,km}$ = Quantity of Zero km modules in the period. This is a randomly generated value from 1 to 30.

Q_{field} = Quantity of warranty claims in the period. The Monte Carlo develops the value for this in each run

	according to the distribution of claims that would be expected for the occurrence level selected for the run
FA = The cost of analyzing Zero km returns.	This is the hourly wage × the time to analyze a unit × number of units returned for the period. The number of hours to analyze a return is a randomly generated value that ranges from 1 to 5 hrs.
NCT = Non-conforming material ticket charge.	This was set at \$533 per incident (i.e., $Q_{0\ km}$).
$Sort$ = The cost of one sort per period.	A sort requires 30 man hours × \$7.25 per hour × number of days for the sort. The number of days for the sort is a randomly generated value that ranges from 2 to 5 days.
$Warranty = Q_{field} \times (0.019 \times Price)$	For Severity rankings in the Conditioned Response region, only 7% of the claims were assigned this cost.
$Legal = 0.0057 \times Price \times Vol_{period}$	This only applies to failures in the Safety / Legal region.

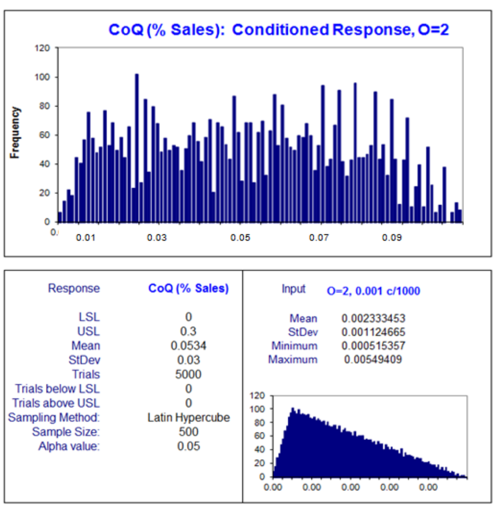
$Price$ = The per unit sales price of the module

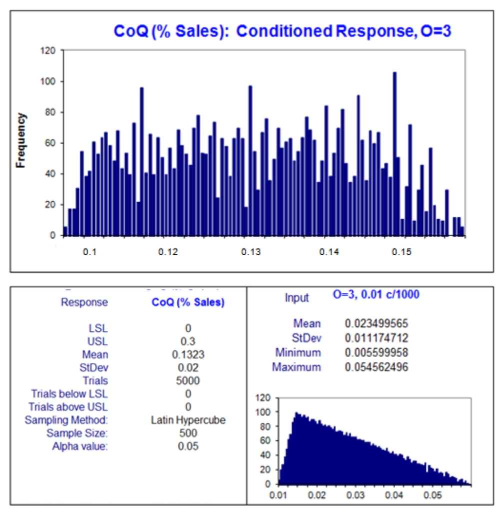
Vol_{period} = The annual sales volume

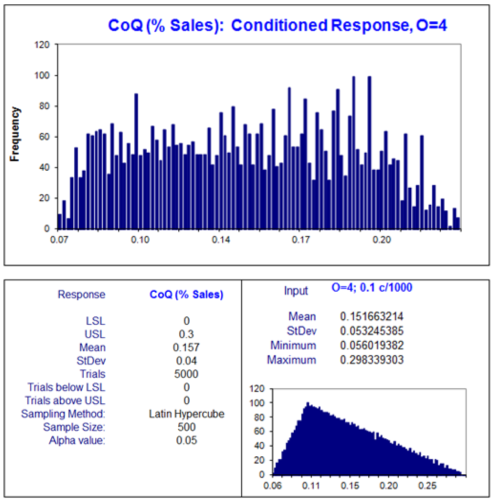
APPENDIX C: RESULTS OF THE MONTE CARLO SIMULATION

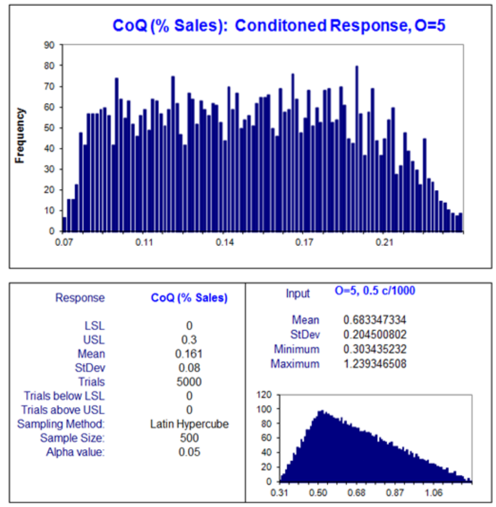
Summary charts of the output of each run of the Monte Carlo simulation. The upper spec limit was set at 0.3% of sales, the value of the warranty accrual. Any portion of the distribution of output values that is located above the USL is shown in red. The box located below and to the right of the output distribution is the distribution of input values.

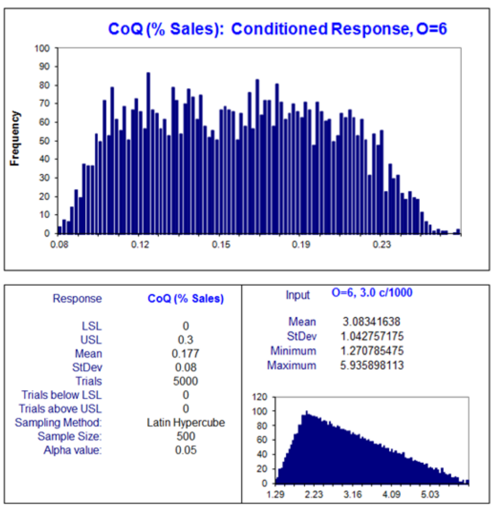
Conditioned response:

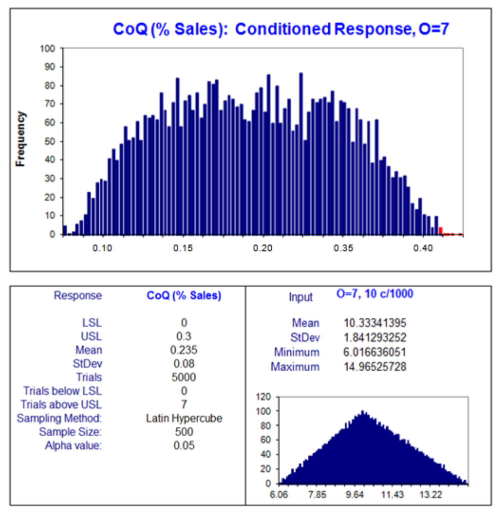


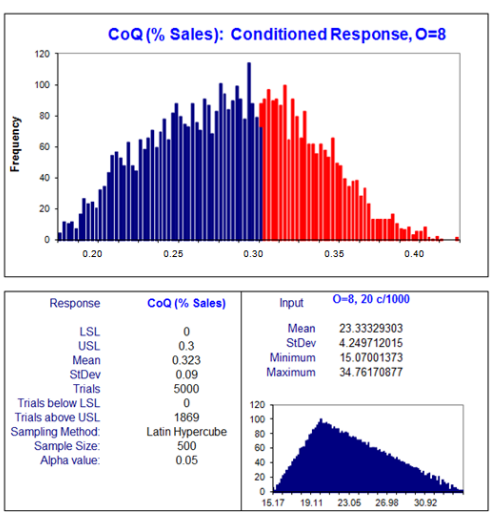


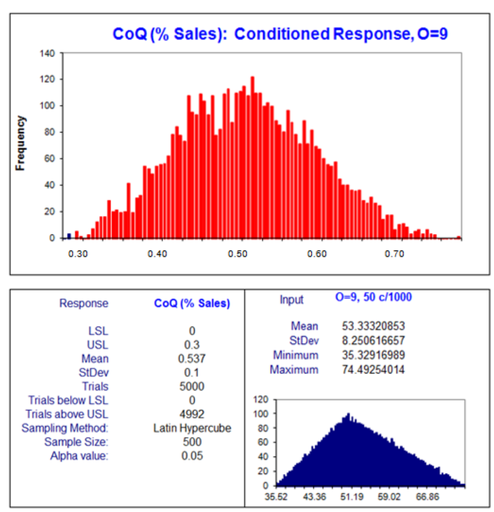

CoQ (% Sales): Conditioned Response, O=4
Frequency
0.07 0.10 0.14 0.17 0.20
Response CoQ (% Sales)
LSL 0
USL 0.3
Mean 0.157
StDev 0.04
Trials 5000
Trials below LSL 0
Trials above USL 0
Sampling Method: Latin Hypercube
Sample Size: 500
Alpha value: 0.05
Input O=4; 0.1 c/1000
Mean 0.151663214
StDev 0.053245385
Minimum 0.056019382
Maximum 0.298339303
0.06 0.11 0.15 0.20 0.25

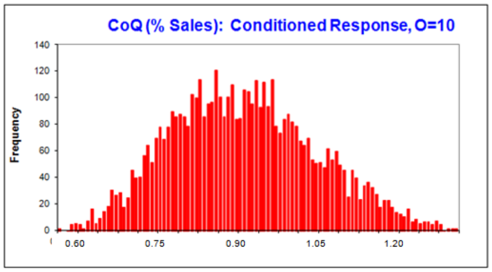

CoQ (% Sales): Conditoned Response, O=5
Frequency
0.07 0.11 0.14 0.17 0.21
Response CoQ (% Sales)
LSL 0
USL 0.3
Mean 0.161
StDev 0.08
Trials 5000
Trials below LSL 0
Trials above USL 0
Sampling Method: Latin Hypercube
Sample Size: 500
Alpha value: 0.05
Input O=5, 0.5 c/1000
Mean 0.683347334
StDev 0.204500802
Minimum 0.303435232
Maximum 1.239346508
0.31 0.50 0.68 0.87 1.06


CoQ (% Sales): Conditioned Response, O=6
Frequency
0.08 0.12 0.15 0.19 0.23
Response CoQ (% Sales)
LSL 0
USL 0.3
Mean 0.177
StDev 0.08
Trials 5000
Trials below LSL 0
Trials above USL 0
Sampling Method: Latin Hypercube
Sample Size: 500
Alpha value: 0.05
Input O=6, 3.0 c/1000
Mean 3.08341638
StDev 1.042757175
Minimum 1.270785475
Maximum 5.935898113
1.29 2.23 3.16 4.09 5.03


CoQ (% Sales): Conditioned Response, O=7
Frequency
0.10 0.15 0.20 0.35 0.40
Response CoQ (% Sales)
LSL 0
USL 0.3
Mean 0.235
StDev 0.08
Trials 5000
Trials below LSL 0
Trials above USL 7
Sampling Method: Latin Hypercube
Sample Size: 500
Alpha value: 0.05
Input O=7, 10 c/1000
Mean 10.33341395
StDev 1.841293252
Minimum 6.016636051
Maximum 14.96525728
6.06 7.85 9.64 11.43 13.22

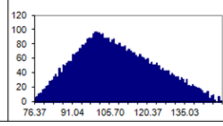

CoQ (% Sales): Conditioned Response, O=8
Frequency
0.20 0.25 0.30 0.35 0.40
Response CoQ (% Sales)
LSL 0
USL 0.3
Mean 0.323
StDev 0.09
Trials 5000
Trials below LSL 0
Trials above USL 1869
Sampling Method: Latin Hypercube
Sample Size: 500
Alpha value: 0.05
Input O=8, 20 c/1000
Mean 23.33329303
StDev 4.249712015
Minimum 15.07001373
Maximum 34.76170877
15.17 19.11 23.05 26.98 30.92


CoQ (% Sales): Conditioned Response, O=9
Frequency
0.30 0.40 0.50 0.60 0.70
Response CoQ (% Sales)
LSL 0
USL 0.3
Mean 0.537
StDev 0.1
Trials 5000
Trials below LSL 0
Trials above USL 4992
Sampling Method: Latin Hypercube
Sample Size: 500
Alpha value: 0.05
Input O=9, 50 c/1000
Mean 53.33320853
StDev 8.250616657
Minimum 35.32916989
Maximum 74.49254014
35.52 43.36 51.19 59.02 66.86

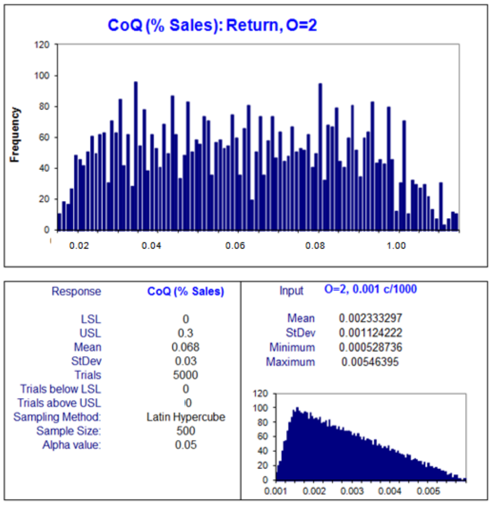


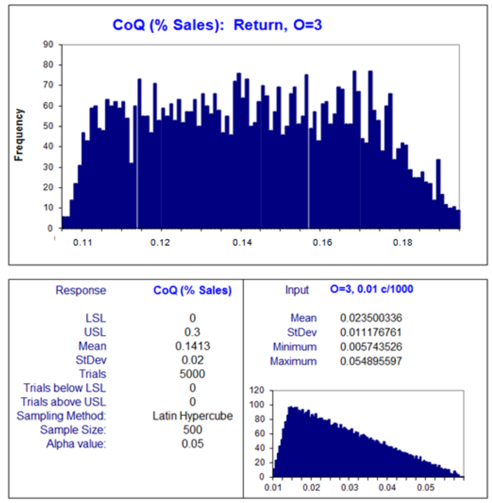
Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	0.933
StDev	0.14
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

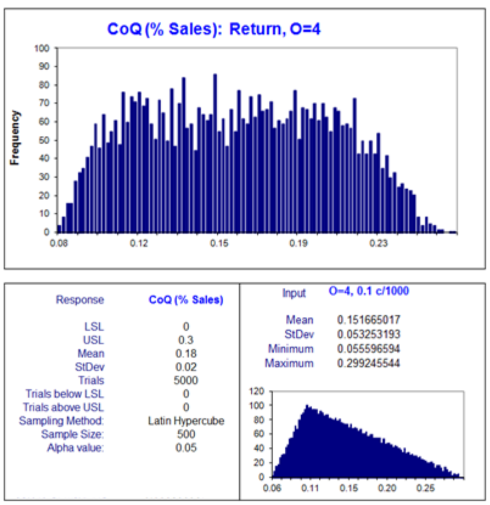
Input	O=10, 100 c/1000
Mean	108.3347589
StDev	15.59258413
Minimum	76.00514174
Maximum	149.3308678

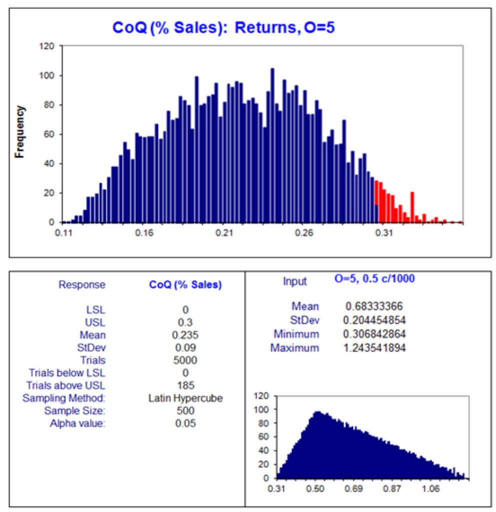


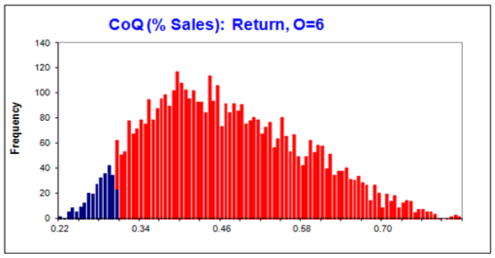
Return / No buy:





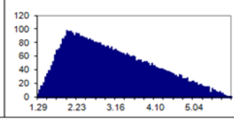


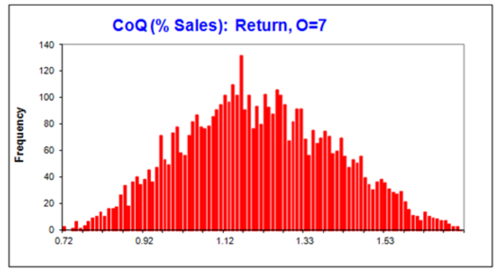




Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	0.481
StDev	0.14
Trials	5000
Trials below LSL	0
Trials above USL	4713
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

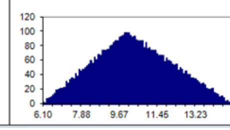
Input	O=6, 2.0 c/1000
Mean	3.083290063
StDev	1.042593423
Minimum	1.265564564
Maximum	5.950133582

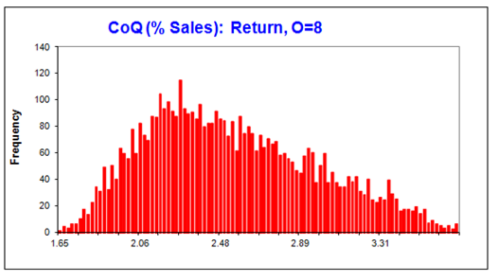




Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	1.23
StDev	0.21
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

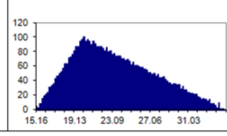
Input	O=7, 10 c/1000
Mean	10.33329539
StDev	1.840889805
Minimum	6.05330306
Maximum	14.97287185

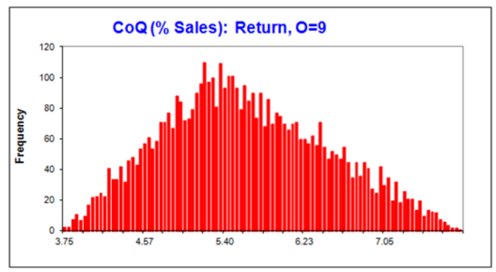




Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	0.255
StDev	0.4
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

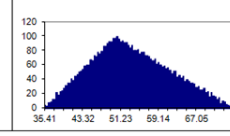
Input	O=8, 20 c/1000
Mean	23.33300008
StDev	4.249501032
Minimum	15.05931346
Maximum	34.89315093

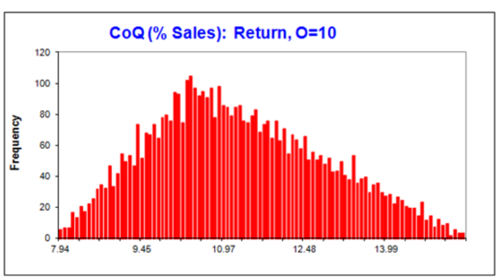




Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	5.59
StDev	0.85
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

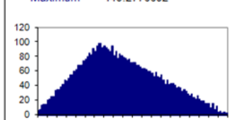
Input	O=9, 50 c/1000
Mean	53.33302141
StDev	8.250105968
Minimum	35.21420392
Maximum	74.75576298



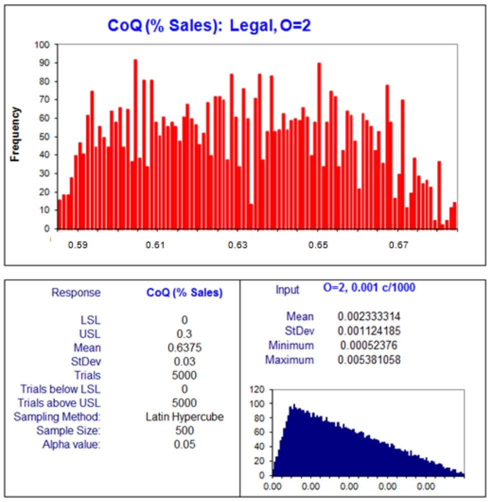


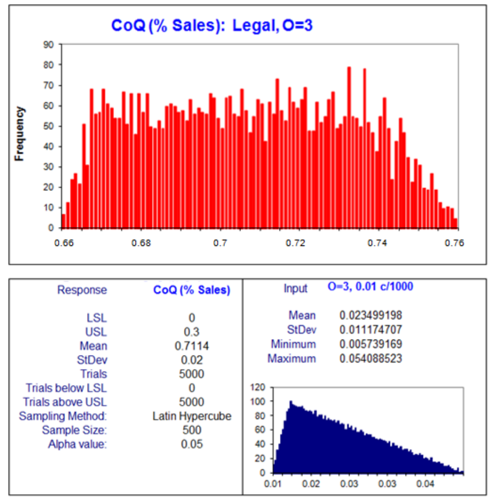
Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	11.26
StDev	1.63
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

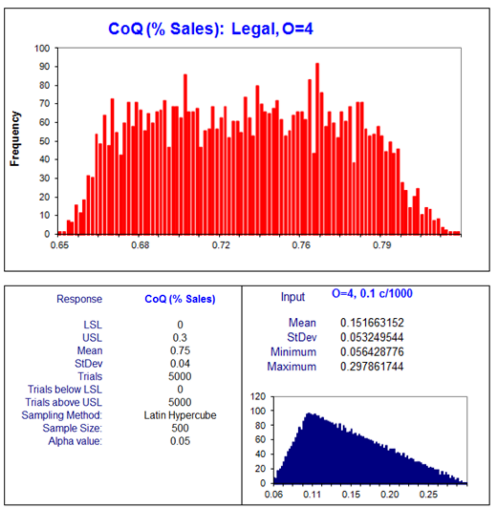
Input	O=10, 100 c/1000
Mean	108.3339113
StDev	15.59141431
Minimum	76.07290593
Maximum	149.2776692

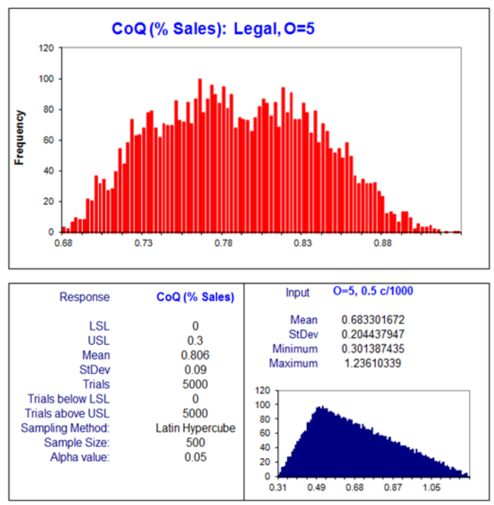


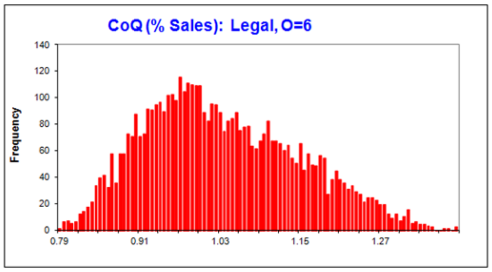
Safety / Legal:





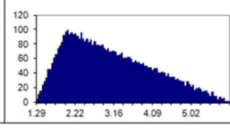


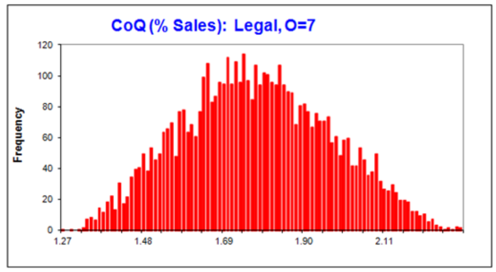




Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	1.05
StDev	0.14
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

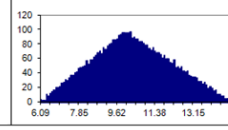
Input	O=6, 2 c/1000
Mean	3.083315771
StDev	1.042556212
Minimum	1.26713698
Maximum	5.935049536

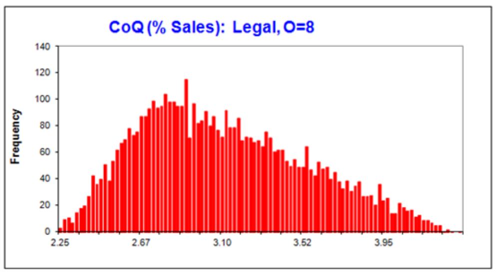




Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	1.796
StDev	0.21
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

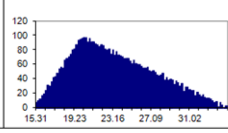
Input	O=7, 10 c/1000
Mean	10.33321255
StDev	1.841174189
Minimum	6.045319234
Maximum	14.866956

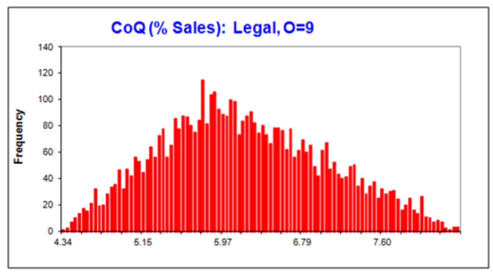




Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	3.12
StDev	0.44
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

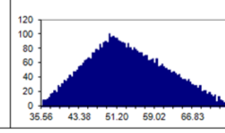
Input	O=8, 20 c/1000
Mean	23.33365591
StDev	4.249733625
Minimum	15.20896361
Maximum	34.8451419

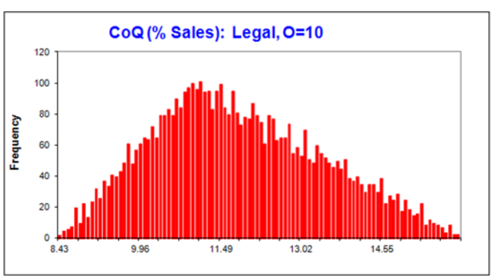




Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	6.16
StDev	0.85
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

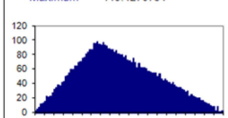
Input	O=9, 50 c/1000
Mean	53.3332712
StDev	8.249451723
Minimum	35.36482447
Maximum	74.45766988





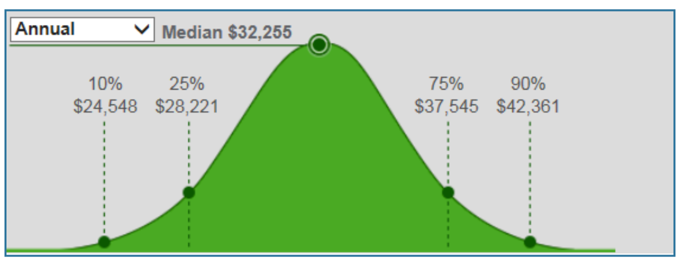
Response	CoQ (% Sales)
LSL	0
USL	0.3
Mean	11.83
StDev	1.63
Trials	5000
Trials below LSL	0
Trials above USL	5000
Sampling Method:	Latin Hypercube
Sample Size:	500
Alpha value:	0.05

Input	O=10, 100 c/1000
Mean	108.3331061
StDev	15.59239282
Minimum	75.34665184
Maximum	149.1270731



APPENDIX D: SALARY SURVEYS USED TO DEVELOP THE LABOR RATE FACTOR

The characterization of the salary of an intermediate level floor assembly worker in the automotive industry by *Salary.com* (retrieved from http://swz.salary.com/salarywizard/Floor-Assembler-I-Job-Description.aspx) (reproduced by permission) is shown below.



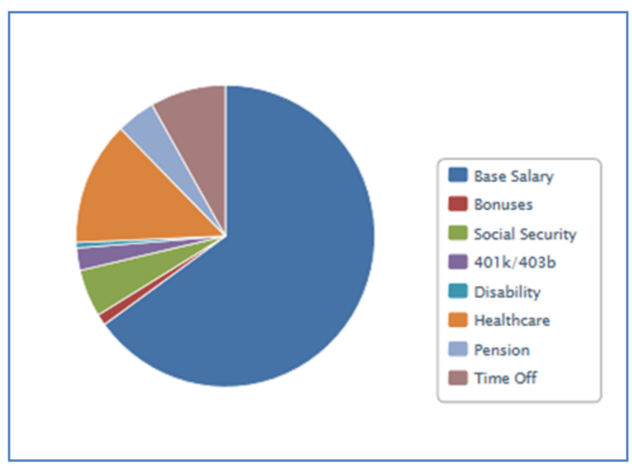
National Averages
Floor Assembler II

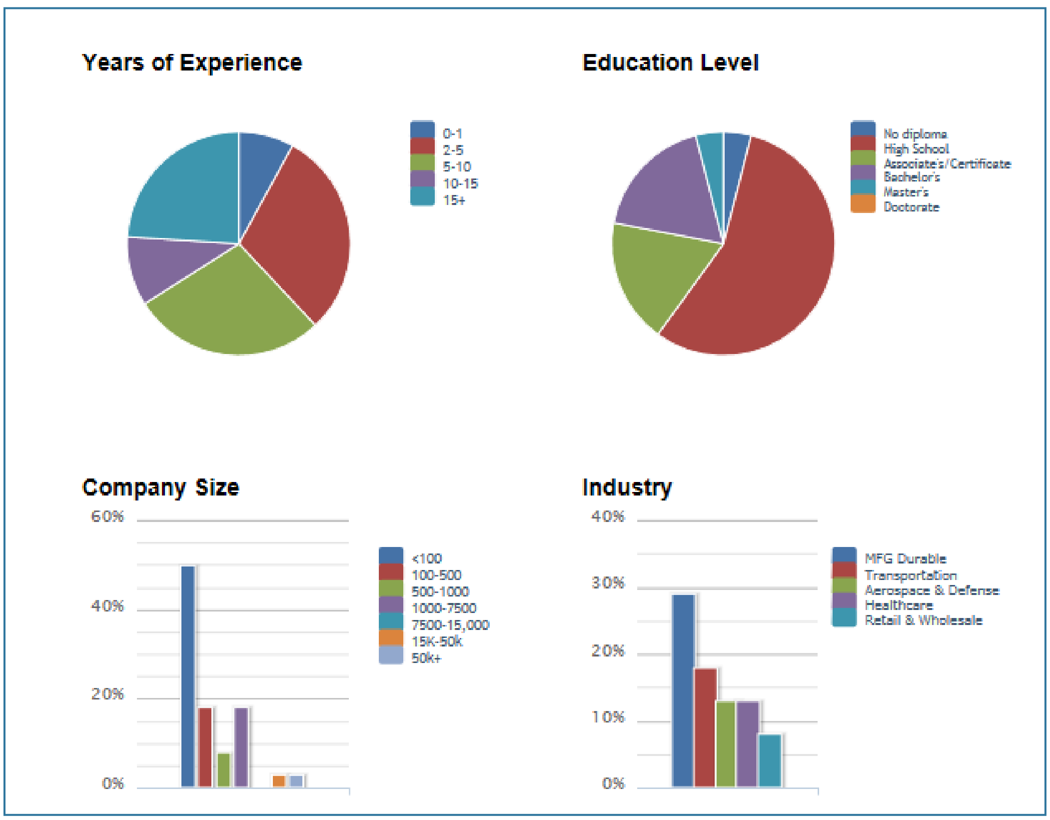
Core Compensation	Median	% of Total
Base Salary	$32,255	65.1%
Bonuses	$591	1.2%
Value of Benefits		
Social Security	$2,513	5.1%
401K/403B	$1,182	2.4%
Disability	$296	0.6%
Healthcare	$6,592	13.3%
Pension	$2,069	4.2%
Time Off	$4,043	8.2%
Total Compensation	**$49,541**	**100%**

Core Compensation is based on averages for this job and does not reflect personal factors used to determine your projected salary range.

Value of Benefits indicates the employer's expected contribution and paid time off.

$ Use the Benefits Calculator to compare your benefits with the industry average.





The Bureau of Labor and Statistics (2014) estimates the mean wage for Electrical and Electronic Equipment Assemblers (occupation code 51-2022), at $32,070 per year. The BLS states: