

CoQ Tradeoffs in Manufacturing Process Improvement and Inspection Strategy Selection: A Case Study of Welded Automotive Assemblies

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ABSTRACT

In today's highly competitive automotive markets manufacturers must provide high quality products to survive. Manufacturers can achieve higher levels of quality by changing or improving their manufacturing process and/or by product inspection where many strategies with different cost implications are often available. Cost of Quality (CoQ) reconciles the competing objectives of quality maximization and cost minimization and serves as a useful framework for comparing available manufacturing process and inspection alternatives.

In this paper, an analytic CoQ framework is discussed and some key findings are demonstrated using a set of basic inspection strategy scenarios. A case of a welded automotive assembly is chosen to explore the CoQ tradeoffs in inspection strategy selection and the value of welding process improvement. In the assembly process, many individual components are welded in series and each weld is inspected for quality. As in series connections any weld failure will lead to either a scrapped unit or an in-field failure, modeling and understanding CoQ tradeoffs in welding and inspection is particularly important.

CoQ tradeoffs in welding process improvement and inspection strategy selection are examined through a probabilistic CoQ model. From an expected value perspective, parametric sensitivity analyses reveal that complex tradeoffs between the welding process, internal failure costs, and external failure costs determine the optimal inspection strategy and the value of welding process improvement. It is demonstrated that welding process improvement may be accompanied by a change in optimal inspection strategy. A key result is that welding process improvement and inspection strategy selection must be performed simultaneously.

This paper also demonstrates that comparing CoQ distributions only by their expected values may be misleading since in many cases the cost distributions are asymmetric. High internal and high external failure costs, welding process non-conformance rates, and inspection method error rates are contributing factors. The alternative metric of expected utility, which captures the decision maker's risk aversion to high cost, low probability events, changes the criteria for optimality to favor process improvement and inspection strategies that minimize external failure events.

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INTRODUCTION

To remain competitive, automotive manufacturers must provide high quality products to their customers. Consider, for example, a product that consists of many components welded in series to form an assembly. Here, the determinant of overall assembly quality is the constituent welds quality of conformance. From a weld quality point of view, when the choice of welding technology is fixed, the manufacturer has two key levers controlling outgoing quality: welding process improvement and weld-level inspection. Different welding

process improvement levels and inspection strategies have unique quality and cost implications that need to be taken into account and compared when seeking to choose the optimal combination of both. Here, a CoQ approach reconciles the two competing objectives of cost minimization and quality maximization helping decision makers choose the optimal inspection strategy and assess the value of welding process improvement.

All manufacturing processes are imperfect. In the case of a welded assembly, manufacturers address this issue by implementing inspection with the goal of distinguishing

between conforming and non-conforming welds. Yet, inspection itself is imperfect and false quality declarations can be made; type I error refers to the false declarations of non-conformance while type II errors refer to false declarations of conforming quality. A CoQ approach assigns a cost to quality of conformance and provides a relatively simple, cost-based way of looking at the cost and quality of conformance tradeoffs in welding process improvement and in inspection strategy selection so that the consequences of both type I and type II inspection errors are comprehended.

The theory of CoQ has been around since Feigenbaums' discussion of total quality control in 1956 [1] and has been since adopted by the American Society for Quality Control. Schiffauerova provides a good overview of the CoQ models found in literature [2]. The most commonly used categorization of CoQ is the prevention-appraisal-failure (P-A-F) model. The P-A-F categorization will be referred to throughout this paper. In the P-A-F model, prevention costs refer to the costs of training, maintenance and process improvement. Appraisal costs include the costs of inspection, whereas failure costs refer to both internal and external failure costs. Internal failure costs are the costs incurred by the producer in correcting for non-conformance including rework, repair and scrap, whereas external failure costs are costs incurred after delivery of a non-conforming assembly to the consumer. These external failure costs include warranty costs as well as loss of goodwill. While type I error rates lead to higher internal failure costs, type II error rates lead to external failure costs.

By understanding the CoQ tradeoffs between available inspection strategies at different levels of welding process improvement, the CoQ framework can help identify the optimal inspection strategy and assess the value of welding process improvement. Modeling and understanding CoQ tradeoffs in welding and inspection is especially important in the case where the failure of one weld will cause the whole assembly to fail. When the internal failure cost implications of the assembly are high, an internal failure caused by detecting faulty welds will lead to expensive rework and potentially scrapping of expensive product components. Meanwhile, an in-field failure will result in costly warranty claims and major damage to the company's goodwill and future sales.

The CoQ framework outlined in this paper addresses key questions pertaining to welding process improvement and inspection strategy selection in the welded assembly. More specifically, the goals of the presented case study are threefold:

- To understand the CoQ implications of the different available weld inspection strategies both from an expected cost and cost distribution point of view using baseline values for all relevant parameters in the assembly plant.
- To examine the circumstances under which a choice of inspection strategy may change. This is done through a parametric sensitivity analysis on key drivers of CoQ and on

parameter values. The latter is particularly important for inspection method error rates as these are commonly difficult to determine.

- To analyze the CoQ savings resulting from welding process improvement and taking into account the possible accompanying changes in optimal inspection strategy.

The remainder of this paper is structured in the following way. A generalized CoQ analytical model is outlined for a single component product in both its expected cost and cost distribution forms. Key findings of the general analytical model are presented using a set of three simplified inspection strategies to discuss basic tradeoffs between inspection strategies as well as the value of manufacturing process improvement. The general CoQ methodology is then tailored to a more complex case of a welded assembly with many components. The case study results are discussed within the context of the three goals discussed above.

ANALYTICAL MODELING OF COQ

In this section the CoQ metric and the analytical cost model for comparing inspection strategies and getting at the value of any manufacturing process improvement are discussed. Two probabilistic cost model formulations are presented; whereas one formulation solely captures the expected cost of an inspection strategy or manufacturing process improvement option, the other formulation provides information regarding the associated cost distribution. Key findings of the analytical formulations are demonstrated using a set of three simplified inspection strategies.

ANALYTICAL MODEL

CoQ Metric

The conflicting objectives of cost minimization and quality of conformance maximization are reconciled into one objective of cost beyond perfect manufacturing minimization. This can be achieved by implementing the CoQ approach of assigning costs to quality of conformance in accordance with Feigenbaum's prevention-appraisal-failure (P-A-F) cost categorization. To compare inspection strategies for a fixed choice of manufacturing process, the P-A-F CoQ elements that must be considered are appraisal, internal failure and external failure costs. More specifically, the metric is defined as the cost beyond perfect manufacturing (CBPM) where,

$$CBPM_{n_{co}} = C_{appr, n_{co}} + C_{int, failure, n_{co}} + C_{ext, failure, n_{co}} \quad (1)$$

$CBPM_{n_{co}}$ captures the excess costs incurred to produce n_{co} delivered conforming units. An excess cost is any cost beyond the required manufacturing and material costs. Note that more than n_{co} items may have to be produced to get the required number, n_{co} . These additional costs are a result of imperfect inspection on the outputs of an imperfect manufacturing process. In the general expression in (1)

appraisal costs are inspection costs; internal failure costs consist of both rework and scrap costs; and external failure costs include costs associated with loss of goodwill and sales and any warranty costs.

While the goal is to get at the CBPM of n_{co} units, the most direct calculation can be done by holding the number of manufacturing process runs constant. For a given number of manufacturing process runs, different combinations of inspection strategies and manufacturing processes will result in different proportions of scrapped units, conforming units sent to the customer, and non-conforming units sent to the customer. Because the number of delivered conforming units, n_{co} , will be different in each case, it is used as a normalization factor. Inherent in this choice of normalization is the assumption that delivered non-conforming units are replaced with conforming counterparts so that (1) can be rewritten on a per delivered conforming unit basis as,

$$cbpm_{co} = \frac{CBPM_{n_{co}}}{n_{co}} \quad (2)$$

Note that when manufacturing process improvement is an option, the expression in (2) is extended to include the unit cost of manufacturing, c_p . The new CoQ metric, defined as the cost of imperfect manufacturing and inspection per delivered conforming unit can be expressed as,

$$cimi_{co} = c_p + \frac{CBPM_{n_{co}}}{n_{co}} \quad (3)$$

Any attempt to analyze $cbpm_{co}$ or $cimi_{co}$ must capture the scenario specific probabilistic implications of manufacturing process non-conformance rate and inspection errors. Both $cbpm_{co}$ and $cimi_{co}$ are random variables and analytical expressions are needed to compare different inspection strategy and manufacturing process improvement options analytically both from an expected cost and cost distribution perspective.

Expected Cost Formulation

One way to characterize $cbpm_{co}$ (or by extension, $cimi_{co}$) is by its expected value. In (2) the number of delivered conforming units, n_{co} , is related to the number of scrapped units, n_s , non-conforming items delivered, n_{nco} , and manufacturing process runs, n_{pr} through the relation,

$$n_{pr} = n_{co} + n_{nco} + n_s \quad (4)$$

where n_{co} , n_{nco} , n_s are mutually exclusive discrete random variables that follow a multinomial joint probability mass function with parameters n_{pr} and $p = (p_{co}, p_{nco}, p_s)$. The cost beyond perfect manufacturing incurred in achieving n_{co} delivered conforming units in (1) consists of appraisal, internal failure costs, and external failure costs specific to the

choice of inspection strategy being modeled. A form of the CBPM model that is convenient for determining the expected value is

$$CBPM_{n_{co}} = n_s \cdot c_s + n_{nco} \cdot c_{nco} + \sum_i \sum_j n_{I_{ij}} \cdot c_{I_i} + \sum_{k=1}^l n_{R_k} \cdot c_R \quad (5)$$

Here $n_{I_{ij}}$ is the number of units being inspected by inspection method ij times and n_{R_k} is the number of units being reworked k times out of a maximum l , the specified rework limit. Note that the limits on i and j are subject to the number of inspection methods available and the maximum possible inspection iterations of each. In (5) c_{I_i} is the unit cost of inspection method i , c_R the unit rework cost, while c_s and c_{nco} are the unit costs of scrap and external failure respectively. In this model there is no salvage value. Hence, the unit scrap cost is defined to be the sum of unit manufacturing process (c_p) and material cost (c_M). Unit external failure cost is the sum of the scrap value and any additional external failure premium (c_f) which may include an allocation for loss of goodwill or sales (7). Hence,

$$c_s = c_p + c_M \quad (6)$$

$$c_{nco} = c_p + c_M + c_f \quad (7)$$

In (5), n_s , n_{nco} , $n_{I_{ij}}$ and n_{R_k} are dependent random variables with a discrete multivariate distribution. Individually the variables behave as binomially distributed random variables. Substituting (6) and (7) into (2) and (5) allows $cbpm_{co}$ to be expressed as

$$cbpm_{co} = \frac{(n_s + n_{nco}) \cdot (c_p + c_M) + n_{nco} \cdot c_f + \sum_i \sum_j n_{I_{ij}} \cdot c_{I_i} + \sum_k n_{R_k} \cdot c_R}{n_{co}} \quad (8)$$

Note that in (8) n_{co} is also binomially distributed discrete random variable $n_{co} \sim B(n_{pr}, p_{co})$. Hence, the expected value of $cbpm_{co}$ or $cimi_{co}$ for any available inspection strategy and manufacturing process option is difficult to determine because the quantity is a quotient of dependent random variables. However, two simplifying approximations will allow the approximation of expectation of the quotient as the quotient of the expectations,

$$E \left[\frac{CBPM_{n_{co}}}{n_{co}} \right] \approx \frac{E[CBPM_{n_{co}}]}{E[n_{co}]} \quad (9)$$

The first simplifying approximation is that $P(n_{co} = 0) = 0$. This approximation can be justified by considering the multinomial joint probability mass function and the convergence of $P(n_{co} = 0)$ to zero in the limit for large

number of trials n_{pr} and when p_{co} is close to unity. The second approximation is the second-order Taylor series approximation of $\frac{CBPM_{n_{co}}}{n_{co}}$ around $n_{co} = E[n_{co}]$. Hence,

$$E[cbpm_{co}] = \frac{(p_s + p_{nco}) \cdot (c_p + c_M) + p_{nco} \cdot c_f + \sum_i \sum_j p_{I_{i,j}} \cdot c_{I_i} + \sum_{k=1}^1 p_{R_k} \cdot c_R}{1 - p_{nco} - p_s} \quad (10)$$

and,

$$E[cimi_{co}] = c_p + E[cbpm_{co}] \quad (11)$$

Examining the interplay between the scrap, external failure, inspection and rework cost components of $cbpm_{co}$ allows for the exploration of tradeoffs involved in inspection strategy selection and the assessment of the value of manufacturing process improvement. The probabilities p_{nco} , p_s , $p_{I_{i,j}}$, p_{R_k} specific to the inspection strategy being modeled and are functions of manufacturing process non-conformance rate, inspection error rates, and rework limit.

Cost Distribution Formulation

The expected value equations summarize the cost distributions with a single number. This is a standard approach but it is also a key limitation in the literature as there has been no analysis of how uncertainty may affect decision making in inspection strategy selection and manufacturing process improvement evaluation. The best way to assess this is to use the manufacturing process and inspection strategy specific $cbpm$ and $cimi$ distributions. The origin of a produced items $cbpm$ (and by extension $cimi$) distributions can be explained by considering the following three statements:

- For any given inspection strategy, a unit can follow one of many possible paths where a path is defined as a unique sequence of produced or reworked quality of conformance occurrences and inspection decisions that end in one of three possible events; delivered to the customer and conforming, scrapped, delivered and non-conforming.
- Each path mentioned above has an associated $cbpm$ outcome that depends on the specific number of occurrences of each available inspection method, number of rework attempts, as well as final outcome event.
- For a given inspection strategy, any path with its resulting $cbpm$ outcome has a probability of occurrence which is its own function of manufacturing non-conformance rate and inspection error rates.

A decision tree is a visual representation of all possible paths a manufactured unit can follow in a modeled inspection strategy leading to a final cost outcome corresponding to one of the events: delivered to customer and conforming; scrapped; delivered and non-conforming. Note that a decision

tree developed to model any inspection strategy for a given manufacturing process consists entirely of chance nodes, because all quality of conformance occurrences and inspection decisions are probabilistic. The probability of occurrence of any individual path can hence be obtained by multiplying all conditional probabilities along the path and is displayed alongside its cost outcome. Figure 1 is an example of a decision tree showing four possible $cbpm$ paths alongside their cost outcome and probability of occurrence for a simplified *single inspection* strategy with no allowable rework. Here p is the manufacturing process non-conformance rate, a_1 and b_1 are the type I and type II inspection error rates. $c_{T1,1}$, c_p , c_M and c_f are the inspection, manufacturing process, material and additional external failure costs respectively. $c_p + c_M$ is the scrap value of the product.

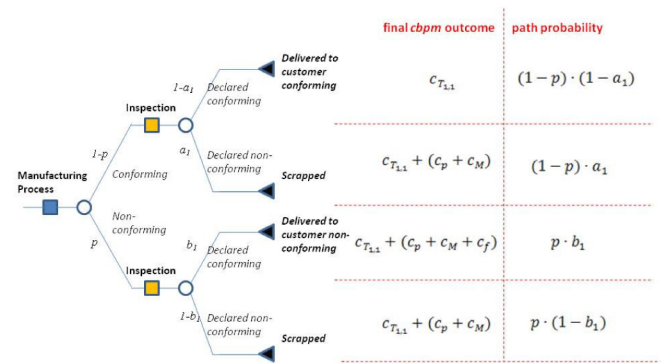


Figure 1. Decision tree for simplified single inspection strategy with no rework showing final cost outcomes and path probabilities.

Although many possible paths exist for any modeled inspection strategy, not every $cbpm$ outcome is unique. In this example, the two paths of conforming declared non-conforming and non-conforming declared non-conforming result in the same outcome consisting of the sum of scrap and inspection costs, albeit with different path probabilities. The set of possible paths and $cbpm$ outcomes depends on the number of inspection methods that may be deployed at any inspection iteration, the rules and arrangement of these inspection methods as well as the maximum allowable rework limit. A generic equation for $CBPM$ of achieving n_{co} delivered conforming products can be formulated:

$$CBPM_{n_{co}} = \sum_{\substack{\text{all unique} \\ \text{cbpm} \\ \text{outcomes } i}} n_i \cdot cbpm_i \quad (12)$$

where n_i is the number of units incurring the unique outcome of $cbpm_i$. In this formulation each $cbpm_i$ outcome is a unique linear combination of the constituent unit costs $\{c_p, c_M, c_{I_i}, c_R, c_f\}$ and belonging to the set of permitted combinations specific to the inspection strategy being modeled. The vector

$N = (n_1, \dots, n_k)$ follows a multinomial distribution with parameters n_{pr} and $p = (p_1, \dots, p_k)$ where p is the vectors of probabilities corresponding to the possible unique cost outcomes $C_{cbpm} = (cbpm_1, \dots, cbpm_k)$. Marginally, each n_i behaves as a discrete binomially distributed random variable with expected value $E[n_i] = n_{pr} \cdot p_i$. Note that the sum of n_i across all unique $cbpm$ outcomes is equal to fixed number of process runs n_{pr} which is itself equal to the sum of the multinomially distributed random variables n_{co} , n_{nco} and n_s

$$n_{pr} = \sum_{\substack{\text{all unique} \\ \text{cbpm} \\ \text{outcomes } i}} n_i = n_{co} + n_{nco} + n_s \quad (13)$$

Using the same approximation for the expected value of a ratio of random variables, $E[cbpm_{co}]$ is expressed as

$$E[cbpm_{co}] = \frac{\sum_{\substack{\text{all unique} \\ \text{cbpm} \\ \text{outcomes } i}} p_i \cdot cbpm_i}{\sum_{\substack{\text{all unique} \\ \text{delivered} \\ \text{conforming} \\ \text{cbpm outcomes } j}} p_j} \quad (14)$$

and $E[cimi_{co}] = c_p + E[cbpm_{co}]$. The set of unique $cbpm$ outcomes and their probabilities are specific to the inspection strategy being modeled and a separate decision tree formulation must be developed for each inspection strategy being examined.

ANALYTICAL RESULTS

To discuss key findings regarding CoQ tradeoffs in inspection strategy selection and manufacturing process improvement a set of three simplified inspection strategies are used as examples (see Figure 2). The analytical formulations for expected cost and cost distributions are applied to the examined inspection strategies.

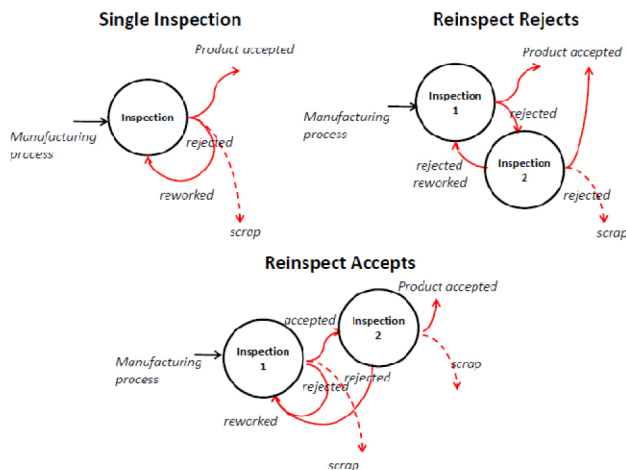


Figure 2. Flow diagrams for three inspection strategies of single inspection, reinspect rejects and reinspect accepts

For illustration purposes, a baseline set of scenarios (Figure 3) is chosen to reflect different approaches to inspection and manufacturing. These scenarios serve as a platform for exploring the dimensions of product internal and external failure costs.

Manufacturing Process Scenario			
		Inexpensive and bad	Expensive and good
Inspection Scenario	Inexpensive and bad	A	C
	Expensive and good	B	D

Figure 3. Base scenarios from which CoQ tradeoffs are explored

The chosen baseline scenarios are combinations of two approaches to inspection and two approaches to manufacturing for the production of the same single component product. The explored scenarios reflect tradeoff decisions that manufacturing decision makers often have to make. The specific parameters for the four baseline scenarios are shown in Table 1. Four simplifying assumptions are made to reduce the complexity of the explored parameter space:

- A positive correlation between unit manufacturing process and rework costs exists. Specifically, rework is set to be twice as expensive as the original manufacturing process.
- Although not always true, inspection error rates are assumed to be symmetric meaning that for any inspection method, the type I error rate is set equal to the type II error rate.
- Inspection methods in the two-tier *reinspect rejects* and *reinspect accepts* strategies are set to have the same unit cost and error rates.
- Rework limit, l , is set to one.