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Cost of quality: Evaluating cost-quality trade-offs for inspection strategies of manufacturing processes

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ABSTRACT

Cost-quality trade-offs are required when manufacturing industries seek to minimize cost and maximize product quality or reliability. We report a challenging cost-quality tradeoff problem for a consumer goods industry where both cost and quality are modeled together. First we present a 10-step systems engineering methodology for quality improvement of manufacturing systems and comprehensively discuss the cost of quality step. The methodology investigates in detail inspection strategies of the manufacturing systems by exploring four alternative strategies. Key elements in this investigation consists of modeling the appraisal costs that involve costs to detect a non-conformed unit through inspection or testing, and failure costs that involve costs of rework, scrap, warranty claims and loss of goodwill and sales. Among the main findings of the research is that optimum inspection strategy can be achieved by modeling the cost savings from each strategy and plotting against non-conforming rates shipped to the customer and additional external failure premium.

1. Introduction

Producing quality and reliable products at a realistic cost has always been a fundamental objective for manufacturers. In recent years, customer expectations for quality at low cost have only intensified. As manufacturers strive to achieve these goals they eventually reach a point where tradeoffs must be made between increasing quality and lowering costs. To guide these tradeoff decisions, the Cost of Quality (CoQ) approach has been developed. This approach models the quality of a system through the costs incurred in providing that quality. As such, the cost of quality can be identified, measured and improved and should be considered an important metric for any manufacturing industry (Sower et al., 2007).

CoQ is better explained as the cost incurred in the design, implementation, operation and maintenance of an organization's quality management system (Youngdahl, 1997). In other words, the cost committed to continuous improvement processes, cost of system, production and service failures, and non-value added activities and wastage in all its various forms (Pursglove and Dale, 1995).

Juran was one of the first authors who developed the concept of quality costing, expressing simply that “all the costs would disappear if no defects were produced” (Juran, 1951). Feigenbaum extended Juran´s concept and studied the quality cost categorization of Prevention-Appraisal-Failure (P-A-F) model (Feigenbaum, 1956). Crosby split the CoQ into conformance costs and non-conformance costs (Crossby, 1979). Schiffauerova & Thomson made a comprehensive survey on the CoQ models comprising four generic models, as presented in 1 (Schiffauerova and Thomson, 2006).

The main contribution of the paper is the evaluation of inspection strategies using the CoQ approach, which to this point has not been applied in detail for a broad range of applications. Also, as part of the evaluation approach, an innovative attempt is made to find a global optimum by developing an intermediate scenario between single and double acceptance sampling strategies. Furthermore, the two key elements that played an important role in establishing the overall evaluation (external failure premium and conformance rates) are explicitly considered in the CoQ model.

The remainder of this paper is organized as follows. The next section discusses the classical P-A-F model that is the most widely used. Then, the 10-step systems engineering methodology for quality improvement of manufacturing systems is presented and step 8 of this methodology i.e. cost of quality is discussed in detail. This is followed by an introduction to the case study of aerosol can manufacturing industry study where the cost of quality analysis is applied. The development of the scenarios and results are discussed in the concluding section where results are compared among the scenarios and future work is presented.

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Table 1
Generic cost of quality models (Schiffauerova and Thomson, 2006).

Generic model	Cost categories
P-A-F models	Prevention + Appraisal + Failure
Crosby´s model	Conformance + Non-Conformance
Opportunity cost models	Prevention + Appraisal + Failure + Opportunity Tangibles + Intangibles P-A-F (failure costs includes opportunity costs)
Process cost models	Conformance + Non-Conformance
ABC models	Value-added + Non-value-added

2. Prevention-Appraisal-Failure (P-A-F) Model Overview

Prevention costs refer to all costs incurred to prevent nonconformance, such as the ones due to scheduled equipment maintenance, tool replacement, investments in worker training, and quality improvement programs. Appraisal costs are the costs involved in attempting to detect a non-conformed unit through inspection or testing. Failure costs are further divided into internal and external failure costs: internal failure costs include costs of rework attempts, and scrap when rework is no longer possible, whereas external failure costs occur when a non-conforming unit is mistakenly delivered to the consumer and fails on field. Examples of external failure costs are warranty claims and loss of goodwill and sales.

Williams et al. (2000) also classified the P-A-F model in terms of various categories; like system failures can result in obsolete stocks, lost items, production or operation delays, additional work, scrap, rectification, late deliveries, additional transportation costs, poor service. Product or service failures result in warranty, product liability claims, product recall, additional customer service costs, and loss of customer goodwill.(Table 1).

Table 2 presents costs that belong to each category in a P-A-F model:

It is clear that there has to be a tradeoff between the maximum possible quality with the lowest possible cost and the Lundvall-Juran curve in Fig. 1 shows this classical view of CoQ tradeoffs. The picture shows that the non-conformance costs decrease at a decreasing rate and the conformance costs increases at an increasing rate, while the quality of conformance increases. This combined effect results in a parabolic curve with a tradeoff point called the economic quality level (EQL).

When putting Fig. 1 into the context of the P-A-F model, the Lundvall-Juran curve defines conformance cost as the prevention costs, while the non-conformance cost as the sum of failure and appraisal costs (Juran et al., 1962).

The CoQ model is now applied to a case study of a consumer goods manufacturing industry. First, systems engineering methodology is introduced.

3. Systems Engineering Methodology

This paper is part of the research that addresses a challenge for a consumer goods industry to improve the final product quality and simultaneously reduces the overall costs. In this regard, a 10-step Systems Engineering methodology for quality improvement of manufacturing systems is developed (Farooq et al., 2015):

1. Define clearly the project scope, problem to be analyzed and identify the team;
2. Develop a complete process mapping and identify the quality control points relevant to the problem identified;
3. Identification of all elements along the production line of a product and collection of all relations between them;
4. Transfer all data to a Design Structure Matrix (DSM), parsed by manufacturing process;
5. Apply mathematical operations to DSM and evaluate and characterize the final DSM;
6. Use the most adequate quality improvement tools to further refine the critical quality characteristics and areas previously identified;
7. Improve the manufacturing process according to the results;
8. Perform cost of quality analysis to enable an informed choice;
9. Evaluate again the relations of elements, deleting the elements that were eliminated and update the DSM;
10. Standardize the results and refine the model over time.

The methodology applied for this research project is based on the DMAIC (Define Measure Analyze Improve Control) approach of Six Sigma. However, in the Define and Measure phase of DMAIC an innovative attempt is made to model the manufacturing system using a Systems Engineering matrix-based tool called Design Structure Matrix (DSM). In this research, a DSM is applied for a quality improvement problem for the first time, enabling an easier interpretation of the relations and interactions between the different system elements.

The key areas highlighted by DSM are further explored through understanding the physics of the problem by applying systems engineering methodologies holistically. Analyzing physics of the problem will provide a closer understanding towards determining the root cause of the problem. In order to have a thorough and systematic root cause analysis appropriate quality improvement tools enable improvement and evaluation of the process.

The Cost of Quality (CoQ) model then integrates the proposed approach, a model that is required to understand the overall costs incurred during sampling strategies, as well as the cost impact of the solution proposed.

Steps 1–7 of the methodology have already been discussed comprehensively. Tavares (Tavares et al., 2013) introduces the application of DSM for complex quality problems. Farooq (Farooq et al., 2014) discusses how a DSM is built for quality improvement projects. In that paper, three different DSMs were built based on the knowledge of the people from the industry (3rd and 4th steps of the methodology). Farooq (Farooq et al., 2013) further analyzes the complexity of the DSM using components modularity metrics (5th step of the methodology). For the application of quality improvement tools, Farooq (Farooq et al., 2015) discussed the challenges faced during implementation of the design of experiments (DOE) and how these challenges were solved by developing an approach of pre-experimental runs (6th and 7th steps of the methodology). The application of DOE tool on the case study showed extraordinary results i.e. analysis of the production process: increasing the productivity by 10% and simultaneously reducing the

Table 2
Example of type of costs that belong to each category (Zaklouta, 2011).

Prevention	Appraisal	Internal Failure	External Failure
Design and development of equipment	Receiving inspection	Scrap	Lost profit/sales
Quality review	Laboratory testing and inspection	Rework and repair	Loss of goodwill
Maintenance and calibration of production and inspection equipment	In-process inspection	Rescheduling due to downtime	Warranty
Quality training (seminars and workshops)	Field testing (performance tests)	Downgrading	Allowances
Supplier quality audits	Final inspection (100%/sampling inspections)	Overtime to cover production losses	Product recalls
Quality improvement programs	Inspection and test equipment		

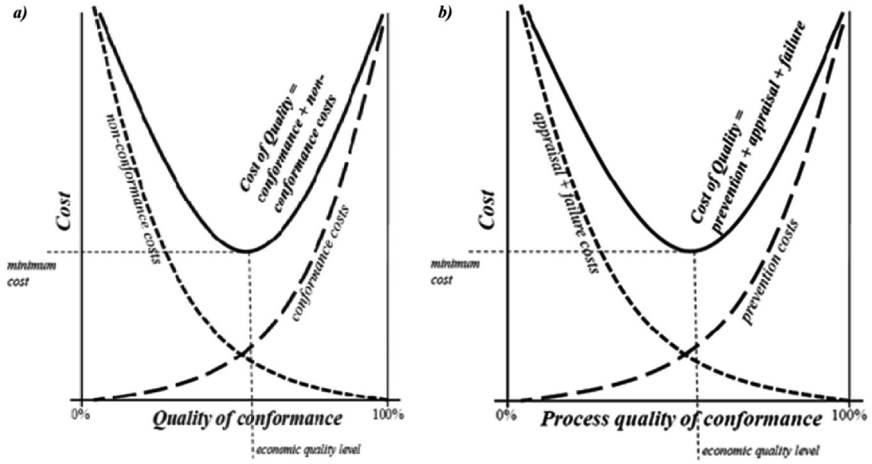

Fig. 1. Lundvall-juran curve depicting relationship between conformance (prevention) and non-conformance (appraisal + failure) costs and the tradeoff point (economic quality level) (Juran et al., 1962).

product defect by more than 65%. In this paper cost of quality model for consumer goods industry is developed, which is the 8th step of the methodology.

The main contributions of this paper can be summarized as follows: (1) Development of a detailed cost of the quality model to evaluate inspection strategies for manufacturing industries. Little research has been reported that examines inspection strategies using detailed CoQ models, especially for consumer goods manufacturing (Chen and Wu, 2014; Wu, 2012; Wetherill, 1977; Borget et al., 2006). (2) Development and evaluation of an intermediate scenario between single and double acceptance sampling strategies. This is required when the acceptance number is very small and the defective percentage is relatively high. The standard single acceptance sampling (Schilling and Garvey, 2008) may not always be a good approach for a low cost product with a high production rate, because many lots will be rejected and scrapped, thus increasing the overall costs. Therefore, in order to find a better alternative solution, a revised single sampling plan is proposed that only rejects the non-conforming units in the sample rather than the complete batch. (3) Identification of two key elements of inspection strategies during the evaluation process, external failure premium and percentage of conformance shipped to the customer. (4) Application of results of the design of experiments to estimate the conforming and non-conforming rates. In the previous research (Zaklouta, 2011), these rates are mostly estimated based on expert knowledge or computer-designed experiments but in this research real-life experimental results were recorded.

Prior to developing a CoQ model, the case study of aerosol can manufacturing industry is first discussed in detail.

4. Case Study

An international consumer goods manufacturing industry named Colep, whose main product is a three-piece tin plate aerosol can, is facing a strong challenge to improve the quality of its products. Although the industry is producing aerosol cans with a quality already above the international rules and regulations, customers are always in the quest of even higher quality and defect free products. This situation accounts for high financial costs and dissatisfied clients, compromising in the long run the dominant position of this manufacturer worldwide.

4.1. Product description

The aerosol can produced by the company is a three-piece tin plate aerosol can, a simple product composed mainly by three major parts: the top, the bottom and the body, as shown in Fig. 2. The company

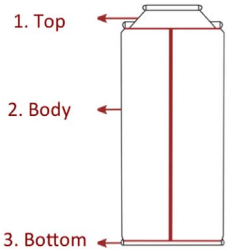

Fig. 2. Three-piece tin plate aerosol can.

manufactures both the empty and filled aerosol cans. However, the objective is to improve the final quality of an empty aerosol can, therefore study of the valve, actuator and cup, which are the additional parts in filled aerosol can, are out of scope for this research.

4.2. Process description

The complete aerosol manufacturing process is fairly complex and with a high number of intricate steps, but for the current research, a comprehensive understanding of the high-level production processes is sufficient. A three-piece tin plate aerosol can passes successively by the following production areas: primary cutting, varnishing & lithography, secondary cutting and stamping & assembly. Following the assembly process, the aerosol cans are passed through a combination of inspection processes in order to guarantee that the products leaving the factory are conformed. These inspections processes are analyzed using CoQ model because during the investigation there was no single method used that could assess the trade-offs for overall quality costs.

	Conforming	Non-conforming
Declared conforming	Ideal	Type II error
Declared non-conforming	Type I error	Ideal

Fig. 3. Type I and type II errors.

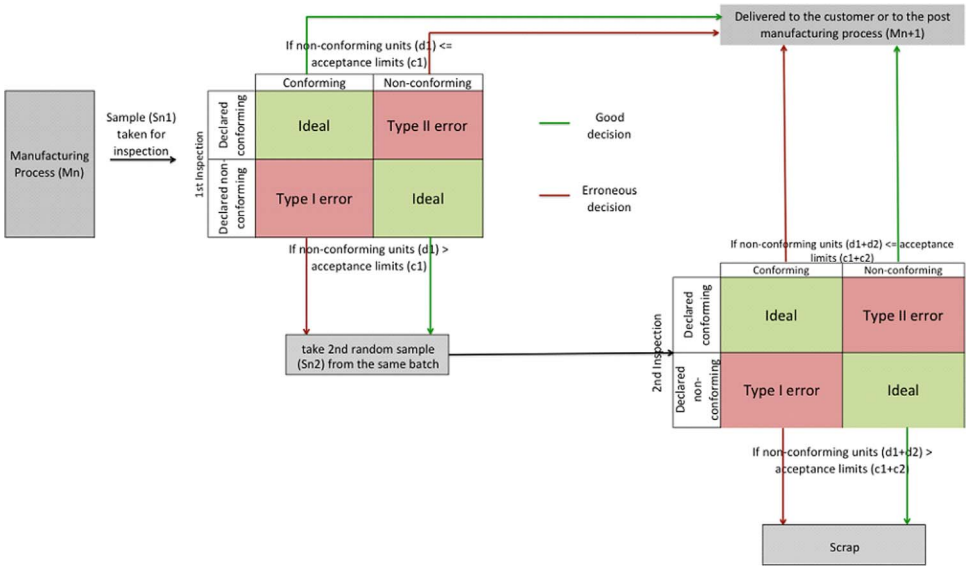

Fig. 4. Representation of a double stage acceptance-sampling flow diagram.

5. Application of CoQ model to analyze inspection strategies

There are two types of inspections performed at Colep: the first one consists in 100% inspection of aerosol cans and the second one is based on acceptance sampling through a manual waterbath system. In 100% inspection, all aerosol cans are inspected through the automatic inspection equipment whereas; in acceptance sampling only few aerosol cans are selected as a sample from the lot for inspection. Prior to develop a cost model of the actual system, it is important to investigate the current sampling strategy of manual waterbath systems as well as to propose alternate sampling strategies, comparing their results.

Acceptance sampling is one of the important elements in the P-A-F model of CoQ (Montgomery, 2009). A simple acceptance sampling strategy operates by considering a lot size of S, and taking a random sample of S_n units from the batch. If there are more than a pre-defined number of c defective units in the sample, the whole lot is rejected and scrapped. Thus, a single-sampling plan for attributes is characterized by the sample size S_n and the acceptance number c. There are various sampling plans widely known, including single, double, multiple and sequential sampling. Also, there are many schemes to measure the performance of these sampling plans, such as operating characteristic curve (OC) that plots the probability of accepting the batch versus percent defectives (Montgomery, 2009). Dodge and Roming defined a scheme, which includes two separate plans for lot tolerance percent defective (LTPD) and average outgoing quality limit (AOQL) (Juran and Godfrey, 1998). Other schemes include decision theory schemes (Wetherill, 1977) and Bayesian sampling scheme (Chen et al., 2007). Dodge (1943) developed a continuous sampling scheme that begins with 100% inspection, and when a defined quantity of units are free of non-conformities, then the sampling plans are deployed. Similarly, if the number of non-conforming units is more than the defined acceptable limits while sampling, 100% inspection is again resumed.

When sampling takes place and because inspection is never 100% reliable and involves human errors, two errors might always occur, namely the type I and type II errors. Type I error indicates false rejections of the conforming quality, whereas type II error indicates false acceptance of non-conforming quality, as shown in Fig. 3.

The type of acceptance sampling strategy applied in Colep at the assembly lines is a double stage acceptance sampling. Before developing the CoQ model for this double stage sampling strategy, a process based cost model is first developed.

The following sections are organized as follows: first, a Process Based Cost Model (PBCM) is developed, estimating the fixed and variables costs in order to manufacture a single aerosol can. Then, equations are developed for individual processes (welding, seaming, and 100% testing) that will be useful in developing a CoQ for all the scenarios. Then, the as-is double stage sampling strategy of the assembly line under analysis is modeled and all formulations related to CoQ are developed. Similarly, all relevant formulations for proposed strategies are developed and discussed. The results from these scenarios are only discussed at a later section, where the findings for all the scenarios considered are compared.

5.1. Scenario A - Double stage acceptance sampling strategy

The type of sampling strategy currently applied in the assembly line is a double stage acceptance sampling strategy.

In a double stage sampling, first a sample of units S_{n1} is randomly collected from a batch or lot. A decision is made based on a sampling plan that specifies the non-conforming units d_1 and the acceptance number c_1, among acceptance, rejection or continuing inspection of the batch. If d_1 is greater than c_1, a second sample S_{n2} is taken from the same batch otherwise the batch is accepted and shipped to the customer or to the posterior manufacturing process.

If the second sample is taken, the information from both the samples, including non-conforming units d_2 and acceptance number c_2 for the second sample, is combined in order to reach a decision of acceptance or rejection of the lot. A general scheme for the double stage sampling is shown in Fig. 4.

Fig. 5 illustrates the strategy of double stage acceptance sampling applied for the selected assembly line in Colep. The type of double acceptance sampling used by Colep is based on the military standard plans, the most widely known acceptance-sampling system (in the present case, for attributes). There are different types of double-sampling schemes, but Colep adapts and slightly alters them according to the customer. An important point to highlight is that, in the second sample, instead of analyzing all lot, the different pallets that comprehend the lot of aerosol cans are analyzed one-by-one.

For the case of double stage acceptance sampling, the simplifying assumptions made are shown in Table 3.

First step is to calculate the average number of units sampled, S_n. In this case, the two samples taken are expressed in terms of percentage to the lot or batch size S_b due to limitation of the manual waterbath machine to sample limited aerosol cans. Therefore, these two samples are expressed in terms of percentages rather than a fixed sample size

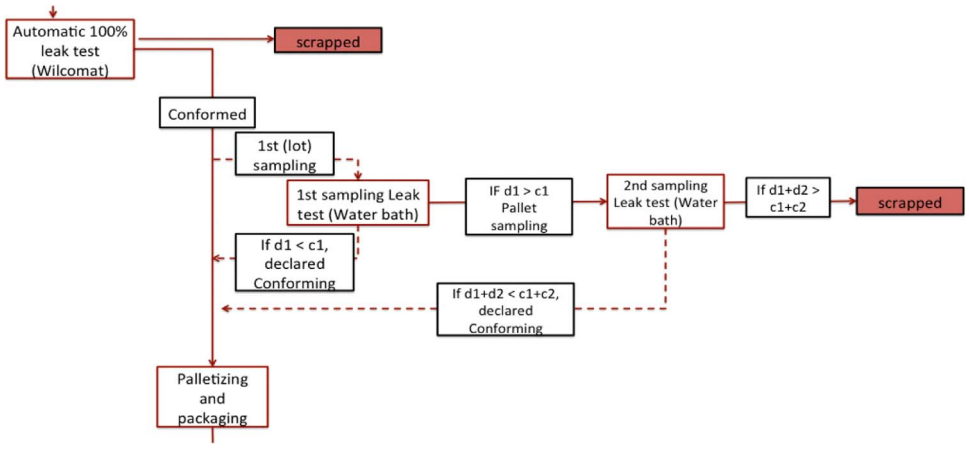

Fig. 5. Schematic representation of double stage accepting sampling.

i.e. P_{sn1} and P_{sn2}. For example, if the lot size is 10,000 units and the sample size is 125, then the input data given in the model was 1.25% for the 1st sample. The maximum % of units sampled by a single manual waterbath leak-testing machine is assumed to be 1.5% of the total production.

The total number of units of the first sample taken in a theoretically finite time is N_p. The probability that the second sample is taken from the same batch is p_r, with a probability of being rejected and scrapped is p_s. Here S_n is the sample of units that is randomly drawn from a batch or lot of size S_b.

$$S_n = M_{n+1} + (N_p * P_s * S_b)$$

$$N_p = APV/S_b$$

Where M_{n+1} is the total number of units produced at the subsequent (post) manufacturing process (see Fig. 4); APV is the annual production volume, and p_s is the probability of rejecting and scrapping the batch.

The Inspection cost ($C_{Inspection}$) has two components, first is the fixed cost (C_{Fxed}) that is the cost of the testing equipment ($C_{Equipment}$) and the second is the variable cost ($C_{Variable}$) that is the cost of testing the sample ($C_{Testing}$) plus cost of scrapping the lot (C_{Scrap}).

Table 3
Conditions for scenarios A, B, C AND D.

Scenario A	Scenario B	Scenario C	Scenario D
Units are produced at a very high production rate (e.g. 100 units/min);			
Cost of a unit is very low;			
None of the rejected non-conformed units are reworked;			
Batch size or lot size is the same throughout the production year.			
All non-conforming units shipped to the customer are detected non-conformed.			
Cost of testing a unit is low;	Cost of testing a unit is very high;		
Rejection rate is relatively small;	Rejection rate is relatively high;	Rejection rate is relatively small;	
External failure cost is relatively high;	External failure cost is high;	External failure cost is relatively high;	External failure cost is small
Whole lot is rejected		Only non-conformed unit is rejected from the sample not the whole lot.	No sampling scheme

$$C_{Inspection} = C_{Fixed} + C_{Variable}$$
$$C_{Fixed} = C_{Equipment} = PMT(\text{interest rate, payment periods, present value})$$
$$C_{Variable} = C_{Testing} + C_{Scrap}$$
$$C_{Testing} = ((S_n * P_{sn1}) + (p_r * N_p * P_{sn2})) * C_{i,Testing}$$
$$C_{scrap} = p_s * N_p * S_b * C_{i,Scrap}$$

Where C_i is the unit cost

The probability of taking the second sample, assuming that the number of rejected units in the sample follows a binomial distribution is:

$$p_r = 1 - \sum_{d1=0}^{c1} p_{d1}^{d1} \frac{S_n !}{d!(S_n - d1)!}(1-p_{d1})^{S_n - d1}$$

The probability of rejecting and scrapping the batch is:

$$p_s = p_r * (1 - \sum_{d2=0}^{c2} p_{d2}^{d2} \frac{S_n !}{d!(S_n - d2)!}(1-p_{d2})^{S_n - d2})$$

Where p_{d1} is the percent lot defective for the first sample, p_{d2} is the percent lot defective for the second sample.

5.2. Scenario B - Single stage acceptance sampling strategy

The first alternative sampling strategy proposed is the single stage acceptance sampling, i.e. a single-sampling plan, where a sample of units S_n is randomly drawn from a batch or lot of size S_b. Based on the number of observed defectives in the sample, a decision is made between acceptance and rejection of all batch. If the number of non-conforming units d is greater than the acceptance number c, all batch is rejected; if the number of non-conforming units is less than or equal to d, the lot is accepted. A declared conformed batch is shipped directly to the customer or to the post manufacturing process, whereas a non-conformed batch is rejected and scrapped. A general scheme for single stage acceptance sampling is shown in Fig. 6.

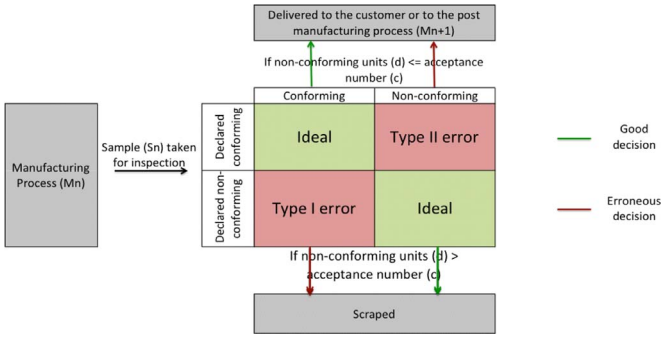

Fig. 6. Representation of a single stage acceptance-sampling flow diagram.

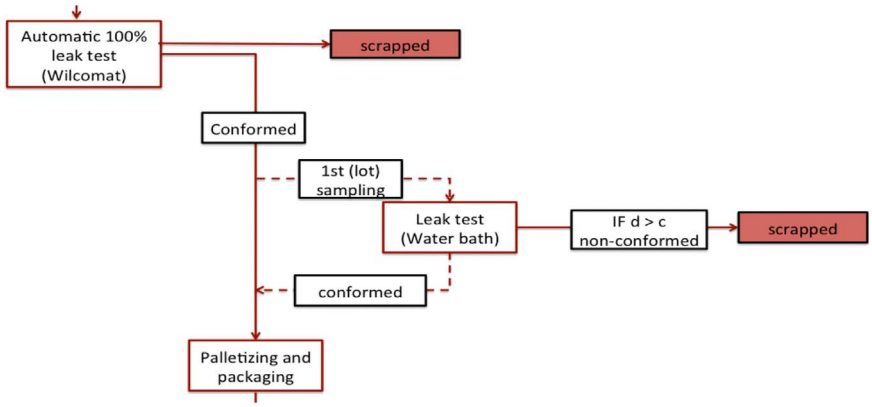

Fig. 7. Schematic representation of single stage acceptance sampling.

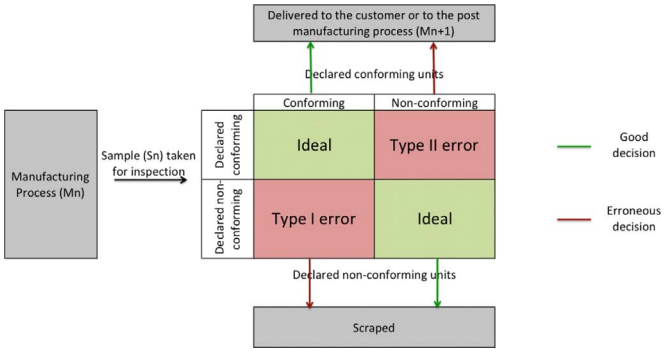

Fig. 8. Representation of a single stage revised acceptance-sampling flow diagram.

In the current study, several simplifying assumptions are made in order to drive an expression and are shown in Table 3:

Fig. 7 illustrates the strategy of the single stage acceptance sampling proposed for the assembly line in Colep.

The average number of units sampled S_n is essential in formulating an expression for costs. For a single acceptance sampling strategy, S_n depends primarily on the total units produced at the post manufacturing process (M_{n+1}), number of samples taken throughout the production period (N_s), probability of rejecting and scrapping the batch (p_s), and percent of units measured per batch (p_b):

$$S_n = M_{n+1} + (N_s * p_s * S_b * p_b)$$

The Inspection cost ($C_{Inspection}$) has two components: the first is the fixed cost (C_{Fxed}) that is the cost of the testing equipment ($C_{Equipment}$), and the second is the variable cost ($C_{Variable}$), that is the cost of testing the sample ($C_{Testing}$) plus the cost of scrapping the lot (C_{Scrap}).

$$C_{Inspection} = C_{Fixed} + C_{Variable}$$
$$C_{Fixed} = C_{Equipment} = PMT\ (\text{interest rate},\ \text{payment periods},\ \text{present value})$$
$$C_{Variable} = C_{Testing} + C_{Scrap}$$
$$C_{Testing} = N_s * S_b * p_b * C_{i,\text{Testing}}$$
$$C_{Scrap} = N_s * p_s * S_b * p_b * C_{i,\ \text{Scrap}}$$

Where C_i is the unit cost

The probability of scrapping a lot with a percent defective in the lot (p_d) is:

$$p_s = 1 - \sum_{d=0}^{c} p_d^{\,d} \frac{S_n\ !}{d!(S_n - d)!}(1-p_d)^{S_n - d}$$

If the acceptance number c is very small and the percentage defective p_d is relatively high, the standard single acceptance sampling may not always be a good approach for a low cost product with a high production rate. It is evident in this case that many lots will be rejected and scrapped, thus increasing the overall costs. Therefore, in order to find a better alternative solution, a revised single sampling plan is proposed that only rejects the non-conforming units in the sample rather than the complete batch. It is important to note that this method would not be named as an acceptance-sampling plan, as it is not taking any judgment of the lot quality based on the sample.

5.3. Scenario C - Single stage revised sampling strategy

This is one of the main contributions in this paper where a revised strategy is proposed that is similar to single stage acceptance sampling. In this strategy, a sample of units S_n is randomly drawn from a batch or

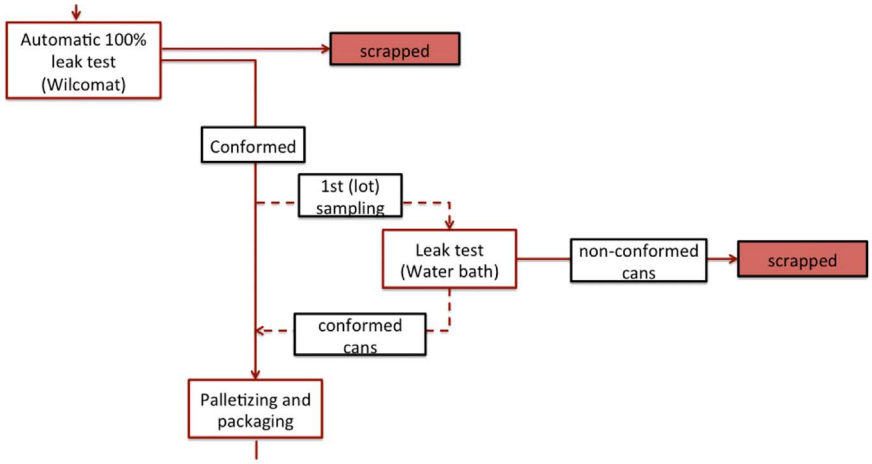

Fig. 9. Schematic representation of single stage revised acceptance sampling.

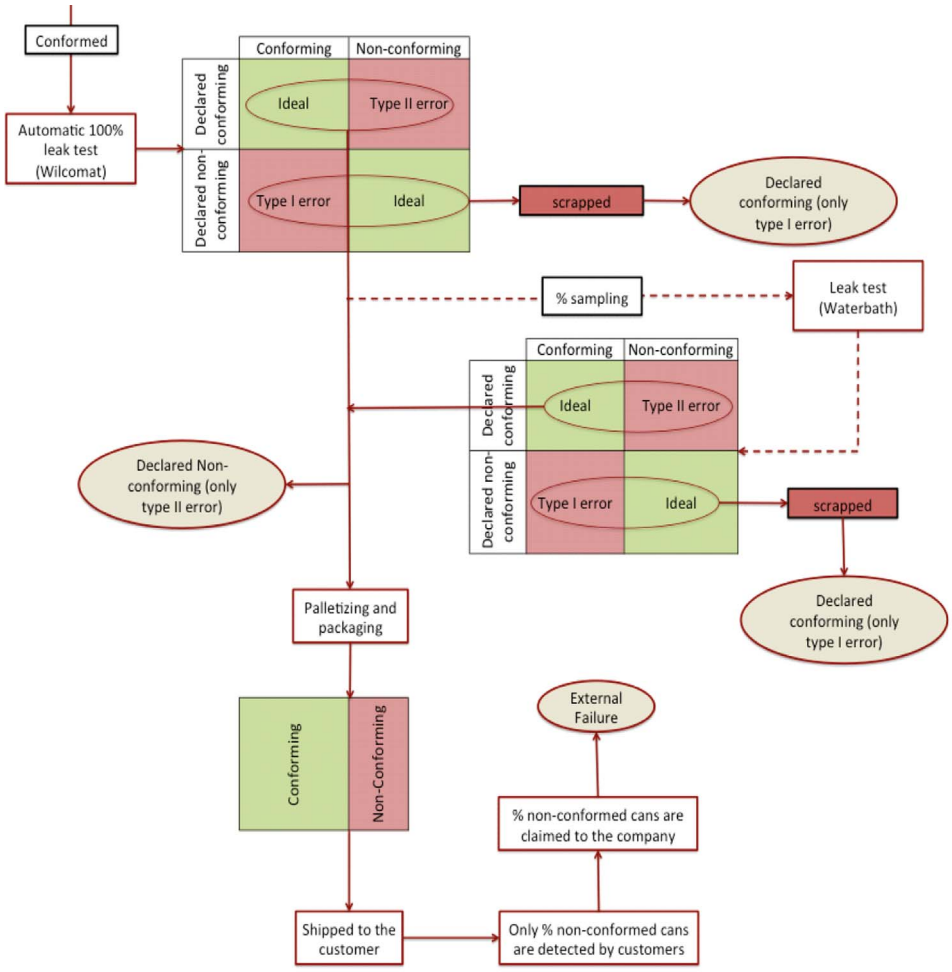

Fig. 10. Explaining external failure, declared conforming and non-conforming rates.

a lot of size S. However, in this revised case only a unit from the sample is either declared conforming or non-conforming following the inspection process. A declared conforming unit is shipped directly to the customer or to the post manufacturing process, whereas only the non-conforming units in the sample are rejected and scrapped, instead of scraping the complete lot. A general scheme for this single stage revised acceptance sampling is shown in Fig. 8.

For the revised single acceptance sampling following simplifying assumptions are made and shown in Table 3. Fig. 9 illustrates the strategy of the single stage revised sampling strategy proposed for the assembly line in Colep.

Similar to the strategy followed in single stage acceptance sampling, first it is depicted the number of units sampled and the expression that calculates the costs. For a revised single acceptance strategy, Sn depends primarily on the total units produced at the post manufacturing process (M_{n+1}), number of samples taken throughout the production period (N_s), percent defective in the lot (p_d), batch size (S_b), and percent of units measured per batch (p_b):

$$S_n = M_{n+1} + (N_s * p_d * S_b * p_b)$$

$$C_{Inspection} = C_{Fixed} + C_{Variable}$$
$$C_{Fixed} = C_{Equipment} = PMT\ (\text{interest rate},\ \text{payment periods},\ \text{present value})$$
$$C_{Variable} = C_{Testing} + C_{Scrap}$$
$$C_{Testing} = N_s * S_b * p_b * C_{i,Testing}$$
$$C_{Scrap} = N_s * p_d * S_b * p_b * C_{i,Scrap}$$

5.4. Scenario D - No waterbath inspection strategy

When no inspection is performed apart from the 100% automatic leak testing, then the process flow is simple and straightforward. Also, there is no need to develop any cost formulations for this scenario.

5.5. Defining quality of conformance rates and external failure costs

Prior to presenting the final results of this analysis, it is necessary to discuss the concept of declared conforming and non-conforming rates, as well as external failure costs. The flow diagram of Fig. 10 introduces these concepts.

5.5.1. Declared Conforming and non-conforming rates for 100% Leak Testing

Following the 100% testing of the aerosol cans, there are two possibilities: either the cans are declared non-conforming and immediately scrapped, or declared conforming and sent to the next production process.

Currently, neither the leaky aerosol cans nor the false positives at the assembly line are counted, which makes the estimation of the non-conformance rate quality difficult. A reference value was taken from the Design of Experiments (DOE) results – step 6 of the methodology, also revisited here in Table 4, showing a range of false positives (or type I error) between 0% –86% with an average of 26% (Column A). This is one of the important contributions from this paper where the results are directly taken from the experiments rather assumed or simulated.

Table 4
False positive analysis of 100% leak testing machine.

Leak measurements (100% Wilcomat machine)					
Experiment #	X Rejections (measuring through Wilcomat machine)	Y Rejections (validation of wilcomat rejections using waterbath)	Z – total sample size	1 - Y/Z % Conformance	A = 1-Y/X % False positives or type I error
2R1	8	7	400	98.25%	12.50%
2R2	1	1	400	99.75%	0.00%
2R3	14	2	400	99.50%	85.71%
2R4	127	116	400	71.00%	8.66%
2R5	14	13	400	96.75%	7.14%
2R6	5	2	400	99.50%	60.00%
2R7	33	26	400	93.50%	21.21%
2R8	33	29	400	92.75%	12.12%
2R9	3	2	400	99.50%	33.33%

5.5.2. Declared Non-Conforming rates

In the case of declared non-conforming cans at either stage, there is a possibility that the testing machine results in false positives (type I error) and, despite the fact that aerosol cans are good they are nevertheless scrapped. As a final result, material costs are increased.

It is important here to discuss briefly about the Design of Experiments that were performed by the co-authors along with the team at the company. A full factorial analysis (total experiments of 9) was selected between the two important factors to explore broader results. The sample size of 400 units was chosen and the working principle of these 400 units is defined below:

This working principle first addresses the issue of dividing the 400 samples per type of response variables (conductance test, 100% sampling using automatic wilcomat machine, and manual water bath system) i.e. how many aerosol cans will be allocated for each of the response variables:

- 100% of the cans made the conductance test: during this process the automatic rejection from welding monitoring system was disabled, which means that all the cans were transported to the subsequent processes;
- If a can is rejected or accepted at 100% testing machine, then this can will go through the manual waterbath test (rejected can is tested with waterbath for validation only);
- If a can is rejected at waterbath test, then this can will not do any other test;
- If a can is accepted at the waterbath test, then this can will be stored and will not do any other test.

Following the planned experiments, the team noted down the response variables as shown in Tables 4, 5. Although, it is difficult to choose any single number from Table 4 because it is not known which combination of factors the assembly line works, but after discussing with the team members (based on their several years of experience and limited historical data) as well as analyzing the table results, a range of 10% –20% of false positive (column A) looks appropriate.

Table 5
Rejections from the manual waterbath machine.

Experiment #	Rejections	Total	%
2R1	52	400	13.00%
2R2	5	400	1.25%
2R3	5	400	1.25%
2R4	56	400	14.00%
2R5	5	400	1.25%
2R6	0	400	0.00%
2R7	14	400	3.50%
2R8	17	400	4.25%
2R9	1	400	0.25%

Table 6
Quality of conformance and non-conformance rates for 100% leak test machine.

Declared state / True state	Conforming	Non-conforming
Conforming	99.5%	0.5%
Non-conforming	15%	85%

5.5.3. Declared conforming rates

Similarly, for declared quality of conformance rates, the conformed aerosol cans from the 100% leak testing machine need to be evaluated: how many cans are shipped as being conforming, that are in fact non-conforming cans (or type II error). Similar reference is taken from the results of DoE, and the rejections of manual waterbath presented in the paper are revisited here in Table 5.

Table 5 shows a range of rejections from 0% –14% with an average of 4.3% and a median of 1.25%. By analyzing these rejections as well as discussing with the team members (based on their several years of experience and limited historical data), a consensus about the appropriate value for the quality of declared conformance that is actually non-conforming units sent to the customer was set at 0.25% –1.25%.

A summary of the quality of conformance and non-conformance rates is presented in Table 6. In the table, a fixed value rather than a range is considered for further calculations. In the later sections, a sensitivity analysis that shows a wider range of conformance and non-conformance values is presented and discussed.

5.5.4. Declared Conforming rates for manual waterbath leak tests

The current claims data available to the industry are limited and it is not possible to correlate these claims with the internal production data, exploring further the values of conformance rates for manual waterbath tests. A discussion session was conducted between the production team members, and a consensus was reached around the values shown in Table 7.

The chances of finding a conformed aerosol can (type I error), after it has been declared non-conformed is very low, and its value was estimated to be 0.01%.

5.5.5. External Failure

External failure occurs when a declared conforming aerosol can fail on the field or at the customer facility, as shown in Fig. 10. Furthermore, the non-conforming cans that are declared conforming are not always detected by the customer. However, data concerning the number of non-conforming cans sent to the customer and the number of non-conforming cans detected by the customer is not known. Analyzing this data limitation, an assumption is made in the calculations that all the non-conforming cans (type II error) sent to the customer which were declared as good parts, will be detected by the customer's detection systems. As a result, the overall cost per piece will increase slightly, but the comparison among the different scenarios is still valid and conclusive.

When an aerosol can fail on the field there are two types of costs involved in it: tangible and intangible costs. Tangible costs are material, transportation, labor, production, and testing of the product

Table 7
Quality of conformance and non-conformance rates for waterbath leak test.

Declared state / True state	Conforming	Non-conforming
Conforming	99.95%	0.05%
Non-conforming	0.01%	99.99%

at the customer facility. In other words, it is the cost per piece plus transportation and testing costs. Intangible costs are loss of goodwill, company image, and customer dissatisfaction.

Tangible costs are easier to estimate than intangible costs, because it is evident that intangible costs are not measureable. Furthermore, for the particular case of the aerosol´s product quality and considering its crucial importance to Colep, intangible costs overshadowed the tangible costs. Thus, in order to consider the impact of intangible costs in the cost of the quality model, a higher external failure value must be considered. After discussion, the initial value was estimated to be €12. The value for an external failure is only an estimate and it is recognized that finding an exact value requires extensive market research. Therefore, for an external failure, a sensitivity analysis is performed in the next sections to assess the impact of different external failure values on the scenarios.

The quality of conformance rates and external failure costs estimated in this section are the baseline values for all the four scenarios.

5.6. Results, discussions and comparison among the scenarios

In order to evaluate the costs among the scenarios, a cost savings comparison is performed considering scenario A (double sampling – baseline scenario) to be the reference to all other scenarios. This can be investigated by analyzing the sensitivity of the following set of parameters:

- Additional external failure premium;
- Percentage (%) Conformance (fraction non-conforming) shipped to the customer.

5.6.1. Sensitivity analysis of cost savings per piece and additional external failure premium

For this analysis of the cost savings per year, only the additional external failure premium is varied, while all the discussed parameters are kept at their baseline values. As discussed, the baseline for external failure premium is set at €12, which gives scenario C as the strategy that minimizes the total cost per piece (shown in Fig. 11).

All the scenarios show linear function to the external failure premium where slopes are equal to the respective probability of the occurrence of external failure. Scenario A that was set as a reference to all other scenarios is fixed at €0. Scenario D has the highest magnitude of slope, which makes sense because while no manual waterbath inspection in-place, increasing the external failure premium would increase drastically the overall cost per piece. Scenarios B and C have approximately the same slope, showing different cost savings per year, which also makes sense because scenario C was adapted for this particularly case and the number of non-conforming units that are scraped is much lower. If the acceptance number for scenario B is increased then it will give the same result as scenario C however practically it is not possible to implement scenario B with higher acceptance number due to lower defective rates and therefore scenario C come into play an important role here.

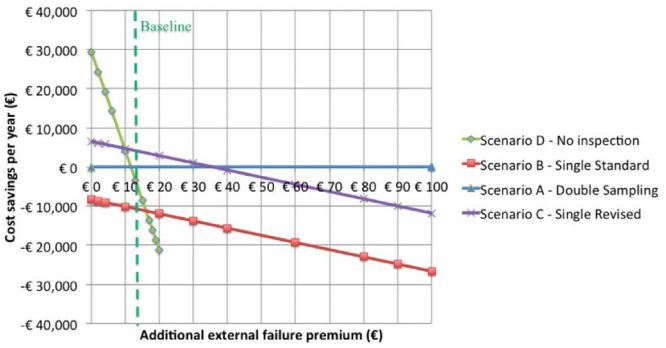

Fig. 11. Cost savings versus additional external failure premium.

Concluding the sensitivity analysis of additional external failure premium, one can say that for the current baseline value of €12, scenario C looks appropriate. However, this baseline value is merely an estimate and the exact value is hard to achieve without extensive market research. Therefore, adding to this conclusion, if the external failure premium would lie within the range of €0 - €10, then scenario D would be the one that minimizes the overall costs. If the external failure premium lies between the range of €11 - €35, then scenario C minimizes the overall costs. For a value of the external failure premium above €35, scenario A would be the most appropriate, minimizing the overall costs.

The maximum cost savings from this analysis is €30,000/year. This can be possible for such customers that are not serious about the small non-conforming units detected at their facility and do not add any external failure premium costs. For such conditions no inspection becomes a better situation.

5.6.2. Sensitivity analysis of cost savings per piece and percentage conformance (fraction non-conforming) shipped to the customer

Similarly to previous analysis, only the percentage conformance (fraction non-conforming) shipped to the customer is varied to evaluate its effect on the cost savings per year, while all the other parameters are kept at baseline values. In this analysis, conformance rates are considered only for the 100% leak-testing machine and the conformance rate is incrementally increased from an initial value of 98.6–99.8%. The baseline for conformance rate was estimated at 99.5%, as shown in Table 6. The results, as shown in Fig. 12, validate the previous conclusion that scenario C minimizes the overall cost per piece.

Scenario B is the most sensitive while scenario D is the least sensitive to changes in the conformance rates. At higher levels of conformance rates, difference in cost savings becomes very small among all the scenarios. This might be due to the fact that most of the units are according to specifications, being less likely to scrap any batch or perform extra sampling strategy, making scenario D (no inspection) the ideal one. Similarly, scenario C is optimal when conformance rates are lower due to less scrapping and less sampling of units. These conditions may change, while increasing or decreasing the external failure value.

The maximum cost savings from this analysis is approximately €60,000/year. This can be possible for such a situation when internal non-conformance rates are very high and therefore scenario C becomes a preferred and better option.

From the analysis of Figs. 11 and 12, scenario B is the only scenario that never achieved an optimal condition (looking throughout the range of external failure costs and conformance rates). Whereas, for all the other scenarios (A, C, and D) somewhere in the graphs leads to an optimal condition. Therefore, in order to investigate the behavior of the

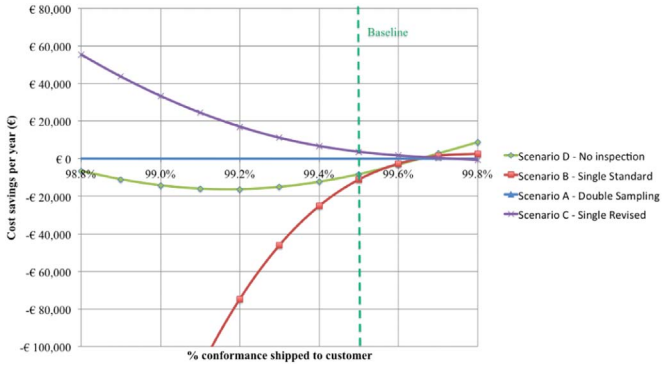

Fig. 12. Cost savings versus % conformance (fraction non-conforming) shipped to the customer.

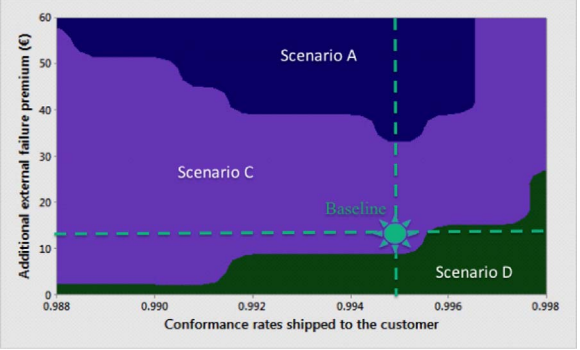

Fig. 13. Contour plot of scenarios A, C and D.

two parameters (conformance rates and external failure costs) together along with the three scenarios (A, C, and D) a 3D-contour plot is developed, as shown in Fig. 13.

The contour plot is a representation of the previous two sensitivity analyses in 3-D, plotting conformance rates on the x-axis and external failure premium on the y-axis. The contour plot allows understanding the sensitivity of both the parameters, drawing a boundary around all the scenarios. This contour plot can be utilized as a management tool for industry executives to select the most suitable and cost effect inspection strategy. Furthermore, the cost modeled in this paper is the cost that incur not only due to internal failure as well as due to external failure, which can encourage quality managers to make this contour plot a good practice for daily decision making.

6. Conclusion

This paper has successfully developed and discussed cost of quality model for the consumer goods industry that is facing a strong challenge to improve its product quality. The research analyzes the inspections strategies for the four scenarios including the as-is condition, which is regarded as a baseline scenario. The overall costs can be saved up to $60,000/year while varying external failure premium and non-conformance rates shipped to the customer. The results showed that:

- The current as-is condition of the assembly line, scenario A (double acceptance sampling plan) can be justified as an optimal strategy if the external failure cost is very high, when the range of conformance is between 98.8% −99.65%.
- For higher conformance rates than 99.65%, scenario C (revised single sampling plan) becomes ideal, this might be due to lower appraisal (sampling) and internal failure (scrapping) costs of this scenario when compared with scenario A.
- If the external failure costs are too small like, for example, between €0 – €10 then no inspection becomes ideal for most of the rates of conformance, because sampling and scrapping units increases the overall costs, making scenario A and C not appropriate anymore.
- Overall, Scenario C dominates the contour plot especially at the mid values of external failure premium.

This manuscript contributes to the development of cost of quality models for manufacturing systems where evaluation of inspection strategies is needed. Innovation is accomplished by developing an intermediate scenario between the single and double sampling strategies to generate a global optimum. Also, results from design of experiments that were performed on the shop floor were used to model the conformance and non-conformance rates. In most problems, these conformance rates are defined either based on the knowledge of experts or through computer simulations. Furthermore, the scenarios are plotted using a contour plot that can be utilized as a management tool to choose what is the most suitable inspection strategies with relation to conformance rates and external failure premium. Quality managers can also plot other relations in this contour plot and make the best decision.

There are two areas that can be additionally explored in the future to further reduce the overall cost, improve the final product quality, and strengthen the Systems Engineering methodology: (1) updating the corrected NCM with new knowledge acquired during the implementation phase of the methodology (step 9 of the methodology); and (2) applying the general methodology of Systems Engineering for quality improvement of manufacturing systems to other types of industries, in order to better assess the validity of the framework.

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