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Quality costs and Industry 4.0: inspection strategy modelling and reviewing

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Abstract

Inspection strategy (IS) is a key component impacting quality costs. Although often considered an inflexible output of initial quality plans, it may require revisions given the dynamic quality situation of the manufacturing system. It is from this background that the present study aims to model and compare different IS based on the cost of quality (CoQ) approach for a case study in the automotive manufacturing industry. While many computational inspection strategy models (ISMs) are available in the literature, most of them face application challenges and struggle to incorporate real-world data. The present study addresses this gap by developing a model that not only represents a real testing station in a manufacturing line but also uses historical production data. Additionally, in relation to model inputs, this study explores the challenges and opportunities of acquiring reliable quality cost estimates in the Industry 4.0 context. Among the main contributions of this work, the developed CoQ-based ISM can be used as a decision-making aiding tool for inspection revision and improvement, while conclusions about quality cost data collection in the industrial digitalization context can help advance the CoQ approach in practice.

Keywords Continuous improvement · Cost of quality · Industry 4.0 · Quality control · Simulation

1 Introduction

Smart manufacturing or the Industry 4.0 paradigm [1] has come to revolutionize manufacturing through high automation and data exchange levels. As a consequence, automotive electronics and other high-tech industries deal with the increasing complexity of products, processes, and systems, which according to Colledani et al. [2] is one of the major challenges for production quality. Indeed, developing software-intensive embedded systems is a significant challenge given the integration of a variety of constraints, such as real-time performance, design, and functional safety [3]. In this context, appraisal activities, such as inspection and testing, are essential to meet product specifications and are also key drivers of production time and cost.

That is why manufacturers often deal with two conflicting objectives: minimizing cost and maximizing quality of conformance [4], which can be understood as the ability of a product or process to meet its design specifications. Therefore, quality, although an intangible concept, must be translated into tangible, cost-related factors in order to guide decision-making from the manufacturing line to upper management. It is rooted in this environment that the cost of quality (CoQ) approach proves its relevance.

The CoQ helps quantify the quality of a production system through the costs incurred in attaining that same quality. Consequently, inspection-related costs are a critical component of the total CoQ. Often, inspection activities are defined at pre-production stages (a.k.a., inspection planning (IP)) including but not limited to defining relevant inspection characteristics, designating the stations at which product characteristics will be tested, how they will be tested, and to what extent. These factors are also known as IP decisions [5], "inspection strategy" (IS) [6], or specifications of the "quality control plan" (QCP) [7], according to which test stations should also be provided, *e.g.*, with the appropriate equipment, personnel, and data recording systems [8].

As expected, all these arrangements come with a cost, especially when it is necessary to acquire new equipment or software. However, it is necessary to calculate the total return on (inspection) investment, as a means to justify the selected IS. Along these lines, many works propose inspection strategy models (ISMs) based on CoQ, such as

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Sousa and Nunes [9] and Zaklouta and Roth [10]. These ISM models are seen as tools for decision-making support [11, 12]. Usually, they investigate the implementation of an economically appropriate level of inspection effort by finding a balance among different cost components related to the inspection process, such as failure rate, production capability, errors type I and type II, as well as internal and external related costs [5, 9, 13, 14].

However, most authors do not report the practical adoption of ISMs in the industry. This lack of practical application may be due to the complicated mathematical apparatus of the models [15], or because the models simplify the problem too much by neglecting realistic conditions of industrial environments [16]. In addition, a lack of knowledge on how to measure the high number of model parameters/variables is considered a critical aspect that inhibits the use of these models [7, 15]. This is one of the gaps the present study addresses through the development of an applied model.

Additionally, IS, after being initially established based on the customer requirements and the optimal allocation of the company's internal resources, must be continually evaluated to be adapted according to the company's continuous improvement practices [17]. IS revision is necessary to ensure the required product quality to the customer, to reduce appraisal costs (e.g., by adjusting inspection processes that are obsolete due to sufficient process capability), and to reduce failure costs (e.g., caused by ineffective or inefficient inspection activities) [17]. For instance, Karimi-Mamaghan et al. [5] proposed an agile integrated plan to respond to inspection-machining needs while still controlling costs and quality. The authors also employed a numerical example to validate and verify their plan. However, in practice, the revision of IS in the context of automotive electronics seems an under-researched topic. Likewise, CoQ assessment concerning ISM has significant potential to be explored further [18, 19]. There is a lack of studies on economic analysis or detailed impacts on CoQ that justifies necessary investments in processes [20].

From this background, the present study aims to develop a CoQ-based ISM to be used as a decision-making aiding tool for IS revision. The model is developed for a case study in the automotive electronics industry, which is inserted in the Industry 4.0 context. An ongoing production process is assessed as a means to evaluate the need for revising inspection arrangements. The computational simulation together with scenario and sensitivity analysis are employed to answer the following research question "How different IS applied at a particular test station would impact the CoQ?" Additionally, this study also aims at determining "What are the challenges and opportunities of acquiring reliable quality cost estimates in the Industry 4.0 context?" The former focuses on the importance of IS revision for continuous improvement, whereas the latter targets the aforementioned problem of ISM application.

Concerning the selected research approach, i.e., case study, it combines the need for applied CoQ-ISM with an opportune business environment, considering automotive electronics' increasing complexity and digitalization of products and processes, rigorous quality control mechanisms, and elaborated quality and productivity systems.

The rest of this paper is organized as follows: Section 2 presents the theoretical background. Section 3 presents the methods. A real case study is presented in Sect. 4, followed by the model in Sect. 5. Sections 6 and 7 present the results and discussion, and, finally, conclusions are down in Sect. 8.

2 Theoretical background

This section brings, first, a brief overview of the best-known CoQ approaches, followed by a review of studies presenting ISM, also denoted as quality control models or quality control strategy models in the literature.

2.1 CoQ approaches

As quality costs have many components and can be relatively hard to foresee, several approaches to estimate the CoQ have been proposed in the literature. In general, CoQ approaches can be divided into five groups: (i) prevention, appraisal, and failure (PAF); (ii) Crosby's approach; (iii) opportunity cost; (iv) process cost; and (v) activity-based costing (ABC). These approaches offer different ways to identify quality-related costs according to certain categories.

In the 1950s, Juran [21] introduced the concepts of "quality costing" and "economics of quality." Later, Feigenbaum [22] proposed the now widely accepted quality-cost categorization of PAF costs. The basic suppositions of the PAF approach are that investment in prevention and appraisal activities will reduce failure costs and that further investment in prevention activities will reduce appraisal costs. PAF is also adopted by the Portuguese Standard NP 4239:1994 [23], which disposes bases for quantifying the CoQ. Most IS models are based on the PAF classification. Examples include Farooq et al. [24] and Zaklouta et al. [10].

Alternatives to the PAF classification include Crosby's [25] approach based on quality as "conformance to requirements," in which the CoQ is defined as the sum of the price of conformance and the price of non-conformance. The cost categories of Crosby's [25] model are similar to the PAF scheme. The price of conformance is the cost involved in assuring that things are done right the first time, which includes actual prevention and appraisal costs (i.e., cost of good quality), while the price of non-conformance is the money wasted when work fails to conform to customer requirements, usually calculated by quantifying the cost of correcting, reworking, or scrapping, which corresponds to failure costs (i.e., cost of poor quality). An example of an ISM model that employed Crosby's approach was developed by Tuominen [26].

The process cost approach, proposed by Porter and Rayner [27], represents quality cost systems that focus on the process rather than products or services. Other approaches to determining the CoQ include the ABC [28] and the opportunity (or intangible) cost approach [29].

2.2 Inspection strategy models

Quality control is one of the major concerns in manufacturing systems, and quality managers always deal with complex and multifaceted decisions about allocating inspection resources and facilities most efficiently and economically [16]. More and tighter inspection will normally induce a higher product quality—in terms of meeting product specifications—but will also result in higher costs of appraisal and prevention costs. The IS should quantify this trade-off and establish ways of finding an economic optimum for the CoQ.

There are many works assessing IS based on CoQ modeling in different sectors and products, for example, in the automotive industry (e.g., vehicle induction braking system in (Sousa and Nunes [30])) and in the consumer goods manufacturing industry (e.g., aerosol can in Farooq et al. [24]). In addition, there are also generic ISMs for serial multistage manufacturing systems and markets with high levels of customization [31, 32]. Table 1 shows a non-extensive list of works that used a CoQ approach to define an IS, together with their main objective and application context. Since not all authors clearly stated their CoQ approach, it was established by assessing each work methodology.

Next, Table 2 presents the solution techniques used in the ISMs. Several authors considered sensitivity analysis in their work (e.g., [30, 41]).

2.3 Estimation of ISM parameters

Although the estimation of cost variables may not be straightforward in real cases, prior knowledge of the production process and historical data can help [42]. To utilize quality cost data in control processes, the information must be both gathered and reported to the relevant people in a timely manner. It is necessary to have an assessment method that is flexible, sensitive, fair, and fast [43]. If these requirements can be met, quality cost data can be a powerful source of information for ISMs and quality management.

Any solid IS will have to consider the needs of various stakeholders and make reasonable trade-offs between its objectives [44]. These stakeholders may be from different companies and different departments within each company, and the coordination and cooperation among them in achieving the right inspection balance between conflicting quality-costs goals are seen as a key issue for success [2]. Nevertheless, it is claimed that IS is often derived from a weak information basis and therefore relies on the experience of the quality planner [45] or is based upon traditions, standards, and procedures that do not provide the optimum balance of quality assurance versus cost and time [46].

Academic research on the "real-world" implementation of ISM considering quality costs is still limited. It is complicated to consider all the different user requirements and contextual variables needed in real manufacturing processes [15]. Overall, the models underestimate or ignore some aspects of the real problem, which can result in the computation of either unrealistic or unfeasible solutions, or solutions that do not capture domain-related characteristics [47]. It is generally difficult to obtain a model of an optimization problem that reflects all aspects of the real decision-makers' difficulty. Consequently, the errors and the uncertainty associated with the estimated values of process variables influence the accuracy of results [30]. Therefore, it is important to consider the sensitivity of the assessment by considering the uncertainty and vagueness inherent in a real environment.

3 Methods

Conceptually, this work employs the approach to CoQ used by Sousa and Nunes [7] to develop a computational model concerned with selecting the best IS based on an expected CoQ. However, it is developed for a different case study context, for a new specific production process, and based on its respective defect handling system. The PAF approach is employed to determine quality cost components to be inserted in the developed ISM. Here, two different inspection extents (i.e., no control and 100% inspection) at a testing station are evaluated for a case study in the automotive electronics industry. An ongoing production process is assessed as a means to evaluate the need for revising inspection arrangements. Secondary data available from the Company's reports and databases were gathered to provide inputs to the model.

Given the number of parameters required to select the best IS and the complexity of the problem, the computational model was implemented in Microsoft Excel. The uncertainty of quality cost parameters prompted the utilization of Monte Carlo simulation and sensitivity analysis, which was performed with an academic license of the add-in tool for Microsoft Excel, @RISK 8.1 from Palisade (https://www.palisade.com/risk/).

Table 1 Inspection strategy models

	Objective	Application context (if applied)	CoQ approach
[33]	To describe quality cost models to compare the behaviors of different technological processes and different inspection strategies (no inspection/statistical process control/100% inspection)	Surface-mount technology production line (for printed circuit board)	Process cost
[34]	To investigate and evaluate the inspection strategies with respect to quality, cost, and time using the QUINTE simulator	Manufacturer of mobile hydraulic products manufacture of stub shafts	Process cost
[35]	To develop an optimization model considering the cost of adjusting manufacturing processes to reduce or eliminate rejected pieces	Seat manufacturing company	Process cost
[10]	Analytic COC framework inspection strategy scenarios	Welded automotive assemblies	PAF
[26]	To compare different inspection strategies and for creating an understanding of the structure of the costs of bad quality in automotive manufacturing	Front subframes (a.k.a. engine cradles) or instrument panel supports (a.k.a. cross car beams)	Crosby’s approach
[36]	To investigate the adaptability of a modified activity-based costing model in the evaluation of cost regarding the activities in tolerance allocation, process planning, and inspection planning	Automotive industry (cover intermediate shaft part)	ABC
[16]	To find optimal inspection policies in serial multistage production processes to minimize total inspection cost where the cost components are described using fuzzy numbers	A serial multistage manufacturing system	Process cost
[37]	To develop an optimization framework for process inspection planning based on a mixed-integer linear programming model that tries to make a trade-off between cost and quality	Solid frame with 15 different quality characteristics in a car manufacturing company	Process cost
[38]	To develop an optimal inspection policy for the multi-station manufacturing system subjected to quality shifts to minimize total quality-related costs	Mobile phone shell production	Process cost
[24]	To evaluate inspection strategies using the COQ approach to find a global optimum by developing an intermediate scenario between single and double acceptance sampling strategies	Consumer goods manufacturing industry/three-piece tin plate aerosol can	PAF
[32]	To propose a cost-driven decision-making framework to formulate costs of the spatial distribution of microstructural defects and the corresponding control actions, based on in situ melt pool images	Laser-based additive manufactured process (thin wall fabrication)	Process cost
[39]	To provide a stochastic dynamic programming model for designing the quality control plan in a manufacturing process, which allows obtaining the desired level of control with the lowest cost	Multi-stage manufacturing systems	PAF
[30]	To propose a model to select the control strategy that minimizes quality costs considering parameters uncertainty	Vehicle induction braking system	PAF
[40]	To find a suitable trade-off between inspection time and internal and external quality costs to increase reliability benefits	Stochastic scheduling of a two-machine flow shop robotic cell with controllable inspection times	Process cost
[15]	To propose an approach to the planning and optimization of quality inspections within a multistage manufacturing process based on quality costs and the value added to the production process by inspections	Surgical scissors	PAF
[5]	To develop an agile integrated inspection-machining planning model to simultaneously make inspection and machining decisions considering cost, quality, and time	Solid frame with 15 different quality characteristics in a car manufacturing company	Process cost

Table 2 Solution techniques in ISM

References	Solution approach	Sensitivity analysis
[33]	Mathematical modelling	Yes
[34]	Simulation	No
[35]	Mathematical modelling	No
[10]	Mathematical modelling/discrete event simulations	Yes
[26]	Mathematical modelling	Yes
[36]	Modified activity-based costing model	Yes
[16]	Particle swarm optimization	Yes
[37]	Mixed-integer mathematical programming integrated with the Taguchi loss function and Monte Carlo methods and genetic algorithm to obtain near-optimal solutions	Yes
[38]	An integrated algorithm combining heuristic rule and tabu search	Yes
[24]	Mathematical modelling	Yes
[32]	Multi-layer perceptron/self-organizing map/self-organizing error-driven neural networks/fluid genetic algorithm	No
[39]	Dynamic programming	No
[30]	Mathematical modelling/Monte Carlo method	Yes
[40]	Stochastic bi-objective optimization	Yes
[15]	Mathematical modelling/added value	Yes
[5]	Differential evolution algorithm and a machine-learning-based iterated local search, integrated with the Taguchi loss function and Monte Carlo methods	Yes

The model validation process followed what was proposed by Landry, Malouin, and Oral [48]: conceptual validation, logical validation, experimental validation, operational validation, and data validation. For doing so, interviews took place with quality specialists inside the Company and the academia. The conceptual model is valid as it is based on the current defect handling at FCT50, as described in Section 4.2. All pertinent variables were included in the model. Model's sensitivity to changes in certain parameters was also tested. The model tested two inspection extent strategies that are aligned with realistic choices of reducing inspection costs while using a mix of historical data and estimates for certain model parameters. The accuracy of model results, however, could not be established given the absence of a CoQ control for the case study.

Risks and opportunities concerning quality cost estimations in the Industry 4.0 context were gathered through a qualitative analysis based on the literature on CoQ approaches and industry practices identified from the case study.

4 Case study

The Company where the case study took place is a subsidiary of a large German international organization, related to the mobility sector, more specifically, automotive electronics and car multimedia technologies. Its location is not disclosed herein due to confidentiality reasons. The Company is growing towards automation and data exchange in technology and processes within the manufacturing industry, which places it in the Industry 4.0 context.

The control plan explored in this paper is associated with the production of an infotainment system, a multi-functional interactive hardware and software device that provides information (e.g., fuel level, parking assistance), communication (e.g., Bluetooth), and entertainment (e.g., audio/video, radio) services during automobile use [49]. Many components/sub-assemblies that compose the complete device are built in-house. Basically, there are distinct production chains, e.g., to assemble the printed circuit board, to bond the glass and the display, and to assemble this set to the carrier frame. In the final assembly line, which is the focus of this paper, additional parts, such as covers and screws, are assembled to produce a complete device.

4.1 Inspection planning

The procedure applied in the Company for IP activities can be divided into two phases. The first phase is related to inspection characteristics' identification and analysis. Accordingly, IS and test procedures are developed along with resource requirement. Thus, the second phase deals with the inspection process conception and allocation.

The input for the definition of the quality characteristics comprises the drawings, CAD, part lists, functional analysis from product and process FMEA (failure mode and effect analysis), quality function deployment (QFD), and the

Company planning guidelines. The FMEA version used was based on VDA (*Verband der Automobilindustrie*), which is the German association for automotive manufacturers. However, the Company's new projects are following the FMEA version based on both VDA and AIAG (Automotive Industry Action Group).

To define the characteristics to be inspected, it is also necessary to have information regarding legal and safety requirements, customer requirements, and lessons learned from previous customer complaints. Based on a set of Company's defined rules (not disclosed here due to their confidential status), product and process characteristics are categorized into three levels: A, B, and C classes. This classification is basically based on the robustness of both the characteristics and the manufacturing method. The characteristics are functionally robust if they are barely sensitive to variability, i.e., do not fail solely and immediately upon exceeding the tolerance band. Regarding manufacturing method robustness, product characteristics are analyzed regarding the likelihood of exceeding the tolerance limit when using the chosen manufacturing method. Each characteristic class (A, B, and C) implies a different IS during the product manufacturing lifecycle.

Within the overall documentation provided regarding the IP process in the Company, there is no indication of when the quality costs are taken into account. When questioning a Testing Engineer about it, he answered that in the industrialization process at the Company, some teams think about costs, estimate them, and present a layout proposal in the industrialization decision.

4.2 Defect handling

Within a manufacturing line in the Company, there are testing stations (TS) and work stations (WS). While the TS are devoted to inspection/testing activities, the output of each WS is also checked against the required quality by both the operators and the WS themselves, during its production/assembly. The devices classified as defective at any WS or TS are conveyed to the technical analysis station, which is offline. In this analysis station (AS), a technician checks whether the rejected device is actually defective.

When the analysis technician considers the device as not defective (labelled as "s-case," i.e., in specification), it returns to the WS or TS where it was previously considered as failed (or an even earlier station, depending on each situation) to be inspected again.

Else way, when the device is confirmed as defective, it is disassembled, part by part, until the defective one is removed. The components that are being dismantled until the defective one is found can be reused or not, according to a predefined set of rules called "reuse matrix," which is specific for each project. The defect is always classified according to a defect directory before replacing and scrapping its defective portion.

The AS technician has some equipment and can perform the repair in some cases, e.g., to replace a foil that was improperly assembled. In other cases, when further analysis or intricate rework is necessary, the part is dispatched to the electrical laboratory. After being repaired, the part returns to the process.

The described handling process of a defective part from a TS is summarily represented in Fig. 1. Products classified as failed by any WS follow the same procedure from AS onwards.

4.3 Final assembly line

The final assembly line consists of 18 stations, as represented in Fig. 2. Some of them involve automatic and manual operations for assembly (i.e., WS) while others are TS (in gray), such as the functional circuit test (FCT) stations. FCT is a class of automatic and objective TS that functionally tests the assembled printed circuit at the beginning of the final assembly line (FCT20) and after, when it is attached to other product parts, constituting the complete device (FCT50). Examples of quality characteristics/functional blocks tested in FCT50 are light sensor calibration, brightness measurement symbols, fuel bars brightness, and night illumination adjustment, just to cite a few. Currently, the inspection extent at FCT50 is 100%, which means that all units that pass through that station are inspected.

5 CoQ modeling

While Fig. 2 maps a generic situation reflecting the current approach of the Company for handling defective parts, Fig. 3 also encompasses the elements pertinent to the model being proposed in this paper. Therefore, it specifies the TS in question (FCT50), along with several parameters and costs elements, as follows:

- N_p: number of units passing through the FCT50
- P_d: proportion of defectives in FCT50
- F_d: false defectives (type I error)
- F_n: false compliant (type II error)
- $C_{inspection}$: unitary inspection cost (€/unit)
- $C_{analysis}$: unitary analysis cost (€/unit)
- C_{repair}: unitary repair cost (€/unit)
- $C_{reinspection}$: unitary reinspection cost (€/unit)
- C_n: unitary cost of passing a defective unit to the next process (€/unit)

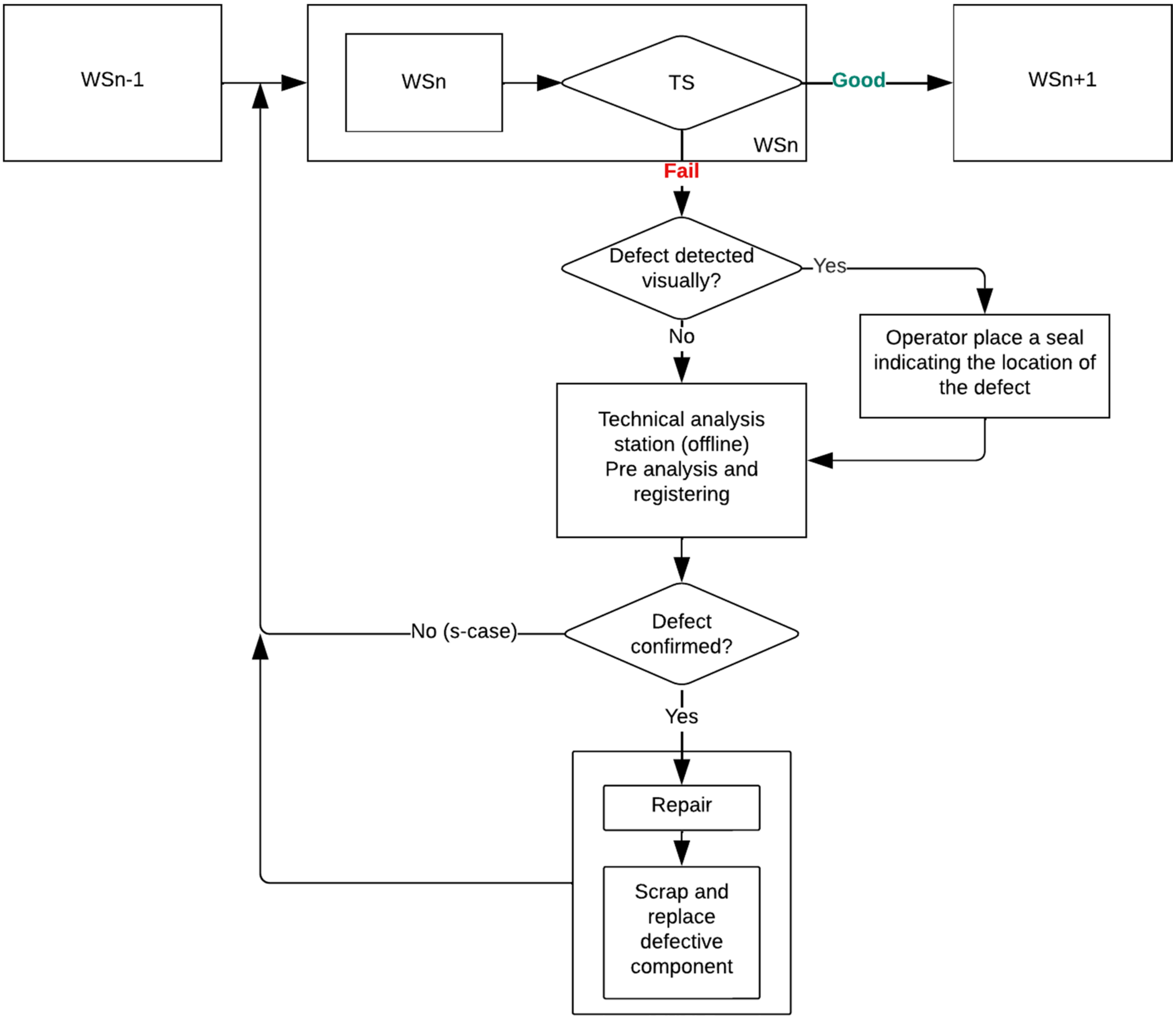


Fig. 1 Current defect handling scheme at the Company

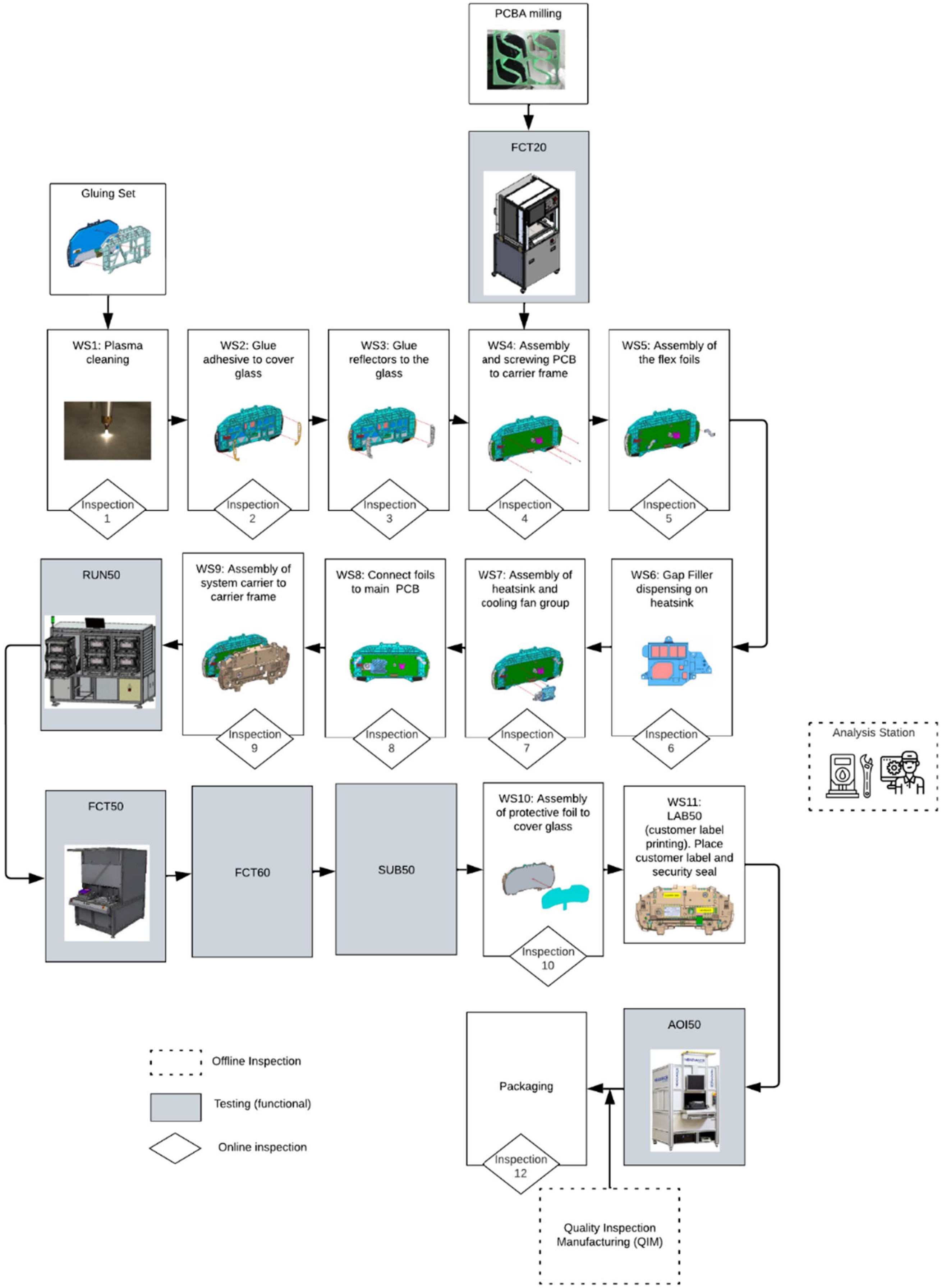
5.1 Model parameters

The parameters were estimated based on a database containing the results of tests carried out, i.e., secondary data already available at the Company. The secondary data refers to the year 2020 for the analyzed product (i.e., an infotainment system) in the FCT50.

Given these data, P_d was estimated as the geometric mean between the failed and produced products, i.e., 4.5%.

The estimated proportion of false defectives (F_d) (type-I error) was estimated based on the count of s-cases within the failed devices, i.e., the cases in which the analyst spotted improper rejections by the inspection/test system. The average of s-cases for the year 2020 in this station and this production line was 1.9%. There is the human factor associated with registering s-cases, which implies an uncertainty associated with this estimation of F_d. Therefore, this uncertainty was defined as [0.002; 0.019; 0.06] with a triangular distribution centered at 1.9%.

The Company usually defines product specifications tighter than initial customer specifications so that errors are forced on one side of the specification. The TS measures several quality characteristics, and whenever one of them happens to be outside the tight-imposed tolerance limits, the product will "fail" at the station. This can increase false defectives given by the measurement system while reducing false compliance (type-II error). Nevertheless, the false non-defectives (F_n) were assumed as in [10]: type-I equal to the type-II error. The uncertainty was also defined as [0.002; 0.06]; however, the uniform distribution (rectangle-shaped)


PCBA milling
FCT20
Gluing Set
WS1: Plasma cleaning
Inspection 1
WS2: Glue adhesive to cover glass
Inspection 2
WS3: Glue reflectors to the glass
Inspection 3
WS4: Assembly and screwing PCB to carrier frame
Inspection 4
WS5: Assembly of the flex foils
Inspection 5
RUN50
WS9: Assembly of system carrier to carrier frame
Inspection 9
WS8: Connect foils to main PCB
Inspection 8
WS7: Assembly of heatsink and cooling fan group
Inspection 7
WS6: Gap Filler dispensing on heatsink
Inspection 6
Analysis Station
FCT50
FCT60
SUB50
WS10: Assembly of protective foil to cover glass
Inspection 10
WS11: LAB50 (customer label printing). Place customer label and security seal
AOI50
Packaging
Inspection 12
Quality Inspection Manufacturing (QIM)
Offline Inspection
Testing (functional)
Online inspection

◂**Fig. 2** Production flow for the final assembly line

was used in the simulation rather than the triangular one (triangle-shaped).

5.2 CoQ elements

The total CoQ encompasses many CoQ elements (C_{repair}, $C_{analysis}$, $C_{reinspection}$, and C_n, and $C_{inspection}$), as represented in Fig. 3. The assessment of these elements is outlined next.

The accounting department of the Company handles the internal failure costs by production lines considering the costs of rework, scrap, and replacement. There are no computed unitary costs related to the inspection activities. As both the inspection and reinspection happen in the same equipment, the estimates for the cost of inspection ($C_{inspection}$) and reinspection ($C_{reinspection}$) were considered the same. Therefore, these costs were assessed by considering the sum of fixed and variable costs per piece. The fixed costs comprise the costs of the hardware and software used for automated testing, e.g., machine, tool license, and acquisition costs, while the variable costs consider the operators. It was necessary to get information within the testing department regarding the first items, while the cost estimate for operator activities was gathered along with the accounting department. The estimated unitary $C_{inspection}$ and $C_{reinspection}$ costs resulted in 0.45€/unit.

The analysis cost ($C_{analysis}$) was also not yet been carried out by the Company. This data was estimated together with the accounting department, similar to the analysis carried out for other operations that require human operators.

The cost of repair (C_{repair}) includes both the costs of the operator performing repairs and the cost of scrapping and replacing the eventual defective parts. The last was estimated considering the historical data regarding different defect types and their associated costs. The data on the types of defects found during the assembly processes is entered into the database by the production line managers. Therefore, it was necessary to contact the manufacturing department to obtain these data. Accordingly, it was possible to calculate the weighted average, which resulted in 5€/unit.

The cost of passing a defective unit to the next station (C_n) was estimated purely based on expert opinion within the Company and academia.

The list of model parameters (N_p, P_d, F_d, and F_n) and cost elements (C_{repair}, $C_{analysis}$, $C_{reinspection}$, and C_n) of the ISM is presented in Table 3. Many difficulties were faced in obtaining these values. Accordingly, some parameters and cost estimative are associated with more or less uncertainty. The definition, estimated value, and uncertainty intervals of parameters are also presented in Table 3.

5.3 Unitary CoQ computation

The equations behind the calculus of the total CoQ per product unit are presented next. Based on the PAF approach, the total CoQ comprises the failure-related costs (C_{repair}, $C_{analysis}$, $C_{reinspection}$, and C_n) and the appraisal-related cost ($C_{inspection}$). The $C_{reinspection}$ is not computed within the category of appraisal cost, as it is incurred due to internal failure.

The total CoQ of using 100% inspection is expressed by Eq. (1), while the unitary CoQ is expressed by Eq. (2):

$$\begin{gathered} Total\ CoQ_{100\%inspection} = \left(C_{inspection}.N_p\right)+ \\ \left[C_{analysis}.N_p.\left(P_d + F_d - F_d.P_d - P_d.F_n\right) + C_{repair}.N_p.P_d\left(1 - F_n\right)\right. \\ \left.+C_{reinspection}.N_p.\left(P_d + F_d - F_d.P_d - P_d.F_n\right) + C_n.N_p.P_d.F_n\right] \end{gathered} \tag{1}$$

$$Unitary\ CoQ_{100\%inspection} = \frac{Total\ CoQ}{N_p} \tag{2}$$

where

N_p. $C_{inspection}$ is the overall cost of 100% inspection;

$C_{analysis}$. N_p. $(P_d + F_d - F_d.\ P_d - P_d.\ F_n)$ is the overall cost of analysis;

C_{repair}. N_p. $P_d(1 - F_n)$ is the overall cost of repair;

$C_{reinspection}$. N_p. $(P_d + F_d - F_d.\ P_d - P_d.\ F_n)$ is the overall cost of reinspection; and

C_n. N_p. P_d. F_n is the overall cost of passing defective units to the next station.

6 Results

This section presents the simulation results for the CoQ for 100% and no-inspection strategies. In the 100% inspection case, it is also presented the effects of a hypothetical investment in the manufacturing line to reduce the proportion of defective units (Pd) on the total CoQ per product unit.

6.1 CoQ: 100% inspection

As mentioned before, all product units that pass through FCT50 are tested (i.e., 100% inspection). Even though this is the current IS at the TS, there is no indication about its total CoQ within the Company's reports and databases. Therefore, the developed model was used to calculate it through the estimates and equations shown in Sect. 5. Accordingly, Fig. 4 presents the histogram obtained from the Monte Carlo simulation results, which show a unitary total CoQ of 0.61€/unit, which can be found between 0.5984 and 0.7207€/unit within a 90% confidence interval for the 100% IS.

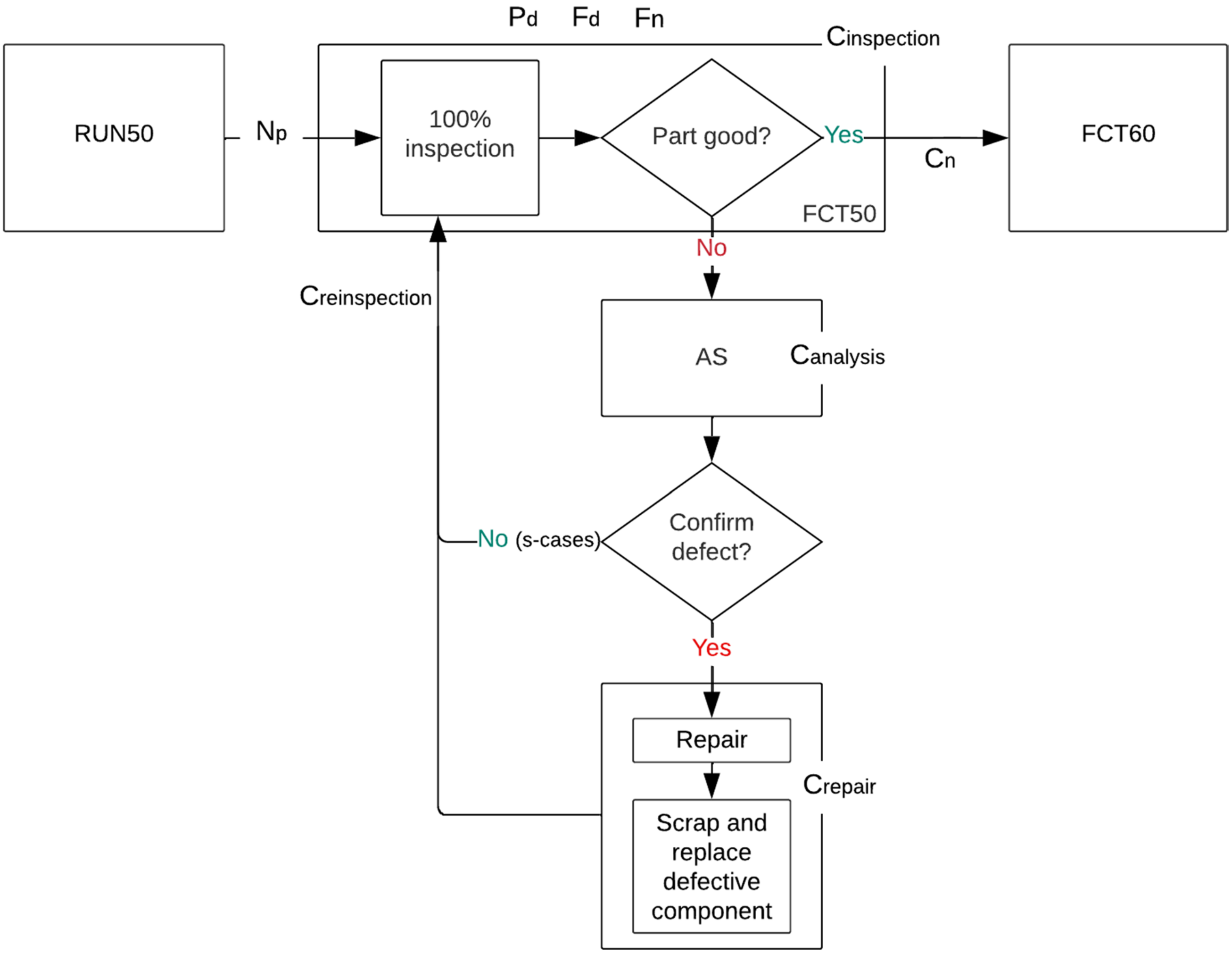


Fig. 3 Conceptual model of the current defect handling at FCT50 along with its costs and parameters

Table 3 Model parameters

Abbreviation	Description	Value	Uncertainty
Pd	Estimated proportion of defective units	0.045	
Fd	Estimated proportion of false defectives given by the measurement system	0.019	[0.002; 0.06]
Fc	Estimated proportion of false non-defectives given by the measurement system	0.019	[0.002; 0.06]
$C_{inspection}$	Estimated average unitary inspection cost	0.45	[0.405; 0.495]
C_{repair}	Estimated average cost of repairing a defective unit	2	[1.5; 4]
$C_{analysis}$	Estimated average unitary analysis cost	0.5	[0.35; 0.75]
$C_{reinspection}$	Estimated average unitary reinspection cost	0.45	[0.405; 0.495]
C_n	Estimated average cost of passing a defective unit to the next process	20	[15; 30]

Figure 5 shows the tornado diagram that displays parameters with a higher influence on the total CoQ. The $C_{inspection}$ and C_{repair} have the highest impacts on the total CoQ. This also means that the objective function is more sensitive to the change of these costs than to the change of $C_{analysis}$ and C_n

By acknowledging that changes in process values would result in different values in the total CoQ, a scenario is presented supposing there was an investment in the production line to reduce P_d. Therefore, assuming the investment

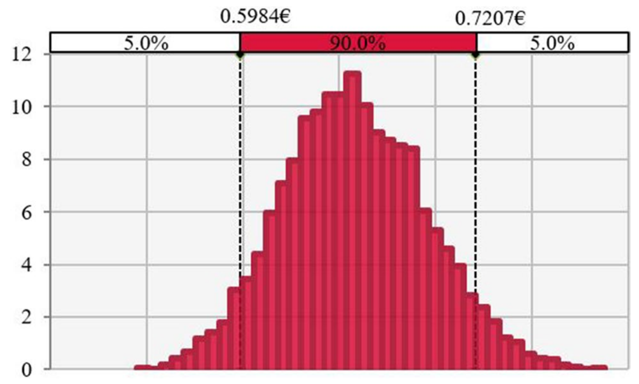


Fig. 4 Unitary total CoQ histogram with a 90% confidence interval for the 100% inspection. Source: Output from @RISK

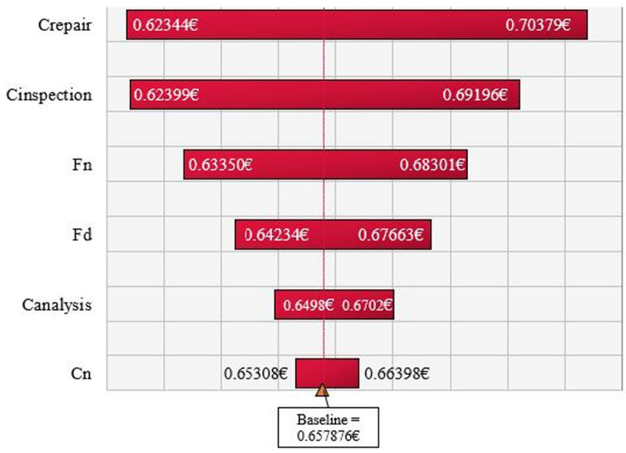


Fig. 5 Sensitivity analysis, ranking inputs variation effects on the unitary total CoQ. Source: Output from @Risk

Table 4 Average unitary total CoQ within a 90% confidence interval

Pd	Min (5%)	Average	Max (95%)
4.5%	0.5984€/unit	0.61€/unit	0.7207€/unit
1%	0.4783€/unit	0.50€/unit	0.5563€/unit

resulted in a reduction in the proportion of defectives from 4.5 to 1%, the unitary CoQ would perform as shown in Table 4.

6.2 CoQ: no inspection

Some quality characteristics must be mandatorily inspected during the production process, for example, those related to safety, legislation, or even customer requirements.

In the hypothetical situation of "no inspection" presented here, it is assumed that these characteristics would be inspected in another TS. Indeed, even for characteristics that are inspected at the initiative of the Company rather than by external mandate, the complete absence of control is probably not the best solution, especially in cases of processes that are not as robust.

Considering the context of the automotive electronics industry, inspection followed by analysis and repair activities helps to explain why some type of quality problem occurs, which is useful information for product and process improvement. By working on these tasks, analyzing defects and performing root cause investigations, quality engineers gain valuable information. However, when the process capacity is already quite robust, it is plausible to assume that some characteristics can only be controlled during the pre-production phase, where product samples are manufactured, instead of being inspected at 100% during the mass production phase.

Nevertheless, if there is no inspection, it is expected that more defective units would be handed over to the next process compared to the current situation of 100% inspection. In this scenario, the relevant parameters are related to the expected cost of defective units delivered to the next process. The total CoQ of no inspection is expressed in Eq. (3), while the unitary CoQ is expressed in Eq. (4).

$$Total\ CoQ_{no-inspection} = \left[C_n.N_p.P_d \right] \tag{3}$$

$$Unitary\ CoQ_{no-inspection} = \frac{Total\ CoQ_{no-inspection}}{N_p} \tag{4}$$

where

$C_n.\ N_p.\ P_d$ is the overall cost of passing defective units to the next station.

The $Unitary\ CoQ_{no-inspection}$ results in 0.90€/unit. By supposing the same alternative scenario of an investment in the production line to reduce P_d from 4.5 to 1%, the $Unitary\ COQ_{no-inspection}$would reduce from 0.90 to 0.20€/unit, respectively.

7 Discussion

7.1 CoQ: no inspection

After simulating the current 100% IS at FCT50, an average unitary total CoQ of 0.61€/unit was found. This value was absent from the Company's data for the TS since quality-related costs are considered only at pre-production stages as estimates for the whole manufacturing process. However, it is reasonable according to specialists of the Company, which were consulted at the "face validation" step.

Even though the process is already highly robust at the Company, an inspection investment to reduce the proportion of defects from 4.5 to 1.0% could reduce the $Unitary\ CoQ_{100\%\ inspection}$ from 0.61 to 0.50€/unit. Lesser defects could be achieved, e.g., through better machinery, better supplied raw material, and training to the assembling operators. Nonetheless, such inspection investment must be justified through an analysis of its return considering acquisition and operational costs, the number of units being produced, among other factors.

As for the no-inspection scenario, a higher average unitary total CoQ was obtained ($Unitary\ CoQ_{no-inspection}$=0.90€/unit) since more defects would proceed downstream. Other works that found a similar result when comparing 100% to no inspection ($Unitary\ CoQ_{100\%\ inspection} < Unitary\ CoQ_{no-inspection}$) include [7, 15].

The reduction in the proportion of defects (from 4.5 to 1.0%) for the no-inspection scenario, however, was the most impactful in terms of unitary CoQ, reducing it to 78% ($Unitary\ CoQ_{100\%\ inspection}$ from 0.90 to 0.20€/unit)

The interdependencies of quality testing activities can be used to harmonize inspection processes. By analyzing the character of the relationships, it is possible to harmonize certain test activities to reduce the total test effort. At best, it is possible to eliminate costly quality testing activities carried out at the production stage, shifting the inspection focus to earlier or even later stages of the product life cycle. Optimizing and aligning interrelated quality testing activities throughout the product lifecycle requires a deep understanding of the interconnectedness of quality inspections. Effective alignment of quality testing activities relies heavily on existing experience.

The choice of the most appropriate IS for assessing the quality of certain product characteristics is a non-trivial problem. The variety of products that can be produced with the existing technologies makes it difficult to standardize and adopt a unique inspection procedure [42]. Moreover, there may be several eligible and suitable alternatives for the considered production among all the different possible inspections [42]. Zaklouta and Roth [10] point out that manufacturing process improvement often coincides with a need to change IS choice, thereby indicating that manufacturing process and IS selection should not be performed independently of each other. Therefore, a collaborative inspection planning, integrating both the inspection plan and the production plan, is critical to improve profit [50].

Decision-making strongly requires indicators that assess the relevance of several alternatives. Indeed, to find out what are the most adequate ISMs, decision-makers need to compare them, and additional aspects must be considered rather than the cost. The possible ISM solutions to be compared should be proposed by the planners themselves, or at least by bringing in their background knowledge. Even after modelling them and getting the total CoQ of each one, the final decision must consider other factors other than just the cost. The total CoQ of the current policy can be used as the benchmark compared against, and then test the cost performance of the other comparative policies.

7.2 Quality cost data: Industry 4.0 risks and opportunities

The ISM must be (1) consistent in the assessment approach to be applicable in different cases with varying granularity of information, (2) based on indicators precise enough to provide an accurate performance assessment, and (3) flexible enough to be expanded and incorporate uncertainties and variations.

The first challenge is how to translate business requirements and demands into model parameters and data requirements for modellers. The interface between processes is a great opportunity for improvement for companies. The proposed ISM integrates aspects that are normally not integrated, relating operational issues with costs, helping to fill this gap.

In manufacturing, where systems are complex and dynamic, there are many sources of variation. To develop a useful and sustainable ISM, it is necessary to keep its parameters up-to-date, which requires investments consisting in the deployment, provisioning, operation, and management of CoQ data, mainly with regard to the evaluation and failure categories. As data plays a key role in this regard, managing the data pipeline effectively and aligning data curation efforts with goals and requirements are the key differentiator.

Therefore, as the necessary data can be stored in different departments, as in the case reported in this article, it is necessary to maintain an open and cross-functional communication, for example, between the design, manufacturing, quality, testing, and accounting teams, building bridges and reaching consistent and coordinated goals. Indeed, the expertise of several departments needs to be brought in before a comprehensive model for assessing and addressing the CoQ for ISM is achieved. A structure like the one proposed by Yang et al. [51] to improve the representation and sharing of knowledge can be used to deal with the different demands needed in ISMs.

Considering the context of Industry 4.0, it is clear that the existence of a large amount of data available, intelligent algorithms, and computational power does not mean that there will be a direct solution to optimize production processes and inspections. In this sense, economic analysis studies or detailed impacts on the CoQ are necessary to justify the necessary investments in the processes [20]. Therefore, it is important to continually improve means to assess quality costs in terms of accuracy and fairness.

The research findings attempted to assist the business managers to better understanding the current ISM practices considering the associated CoQ. By modelling alternatives, the model allows challenging current production line schemes by proposing more fine-grained ones where the total CoQ is reduced, i.e., the model enables the assessment and benchmarking of different IS. This comparison between alternatives can be useful, for example, for justifying the investment in more precise equipment if the model shows the total CoQ pays it off. In other words, the model could be used to show the management a digital twin of the reality, along with the costs.

Nevertheless, the right answer to domain complexity does not have to be algorithmic complexity—it has to be simplicity. Simplicity opens ways to create an interactive setup that involves experts without overwhelming them. If truly involved, an expert will understand and accept the results and turn them into action/into feasible solutions. Any analysis support must fit into the users' mindset, their language, and their workflow. Therefore, human involvement and creation of a quality culture can be achieved in the Industry 4.0 context and not only focusing purely on the technological dimension [20].

On one hand, among risks posed by Industry 4.0 paradigm in relation to obtaining and managing quality cost parameters, one can cite the data overwhelming and the lack of integration and sharing. On the other hand, smart manufacturing environments create opportunities for enhanced data management, as well as real-time monitoring and quality control. These aspects are likely to contribute to higher quality outputs once translated into costs, as the proposed ISM.

Hence, the main opportunities for quality data acquisition in relation to digitalization are gleaning it automatically, e.g., through machine sensors, and directly fed it into a digital manufacturing database that would also hold the relevant quality costs. Therefore, it would be possible to build a digital twin of the inspection stations considering the CoQ, to better inform the process in real-time, and be used to dynamically control the process for optimal results. Regarding the necessary quality cost estimates, given their confidential nature, they could be communicated to this database using Industry 4.0 technologies, e.g., blockchain, for traceability and controllability.

8 Conclusions

This paper focuses on the development of a simulation model for studying the differences in CoQ under alternative control plans. The model was developed and conducted using real-life data related to a functional testing station of an infotainment system, providing valuable insights into the behavior of the different components of the quality plans and their impact on the CoQ while balancing manufacturers' two conflicting objectives: minimizing cost and maximizing quality of conformance. Specifically, the results have shown the estimation of the total CoQ by budgeting inspection and failure costs for the analyzed case and provided evidence to justify and support the implementation of CoQ models.

Overall, several significant findings have emerged from this research that have both managerial and theoretical implications. From a quality management literature perspective, this study directly addresses recent calls for more research about CoQ assessment, which is under-researched and has significant potential to be explored further [18, 19]. While most of the research so far on ISM has been based on fictional data, the model was developed and conducted using real-life data related to a functional TS of an infotainment system.

From a managerial viewpoint, the results highlight the relevance of well-designed and constantly monitored quality cost assessment for the development of QCP, robust decision-making, and the continuous improvement of the production system. At the very least, the study provides a decision-making structure to design or invest in new production lines considering the potential referred to in the literature and offered by the CoQ approach. The developed work also underscores the relevance of IS revision and the challenges of finding useful information for determining the parameters and quality costs among large production datasets.

As this research is exploratory, the findings are empirically driven based on the case analyzed. The validity and generality of the cost assessment carried out and applied in this model are limited to the specific industrial framework, as the input parameters are contextual. Moreover, a serious limitation of this work relates to the absence of historical data and control for the CoQ elements in the Company, which did not allow the complete validation of the proposed model. The same is true for some parameters that had to be estimated in the model.

Future research is needed to expand the model for more complex process configurations, including more WS. In relation to quality cost acquisition, the development of digital twins for IS revision and data integration platforms, in which the CoQ could be directly obtained from. In addition, further investigation could also look at different IS scenarios. While this study only compares the no-inspection scenario with the current 100% inspection (with reinspection of rejects), explored dimensions of IS may also include scenarios such as reinspection of accepts [10], comparison between inspection equipment options [26], and a "middle-ground" strategy between 100% inspection and no inspection.

Author contribution Angélica Muffato Reis, Lino Costa, and Sérgio Sousa contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Angélica Muffato Reis, Alaíze Dall-Orsoletta, and Eusébio Nunes. The first draft of the manuscript was written by Angélica Muffato Reis and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

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