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FOREWORD

Welcome to the 2nd International Conference on Quality Engineering and Management!

After the successful organization of the **1st International Conference on Quality Engineering and Management** in 2014, it is our pleasure to welcome you to the conference **2nd edition** at the University of Minho, again in the historic city of Guimarães, Portugal. This event combines two areas that are not usually brought together: Quality Engineering and Quality Management. We hope that the results of our effort will translate into a successful venture, making gradually of this conference an important scientific event in the field of Quality. As was our aim, since the beginning, the conference covers different topics related to Quality Management and Quality Engineering, including Standards, Continuous Improvement, Supply Chain Quality Management, Management Systems, Six Sigma, Quality Tools, Quality Management in Higher Education, Quality Management in Services and Total Quality Management.

In this 2nd edition the balance between Quality Management papers and Quality Engineering ones is more clear, thus accomplishing one of the fundamental goals of this conference. Approximately 120 papers have been submitted and almost 85 were accepted for presentation, after review from the Conference Scientific Committee. Additionally, some of these papers were selected by the Scientific Committee to be considered for a special issue that will be published by the International Journal of Quality and Reliability Management (SCOPUS indexed journal). Papers accepted correspond to authors from all around the world, with more than 20 countries represented at this level. Therefore, a warm acknowledgment to all speakers and authors is well deserved – Thank You! The success of this second edition derives from their efforts and participation!

We would like to thank all of our four keynote speakers, who will be with us during the two days of the event: **Eric Rebentisch**, **Jiju Antony**, **Lars Sorqvist** and **Marco Reis**. We have here the chance to listen to their contributions and new research development insights, coming from some of the most influent current Quality Academicians. Many thanks also to all the excellent work carried out by the Scientific Committee during the papers selection process. We must acknowledge as well the institutional support received from the School of Engineering of the University of Minho, University of Coimbra, University of Girona, International University of Catalunya, Portuguese Association for Quality, Algoritmi Research Centre, Luso-American Foundation, American Society for Quality, Portuguese Institute for Quality, Brazilian Association of Production Engineering, Brazilian Society of Quality and Excellence in Management, Quality for Excellence Consultancy, BQualidade, Target and Cempalavras.

Again, let's take advantage of this great opportunity and make with your contributions an event with Quality, shared and built by such a top level group of participants!

Enjoy your conference! Thank you all!

University of Minho, July 14, 2016.

Paulo Sampaio (Conference Chair)

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Evaluating quality-inspection effectiveness and affordability in short-run productions

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Department of Management and Production Engineering, Politecnico di Torino, Turin, Italy

ABSTRACT

Purpose – Illustrating a practical method for supporting the design of quality inspections in short-run and single-unit manufacturing processes.

Design/methodology/approach – Processes are decomposed into a number of steps, which are potentially critical to defect generation. Several parameters concerning effectiveness and cost of the inspections are identified and aggregated into a probabilistic model for representing the process propensity to produce defects. Two indicators related to the effectiveness and cost of inspections are defined and tested through a case study concerning a short-run manufacturing process in the automotive industry.

Findings – The combined use of the proposed indicators allows to support the selection of the more appropriate inspection procedures, in a simple and practical way.

Research limitations/implications – The above indicators and probabilistic model rely on the following simplifying assumptions: (i) possible occurrence of a single defect typology in each step, and (ii) absence of correlation between the parameters related to different steps. Future research will focus on developing more general probabilistic models and identifying practical methods to estimate the relevant parameters.

Practical implications – The proposed model and indicators may be applied to a variety of industrial contexts, related to short-run and single-unit productions.

Originality/value – The proposed model and indicators allow to identify the more effective and affordable inspection procedures for short-run and single-unit productions. Their quantitative connotation represents an important novelty with respect to the classical qualitative approaches. Also, the proposed model and indicators take account of possible inspection errors.

Keywords: Quality inspection, Short-run, Inspection effectiveness, Inspection cost.

Paper type: Research paper

1. INTRODUCTION

The manufacturing of complex products is typically organized into several steps: acquisition of raw materials, processing, assembly, functional testing, etc. Quality inspections are usually performed to check whether specifications and functional requirements are satisfied, and to identify defects and/or anomalies. Inspection may be governed by strict or non-strict rules (e.g., periodical controls, fixed-percentage control, etc.) and organized through well-defined or heuristic procedures.

More specifically, if an inspection is performed, it may be conducted in four different ways: (i) simple inspection, that is to inspect a single item once; (ii) fractional inspection, that is to inspect a fixed fraction of items in a batch, where zero and one (full batch) are the two extreme cases; (iii) repeated inspection, that is to inspect the same item(s) more than once; and (iv) dynamic inspection, that is to inspect items in a batch sequentially and a decision of whether to reject or accept the batch is made dynamically instead of at a fixed fraction (Mandroli et al., 2006).

The inspection strategies are significantly affected by the production volume. In the case of mass production, Statistical Process Control (SPC) techniques can be straightforwardly applied (Montgomery, 2013). On the other hand, in the case of productions of single units, small-sized lots (i.e., the so-called *short-runs*) or in the start-up of a process, most of the SPC techniques are inappropriate (Del Castillo et al., 1996; Marques et al., 2015).

The present paper analyses the quality-inspection procedures for short-run and single-unit manufacturing processes, focussing on the individual *operations* or *manufacturing steps* that they consist of. The paper provides some guidelines for supporting the design and assessment of suitable inspection procedures, through the definition of a probabilistic model for defect prediction. In other words, the paper tries to answer the following research question: *considering a short-run or single-unit manufacturing process with several possible inspection procedures, how the more effective and affordable ones can be determined?*

Two types of errors are associated with an inspection: (i) the wrong rejection of a conforming unit, which is known as type-I error; and (ii) the erroneous acceptance of a nonconforming unit, which is known as type-II error (Mandroli et al., 2006). However, some authors simply assumed a perfect inspection and some other authors only considered one of the two types of error (Lee and Rosenblatt, 1987; Veatch, 2000). In the present paper, both types of errors are taken into account (Raz and Kaspi, 1991; Shiau, 2002).

The construction of the probabilistic model is based on the following phases:

I. estimating the probability of occurrence of defects and that of (not) detecting them, in each manufacturing step;
II. combining the above probabilities into a model, which depicts the overall effectiveness and affordability of the inspection procedure.

This model has both an analytical and predictive connotation. Currently, similar approaches are mostly implemented in the software engineering field (Rawat and Dubey, 2012). Furthermore, inspection-oriented quality-assurance strategies are mainly aimed at identifying optimal formulations (Jewkes, 1995). In the present paper, the problem of comparing several possible inspection procedures is dealt with.

The remainder of the paper is organized into four sections. Sect. 2 illustrates the probabilistic model and its characteristic parameters. Sect. 3 describes two practical indicators, which depict the overall effectiveness and affordability of an inspection procedure; the description is supported by several examples. Sect. 4 presents a structured case study, concerning the application of the proposed model and indicators in the short-run production of components for luxury cars. Sect. 5 summarizes the original contributions of this research, focussing on its implications, limitations and possible future developments.

2. MODEL DEFINITION

2.1. Assumptions

Let us decompose the production process into *manufacturing steps* or just *steps*, i.e., individual operations providing an added value to the final product. The proposed model is based on the following hypotheses:

1. For each step, there can be one-and-only-one defect typology.
2. Defects originated in the different steps are uncorrelated.
3. The occurrence of defects and that of inspection errors are uncorrelated.

The first hypothesis is not so stringent, as the totality of the defects in a single step can be interpreted as a unique “macro-defect”. On the other hand, the second and third hypotheses may sometimes not be satisfied.

2.2. Parameter definition

Each i-th step of the production process is modelled with a Bernoulli distribution (Montgomery, 2013). Then, each step can be described through three parameters:

- p_i: probability of occurrence of the defect in the i-th step (i.e. the parameter of the Bernoulli distribution);
- α_i: probability of (erroneously) detecting the defect when it is not present in the inspection in the i-th step (*false defect* or *false positive*);
- β_i: probability of not detecting the defect when it is present in the inspection in the i-th step (*false negative*).

The index i is included between 1 and m, i.e. the total number of steps.

The first parameter concerns the quality (or, reversing the perspective, defectiveness) of the process, while the other two parameters concern the quality of the inspection.

The above parameters are usually difficult to estimate. Since p_i is related to the characteristics of the process and its propensity to generate defects, an *a priori* estimate of this parameter can be obtained through adequate defect-generation models; alternative approaches may be based on empirical methods (e.g., use of prior experience) and/or simulations. On the other hand, the estimation of α_i and β_i is related to the type-I and type-II errors, which strictly depend on the inspector activity and inspection procedure (Tang and Schneider, 1987; Duffuaa and Khan, 2005).

2.3. Conceptual representation of the process

The graph in Figure 1 represents a generic production process with m steps in series. The graph in Figure 2 represents another production process, consisting of two steps in parallel, followed by a third one (in series). More complex processes can be represented using graphs with mixed structures (in series and in parallel). Consistently with what described in Sects. 2.1 and 2.2, each (i-th) step can be associated with three parameters (p_i, α_i, β_i).

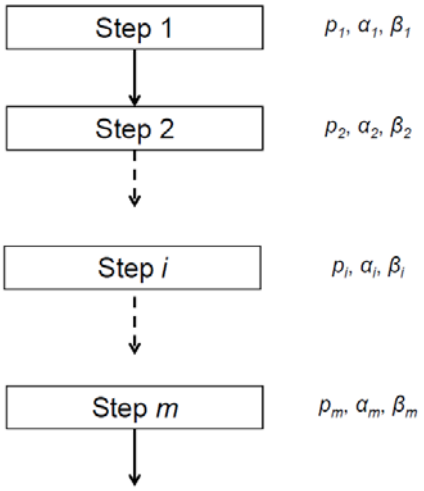

Figure 1 – Representation of a production process with *m* steps in series.

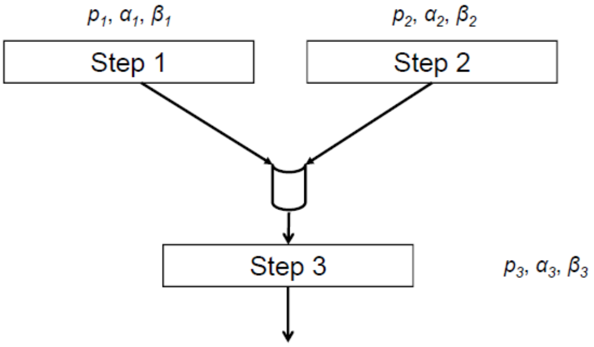

Figure 2 – Representation of a production process with two steps in parallel, followed by a third one (in series). Logical *AND* operator is exploited.

2.4. Model formulation

The following probabilities can be calculated for each (*i*-th) step:

$$P(\text{detecting the defect in the step } i) = p_i \cdot (1-\beta_i) + (1-p_i) \cdot \alpha_i \tag{1}$$

and

$$P(\text{not detecting the defect in the step } i) = p_i \cdot \beta_i + (1-p_i) \cdot (1-\alpha_i) \tag{2}$$

where *i* is included between 1 and *m*, i.e. the total number of steps.

In the case the defect is detected, it will be *authentic*[1] with a probability $p_i \cdot (1-\beta_i)$ or *false* with a probability $(1-p_i) \cdot \alpha_i$ (see Eq. (1)). On the other hand, in the case no defect is detected, this will be the result of an inspection error (false negative) with a probability $p_i \cdot \beta_i$, or will be due to the real absence of any defect with a probability $(1-p_i) \cdot (1-\alpha_i)$. The above probabilities represent the "elementary bricks" for the construction of some indicators depicting the performance of the inspection procedures, which are presented in Sect. 3.

Considering a generic process with *m* steps, irrespectively from being in series, parallel or mixed structure, the above probabilities can be combined together:

---

[1] i.e., a defect, which is actually present.

$$P\left(\text{detecting the defects in all the } m \text{ steps}\right)=\prod_{i=1}^{m}\left[p_i\cdot(1-\beta)_i+(1-p_i)\cdot\alpha_i\right] \tag{3}$$

and

$$P\left(\text{not detecting the defects in all the } m \text{ steps}\right)=\prod_{i=1}^{m}\left[p_i\cdot\beta_i+(1-p_i)\cdot(1-\alpha_i)\right] \tag{4}$$

It is possible, more generally, to calculate the probability of detecting the defects in *k* out of *m* steps, where *k* is included between 1 and *m*, by using binomial-like models.

The probabilities in Eqs. (3) and (4) are related to the complexity of the process, in terms of number of steps (m), quality of the process (p_i), and quality of the inspection (α_i and β_i) in each step.

3. PROPOSED INDICATORS

Different kinds of inspection activities may be adopted for checking the conformity of the output of a specific manufacturing step, e.g., visual check, dimensional verification, etc. (Dowling et al., 1997; See, 2012). In order to compare the effectiveness and affordability of the alternative inspection activities, the two indicators discussed in the following subsections can be used (Ng and Van Hui, 1997; Wang et al., 2010).

3.1. Inspection effectiveness

Let us consider m Bernoulli random variables (X_i), defined as follows:

- $X_i = 0$: when (i) an authentic defect is detected or (ii) no defect is present in the ith inspection.
- $X_i = 1$: when an authentic defect is not detected in the ith inspection.

According to the model formulated in Sect. 2.4, the following relationships hold:

$$\begin{aligned}P(X_i=0)&=p_i\cdot(1-\beta_i)+(1-p_i)=1-p_i\cdot\beta_i\\ P(X_i=1)&=p_i\cdot\beta_i\end{aligned} \tag{5}$$

where i is included between 1 and m. Therefore, the mean number of authentic defects unnoticed in the ith inspection is:

$$E(X_i)=p_i\cdot\beta_i \tag{6}$$

which is obviously a quantity included between 0 and 1.

Thus, the mean total number of authentic defects, which are not detected in the overall inspection procedure is:

$$D=\sum_{i=1}^{m}E(X_i)=\sum_{i=1}^{m}p_i\cdot\beta_i \tag{7}$$

The variable D provides an indication of the overall effectiveness of inspections.

3.2. Inspection cost

The total cost for inspection and defect removal related to each (ith) step may be expressed, as a first approximation, as follows:

$$C_{tot,i}=c_i\ +\ NRC_i\cdot p_i\cdot(1-\beta_i)+\ URC_i\cdot(1-p_i)\cdot\alpha_i\ +\ NDC_i\cdot p_i\cdot\beta_i \tag{8}$$

where:

- c_i is the cost of the ith inspection;

- *NRC_i* is the necessary-repair cost, i.e., the necessary cost for removing the defect;
- *URC_i* is the unnecessary-repair cost, i.e., the cost incurred when identifying false defects; e.g., despite there is no cost required for defect removal, the overall process can be slowed down, with a consequent extra cost.
- *NDC_i* is the cost of undetected defect, i.e., the cost related to the missing detection of defects.

Apart from the estimates of the probabilities p_i, α_i and β_i, the calculation of the total cost therefore requires the estimate of additional cost parameters. In general, c_i and NRC_i are known costs, URC_i is generally known or easy to estimate, while cost NDC_i is difficult to estimate since it may depend on difficult-to-quantify factors, such as image loss, after-sales repair cost, etc.

The total cost for inspection and defect removal related to the overall production process can be expressed as:

$$C_{tot} = \sum_{i=1}^{m} C_{tot,i} \tag{9}$$

When comparing two or more inspection procedures, the costs related to the $NRC_i \cdot p_i \cdot (1-\beta_i)$ contributions must be excluded, since they have an opposite behaviour against the variation of β_i in comparison to the other contributions depending from α_i and β_i, i.e. $URC_i \cdot (1-p_i) \cdot \alpha_i$ and $NDC_i \cdot p_i \cdot \beta_i$. In fact, when α_i and β_i decrease/increase, $URC_i \cdot (1-p_i) \cdot \alpha_i$ and $NDC_i \cdot p_i \cdot \beta_i$ decrease/increase while $NRC_i \cdot p_i \cdot (1-\beta_i)$ increases/decreases producing a compensation effect which biases the comparison between the procedures. Hence, from equation (8), the cost related only to the inspection procedure is:

$$C^*_{tot,i} = c_i + URC_i \cdot (1-p_i) \cdot \alpha_i + NDC_i \cdot p_i \cdot \beta_i \tag{10}$$

Accordingly, the corresponding total cost related only to the inspection procedure for the overall production process is:

$$C^*_{tot} = \sum_{i=1}^{m} C^*_{tot,i} \tag{11}$$

The indicator C^*_{tot} provides a preliminary indication of the cost related exclusively to the inspection procedure in use. In this sense, it can be used as a proxy for inspection affordability.

3.3. Examples and remarks

Let us now focus the attention on a didactic example. A production process consists of *m*=5 steps with three different inspection procedures:

- Procedure *A* in which two steps only (i.e., step 1 and 5) are subject to inspection;
- Procedure *B* in which the totality of the steps are subject to inspection.
- Procedure *C* in which the totality of the steps are not inspected.

The effectiveness of the three alternative inspection procedures can be evaluated using the indicator defined in Eq. (7). The mean total number of (authentic) defects, which are not detected in the three procedures are respectively:

$$\begin{aligned} D_A &= p_1 \cdot \beta_1 + p_2 + p_3 + p_4 + p_5 \cdot \beta_5 \\ D_B &= p_1 \cdot \beta_1 + p_2 \cdot \beta_2 + p_3 \cdot \beta_3 + p_4 \cdot \beta_4 + p_5 \cdot \beta_5 \\ D_C &= p_1 + p_2 + p_3 + p_4 + p_5 \end{aligned} \tag{12}$$

in which, for a generic *i*th step with no inspection, the corresponding β_i was replaced with 1. Assuming that the β_i related to a generic *i*th step with inspection has the same value irrespective of the inspection procedure, it follows that:

$$D_C \geq D_A \geq D_B \tag{13}$$

Not surprisingly, the procedure *C* is the worst one in terms of effectiveness. From the viewpoint of inspection cost, by applying Eq. (11), it is obtained:

$$\begin{aligned} C^*_{tot,A} &= c_1 + URC_1 \cdot (1-p_1) \cdot \alpha_1 + NDC_1 \cdot p_1 \cdot \beta_1 + NDC_2 \cdot p_2 + NDC_3 \cdot p_3 + \\ &\quad + NDC_4 \cdot p_4 + c_5 + URC_5 \cdot (1-p_5) \cdot \alpha_5 + NDC_5 \cdot p_5 \cdot \beta_5 \\ C^*_{tot,B} &= \sum_{i=1}^{5} \left[c_i + URC_i \cdot (1-p_i) \cdot \alpha_i + NDC_i \cdot p_i \cdot \beta_i \right] \\ C^*_{tot,C} &= \sum_{i=1}^{5} NDC_i \cdot p_i \end{aligned} \tag{14}$$

So, if the *i*th step is not subject to inspection, then $c_i = 0$, $\alpha_i = 0$ and $\beta_i = 1$. Assuming that, for the step with inspection, the parameters (probabilities and costs) are known, the cost C_{tot} can be calculated and the alternatives inspection procedures compared with each other.

For example, if the c_i values tend to be higher than the URC_i values and the p_i values are relatively low, then the procedure *C*, in which all the steps are not subject to inspection, will be likely to be more convenient than the others. Conversely, if the c_i values tend to be low and the p_i values tend to be high, then the procedure *B*, in which all the steps are subject to inspection, will be likely to be more convenient than the others.

4. PRACTICAL CASE STUDY

4.1. Process description and modelling

Let us now consider an automotive manufacturing process aimed at producing the front fender of a luxury car. Due to the relatively small number of parts produced over time, it can be considered a short-run production. The manufacturing process is organized into four main operations: three welding operations in three different working locations (ops. 10, 20 and 30) and a final activity of calibrating and assembly (op. 40). Figure 3 shows, as an example, one the welding operations (op. 30), while Figure 4 shows the calibrating and assembly operation (op. 40).

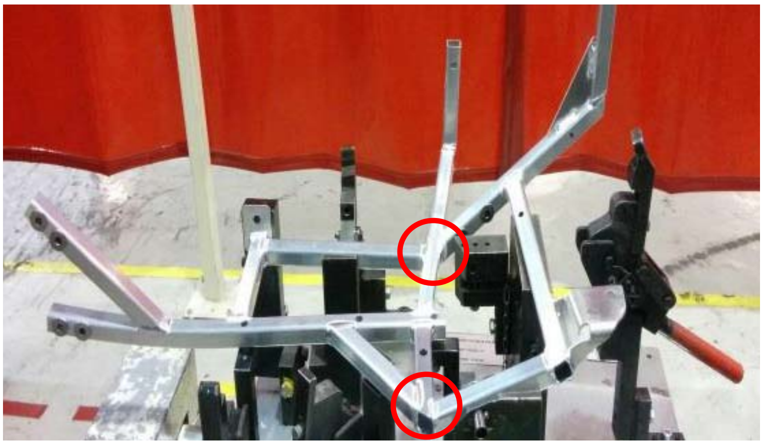

Figure 3 – Welding operation no. 30. Red circles show the corresponding weld areas.

Figure 4 – Calibrating and assembly operation (op. 40).

The two last operations involve the use of a calibrated artefact for dimensional verification of the frame geometry and then the assembly of brackets and bushings. Each of the three welding operations should be preceded by a corresponding activity of set-up of welding parameters (ops. 10’, 20’ and 30’). Therefore, the process can be divided into seven total steps (three for set-up, three for welding and one of calibrating and assembly), as represented in Figure 5.

Set-up operations are in series with the relevant welding operations. The three pairs of set-up and welding operations are in parallel with each other and followed by the (unique) operation of calibrating and assembly (op. 40).

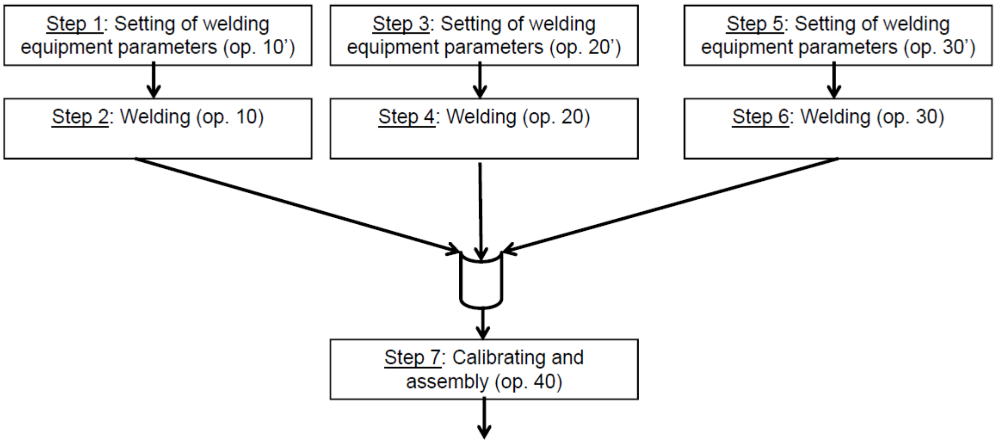

Figure 5 – Flow chart representing the production process exemplified.

For the same process of interest, two alternative inspection procedures are compared. In the first procedure, self-inspections are performed after welding operations (ops. 10, 20 and 30) and a final inspection is performed by an appointed staff after the calibrating and assembly operation (op. 40). Figure 6 represents the production process integrated with the first inspection procedure.

In the second inspection procedure, the individual self-inspections are performed after each of the seven steps (see Figure 7).

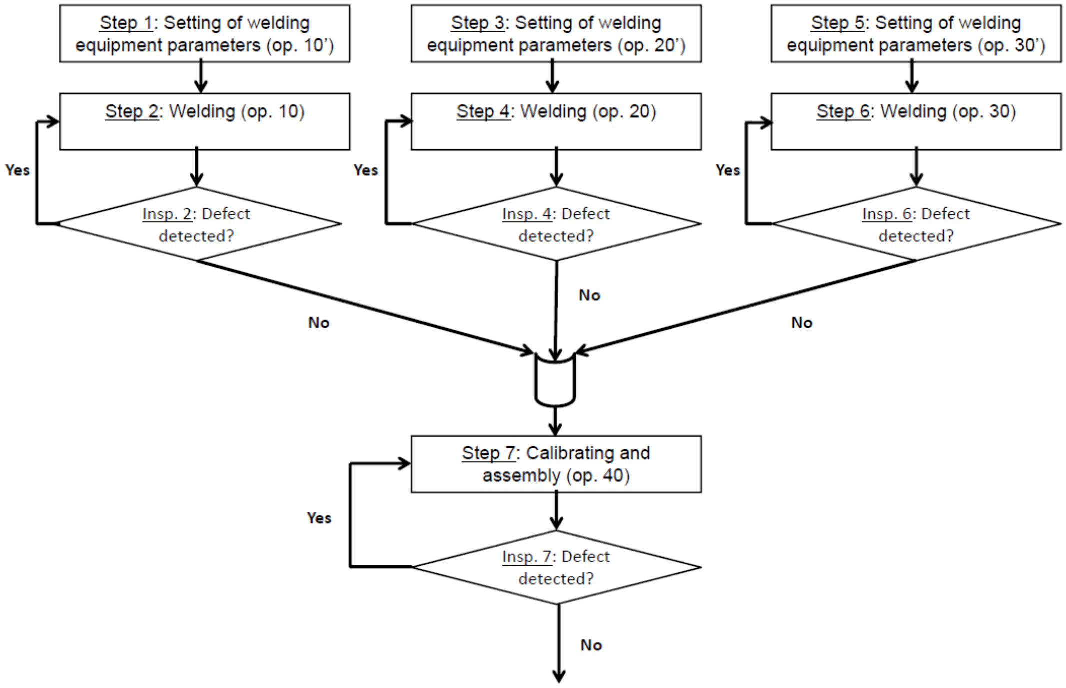

Figure 6 – Flow chart representing the production process, integrated with the first inspection procedure. A self-inspection is performed after the steps 2, 4 and 6, while an inspection by an appointed staff is executed after the step 7.

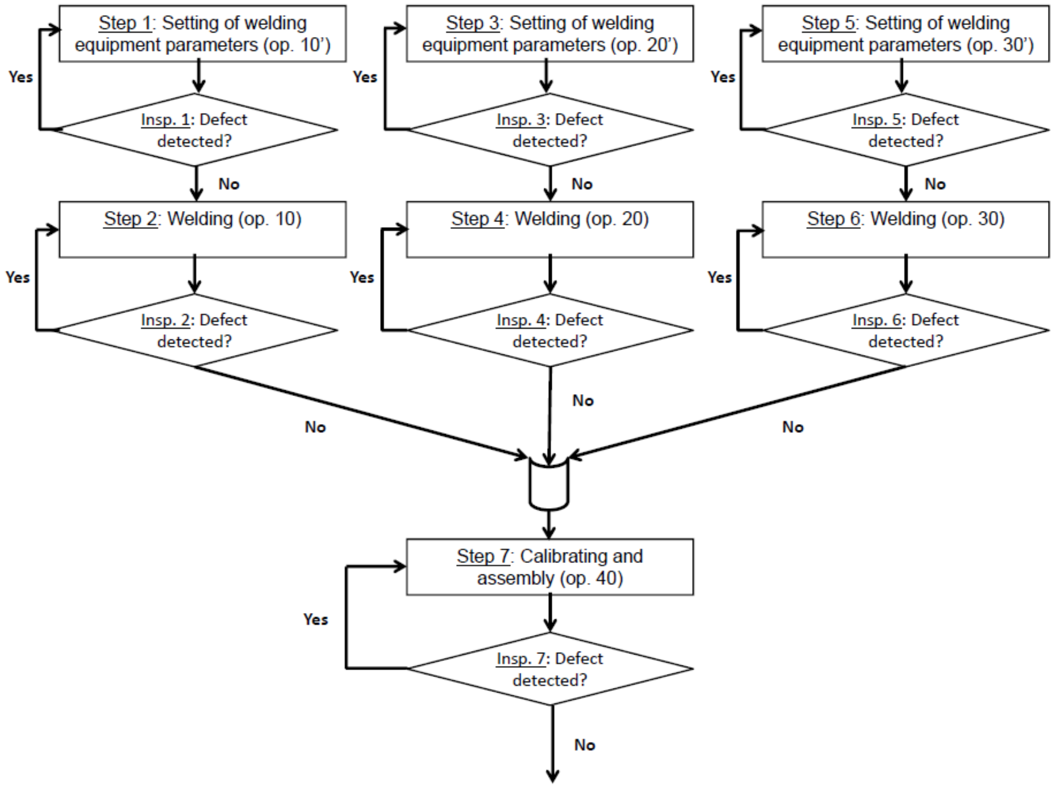

Figure 7 – Flow chart representing the production process, integrated with the second inspection procedure. A self-inspection is performed after each of the seven steps.

4.2. Comparison of inspection procedures

The indicators described in Sects. 3.1 and 3.2 were applied to compare the two inspection procedures introduced in Sect. 4.1. Tables 1 and 2 report estimates based on prior experience of the indicators for each process step, considering the first and the second inspection procedure respectively. Estimates of cost parameters are just indicative because their actual values are confidential.

Table 1 – Estimates of probabilities and cost parameters related to the first inspection procedure. The parameters that did not need to be estimated are italicized.

Step no.	**Operation type**	p_i [%]	α_i[%]	β_i [%]	c_i [€]	**URC**$_i$ [€]	**NDC**$_i$[€]
1, 3, 5	Set-up parameters	0.1	*0.0*	*100.0*	*0*	10	100
2, 4, 6	Welding	5.0	1.5	1.0	10	150	400
7	Calibrating and assembly	1.0	4.0	2.0	50	200	500

Table 2 – Estimates of probabilities and cost parameters related to the second inspection procedure.

Step no.	**Operation type**	p_i [%]	α_i[%]	β_i [%]	c_i [€]	**URC**$_i$ [€]	**NDC**$_i$[€]
1, 3, 5	Set-up parameters	0.1	1.0	0.5	5	10	100
2, 4, 6	Welding	5.0	1.5	1.0	10	150	400
7	Calibrating and assembly	1.0	2.0	1.5	20	200	500

For both the inspection procedures, it is supposed that the p_i values related to steps 1, 3, 5 and steps 2, 4, 6 are coincident, while those related to step 7 are independent:

$$\begin{aligned} p_{setting} &= p_1 = p_3 = p_5 \\ p_{welding} &= p_2 = p_4 = p_6 \\ p_{calibrating} &= p_7 \end{aligned} \tag{15}$$

Similar considerations apply to the other parameters, i.e. α_i, β_i, c_i, URC_i and NDC_i.

Let us now focus the attention on the calculation of the indicators D and C^*_{tot}, defined in Sects. 3.1 and 3.2. Eq. (7), related to the effectiveness of inspections, becomes:

$$D = 3 \cdot p_{setting} \cdot \beta_{setting} + 3 \cdot p_{welding} \cdot \beta_{welding} + p_{calibrating} \cdot \beta_{calibrating} \tag{16}$$

while Eq. (11), related to inspection costs, becomes:

$$\begin{aligned} C^*_{tot} = 3 \cdot c_{setting} &+ 3 \cdot URC_{setting} \cdot \left(1 - p_{setting}\right) \cdot \alpha_{setting} + 3 \cdot NDC_{setting} \cdot p_{setting} \cdot \beta_{setting} + \\ + 3 \cdot c_{welding} &+ 3 \cdot URC_{welding} \cdot \left(1 - p_{welding}\right) \cdot \alpha_{welding} + 3 \cdot NDC_{welding} \cdot p_{welding} \cdot \beta_{welding} + \\ + c_{calibrating} &+ URC_{calibrating} \cdot \left(1 - p_{calibrating}\right) \cdot \alpha_{calibrating} + NDC_{calibrating} \cdot p_{calibrating} \cdot \beta_{calibrating} \end{aligned} \tag{17}$$

Table 3 reports the numerical values of D and C^*_{tot}, calculated for both the inspection procedures, using the parameters in Table 1 and Table 2 respectively.

Table 3 – Indicators values calculated for the two inspection procedures.

Indicator	***First procedure***	***Second procedure***
D	0.0047	0.0017
C^*_{tot} [€]	95.33	76.35

This result shows that the second inspection procedure is significantly better, as it has lower mean total number of undetected defects (D) and mean total inspection cost (C^*_{tot}).

For the purpose of example, Figure 8 shows the 3D surface plot of D, for the second inspection procedure, as a function of $p_{welding}$ and $p_{calibrating}$, while $p_{setting}$, $\beta_{setting}$, $\beta_{welding}$ and $\beta_{calibrating}$ are kept constant to the values shown in Table 2. In this situation, the effect of $p_{welding}$ is predominant.

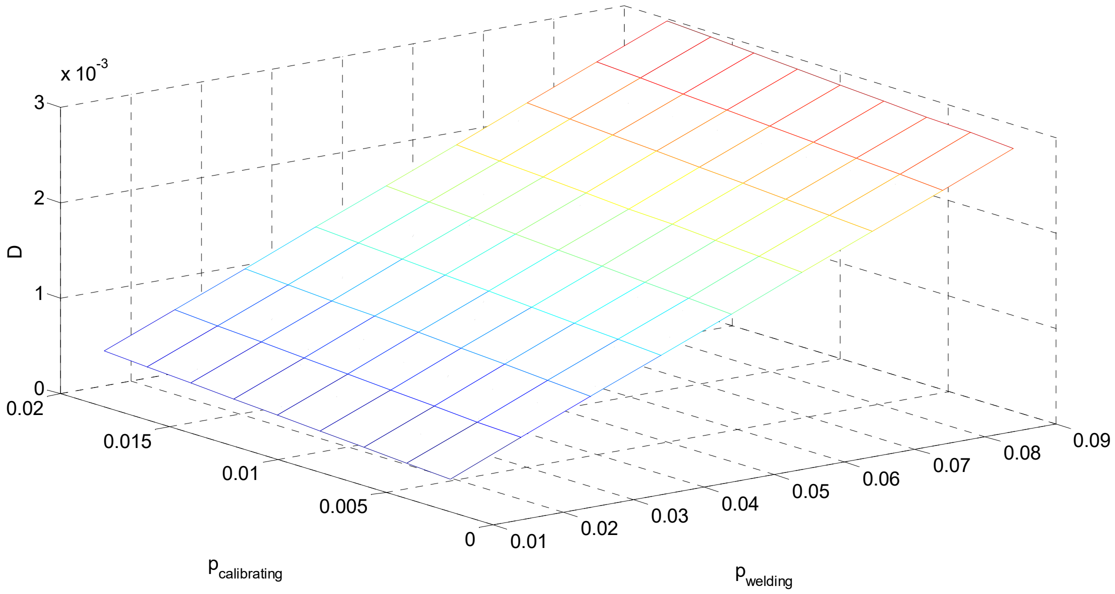

Figure 8 – 3D surface plot of D for the second inspection procedure, against $p_{welding}$ and $p_{calibrating}$.

5. CONCLUSIONS

In manufacturing processes, the inspection strategy is strictly related to the production volume. SPC techniques are popular for mass productions, although difficult to manage for short-run and single-unit productions. This paper examined the latter ones, defining an overall probabilistic model for defect prediction.

Also, two indicators for estimating the expected inspection effectiveness and cost were defined. According to a cost-benefit logic, the combined use of these indicators makes it possible to compare two or more inspection procedures in order to select the more effective and affordable for a process of interest.

The model and the indicators proposed in this paper may be exploited for a wide range of industrial process. An application example concerning a short-run production in the automotive industry exemplified the comparison of two different inspection procedures.

The major limitation of the probabilistic model and the proposed indicators is that they require the estimation of various not-so-easily-quantifiable parameters (i.e., p_i, α_i, β_i, c_i, URC_i, NDC_i). A thorough understanding of the process of interest and the opinion of experts may contribute to overcome this limitation (at least partially).

Another limitation concern the simplifying assumptions introduced, i.e., (i) a single type of defect for each manufacturing step and (ii) the absence of correlation between the parameters related to the different steps.
Future research will concern the development of defect-generation models for estimating the parameters p_i, α_i, β_i. Also, it is planned to develop a statistical model for estimating the dispersion of the output parameters D and C_{tot} with respect to that of the input parameters p_i, α_i, β_i, c_i, URC_i and NDC_i .

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