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## Design of an integrated quality-assurance strategy in production systems

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## Abstract

High-quality of products is a critical issue for manufacturers to maintain their competitiveness in global markets. For this reason, more attention has been paid by operations managers and academics about the design of quality-assurance strategies, acceptance sampling plans and inspection allocation problems. In the last decades, international research has studied and introduced several models and approaches to investigate these issues.

The purpose of this paper is to provide a new methodology for designing and selecting correct integrated quality-assurance strategies, defining cost models for acceptance policies and inspection station configurations.

Generally, high-quality of items is guaranteed avoiding defects, mainly caused by nonconforming components, due to instantaneous and standard infant mortality. Thus, the optimal acceptance policy is defined in order to reduce the instantaneous infant mortality defects. A close formulation has been introduced to determine easily and quickly the optimal percentage of checked items. Furthermore, the more convenient inspection station configuration is determined in order to minimize the expected total cost, composed by testing, inspection and penalty cost elements. The innovative concept of defect rate as an inspection time variable dependent has been introduced.

The impact of different economic and survival parameters on designing inspection policies is also investigated. Finally, a real case study demonstrates the applicability of this methodology in real production systems and several considerations are reported about the future researches, that the authors will carry out.

Keywords: quality-assurance strategy, acceptance policy, inspection allocation problem, time-dependent defect rate, cost models, case studies

## 1. Introduction and literature review

One of the most important problems that companies have been focusing on for the last 20-30 years is quality. The increasing competitiveness of markets lead quality to become widely regarded as a key element for success in business, especially in manufacturing industries.

From a productive point of view, quality can be defined as the fraction of goods that are produced correctly at the first time. In general terms, all production systems are technologically incapable to guarantee total quality of finished products and the main costs that occur in the after sale services for these items are typically warranty and penalty costs, linked to the infant mortality of products.

Furthermore, the extension of supply chain at global levels, such as the adoption of suppliers which production plants are placed in developing countries, in order to reduce the purchased component cost, has involved to evident reductions of quality in these items.

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3 From a customer satisfaction point of view, this kind of defect is unacceptable and  
4 reduces confidence in customers. They are mainly caused by defects on design and  
5 production of products and on low quality assembled or used items in finished  
6 products.  
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12 Consequently, a defect in a finished product can be caused by two kinds of fault.

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15 The first one is the Instantaneous Infant Mortality Defect (IIMD). It occurs at time 0  
16 when an item does not guarantee several required features. The second group of  
17 defects depends on standard infant mortality and it is called Standard Infant Mortality  
18 Defect (SIMD). The correct acceptance policy permits to detect first type of defects  
19 (IIMD), defining how and how many items have to be checked during the acceptance  
20 phase, typically with on-off tests.  
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30 Then, the right inspection station configuration allows to find defects belonging to the  
31 second group of defects (SIMD). Generally, the objective of inspection is to detect  
32 defective items as soon as possible and then to formulate appropriate treatments. As a  
33 consequence, one of the problem is to choose the locations to insert inspection  
34 stations inside production systems, which defects can be found during the testing and  
35 how defected items have to be treated.  
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44 Thus, it has become more and more important to define an high effective quality-  
45 assurance strategy, establishing the correct mix of acceptance policies on purchased  
46 items and on inspection station configurations in the production systems, in order to  
47 minimize the total quality cost of analyzed production system.  
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53 In the last decades, many research efforts have been conducted to study the quality of  
54 components and finished products in different production systems and to evaluate its  
55 effects in the production costs and performance (Battini et al., 2007, 2008, 2009a,  
56 2009b, 2009c, Persona et al., 2007, 2009).  
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3 High quality of products required by customers has involved in definition of quality-  
4 assurance strategy. General surveys on this problem have been introduced by Raz  
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8 (1986) and well completed by the more recent work of Mandroli, Shrivastava, and  
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11 Ding (2006).

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13 According to this latter research, the quality-assurance strategy has the aim to allocate  
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15 the economically appropriate level of inspection activities, between acceptance  
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17 policies and inspection allocation configuration, balancing the various cost  
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19 components of inspection, repair, replacement due to detection tasks and the warranty  
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21 penalty when a defective product reaches the customer.  
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25 Consequently, the main questions that an operations manager has to solve regard how  
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27 many purchased the components have to be checked and where should the inspection  
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29 station be allocated inside the production system, in order to guarantee high-quality  
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31 levels at lower costs.  
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### 34 35 ***1.1 Contributions on acceptance policy***

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37 One of the elements that has to be optimized is the acceptance policy on  
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39 purchased components in order to minimize the introduction of nonconforming items  
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41 in production systems, reducing the cost of defective finished products.  
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45 Different acceptance policies are used in manufacturing control strategy, depending  
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47 on category of items, production systems, final markets and others.  
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51 Often, one of these is the 100% inspection of items. In this case, checking all items  
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53 brings to a high total inspection cost but no penalty cost due to the scrap or  
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55 replacement of all defective items.

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57 Viceversa, using no inspection policy, as acceptance strategy, permits to eliminate the  
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59 inspection cost but increases the penalty one due to all the defective products that  
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were not eliminated from the production system.

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3 Another frequent policy is the acceptance sampling, where only a percentage of total  
4 items is checked. Dodge and Romig (1959) were the first ones to develop and  
5 introduce the inspection tables to define the right acceptance sampling. This study  
6 was originally applied by the U.S. military to the test bullets during World War II. If  
7 every bullet were tested in advance, no bullet would be left to ship. On the other hand,  
8 if none were tested, malfunctions might occur in the battlefield with potentially  
9 disastrous results (Military Standard 105E, 1989).

10  
11 International Normative has been introduced to give guidance for acceptance  
12 sampling of products, during the last years. Since these standards do not take quality  
13 cost directly into account, the economic aspect of this issue has been widely  
14 investigated by international researchers, in several books and scientific papers  
15 (Montgomery, 2001).

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17 In Tagaras (2001), a section is dedicated to the economic evaluation of acceptance  
18 sampling plans while more detailed information has been treated in Hald (1981).

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20 Relevant surveys about the contributions on this field have been written by Wetherrill  
21 and Chiu (1975) and by Wall and Elshennawy (1989), giving extensive references to  
22 economically optimum sampling strategies.

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24 In particular, several studies have examined the problem using linear cost models and  
25 others using Bayesian or Taguchi approaches (Barad, 1986, Case and Bennet, 1977,  
26 Chen et al., 2004a, 2004b, Ferrell and Choker, 2002, Gonzalez and Palomo, 2003, Lee  
27 and Tagaras, 1992, Malakooti and Balhorn, 1987, Tagaras and Lee, 1987).

28  
29 An interesting research has been carried out by Nikolaidis and Nenes (2009), where  
30 they have evaluated the cost of implementation of single-sampling plans by attributes  
31 that are recommended by normative and then compared it against the respective cost  
32 of the optimum acceptance sampling plans.

## 1.2 Contributions on inspection allocation policy

An extensive literature has been developed in the last decades about designing the right assurance-quality strategy, regarding the inspection allocation problem, especially the definition of correct inspection station configuration.

The introduction of inspection stations in a production system is an additional cost. At the same time, it is a profitable action because of benefits gained by the anticipating detection of defective items during the production process, avoiding the advancing on the production systems of nonconforming items and finally the sales of low-quality finished products.

Lindsay and Bishop (1964) have first studied the inspection allocation problem policy, introducing a general total cost, composed by inspection and scrap costs. They have applied a computational procedure based on dynamic programming to solve the problem.

Other researchers have investigated the problem also including other costs, like diagnosis and repair cost, loss resulting from removal of a unit perceived to be nonconforming less any applicable salvage value and penalty associated with shipping a nonconforming unit (Kakade et al., 2004, Lee and Unnikrishnan, 1998, Rau et al., 2005, Shiau, 2002). Viswanadham, Sharma and Taneja (1996) have studied dynamic and integer programming methods, using genetic algorithms and simulated annealing. Bai and Yun (1996) have introduced an inspection effort allocation model for a serial multi-stage production system, characterized by a limited number of inspection machines and by the constrain between rate of inspection and production. They have proposed a heuristic allocation algorithm using dynamic programming. Rau and Chu (2005) have considered inspection allocation problems for serial production systems with different types of workstations and different possibilities to treat detected



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3 nonconforming units. A profit model has been developed and a heuristic solution  
4 method has been introduced. Other researchers have addressed the problem of  
5 performance analysis in the presence of inspections (Narahari and Khan, 1996). The  
6 interest has been in investigating the effect of inspections on performance, like  
7 throughput rate, in different manufacturing systems.  
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### 16 ***1.3 Structure of research***

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19 After this introduction and the extensive literature review, this paper is based  
20 on the methodology used for the research and organized as follows. Section 2 will  
21 introduce the scope of research, covering the lack of international scientific  
22 contributions and giving a general methodology to design an integrated approach to  
23 assurance-quality strategy. Section 3 will explain the general assumptions and  
24 characteristics of proposed methodology and then the subsections 3.1 and 3.2 will  
25 introduce and investigate the cost models for the acceptance policy and the inspection  
26 allocation configurations.  
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29 Section 4 will introduce a real case application and finally in section 5, general  
30 discussions and conclusions will highlight the relevance of this research and introduce  
31 further future works.  
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## 46 **2. Scope of Research**

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48 The analysis of international scientific contributions has demonstrated that it is  
49 important to consider both the aspects of acceptance policy and inspection station  
50 configuration, during the design of quality-assurance policy, but no research has  
51 developed an integrated approach, yet.  
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3 Therefore, the purpose of this research is to design an integrated quality-assurance  
4 strategy that includes both the optimization of acceptance policy and the correct  
5 inspection station configuration.  
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10 Particularly, due to the insufficient adoption of international normatives, this research  
11 introduces a new model to estimate the percentage of items to be checked based on  
12 some elements described here below, such as inspection unit cost and unit penalty  
13 cost.  
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19 Furthermore, an innovative cost model for inspection station configuration has been  
20 developed in order to consider also the probability to detect defective items as a time  
21 dependent variable. In fact, as raised from the literature review, all the contributions  
22 use a constant or random value to model the defect rate of each inspection (Mandrolì,  
23 Shrivastava and Ding, 2006).  
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31 In detail, the developed methodology permits to improve the quality of products more  
32 than the previous ones, considering these important aspects:  
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- 35 • **Integrating Approach:** Total quality of products is considered, including also  
36 IIMD and SIMD, while no contribution has studied it, yet. This integrated  
37 approach allows to reach better quality results because it takes into  
38 consideration all kinds of defect, minimizing related total cost model.  
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- 45 • **Acceptance Policy:** Regarding IIMD and acceptance policy, the proposed  
46 methodology developed a cost model, based on real application and industrial  
47 requirements, while International Normative does not consider economic  
48 impacts of acceptance policy. Only Nikolaidis and Nenes (2009) have  
49 introduced a cost evaluation of simple-sampling policy. The proposed model  
50 simplifies the application of decision making process in acceptance sampling,  
51 with several assumptions explained in the next section.  
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- **Inspection Station Configuration:** As well defined in Mandroli, Shrivastava and Ding (2006), defect rate is the quantity of defective items manufactured by a process at a station. Consequently, the inspection station configuration is defined using different defect rates. Some authors have assumed a known constant defect rate, while others have used random rate approach. As resulted by this literature overview, no research has studied the inspection station configuration using a time-dependent defect rate, while the proposed methodology permits to include this aspect into the quality-assurance policy definition. In fact, the defect rate depends on SIMD, and the occurring probability of this kind of defect is function of time, as well shown in typical bathtub curve of failure rate. Therefore, it is very important to consider the time-dependent defect rate in order to define the optimal inspection time, guaranteeing a certain quality level. In the model proposed in the following sections, the general assumption is that non-conforming items detected during inspection activities are subjected to infant mortality failure modes, described by Weibull distribution estimated by the occurred failures.

In the next sections, several total cost models has been introduced and for each cost element an extensive discussion has been done.

Several scenarios of acceptance sampling and configurations of allocation of inspection stations are studied and compared each other. The more convenient design is defined with the proposed model, considering several aspects, such as total defective percentage and unit cost elements.

### 3. Cost models for quality-assurance strategy definition

Usually, operations managers try to increase the quality level of production systems which they manage, for the above mentioned reasons.

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3 Figure 1 shows a general procedure to follow in order to design an optimal quality-  
4 assurance strategy. This procedure has been developed from the authors' experience  
5 and with the help of several relevant operations managers.  
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22 During Phase 1, Data Collection about defective finished products is often carried out  
23 to understand the main causes of faults and to define the more efficient improvement  
24 actions, typically using a Pareto Analysis, to reduce the infant mortality failures. The  
25 main causes of low quality are defined with a Failure Analysis and usually they are  
26 related to the wrong design and imperfect production and to low quality of  
27 **manufactured** or used items in finished products.  
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Consequently, continuing the definitions introduced before, the principal causes of defects, which are subjected to quality-assurance strategy, can be listed into two groups (Defect Classification):

- ***Instantaneous Infant Mortality Defect (IIMD)***, that is when an item does not work at time 0 or when it has not several required features, such as particular geometric dimensions or fixed electrical characteristics. The impact of this type of defect on quality of finished products can be reduced using the appropriate acceptance policy.
- ***Standard Infant Mortality Defect (SIMD)***, that is when an item does not work properly at the first times of its life, normally in the first minutes, such as material defects, design blunders, errors in assembly and production process.

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Typical examples of SIMD are fails in electronic components, like main-boards for command of mechatronic systems, or defects in mechanical components, such as die-casting items with cracks due to wrong cooling process. The introduction of inspection stations in production systems permits to increase the quality, maintaining low total costs.

Therefore, in Phase 2, it is necessary to apply a cost model for the acceptance policy, optimizing the percentage of items to check, based on inspection and penalty unit costs, and a cost model to evaluate the different inspection stations configurations, based on time-dependent defect rates.

Finally in Phase 3, the operations managers can define the optimal quality-assurance strategy combining the results of previous phase.

In the next subsections, the mathematical models will introduce and discuss the two aspects of quality-assurance strategy, while methodologies for Phase 1 of this procedure will not be treated in this paper and it will make reference to the classical approaches presented in literature and in practice.

### ***3.1 Acceptance Policy – Mathematical Definition and Discussions***

The IIMDs are one of the causes of defective finished products. The quality-assurance strategy have to guarantee high quality levels, also avoiding the introduction of defective purchased components in finished products.

An Expected Total Acceptance Cost (ETAC) is modeled in order to consider both the inspection cost and penalty cost. Minimizing this cost function, the acceptance policy defines the percentage of items to check.

As introduced in literature review, there are many cost models for the acceptance sampling all based on international normative and on Bayesian or Taguchi methodologies.

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3 In this research, a particular simplified model has been developed and introduced in  
4 order to extend its application in many manufacturing systems and to simplify the use  
5 of this model. The introduction of very simple close analytical formulations allows  
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In this research, a particular simplified model has been developed and introduced in order to extend its application in many manufacturing systems and to simplify the use of this model. The introduction of very simple close analytical formulations allows the wide use of this model and its application in real cases because of the introduced cost elements and quality parameters are typically known for operations and quality managers. If an operations manager uses the normative for acceptance sampling, please refer to Nikolaidis and Nenes research (2009).

However, this model is based on the Nikolaidis and Nenes research (2009) using the following assumptions in order to define the cost functions, burnt from the experience of the authors and interviewing several operations managers:

- A fixed percentage of items is checked at the acceptance station.
- Each defective component found during the control is replaced by the supplier.
- The supplier pays the cost of items replacement.
- The defective items not checked by the initial control can be presented during the production process or after sale.
- The percentages of defective items on the different situations are known.
- In the case of a defect in production process or after sale, all the same components are submitted to 100% inspection.

The Expected Total Acceptance Cost (ETAC) [€/item] is defined as the sum of two elements, the Check Cost (CC) and the Penalty Cost (PC), see formula 1:

$$\mathbf{ETAC = CC + PC} \quad [1]$$

Defining  $x$  as the percentage of checked items and  $C_{ue}$  as the unit control cost [€/item], the Control Cost (CC) is then defined as follows:

$$CC = x * C_{uc} \quad [2]$$

While the Penalty Cost (PC) is proportional function of sample  $(1 - x)$ . In fact, this percentage of items is inserted into the production system. Under this assumption, every defected item, belonging to this sample, could either be found during the manufacturing stages or reach the customer. When a defected item is found, all the sample  $(1 - x)$  has been checked.

Under these statements, the total Penalty Cost can be expressed by the sum of different terms as following:

$$PC = s * (1 - x) * \{CC_p + CC_e + PC_p + PC_e + C_m\} \quad [3]$$

where:

$s$  = maximum percentage of defective components, that depends on the supplier and typically its value is between 0% and 6%;

$CC_p$  = Check Cost of entire sample  $(1 - x)$  when a defect is found during the production process;

$CC_e$  = Check Cost of entire sample  $(1 - x)$  when a defect is found after sale by the customer;

$PC_p$  = Penalty Cost when a defect is found during the production process;

$PC_e$  = Penalty Cost when a defect is found after sale by the customer;

$C_m$  = management cost due to stocking, replacing, recalling and other management activities [€/item].

In detail, each term is defined by the following extended equations:

$$CC_p = [C'_{uc} * NC_p * (1 - x)] \quad [4]$$

$$CC_e = [C''_{uc} * NC_e * (1 - x)] \quad [5]$$

$$PC_p = C'_p * NC_p \quad [6]$$

$$PC_e = C'_p * NC_e \quad [7]$$

where:

$C'_{uc}$  = unit control cost when a defect is found during the production process [€/item];

$C''_{uc}$  = unit control cost when a defect is found after sale by the customer [€/item];

$NC_p$  = percentage of defective items occurred during the production process;

$NC_e$  = percentage of defective items occurred after sale by the customer (note that:

$NC_p + NC_e = 1$  );

$C'_p$  = penalty cost due to the defective items appeared during the production [€/item];

$C''_p$  = penalty cost due to the defective items appeared after sale by the customer [€/item];

$C_m$  = management cost due to stocking, replacing, recalling and other management activities [€/item].

As a consequence, the extended Penalty Cost formulation is:

$$PC = s * (1 - x) * \{ [C'_{uc} * NC_p * (1 - x)] + [C''_{uc} * NC_e * (1 - x)] + C'_p * NC_p + C''_p * NC_e + C_m \} \quad [8]$$

Using the previous formulations, the ETAC can be rewritten as follows:

$$ETAC = x * C_{uc} + s * (1 - x) * \{ [C'_{uc} * NC_p * (1 - x)] + [C''_{uc} * NC_e * (1 - x)] + C'_p * NC_p + C''_p * NC_e + C_m \} \quad [9]$$

Minimizing this total cost function over  $x$ , in order to find the optimal value of percentage of items to check:

$$\frac{\partial ETAC}{\partial x} = 0 \quad [10]$$

$$\frac{\partial ETAC}{\partial x} = C_{uc} - s * (1 - x) * \{ [C'_{uc} * NC_p * (1 - x)] + [C''_{uc} * NC_e * (1 - x)] + C'_p * NC_p + C''_p * NC_e + C_m \} = 0 \quad [11]$$



After several mathematical steps, the optimal value of  $\mathbf{x}$ , called  $\mathbf{x}^*$  is defined by this close expression:

$$\mathbf{x}^* = 1 - \frac{C_{uc} - s * (C'_{p} * NC_{p} + C''_{p} * NC_{e} + C_{m})}{2 * s * (C'_{uc} * NC_{p} + C''_{uc} * NC_{e})} \quad [12]$$

Considering the application constraints, these particular cases have to be considered on formula [12]:

$$\mathbf{x}^* = \begin{cases} 0 & \text{if } 1 - (C_{uc} - s * (C'_{p} * NC_{p} + C''_{p} * NC_{e} + C_{m})) / (2 * s * (C'_{uc} * NC_{p} + C''_{uc} * NC_{e})) < 0 \\ \text{the value of the formula [12]} & \text{otherwise} \end{cases} \quad [13]$$

Using this formula, the operations managers can easily determine the optimal percentage of item to check during the acceptance phase, after having estimated the unit costs and defective parameters.

### *General Considerations and Numerical Examples*

The introduction of several general parameters can simplify the application of this model as follows.

Defining  $C_{APT}$  as the average penalty total cost using the following equation:

$$C_{APT} = C'_{p} * NC_{p} + C''_{p} * NC_{e} + C_{m} \quad [14]$$

and  $C_{ucNC}$  as the unit control cost for nonconforming item occurred during production process or after sale, with the following formulation:

$$C_{ucNC} = C'_{uc} * NC_{p} + C''_{uc} * NC_{e} \quad [15]$$

then, the optimal value of percentage to check,  $x^*$  can be calculated using the simple formulas, considering the application constraints:

$$x^* = \begin{cases} 0 & \text{if } C_{uc}/s > C_{APT} + 2 * C_{ucNC} \\ 1 & \text{if } C_{uc}/s \leq C_{APT} + 2 * C_{ucNC} \end{cases} \quad [16]$$

The proposed model to estimate the expected total cost for the acceptance policy (ETAC) is here discussed with several numerical examples and its behavior is investigated in order to give general guide lines for the practitioners.

Table 1 contains the parameters used in the examples, estimating the typical values occurred in real applications, and figure 2 shows the ETAC function, over the percentage  $x$ , for scenario 1.

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Please Insert Here Table 1.

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Please Insert Here Figure 2.

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Observing formula [16], the optimal value  $x^*$  is function of four simple parameters and its behavior is strictly linked to these as follows:

- the optimal value is directly proportional to parameters  $s$ ,  $C_{APT}$  and  $C_{ucNC}$ ;

- while it is inversely proportional only to parameter  $C_{uc}$ .

### 3.2 Inspection Allocation Configuration – Mathematical Definition and

#### *Discussions*

To guarantee high-quality on finished products, the definition of correct inspection station policy is necessary to reduce the defective products due to SIMDs. The prompt detection of defective items is the main goal of the inspection policy.

A typical inspection activity is the electronic testing for several seconds or minutes of electronic components, such as resistance, main-board, embedded circuit and electric motors. During this phase, several electronic characteristics are measured and compared with the required ones in order to reject the defected items.

Another usual inspection activity is the functioning testing inside production or assembly process, where the operating of mechanical components is checked in order to identify production or assembly defects, such as wrong mechanical coupling or previous errors in assembly/production tasks. Typical examples are driving or control mechanisms, subjected to functioning testing, and fastening systems, under fixing evaluation checking.

The introduction of inspection stations in a production system generates an additional cost but it permits to reduce the penalty costs raised at the end of the process. If a product is inspected at the final step of production process, the penalty cost is higher. To adopt a strategy of inspection, reworking or scrapping at intermediate steps could reduce the penalty cost but increase considerably the inspection costs. Thus, the objective is to determine the optimal inspection station configuration in order to minimize the Expected Total Inspection Cost (ETIC).

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3 As discussed in literature review sections, there are many contributions about the  
4 design of inspection station configuration with an economic point of view.  
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7  
8 The here proposed model defines the defect rate of each inspection station as a time-  
9 dependent variable, while until now, the scientific contributions consider it as a  
10 constant or random value (Mandroli, Shrivastava and Ding, 2006).  
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15 Due to the small time of inspection activities, the identified failures are typical of  
16 infant mortality behaviors. Generally, components and products are subjected to a  
17 decreasing hazard rate in the early period of their lives. Consequently, the efficiency  
18 of an inspection is strictly connected to the time of inspection and to the reliability  
19 behavior of tested components. Different statistical distribution can be used to model  
20 the failure rate. In this paper, Weibull distribution is used because of its flexibility and  
21 ease. General extensions of this distribution could be introduced considering also the  
22 environmental conditions (Battini et al., 2007, 2008, Persona et al., 2009). The  
23 probability of detecting nonconforming items increases for increasing inspection time,  
24 while the probability that a defective product reaches a customer decreases, following  
25 the Weibull distribution.  
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41 Furthermore, the present model would simplify the design of inspection station policy  
42 using several useful parameters. In fact, from the analysis of literature, the  
43 contributions developed in the last decades have introduced many complex models,  
44 with few and limited real applications.  
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50 Here, several inspection stations configurations are compared each other in order to  
51 define the more convenient one. Usually, operations managers have limited and  
52 known number of configurations due to technological constraints, for example the use  
53 of complex test machines. For each inspection station, it is known which are the  
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3 defects that can be found, assuming them statistically independent, and using the  
4 failures frequency analysis also the probability over inspection time to find a defect.  
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6  
7 Starting with these assumptions, the inspection station configurations described by the  
8  
9 models are the following:  
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- 11  
12 • ***In-Line Inspection Configuration:*** the inspection activities are completed  
13 inside the production systems, directly on the components or produced items,  
14 which have to be tested. In this case, the failure is strictly linked to the  
15 components or produced items. All the found defective items are scrapped and  
16 replaced with an additional unit cost (fig. 3).  
17  
18
- 19 • ***Final Inspection Configuration:*** in this case, there is a unique inspection  
20 station at the end of the production system that tests the functioning of  
21 finished products. In this case, it is difficult to define the cause of the failures  
22 and which component or produced items is defective. Consequently, the unit  
23 cost of failure detection is bigger than the previous case (fig. 3).  
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56 The mathematical formulations of models for each configuration are now introduced  
57 and discussed. A list of notations is here reported in order to understand the  
58 mathematical formulations.  
59

60  
*Notations*

*Indices*

$i$  = In-Line inspection station index;

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4  $o$  = Final inspection station index;

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7  $n$  = number of inspection stations;

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11 *Time parameters*

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13  $t_i^c$  = inspection time at station  $i$ ;

14  
15  
16  $t_o^c$  = inspection time at final station  $o$ ;

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20  
21 *Defect parameters*

22  
23  $S_i$  = maximum percentage of defective components or produced items that can be  
24 detected at station  $i$ ; it is the percentage of defective components provided by  
25 supplier. For example  $S_i = 5\%$  means that every 100 checked components, 5 are non  
26 conforming.  
27

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32  $S_o$  = maximum percentage of defective end products that can be detected at final  
33 station  $o$ , defined as follows:  
34

$$35 \quad S_o = \left[ 1 - \prod_{i=1}^n (1 - S_i) \right] \quad [17]$$

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41  $S_o$  is the percentage of defect end-products at the end of **production** process. It is  
42 related to the percentage of each defective component belonging to the final product.  
43 This formula comes from statistical considerations, an end-product is conforming if  
44 all its components are conforming.  
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53  $\alpha_i$  = scale factor of Weibull distribution for components or **pre-manufactured** tested  
54 at station  $i$ ;

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56  
57  
58  $\beta_i$  = scale factor of Weibull distribution for components or **pre-manufactured** tested at  
59 station  $i$ ;  
60

$F_i(t_i^f)$  = probability that a defect occurs before time  $t_i^f$  at station  $i$ , using Weibull formula:

$$F_i(t_i^f) = 1 - e^{-\left(\frac{t_i^f}{\alpha_i}\right)^{\beta_i}} \quad [18]$$

The detection of failure, the defect rate, follows a statistical distribution and it depends on the time spent to inspect the component. For this reason, we have introduced the defect rate as the probability that a defect occurs before a defined time. Increasing inspection time, increasing defect rate. Weibull distribution is used due to its great flexibility.

$F_o(t_o^f)$  = probability that a defect occurs before time  $t_o^f$  at station  $o$ , calculated using this formula:

$$F_o(t_o^f) = \left[ 1 - \prod_{i=1}^n (1 - F_i(t_i^f)) \right] \quad [19]$$

As assumed for formula 17, the formula 19 is derived from statistical considerations. The probability that a single defect occurs during the inspection of end-product is defined by this formula, adapting the traditional models for calculating the reliability of series systems, known the reliability of single components.

#### *Cost parameters*

$c_i^{uc}$  = inspection unit cost per time at station  $i$ ;

$c_o^{uc}$  = inspection unit cost per time at final station  $o$ ;

$c_i^{us1}$  = mean unit cost for remove one defect at station  $i$ ;

$c_o^{us1}$  = mean unit cost for remove one defect at final station  $o$ ;

$c_i^{us2}$  = mean penalty unit cost for a defect occurs after time  $t_i^f$ ;

$c_o^{US2}$  = mean penalty unit cost for a defect occurs after time  $t_o^c$ .

### *In-Line Inspection Configuration Cost Model*

According to the description of this inspection station allocation, introduced before, the expected total cost is the sum of the expected cost of each inspection station, then it can be defined as follows:

$$ETIC_{IIC} = \sum_{i=1}^n (C_i^c + C_i^{S1} + C_i^{S2}) \quad [20]$$

where:

the expected inspection cost at station  $i$ :

$$C_i^c = t_i^c * c_i^{UC} \quad [21]$$

expected defects removal cost at station  $i$ :

$$C_i^{S1} = S_i * [F_i(t_i^c)] * c_i^{US1} \quad [22]$$

Expected penalty cost of defects not removed on station  $i$ :

$$C_i^{S2} = [S_i * (1 - F_i(t_i^c))] * c_i^{US2} \quad [23]$$

### *Final Inspection Configuration Cost Model*

The allocation of inspection activities at the final station can be represented by the following mathematical formulation:

$$ETIC_{FIC} = C_o^c + C_o^{S1} + C_o^{S2} \quad [24]$$

where:

Expected inspection cost at station  $o$ :

$$C_o^c = t_o^c * c_o^{UC} \quad [25]$$

Expected defects removal cost at station  $o$ :



$$C_o^{s1} = S_o * [F_o(t)_o^c] * c_o^{us1} \quad [26]$$

Expected penalty cost of defects not removed on station  $o$ :

$$C_o^{s2} = [S_o * (1 - F_o(t)_o^c)] * c_o^{us2} \quad [27]$$

#### *Selection of Inspection Station Policy*

Using the formulas previously defined, the selection of more convenient inspection station configuration follows these considerations:

- Select In-Line Inspection Configuration if  $EC_{ILC}$  is minor than  $ETIC_{FIC}$  ;
- Select Final Inspection Configuration if  $EC_{FIC}$  is major than  $ETIC_{FIC}$ .

#### *General Considerations and Parameter Analysis*

The definition of defect rate here introduced by formula [18] shows the dependence on inspection time of the probability of defect detection. As our knowledge and as described in Mandroli, Shrivastava and Ding (2006), the defect rate has been defined as a constant or random value. For further readings, see the papers analyzed by (Mandroli, Shrivastava and Ding, 2006).

Furthermore, the more convenient solution of the inspection station allocation problem comes from the comparison of the results of the previous model applied to each configuration. It is important to note that in the final inspection configuration, the probability that a component fails in  $t_o^c$  is strictly linked to the reliability behaviour of components and produced products, as described by formula [19]. At the same time, the percentage of defective end-product is function of each percentage of defective components. Moreover, the mean unit cost to remove one defect at final station  $o$  is much bigger than the similar cost related to station  $i$  because the

inspection at final station checks the entire end products, as described in previous section, while the mean penalty unit costs can be the same because they do not depend on inspection station configuration.

It is important also to determine the threshold of convenience, in function of the percentage of defective items provided by supplier.

Here below an analysis of impacts of defined parameters previously is reported in order to understand their effect on specific threshold of convenience, expressed as  $S^*$ .

To make comparison more general, clearer and easier to understand, several main assumptions have been taken into consideration. Each station has the same defect rate Weibull parameters,  $\alpha_i$  and  $\beta_i$ , same maximum percentage of defective components  $S_i$ , the same inspection time  $t_i^f$  and  $t_i^e$ , and cost parameters values,  $c_i^{MC}$ ,  $c_0^{MC}$ ,  $c_i^{US1}$ ,  $c_0^{US1}$ ,  $c_i^{US2}$  and  $c_0^{US2}$ .

The assumed base scenario is composed by the following parameters values, included in table 2.

Figure 4 shows the threshold of convenience. The dashed curve is related to In-Line Inspection Configuration while the continued one is related to Final Station Configuration. For values lower than  $S^*$ , the more convenient configuration is the final inspection station one, while for values higher than  $S^*$ , the In-Line inspection configuration is the best choice. In this base scenario, the value of  $S^*$  is about 3.00%.

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Please Insert Here Table 2.

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Please Insert Here Figure 4.

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- Firstly, the number of stations has been varied, assuming the values: 3, 5 and 7, indicated in figure respectively with “a”, “b” and “c”. The rest of parameters is fixed as defined in base scenario. As it can be noticed in figure 5, the increasing of number of stations brings to an increased threshold of convenience value  $S^*$ . It is simply a consequence of the higher possibility to anticipate the defection of fault components.

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Please Insert Here Figure 5.

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- The second comparison has been made varying the inspection time control, assuming these values: 30 (“a”), 60 (“b”) and 90 (“c”) seconds. Figure 6 illustrates the three scenarios. Also in this case, the increasing of inspection time brings to an increase of  $S^*$  value. It is well shown that the increasing of  $S^*$  value is strictly linked to the efficiency of defection, following the Weibull distribution of defect rate.

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Please Insert Here Figure 6.

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- Then, the variation of cost parameters has been investigated. In figure 7a the inspection unit cost changes from 0.1 in the base scenario (“a”) to 0.01 (“b”)

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3 and 0.5 (“c”). In figure 7b, the mean unit cost to remove one defect at station  $i$   
4 has been changed from 8 of base scenario (“a”) to 40 (“b”) and 80 (“c”). Then,  
5  
6 the mean unit cost to remove one defect at station  $o$  assumes values as follows:  
7  
8 80 (“b”), 160 (base scenario – “a”) and 320 (“c”), as illustrated in figure 7c.  
9  
10 Finally, figure 7d shows the comparison between base scenario, with mean  
11 penalty unit cost equal to 900 (“a”), and other scenarios with mean penalty  
12 unit costs equal to 450 (“b”) and 1800 (“c”).  
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20 Generally, the increasing of inspection unit cost and mean cost to remove one  
21 defect inside the production system increases the threshold value  $S^*$ , while  
22 increasing value of mean unit cost to remove defect at final station brings to  
23 decreasing value of  $S^*$ . Finally, increasing the mean penalty cost, the  
24 threshold value increases. It is interesting to notice that, for several scenarios,  
25 the more convenient configuration is the In-Line Inspection one, for every  
26 values of maximum percentage of defective components or produced items  $S_i$ ,  
27 see for example figures 7b and 7d.  
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Please Insert Here Figure 7 a-b-c-d.

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- Finally, the change of Weibull shape parameter  $\beta_i$ , from the base scenario value (0.8 – “a”) to two scenarios with values equal to 0.7 (“b”) and 0.9 (“c”)

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3 has been investigated (fig. 8). In this case the increasing of shape parameter  
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5 value brings to the decreasing of threshold value.  
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#### 21 **4. Application to a real case study**

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23 The proposed procedure has been applied to a real case study. The  
24 manufacturing system produces a series of centrifugal pumps, such as multi-stage,  
25 standardized, for low, medium and high flows, with flanged ports. The great  
26 variability of finished products has not permitted to apply the existing approaches  
27 presented in literature due to the high complexity.  
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31 In accordance with the operations manager, the proposed models have been used to  
32 define the optimal quality-assurance strategy, because initially the production system  
33 had no policy for defects detection yet.  
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36  
37 From the application of Phase 1 of procedure, the main IIMDs and SIMDs have been  
38 determined. The Instantaneous Infant Mortality Defects are related to two purchased  
39 components: the pump body and body backplate, where geometrical defects can  
40 occur.  
41  
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43  
44 While the Standard Infant Mortality Defects are functions of operating components,  
45 such as capacitors, bearings and electric motors.  
46  
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48  
49 For the first group of items, during Phase 2, the optimal acceptance policy has been  
50 defined using the parameters, given by the Phase 1, and following the model here  
51 proposed.  
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3 Table 3 reports the values of parameters necessary for the acceptance policy design.  
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5 The Expected Total Acceptance Cost values for initial scenarios, called ETAC(0),  
6  
7 have been included in order to estimate the saving of proposed model, indicated as  
8  
9 follows:  
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$$\Delta ETAC = \frac{ETAC(0) - ETAC(x^*)}{ETAC(0)}$$

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23 It is expressed in percentage value.  
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33 Please Insert Here Table 3.  
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58 Here below, figures 9 and 10 illustrate the curve of ETAC function for the studied  
59 components.  
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Please Insert Here Figure 9.

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17 Successively, for the second type of components, a comparison between In-Line or  
18 Final Inspection Configurations is necessary. Analyzing the existing production  
19 system with the operations managers, two type of configurations can be defined, then  
20 the comparison has been done between these two situations.  
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26 The first inspection stations configuration is characterized by three inspection stations  
27 inside the production process, while the second case proposes a unique inspection  
28 station at the end of production system.  
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33 For each inspection station, from Phase 1, the Weibull parameters of inspection  
34 efficiency have been estimated using the reliability tool of Minitab© software (fig.  
35 11), while other parameters have been evaluated and assumed in collaboration with  
36 operations manager of production system (tables 4 and 5).  
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Please Insert Here Table 5.

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As resulted by the application of proposed models to this case, the more convenient inspection station configuration is the In-Line Inspection Configuration.

In the previous scenario, where no inspection activities have been made, the Expected Total Cost for SIMDs can be evaluated equal to 18.701 €/item.

The saving obtained using the proposed model is about 86 %, in fact the Expected Total Cost reduces its value from 18.701 to 2.595, due to the anticipating of SIMDs detection.

Concluding, the correct quality-assurance strategy defined using the proposed models is composed by the following policies:

- *Acceptance policy:* inspection and check of 52.20 % of Pump Body components, that permits to reduce the ETAC by 5.43 %;
- *Acceptance policy:* inspection and check of 32.40 % of Body Backplate components, with the decreasing of 2.13 % of ETAC;
- *Inspection Station Configuration:* implementation of In-Line Inspection Configuration, with three inspection stations, permits to reduce the Expected Total Cost of about 86 % respect the starting scenario.

## 5. Discussion and Conclusion

In modern markets, products are required with high-quality at lower costs. For this reason, companies try to extend their supply network purchasing several



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3 components from developing countries in order to maintain lower costs. However,  
4 often the components bought from these suppliers have low levels of quality.  
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6 Consequently, manufacturing systems need to control the quality of process and  
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8 products at the lower cost, defining the optimal quality-assurance strategy, composed  
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10 by acceptance policy and inspection station configuration. Several scientific  
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12 contributions have studied this problem in different ways, and without an integrated  
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14 approach that considers both the strategy aspects.  
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20 In this paper, a general methodology to design the correct quality-assurance strategy  
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22 is introduced, defining the connection of acceptance policy and inspection allocation  
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24 problem to two kind of defects: the Instantaneous Infant Mortality Defects (IIMDs)  
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26 and Standard Infant Mortality Defects (SIMDs). In detail, a cost model for  
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28 determining the optimal acceptance sampling is introduced in order to minimize the  
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30 quality cost related to the IIMDs. A close and simple formulation has been derived in  
31  
32 order to solve this problem. Innovative cost models have been developed to choose  
33  
34 the more convenient inspection station configuration, defining the efficiency of  
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36 inspection activities as function of inspection time. No scientific contributions has  
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38 studied this aspect in inspection allocation problems. The effects of several  
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40 parameters have been investigated in order to define the optimal threshold of  
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42 convenience between the types of configurations.  
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48 Finally, the application on a real industrial case has shown the economic advantages  
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50 of the proposed methodology.  
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53 **Some limits of integrating methodologies can be listed as follows:**

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55 • Acceptance policy and inspection station configuration are supervised by  
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57 different managers inside a production system, such as vendors and item  
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3 quality managers for the first issue and operations managers for the second  
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6 one.

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9 • The difficulty to collect data from the production, therefore the need to define  
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11 a correct collection data system and reliability analysis.  
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15 • The necessity to define clear cost elements to use into developed models.  
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19 • Each quality-assurance policy depends on manufactured products.  
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21 In the future, this research will try to solve these limits and the models will be  
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23 extended considering also several different acceptance policies and giving general  
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25 studies about the impact of parameters on more convenient configurations, as for  
26  
27 inspection allocation problems are concerned.  
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**FIGURES CAPTIONS:**

Fig. 1: General procedure for quality-assurance strategy design

Fig. 2: ETAC function over  $x$  for scenario 1.

Fig. 3: In-Line vs Final Inspection Configuration

Fig. 4: Expected Total Inspection Cost (ETIC) for In-Line vs Final station configuration in function of  $S$

Fig. 5: Comparison of ETIC functions varying the number of station

Fig. 6: Comparison of ETIC function varying the inspection time control

Fig. 7: Comparison of ETIC function varying the cost parameters

Fig. 8: Comparison of ETIC function varying the shape parameter.

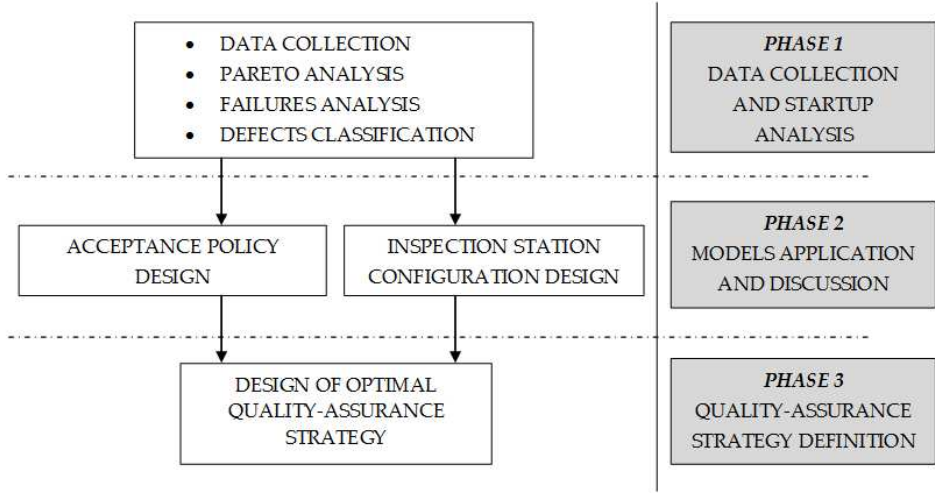
Fig. 9: ETAC function for Pump Body

Fig. 10: ETAC function for Body Backplate

Fig. 11: Defect rate in function of inspection time, for station 1, 2 and 3 (left) and final station (right).

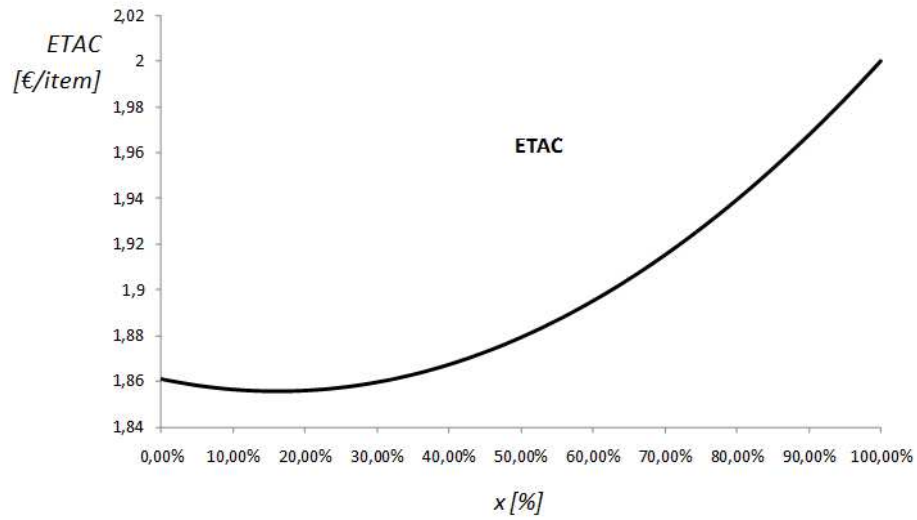


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General procedure for quality-assurance strategy design

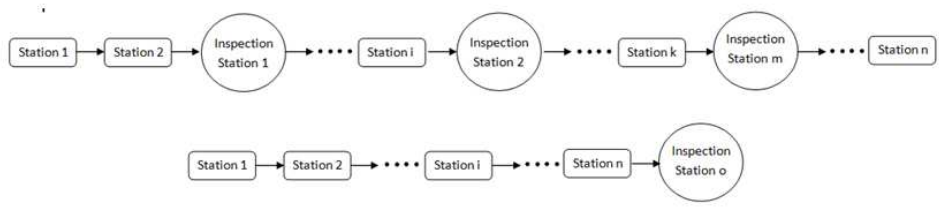
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ETAC function over x for scenario 1

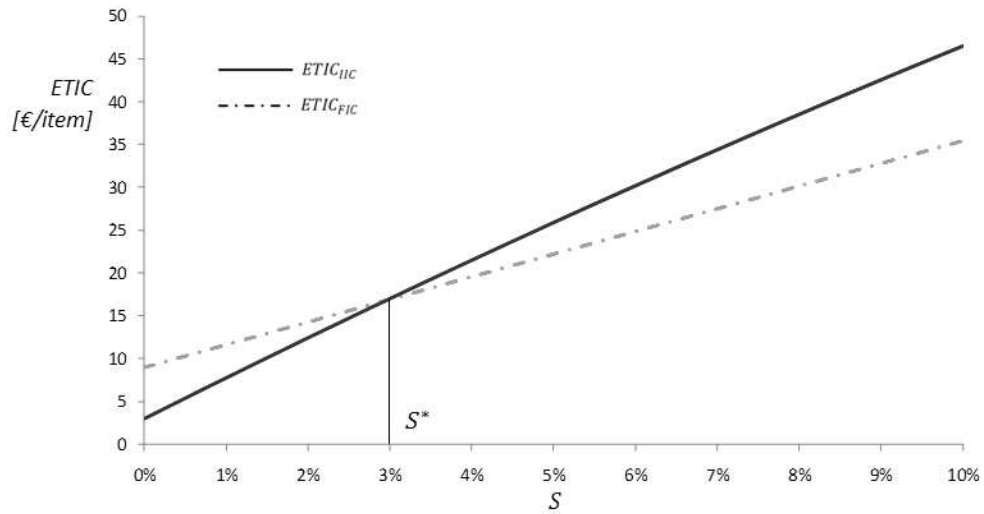
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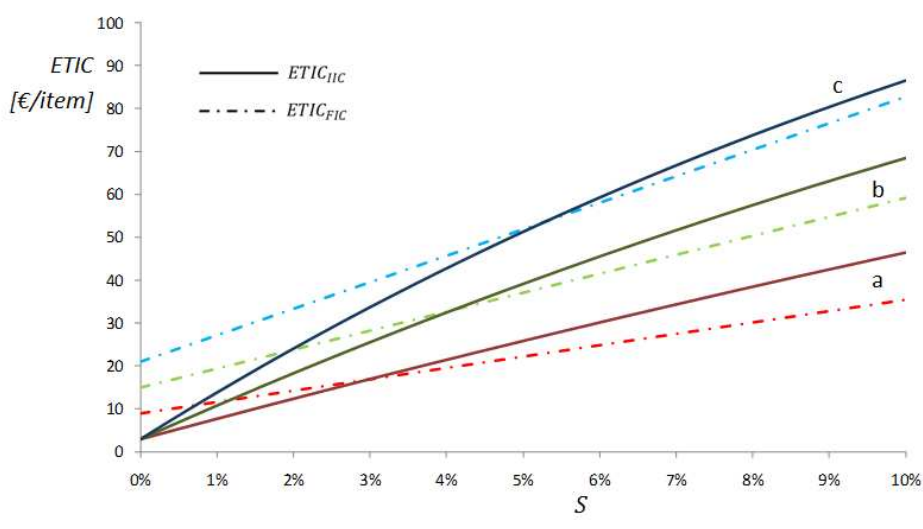
In-Line vs Final Inspection Configuration

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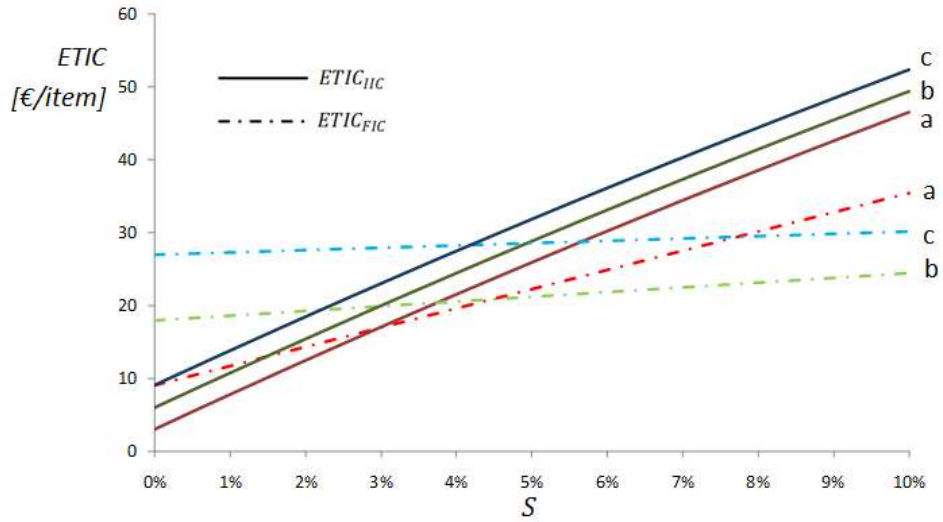
Expected Total Inspection Cost (ETIC) for In-Line vs Final station configuration in function of S

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Comparison of ETIC functions varying the number of station  
71x37mm (300 x 300 DPI)

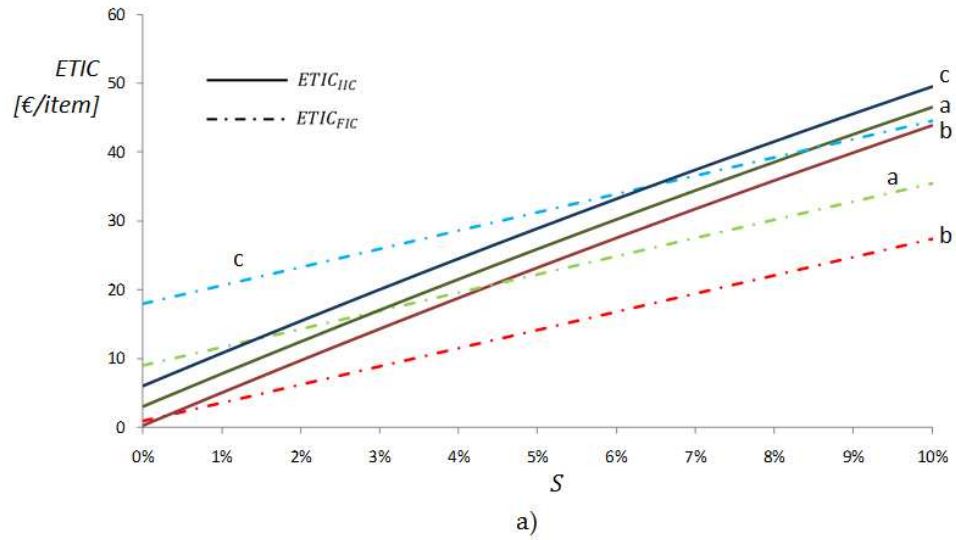
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Comparison of ETIC function varying the inspection time control  
62x34mm (300 x 300 DPI)

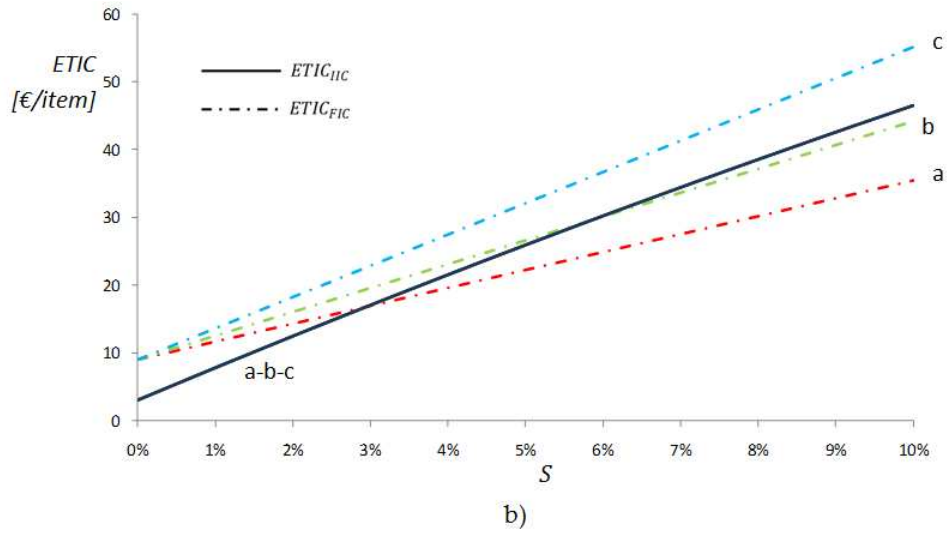
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Comparison of ETIC function varying the cost parameters  
69x38mm (300 x 300 DPI)

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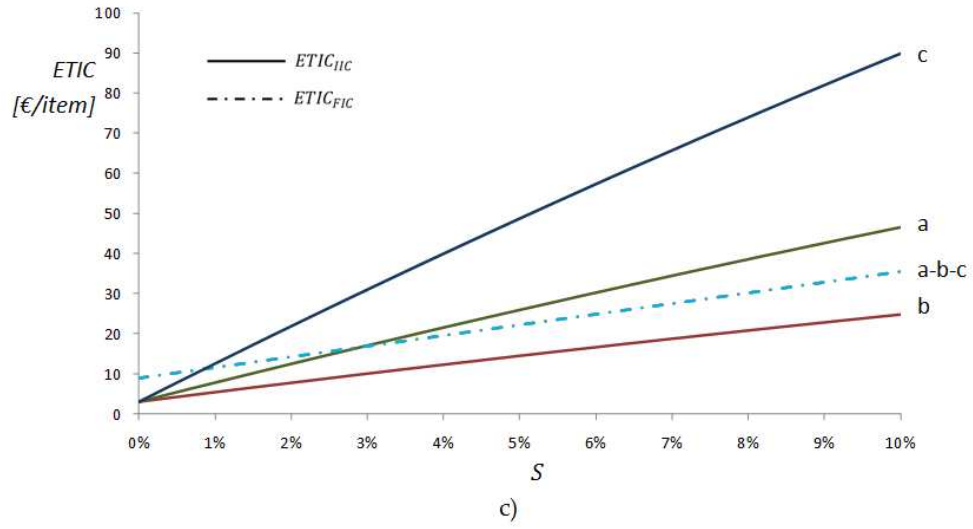


Comparison of ETIC function varying the cost parameters  
70x37mm (300 x 300 DPI)

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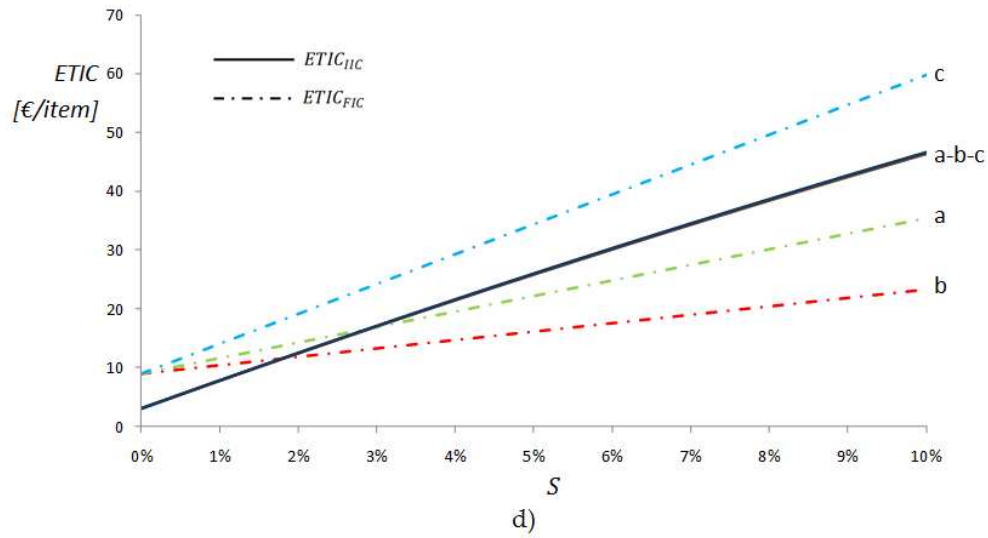


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c) Comparison of ETIC function varying the cost parameters  
71x38mm (300 x 300 DPI)

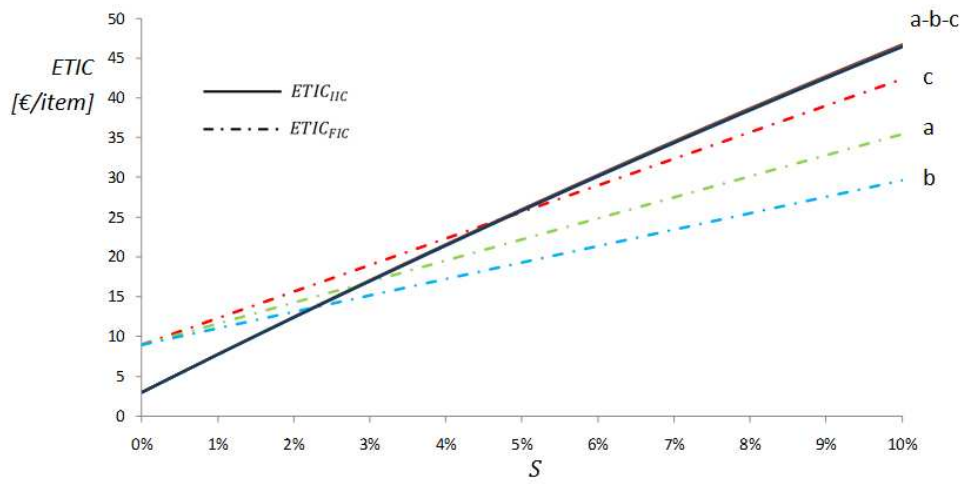
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d) Comparison of ETIC function varying the cost parameters  
69x38mm (300 x 300 DPI)

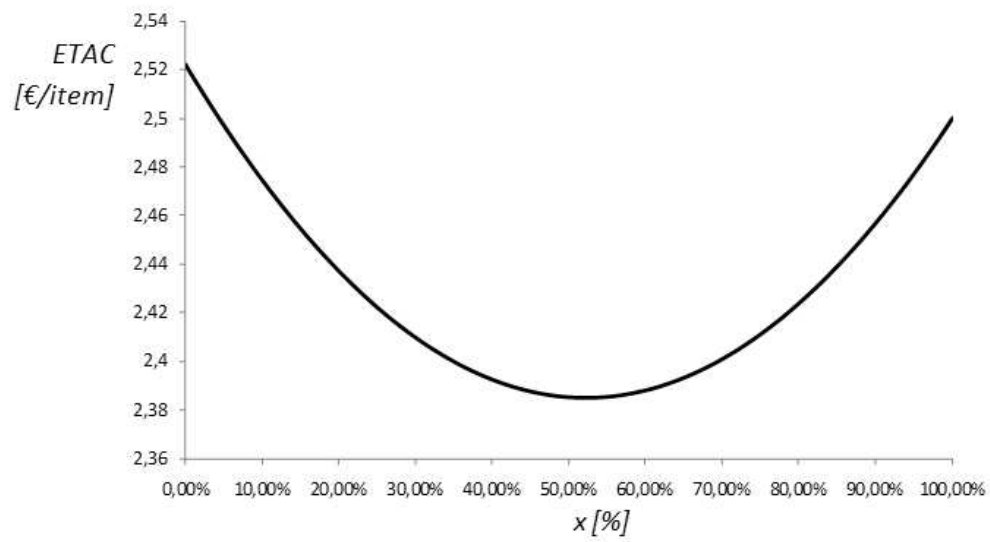
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Comparison of ETIC function varying the shape parameter  
72x36mm (300 x 300 DPI)

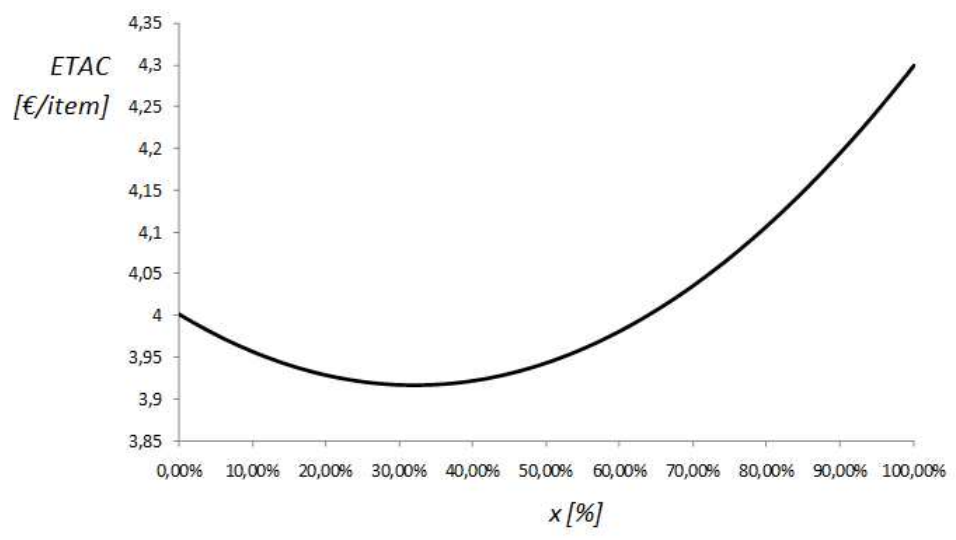
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ETAC function for Pump Body

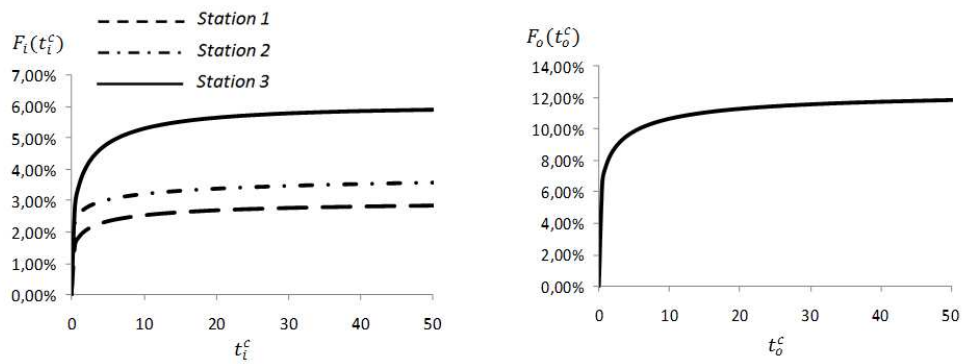
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ETAC function for Body Backplate

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Defect rate in function of inspection time, for station 1, 2 and 3 (left) and final station (right)

<i>Parameters</i>	<i>Scenario 1</i>	<i>Scenario 2</i>	<i>Scenario 3</i>
$\delta$	1.80 %	3.60 %	0.50 %
$C_{ue}$	2.00	4.00	1.00
$C'_{ue}$	8.00	12.00	5.00
$C''_{ue}$	25.00	32.00	24.00
$NC_p$	80.00 %	50.00 %	20.00 %
$NC_e$	20.00 %	50.00 %	80.00 %
$C'_p$	60.00	85.00	70.00
$C''_p$	210.00	240.00	180.00
$C_m$	2.00	6.00	3.00
$C_{ueNG}$	22.80	44.00	40.40
$C_{APT}$	92.00	168.50	161.00
$x^*$	16.18 %	100.00 %	0.00 %
$CC$	0.32	4.00	0.00
$PC$	1.53	0.00	0.91
$ETAC$	1.85	4.00	0.91

Tab. 1: Numerical example of Acceptance policy

Parameters	Description	Scenario
		"BASE"
$n$	number of inspection stations	3
$t_i^e$ and $t_o^e$	inspection time at station $i$ equal to the inspection time for final station $o$	30.00
$c_i^{uc}$ and $c_o^{uc}$	inspection unit cost per time at station $i$ equal to the inspection unit cost per time at final station $o$	0.10
$c_i^{us1}$	mean unit cost for remove one defect at station $i$	8.00
$c_o^{us1}$	mean unit cost for remove one defect at final station $o$	160.00
$c_i^{us2}$ and $c_o^{us2}$	mean penalty unit cost for a defect occurs after time $t_i^e$ at station $i$ equal to the mean penalty unit cost for a defect occurs after time $t_o^e$ at final station $o$	900.00
$\alpha_i$	scale factor of Weibull distribution for components or sub-assembled tested at station $i$	10.00
$\beta_i$	scale factor of Weibull distribution for components or sub-assembled tested at station $i$	0.80

Tab. 2: Parameters for Base Scenario



<i>Parameters</i>	<i>Pump Body</i>	<i>Body Backplate</i>
$s$	2.20 %	3.10 %
$C_{\text{ISO}}$	2.50	4.20
$C'_{\text{ISO}}$	22.00	26.00
$C''_{\text{ISO}}$	28.00	37.00
$NC_p$	86.00 %	64.00 %
$NC_c$	14.00 %	36.00 %
$C'_p$	72.00	48.00
$C''_p$	192.00	192.00
$C_m$	3.00	2.50
$C_{\text{ISO}NC}$	45.68	53.52
$C_{\text{APT}}$	91.80	102.34
$x^*$	52.20 %	32.04 %
$CC$	1.31	1.38
$PC$	1.08	2.54
$ETAC(x^*)$	2.39	3.92
$ETAC(0)$	2.52	4.00
$\Delta ETAC$	-5.43 %	-2.13 %

Tab. 3: Inspection parameters for analyzed components

Parameters	In-Line Inspection Configuration			Parameters	Final Station Configuration
	Station 1	Station 2	Station 3		
$C_i^{inc}$	0.01 €/s	0.01 €/s	0.01 €/s	$C_o^{inc}$	0.01 €/s
$C_i^{MS1}$	1 €/item	2 €/item	1.5 €/item	$C_o^{MS1}$	20 €/item
$C_i^{MS2}$	150 €/item	150 €/item	150 €/item	$C_o^{MS2}$	150 €/item
$\alpha_i$	1.2	0.9	1.5		-
$\beta_i$	0.3	0.2	0.4		-
$t_i^o$	40 s	35 s	26 s	$t_o^o$	40 s

Tab. 4: Case Study Data

	In-Line Inspection Configuration			Final Station Configuration	Initial Scenario (no inspection)
	Station 1	Station 2	Station 3		
$S_i$	3.000 %	4.000 %	6.000 %	$S_o$	12.467 %
$[F_i(t)]_i^o$	2.829 %	3.500 %	5.738 %	$[F_o(t)]_o^o$	12.465 %
$S_i - [F_i(t)]_i^o$	0.171 %	0.500 %	0.262 %	$[S_o - F_o(t)]_o^o$	0.002 %
$C_i^o$	0.400	0.350	0.260	$C_o^o$	0.400
$C_i^{o1}$	0.028	0.070	0.086	$C_o^{o1}$	2.493
$C_i^{o2}$	0.257	0.750	0.393	$C_o^{o2}$	0.003
$C_i^o + C_i^{o1} + C_i^{o2}$	0.685	1.170	0.740		18.701
$EC_{inc}$		2.595		$EC_{EIC}$	2.896

Tab. 5: Defective parameter and Expected Total Costs