Inspection procedures in manufacturing processes: recent studies and research perspectives

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Abstract

Quality inspections are performed in almost every production system to prevent nonconforming products from reaching final customers or end users. Quality inspections are typically performed referring to specific inspection procedures, depending on the production process. Two general inspection paradigms may be identified: online inspection and offline inspection. These are differentiated by the way in which inspections are made. The paper presents a recent survey on new studies on inspection procedures for both paradigms. The main novelty of the study is the identification of new research perspectives in such a highly explored field. New schemes of analysis allow highlighting the research areas which are not adequately covered by the literature. A brief examination of some bibliometric aspects is also proposed.

Keywords: *Quality control, Inspection, Online inspection, Offline inspection, Manufacturing, Defect modeling, Short-run production, Bibliometric analysis*

1. Introduction

Quality is an important factor for performance evaluation of a product. Manufacturing high-quality products is crucial for a company aimed at maintaining a global competitiveness. Quality inspections, i.e. activities of checking products, are an important part of quality control activities (ISO 9000:2015). Standards define "inspection" as an "activity such as measuring, examining, testing or gauging one or more characteristics of a product or service, and comparing the results with specified requirements in order to establish whether conformity is achieved for each characteristic" (ISO 2859-1:1999). Quality inspections are performed in almost every production system to prevent nonconforming products from reaching final customers or end users. In fact, when a defective unit reaches a customer, the firm's ability to compete may be compromised. Inspected products may be parts used for production, semi-finished goods, or finished goods before shipment to the customer. For the various product characteristics, inspections may be performed in a number of ways, e.g. by human inspectors, automated sensing devices, or a combination of both.

Inspection activities may be performed after some or all of the processing activities. In multi-stage production systems, there are many possible locations for an inspection activity; however, sometimes, an inspection must be performed after particular processing activities in order to be effective (Raz, 1986). When, where and how an inspection should be performed is an important and challenging decision in quality control. The various cost and constraint factors as well as operational alternatives interact in an intricate way and make the solution far from trivial (Mandroli et al., 2006). According to these general considerations, quality inspections are typically performed referring to "inspection procedures", specific for each production process.

Many research papers dealing with the formulation and the application of inspection procedures have been published. The present paper provides a detailed survey on recent studies on inspection procedures in order to identify new challenges and new research perspectives. With respect to the past surveys, this paper presents new schemes of analysis, which enable to highlight research areas which are not adequately covered by the literature. A further novelty is a brief analysis of some bibliometric characteristics of examined papers, i.e. the subject areas of the journals and the main keywords provided by the authors.

The remainder of this paper is organized into three sections. Section 2 describes a general taxonomy of the inspection procedures. For the considered classification categories, the relevant analysis attributes or features are defined. Section 3 proposes a literature survey; in particular, main research lines and reference models of inspection procedures are evidenced, and a brief analysis of bibliometric aspects is given. Finally, Section 4 draws some conclusions and identifies new research perspectives in the field of inspection procedures.

2. Inspection procedure taxonomy

In this paper, two classification categories for inspection procedures are considered: (i) general characteristics (Section 2.1) and (ii) modeling structure (Section 2.2). For such categories, the analysis attributes with the relevant classes and the analysis features are respectively defined. Figure 1 summarizes the adopted taxonomy.

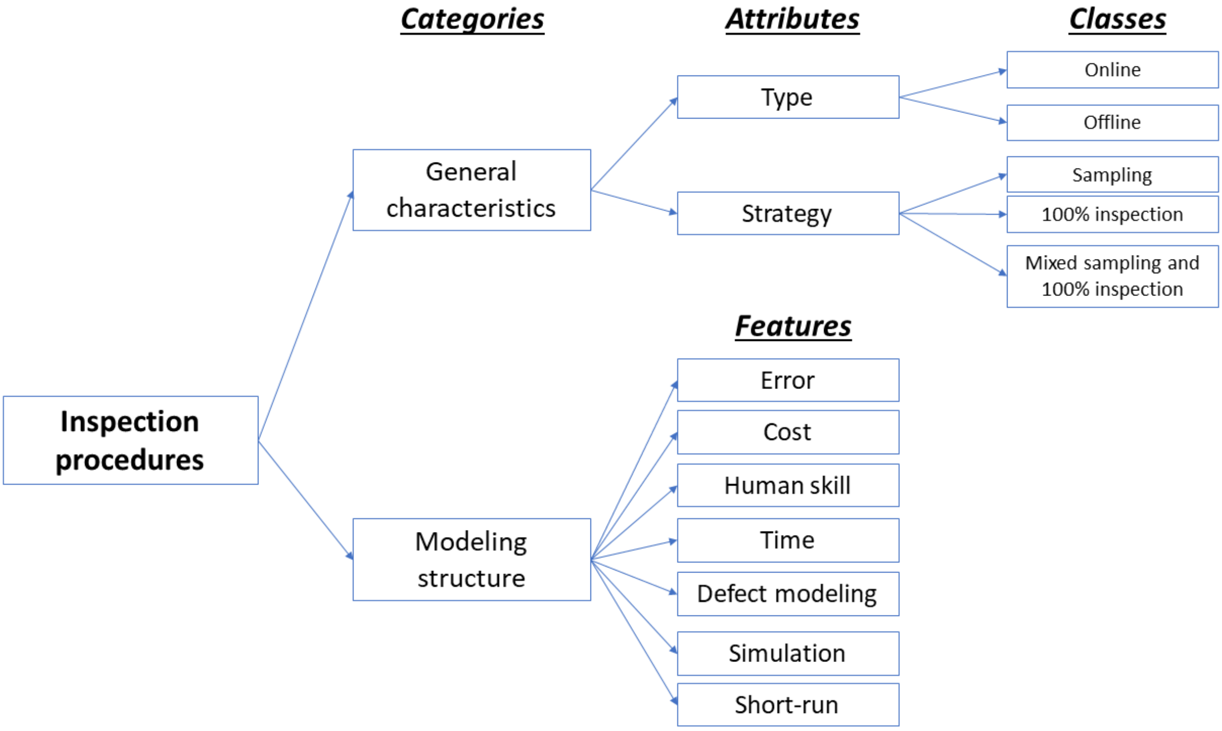


Figure 1. Taxonomy for inspection procedures.

2.1. General characteristics

General characteristics of inspection procedures can be described by the following attributes:

- "Type": online and offline.
  In *online inspection* the units are inspected during the manufacturing process, while in *offline inspection* the units are inspected after the manufacturing process is completed. Traditional online inspection regimes are typically more economical and effective than corresponding offline inspection ones. However, there are situations in which online inspections are infeasible due to operation type and time (Raz et al., 2000). In such cases, an effective approach is to perform offline inspection after preserving the processing order of the product. Offline inspections can be performed at the end of assembly line when the product is finished, or at different stages of manufacturing when the product is semi-finished (Tzimerman and Herer, 2009; Ramzan et al., 2016). The classification into online and offline procedures is the start point of the present survey. Two previous extensive surveys were considered as reference, i.e., respectively, the paper of Mandroli et al. (2006) for online procedures and the one of Kang et al. (2018) for offline procedures.

- “Strategy”: sampling and/or 100% inspection.
  Since 100% inspection may be inefficient and impractical, especially when the inspection is destructive or the inspection cost is high, acceptance sampling plays an important role in the field of statistical quality control (Kahraman et al., 2016; Schilling and Neubauer, 2017). Many papers consider both types of approaches. The same attribute was also considered in the survey analysis by Mandroli et al. (2006) and Kang et al. (2018).

2.2. Modeling structure

Modeling structure of inspection procedures can be described by using the following features:

- “Error”.
  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; Kang et al., 2018). Not all the models of inspection procedures considered these errors. Some authors have simply assumed an error free inspection. Inspection errors may also be intended as lack of inspection capability (Mandroli et al., 2006; Shetwan et al., 2011).
- “Cost”.
  An inspection-oriented quality-assurance strategy attempts to allocate an appropriate level of inspection activity by striking a balance among the various cost components associated with inspection, repair and replacement due to quality failure, and/or the warranty penalty in the case where a nonconforming product has been shipped to customers. Therefore, an inspection-oriented strategy emphasizes a cost-effective production and tolerates a nonzero level of defective production (Mandroli et al., 2006; Kang et al., 2018).
- “Human Skill”.
  In spite of the deficiencies of human fatigue and vulnerability in performance (Bashkansky and Dror, 2016), many manufacturing industries still rely on human labor for the inspection process (Khan et al., 2014; Kang et al., 2018). Thus, quality of the inspection process may depend on the skill of inspectors that affects inspection performance.
- “Time”.
  The inspection time affects the performance of the individual inspector as well as the overall inspection station (Wang et al., 2009; Kang et al., 2018), playing a major role to the total manufacturing costs (Shetwan et al., 2011). Inspection time depends on the product type and its complexity. As the product type varies from basic to complex, the number of performed operations, the variety of components, product size and design also change (Sardar and Lee,

2014). In this way, the inspector will need to check more quality characteristics that will increase the inspection time.

- "Defect Modeling"
  Mandroli et al. (2006) considered the "defect rate", i.e. the proportion of defective items among all items manufactured by a process at a stage. Some authors assumed a known constant defect rate for all operations, whereas others assumed a random rate approach. In the latter case, authors either considered a possible range of defect rates and assigned an occurrence probability for each defect rate or explicitly treated the defect rate as a random variable. Besides, some researchers considered a single defect type, assigned with one variable for the defect rate, whereas others considered multiple defect types, assigned with a vector of defect rates associated with each type of defect. Therefore, Mandroli et al. (2006) considered the four possible combinations, i.e. the four possible situations, for defect rates: (i) single type constant, (ii) single type random, (iii) multiple type constant and (iv) multiple type random. Authors of the present paper prefer to consider, more generally, the "defect modeling", i.e. modeling of defects probability in the different stages of production process.
- "Simulation"
  Research problems in the field of inspection procedures have, generally, an analytical formulation. For their solution, analytical and/or simulative approach may be applied. Even if the former approach is preferable, the latter approach sometimes gives further information or results to be necessary, owing to complexity of the production process.
- "Short-run"
  For a given production process, the performances of the possible inspection procedures are tightly related to the production volume. Recently, authors of the present paper investigated the case of small-sized lot productions, i.e. short-run productions (Franceschini et al., 2018; Genta et al., 2018; Verna et al., 2020). In the case of massive production, Statistical Process Control (SPC) techniques are straightforwardly applied (Montgomery, 2013); on the other hand, in the case of short-run productions, most of the SPC techniques are not easily usable (Marques et al., 2015).

3. Literature survey

3.1. Survey organization

The aim of this section is providing a survey on recent works on inspection procedures in order to identify new research perspectives. Previous surveys, typically, concerned only one of the two inspection paradigms, i.e. online or offline. As mentioned in Section 2.1, the two extensive surveys of Mandroli et al. (2006) and Kang et al. (2018) were considered as reference, respectively for online and offline inspection procedures. The survey of Mandroli et al. (2006) reviews more than 100 papers produced from 1960s to early 2000s. The latter survey significantly extends the previous survey drawn up in eighties (Raz, 1986). Instead, the recent survey of Kang et al. (2018) classifies more than 30 papers produced in the last 15 years, reorganizing the preceding survey of Ramzan et al. (2016). In the present document, the survey of Kang et al. (2018) concerning offline inspection procedures was extended by a literature search performed in Scopus. These papers were analyzed together with a set of recent works on online inspection procedures coming from another Scopus search, which improves and updates the embryonic survey performed by Maheen (2014). Only works presented in peer-reviewed scientific journals were considered, thus examining a total of 66 papers (see Table 3).

In this study, the previous surveys (Mandroli et al., 2006; Kang et al., 2018) were aggregated considering further classification features, according to the taxonomy described in Section 2. In the next subsections, main research lines (Section 3.2) and reference models of inspection procedures (Section 3.3) are described, then a novel literature classification (Section 3.4) and a brief analysis of bibliometric aspects (Section 3.5) are proposed.

3.2. Main research lines

In this section, the literature on inspection procedures, i.e. fundamental research contributions and recent papers considered in the survey (see Table 3), is subdivided into some clusters. These latter identify specific research lines, which include papers with similar research approaches, research aims and application fields. Five main clusters are identified and described in detail. The remaining papers, dealing with specific research problems, will be examined separately.

3.2.1. Multi-stage production systems

First of all, a brief review of the fundamental research contributions on inspection procedures is presented. First papers mainly dealt with inspection allocation in multi-stage production systems. Specifically, Beightler and Mitten (1964) considered the interacting effects between quality control stations associated with the various stages of manufacture of a product. They proposed an inspection allocation model that provides the sequence of interrelated sampling inspection plans which minimizes total unit inspection costs and the cost of accepting nonconforming units. They demonstrated the applicability of dynamic programming to determine the optimal sample size and acceptance number for each inspection station. At the same time, Lindsay and Bishop (1964) developed a general screening inspection program in which inspection levels and locations of inspection points were treated as variables. The model assumes complete inspection of the production run rather than sampling. It is designed to minimize the sum of the unit inspection cost and the cost of lost production due to improper processing. Inspection operations that should be performed at the various stages were identified. In the following years, Britney (1972) was the first to address non-serial production systems. His model assumes perfect inspection and immediate repair of nonconforming units. The total expected cost includes components for unit inspection and repair, fixed repair costs and shipment of nonconforming units. The optimization problem was solved with a branch and bound technique. Hurst (1973) proposed the first model which accounted for both types of inspection errors: rejection of conforming units (type-I) and acceptance of nonconforming units (type-II). The production system was assumed to be serial with only one inspection operation possible after each processing stage, with units perceived to be nonconforming removed from the production stream. Hurst's model is only descriptive, without providing a means for optimizing the system performance. Ballou and Pazer (1982) performed a "what-if" simulation analysis of serial systems with inspection errors. The input to the simulation consisted of the number of stages, the value added at each stage, unit inspection costs, and the penalty cost of the acceptance of a nonconforming unit. The total cost per produced conforming unit was then calculated. In a series of experiments the authors examined the sensitivity of the total cost to the various cost and error parameters of the model. In all the above-mentioned papers inspections were performed online, i.e. during the production process. Afterwards, the offline inspection paradigm has started to develop. Hassin (1984) proposed a search strategy that minimizes the expected number of inspections until identifying the transition unit for a process with a constant failure rate where that last unit is known to be non-conforming. He was the first to refer to inspections performed "offline"; however, he used the terminology of dichotomous search. Raz et al. (2000) were thus the first to propose an actual offline inspection policy, aimed at economic optimization rather than identifying the transition unit of the process. They defined an inspection policy minimizing the sum of inspection and penalty costs. From here on, the two inspection paradigms, online and offline, were definitely established.

Within the framework of online inspections, multi-stage production systems were further examined in recent years, adding substantial contributions to the above described research work. Figure 2 shows a complete manufacturing stage including the three possible types of station, i.e. manufacturing, inspection, and rework or replacement.

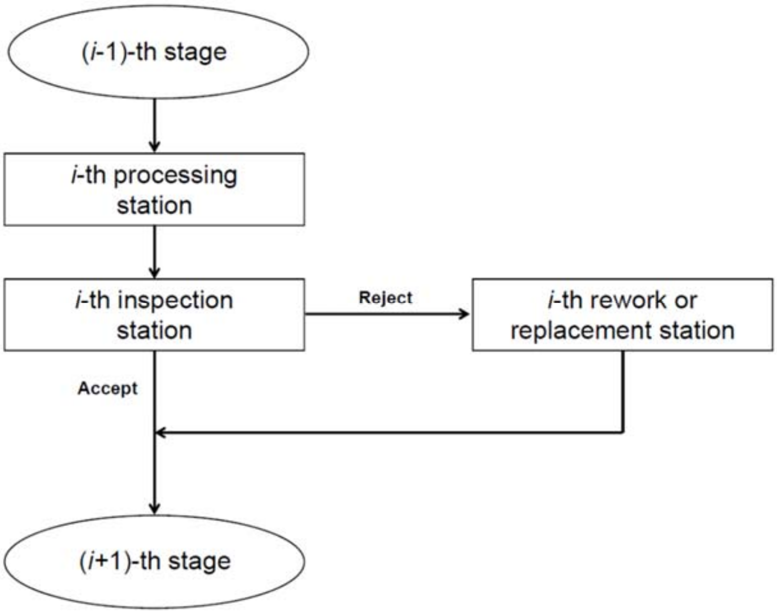


Figure 2. Complete manufacturing stage (*i*-th stage) in a multi-stage production system, readapted from Vaghefi and Sarhangian (2009).

Most of the recently developed quality control and improvement methodologies for multi-stage manufacturing systems are built upon a quantitative modeling of the system, which can be classified into analytical, i.e. based on physical laws, and data-driven, i.e. based on process experimental data (Shi, 2007; Shi and Zhou, 2009). The most widespread analytical method is the “state space model”, which was first proposed for dimensional control by Jin and Shi (1999). In this method, for each manufacturing stage, the key quality characteristics of the product (e.g., the dimensional quality), represented by a “state vector”, are put in relationship with the process error sources (e.g., the fixture errors). The state space model is used to model variation propagation in various multi-stage manufacturing processes, such as machining and assembly (Loose et al., 2010; Li et al., 2017; Yang et al., 2017). On the other hand, data-driven models focus on investigating patterns in the massive historical quality database, without requiring a comprehensive a priori knowledge of the process. These data-driven techniques are often used, e.g., to statistically infer the direct interactions among different stages of production processes (Zeng and Zhou, 2007; Liu et al., 2019). Further, multistage systems provide significant opportunities for the establishment of new methodologies for design optimization, with the goal of quality improvement and reduction of inspection cost. Accordingly, multi-stage systems require the design of quality inspection procedures aimed at optimizing the allocation of inspection resources. Main recent papers on this subject are described below.

Van Volsem et al. (2007) considered the problem of determining the optimal inspection strategy for a given multi-stage production process, i.e. the inspection strategy which results in the lowest total inspection cost, while still assuring the required output quality. They assumed a constant production and inspection rate, perfect inspection and perfect rework. The problem is modelled as a joint optimization of inspection location, type and inspection limits. A solution algorithm based on simulated annealing was developed by Azadeh and Sangari (2010).

Vaghefi and Sarhangian (2009) developed a new mathematical model to optimize inspection plans for multi-stage manufacturing systems with possible misclassification errors. This model minimizes total inspection costs while still assuring a required output quality. Given the model complexity, a simulation algorithm is presented to model the multi-stage manufacturing system subject to inspection and to estimate the resulting inspection costs. Korytkowski (2011) presented an approach for determining the optimal location of inspection stations in multiproduct multistage production system. A genetic algorithm with tournament selection has been adapted to solve the optimization problem. The genetic approach resulted to be suitable for modelling the inspection allocation problem, since the codes used in the chromosome reflect the inspection allocation policies.

Azadeh et al. (2012) proposed a particle swarm optimization algorithm to determine the optimal inspection policy in serial multi-stage processes. The policy consists of three decision parameters to be optimized, i.e. the stages in which inspections occur, the tolerance of inspection and the size of sample to inspect. It is assumed that no inspection errors occur. Total inspection cost is adopted as the performance measure of the algorithm. Subsequently, the authors addressed the problem of finding optimal inspection policies in serial multi-stage production processes when the cost components are described by fuzzy numbers (Azadeh et al., 2015). Since, in practical situations, the precise values of cost components are rarely known, vague and imprecise values are better described by using fuzzy sets, i.e. specific ranges of values (Dubois and Prade, 1980; Klir and Yuan, 1996). The type of inspection (i.e. none, sampling, or full inspection) in each stage and the acceptance limits are considered as decision variables. The size of sample to inspect, when sampling inspection is adopted, is also incorporated into the model as the third decision parameter. The case in which the inspectors are not error-free is also examined.

Rezaei-Malek et al. (2018) developed a mixed-integer mathematical programming model for the integrated planning problem of the part quality inspection and preventive maintenance activities in deteriorating serial multi-stage manufacturing systems. It was assumed that each production stage is deteriorating in time and consequently the probability that a conforming item acquires a defect in each stage increases. The proposed model determines the optimum time and place for the preventive maintenance and part quality inspection activities while minimizing the total manufacturing cost.

Rezaei-Malek et al. (2019a) developed an extensive survey on the existing researches on the optimization of the part quality inspection planning in multi-stage manufacturing systems. Examined papers were classified basing on considered production system characteristics, modelling approaches and solution methodologies. This survey remarked that almost all the authors have ignored manufacturing constraints and have not taken the uncertainty of system into account. Rezaei-Malek et al. (2019b) thus proposed a multi-objective mathematical model, which considers real production constraints and uncertainty of production system, to concurrently plan part quality inspection and preventive maintenance activities.

3.2.2. Short-run productions and defect generation models

Concerning both online and offline inspections, authors of the present paper recently investigated the case of inspection procedures in short-run productions (Franceschini et al., 2018; Galetto et al., 2018; Genta et al., 2018; Verna et al., 2020) by defining new probabilistic models of production process, with the related inspection procedures.

In case of online inspections, authors decomposed a generic manufacturing process into a certain number of steps, i.e. specific operations providing an added value to the end product. The proposed probabilistic model is based on the following simplifying assumptions: (i) a single type of defect for each step, and (ii) the absence of correlation between the parameters related to the different steps. Besides, authors introduced two performance indicators for inspection procedures, related to inspection effectiveness and affordability (Franceschini et al., 2018). The former consists in the expected value of the total number of authentic defects which are not detected by the inspection procedure, while the latter concerns the total inspection cost (including costs of specific inspection activities, necessary repairs, unnecessary repairs and undetected defects). Subsequently, in order to estimate the probability of occurrence of defects in the different steps of production process, authors included defect generation models in the proposed probabilistic model (Genta et al., 2018). In assembly processes, once the elementary operations and the design parameters are known, the 'a priori knowledge' may enable to predict, without any supplementary experimental test, the number of defects which can be generated in each process step, and then the probabilities of occurrence of defects (Hinckley, 1993; Shibata, 2002; Su et al., 2010). These predictions are useful to the producers for designing effective and affordable inspection procedures (Galetto et al., 2018). The block diagram in Figure 3 summarizes the authors' overall proposed methodology in case of online inspections for short-run assembly manufacturing processes.

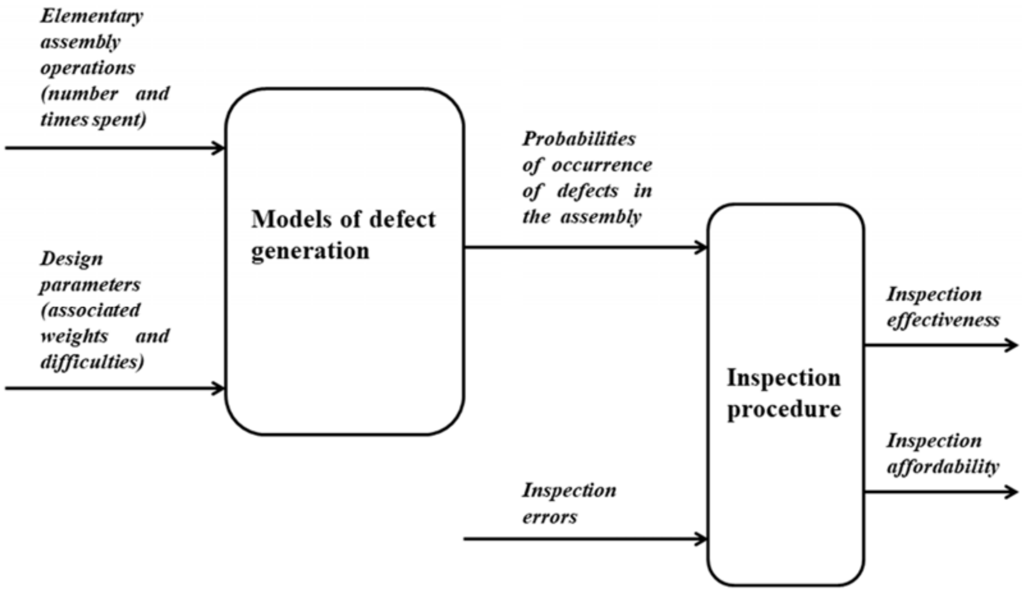


Figure 3. Block diagram of overall methodology for short-run assembly manufacturing processes (Franceschini et al. 2018; Genta et al., 2018).

In case of offline inspections, authors proposed a methodology including the definition of input and output variables, the determination of the mathematical relationship among these variables, the identification of all the uncertainty contributions and the estimation of probabilities of occurrence of defective-output variables (Verna et al., 2020). Then, similarly to the online procedures, inspection errors and inspection costs are estimated, and alternative inspection strategies are compared. Each inspection strategy is again evaluated by the two abovementioned indicators related to inspection effectiveness and affordability (Franceschini et al., 2018). The combined analysis of these indicators allows the manufacturer to choose the most suitable inspection strategy. The proposed approach is applied to an additive manufacturing production in automotive industry.

3.2.3. Systems with multi-characteristic components

Concerning offline inspections, systems with multi-characteristic critical components were examined. Multi-characteristic critical components may be, for example, a part of an aircraft, space shuttle or a gas ignition system. Duffuaa and Khan (2005) proposed for such components an inspection plan in which different inspectors examine different characteristics of each component entering the inspection process. For each characteristic, the components may be classified as meeting specifications, scrap or rework. All the accepted components and those that are found to be meeting specifications at the rework station go the subsequent inspector, who inspects the subsequent characteristic. This chain of inspection continues until all the characteristics have been inspected once. This completes one cycle of inspection. All accepted components, if necessary, go to the next cycle of inspection, and this process is repeated a total of *n* times before the components are finally accepted. Therefore, the accepted components will be those that are accepted in the *n*-th cycle. Figure 4 shows a generic stage (*i*-th stage) concerning a generic characteristic in a cycle of the proposed inspection plan. This inspection plan considers several types of classification errors made by the inspector. Duffuaa and Khan (2005) defined performance measures for the plan and investigated the statistical and economic impact of the several types of inspection errors on these measures. The impact of the errors is studied by conducting sensitivity analysis by means of a software which determines the optimal parameters of the model. They assumed characteristics failures of the components to be statistically independent.

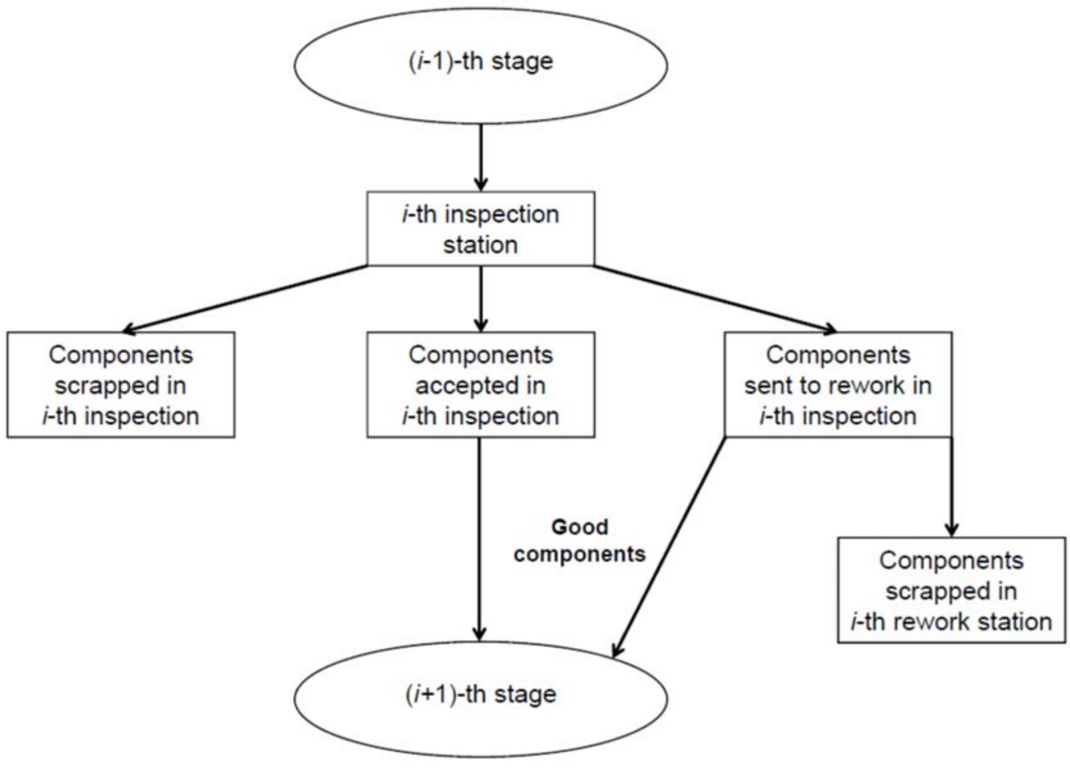


Figure 4. Generic stage (*i*-th stage) concerning a generic characteristic in a cycle of the inspection plan for systems with multi-characteristic critical components, readapted from Duffuaa and Khan (2005).

Subsequently, Duffuaa and Khan (2008) developed a new inspection plan considering statistical dependence of such characteristics failures. The advantage of the new model over the previous one is illustrated for the case of dependency. On the other hand, Elshafei et al. (2006) considered the problem of determination of the inspection sequence of multi-characteristic critical components and the number of repeated inspections for each characteristic. The model considers again the case of several classification of a product by an inspector with respect to a certain characteristic, i.e. as non-defective, to be reworked, or to be scrapped. Possible misclassifications by the inspector are also taken into account. The solution that minimizes the total cost of inspection per accepted component is searched for.

3.2.4. Multi-objective optimization models

Still concerning offline inspections, multi-objective optimization models for process targeting were investigated. Formerly, process targeting problems were usually modeled using a single objective optimization model. Duffuaa and El-Ga'aly (2013a) introduced multi-objective optimization in the process targeting area. They considered a quality characteristic y with two market specification limits, namely L_1 and L_2. Figure 5 shows a schematic flowchart of the production process. 100% inspection is used for product quality control. Products satisfying the first specification limit L_1 are sold in a primary market at a regular price, while products failing the first specification limit L_1 and satisfying the second one L_2 are sold in a secondary market at a reduced price. On the other hand, the product is reworked if it does not satisfy both specification limits.

The multi-objective optimization model developed by Duffuaa and El-Ga'aly (2013a) consists of three maximization objective functions: (i) profit, (ii) income and (iii) product uniformity. Taguchi quadratic loss function is used as a surrogate for product uniformity. Then, the authors considered the case in which the quality of the product is controlled via lot-by-lot acceptance sampling (Duffuaa and El-Ga'aly, 2013b). Finally, the authors assessed the impact of the inspection errors on the optimal parameters and objectives functions values of multi-objectives optimization model for process targeting both in case of inspection sampling plan (Duffuaa and El-Ga'aly, 2015) and 100 % inspection (Duffuaa and El-Ga'aly, 2017).

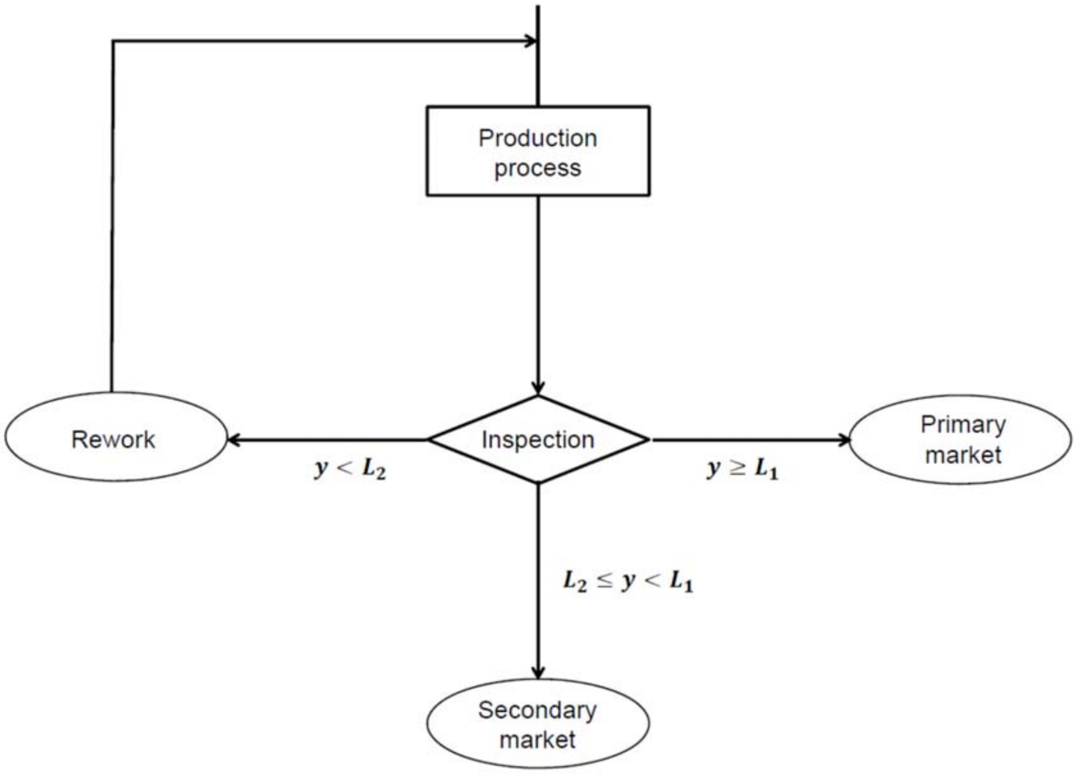


Figure 5. Schematic flowchart of production process in a multi-objective optimization framework, readapted from Duffuaa and El-Ga'aly (2013a).

3.2.5. Economic Order Quantity

Dealing again with offline procedures, the Economic Order Quantity (EOQ), i.e. the simplest and oldest inventory model (Harris, 1913), is often considered. EOQ is the order quantity that minimizes the total holding costs and ordering costs. The traditional EOQ model was extended by Salameh and Jaber (2000) by considering received or produced items with imperfect quality. They assumed that 100% inspections were carried out with an error free screening. The behavior of inventory level (i.e. actual lot size) with respect to time according to Salameh and Jaber's model is shown in Figure 6. It is considered a lot of initial size y being delivered to the buyer in a cycle time T. An inspector identifies the defective items over an inspection period of duration t, therefore, according to Figure 6, (z_1-z_2) is the number of defective items withdrawn from the inventory.

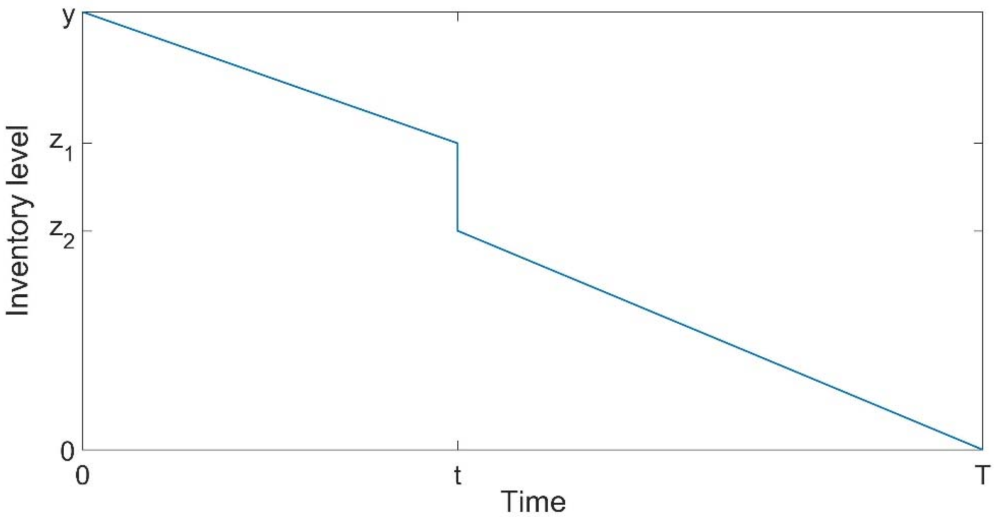


Figure 6. Economic Order Quantity (EOQ) model representing the behavior of inventory level with respect to time, readapted from Salameh and Jaber (2000).

Khan et al. (2010) further extended this model for the case where there is learning in inspection. Their model is realistic since it considers also possible lost sales and backorders. Subsequently, Khan et al. (2011) proposed another improvement of Salameh and Jaber's model by utilizing an imperfect inspection process. Therefore, in addition to the items classified as defective by the inspection process, the items returned as defective from the market are also considered. Such an inspection process involves three costs: (a) cost of inspection, (b) cost of type-I errors, and (c) cost of type-II errors. Later, modifications of Salameh and Jaber's model were investigated in the supply chain context (Khan et al., 2012; Khan et al., 2014; Yao and Askin, 2019).

3.3. Main reference inspection models

By examining the literature on inspection procedures (see Table 3), the models with a more complete structure, in relation to the features described in Section 2.2, are considered as reference models. These models have great descriptive capabilities, since they allow to consider at the same time several modeling features, such as "Error", "Cost" and "Defect Modeling". Furthermore, the selected models are scientifically robust, being experimentally and/or numerically validated in the corresponding papers, and widely accepted by the scientific community, as evidenced by the high citation rate. In the following subsections, the main reference models for both online inspection procedures (Section 3.3.1) and offline inspection procedures (Section 3.3.2) are described.

3.3.1. Reference online inspection models

Concerning online inspections, three reference models are identified. The first two models are proposed in two papers on multi-stage production systems (Vaghefi and Sarhangian, 2009; Azadeh et al., 2015), already mentioned in Section 3.2.1. In order to optimize inspection plans, Vaghefi and Sarhangian (2009) developed a mathematical model minimizing the total inspection cost (*TIC*):

$$TIC = \sum_{i=1}^{r} a_i \cdot [n_i + (1 - P_{ai}) \cdot (N_i - n_i)] \quad (1)$$

where r is the number of inspection stages, a_i is inspection cost per item at stage i, n_i is the number of items to be inspected (sample size) at stage i, N_i is the lot size at stage i, and P_{ai} is the acceptance probability of a lot at stage i. On the other hand, Azadeh et al. (2015) addressed the problem of finding the optimal inspection policy when the cost components are described by fuzzy numbers. In practical situations, exact values of cost components are seldom achieved as they may be vague and imprecise. Such values are well described by fuzzy sets, which encompass a specific range of values allowing the decision maker to have some flexibility in defining the parameters and deal with the uncertainties inherent to real situations (Hu et al., 2011). In particular, the objective function to minimize proposed by Azadeh et al. (2015) is the expected value of the total inspection cost, which is given by:

$$TIC = IC + RC + PC = \sum_{i=1}^{n} (IC_i + RC_i) + PC \quad (2)$$

where n is the number of production stages, IC_i is the fuzzy inspection cost at stage i, RC_i is the fuzzy rework cost at stage i, IC is the fuzzy total inspection cost, RC is the fuzzy total rework cost, and PC is the fuzzy total penalty cost due to delivering defective products to the customer. The third reference model, proposed by Yu and Yu (2007), aims at the determination of an optimal mixed policy of inspection and burn-in, i.e. the process according to which components of a system are tested before being placed in service. Due to inspection errors and high cost of burn-in, how to make a trade-off between them is a challenge for the vendor. Specifically, Yu and Yu (2007) aimed at maximizing the expected profit P_v that the vendor makes in a certain period, under the constraint that the outgoing batch meets an AOQ (Average Outgoing Quality) requirement. Being AOQ defined as the ratio between the number of undetected defective items and the total number of accepted items, it must be lower or equal to a threshold value agreed between producer and vendor. Finally, the expected profit may be expressed as:

$$P_v = P_v(Q, Q_s, Q_b, t_b) \quad (3)$$

where Q is the number of produced parts, Q_s is the number of inspected parts, Q_b is the number of parts put into burn-in, and t_b represents the duration of burn-in procedure.

Table 1 summarizes advantages and disadvantages of selected reference online inspection models.

Table 1. Pros and cons of reference online inspection models.

Paper authors (year)	**Pros**	**Cons**
Yu and Yu (2007)	Determination of an optimal mixed policy of inspection and burn-in (the latter being seldom considered).	Non-consideration of peculiarities of long-term contracts between producer and vendor, such as possible discounts.
Vaghefi and Sarhangian (2009)	Definition of a complete mathematical model to minimize the total inspection costs in multi-stage production systems.	Need of specific simulation optimization methods for solving the multi-stage inspection problems.
Azadeh et al. (2015)	Determination of an optimal inspection policy in a multistage production system when the quality characteristic of the final product depends on all the previous production stages.	Problem studied in a simplified idealistic situation, i.e. with unlimited inspection facilities, without cost constraints, etc.

3.3.2. Reference offline inspection models

Concerning offline inspections, four reference models are identified. The first reference model is proposed in the paper of Duffuaa and Khan (2005) on systems with multi-characteristic critical components, already mentioned in Section 3.2.3. In particular, they aimed at determining the number of inspection cycles n which minimizes the expected total cost per accepted component tc, i.e. the ratio between the expected total cost TC and the total number of accepted components TA, which may be written as:

$$tc = \frac{TC}{TA} = \frac{TCFR + TCFA + TCI}{TA} \quad (4)$$

where $TCFR$ is the total cost of false rejection, $TCFA$ is the total cost of false acceptance, and TCI is the total cost of inspection. In detail, the considered total costs may be expressed as follows:

$$TCFR = \sum_{j=1}^{n} CFR_j \tag{5}$$

$$TCFA = CFA_n \tag{6}$$

$$TCI = \sum_{j=1}^{n} \left(CI_{1,j} + CI_{2,j} \right) \tag{7}$$

where CFR_j is the cost of false rejection in the *j*-th cycle, CFA_n is the cost of false acceptance for all the *n* cycles, $CI_{1,j}$ is the cost of inspection in the *j*-th cycle at regular inspection stages, and $CI_{2,j}$ is the cost of inspection in the *j*-th cycle at inspection stages in rework stations. The described model was subsequently reexamined and developed by the same authors (Elshafei et al., 2006; Duffuaa and Khan, 2008). The second reference model, described by Yu et al. (2009), concerns the determination of a mixed policy between precise inspection and continuous sampling plan CSP-1 (Dodge, 1943). The optimal policy maximizes the unit net profit, which may be written as:

$$NP = \frac{R - TC}{Q} \tag{8}$$

where *R* is the expected overall revenue, *TC* is the expected total cost, and *Q* is the expected production quantity. These three quantities are put in relation with seven parameters: type-I error, type-II error, the selling price of an item, the unit repair cost, the unit return cost, the unit precise inspection cost, and the process defective fraction. The third reference model, proposed by Sarkar and Saren (2016), describes a deteriorating production process, which randomly shifts to out-of-control state from in-control state. A product inspection policy with a warranty period aimed at obtaining reduced inspection costs is proposed. The paper is formulated to minimize the expected total cost per item $C(t,u)$, where t is the production-run length and u is the non-inspected fraction in the batch. In particular, the expected total cost per item may be expressed as:

$$C(t, u) = LC + HC(t) + SC(t) + PcIC(t) + RC(t) + PdIC(u) + DCWC(t, u) \tag{9}$$

where *LC* is the labor cost, $HC(t)$ is the holding cost, $SC(t)$ is the setup cost, $PcIC(t)$ is the process inspection cost, $RC(t)$ is the restoration cost, $PdIC(u)$ is the product inspection cost, and $DCWC(t,u)$ is defective cost and warranty cost. The fourth reference model, described by Ramzan and Kang (2016), is aimed at reducing inspection cost by determining the optimum number of quality inspectors with respect to their skill levels. The total inspection cost per quality inspector *tic* is calculated by:

$$tic = \frac{[L \cdot IQ_l + M \cdot IQ_m + H \cdot IQ_h] \cdot I_r}{L + M + H} \quad (10)$$

where:

- *L*, *M* and *H* are, respectively, the number of inspectors having low, medium and high skills;
- IQ_l, IQ_m and IQ_h are, respectively, the inspected quantity by inspectors having low, medium and high skills;
- I_r is the inspection rate.

It is concluded that inspection cost may be reduced by optimizing the skill level of the quality inspector.

Table 2 summarizes advantages and disadvantages of selected reference offline inspection models.

Table 2. Pros and cons of reference offline inspection models.

Paper authors (year)	**Pros**	**Cons**
Duffuaa and Khan (2005)	Evaluation of statistical and economic impact of classification errors on the performance of a general inspection plan.	Weakness of the proposed model when high confidence estimates of its parameters are lacking.
Yu et al. (2009)	Determination of a mixed policy between precise inspection and continuous sampling plan CSP-1 which maximizes the net profit.	Assumption that the production is always in control, i.e. non-consideration of possible process deteriorations.
Sarkar and Saren (2016)	Development of an economic production quantity model where the process deteriorated based on production of defective products.	Hypothesis of negligible product inspection times.
Ramzan and Kang (2016)	Definition of a multi objective optimization model to minimize the inspection cost which considers human factors.	Non-consideration of variability over time of inspectors' skill level and inspection targets.

3.4. Literature classification

Table 3 illustrates an overall classification of examined literature concerning inspection procedures, basing on the two classification categories defined in Section 2; possible applications considered in the examined papers are also indicated. The first six papers (rows in italic) concern fundamental research contributions on inspection procedures, already discussed in previous surveys (Raz, 1986; Mandroli et al., 2006; Kang et al., 2018). For this reason, the following considerations are limited to the other 66 papers considered in the present survey.

Concerning general characteristics of inspection procedures, a wider bibliography on offline inspection procedures resulted from the literature review. On the other hand, the majority of examined papers considers only acceptance sampling as inspection strategy, being typically more efficient and practical than 100% inspection. Concerning modeling structure of inspection procedures, the majority of papers considers inspection “Error” and/or “Cost”, while about one-half of the papers takes into account “Defect Modeling”. These are three basic features for modeling of inspection procedures. Instead, only about one third of the examined papers considers inspection “Time”, as it is typically difficult to evaluate and standardize. However, as mentioned in Section 2.2, inspection times may significantly affect the inspection performances. Further, the “Human skill” of the inspectors and the possibility of “Short-run” productions are seldom considered. Even if the inspection process is controlled in several instances by means of human labor, only few industrial sectors, e.g. the garment manufacturing industry (Ramzan and Kang, 2016; Kang et al., 2018; Ramzan et al., 2019), allow to study in detail the effect of human factors on process improvement activities. On the other hand, the tight relationship between the performances of the inspection procedures and the production volume is not enough taken into account by the literature. In fact, in the performed literature review, only few papers considering inspection procedures for short-run productions came out (Trovato et al., 2010; Franceschini et al., 2018; Genta et al., 2018; Verna et al., 2020). Finally, about one half of the examined papers adopts a simulative approach for solving the specific research problem, which, as mentioned in Section 2.2, sometimes is necessary owing to the complexity of analytical models. Concerning possible applications of inspection procedures, about one half of the examined papers considers real production configurations, especially in semiconductor and automotive fields. The other examined papers are purely methodological without practical examples.

To better focus the coverage of the examined literature, classification according to general characteristics of inspection procedures is combined with the one relevant to their modeling structure through Venn diagrams. In particular, Figure 7 (a) and (b) put together “Type” with "Error", "Cost" and "Defect modeling", i.e. the more considered modeling features of inspection procedures, as shown in Table 3. Only a limited proportion of the examined papers consider at the same time "Error", "Cost" and "Defect modeling", i.e. about one fourth of the papers for online procedures and one third for offline procedures. These papers include the reference inspection models presented in Section 3.3. Furthermore, Figure 7 allows also making some considerations in terms of research perspectives, which will be discussed in Section 4.

Table 3. Classification of examined literature concerning inspection procedures. The symbol “x” means that the paper considers the specific feature. The first six papers (rows in italic) concern fundamental research contributions, already discussed in previous surveys (Raz, 1986; Mandroli et al., 2006; Kang et al., 2018).

Authors (year)	**Inspection procedures**									
	General characteristics		**Modeling structure**							**Application field**
	Type	***Strategy***	***Error***	***Cost***	***Human skill***	***Time***	***Defect modeling***	***Simulation***	***Short-run***	
Beightler and Mitten (1964)	*Online*	*Sampling and 100% inspection*		*x*			*x*			
Lindsay and Bishop (1964)	*Online*	*100% inspection*		*x*		*x*				
Britney (1972)	*Online*	*100% inspection*		*x*		*x*				*Multi-stage production (generic)*
Hurst (1973)	*Online*	*Sampling*	*x*							
Ballou and Pazer (1982)	*Online*	*100% inspection*	*x*	*x*	*x*			*x*		
Raz et al. (2000)	*Offline*	*Sampling*	*x*	*x*		*x*	*x*			*Food industry*
Duffuaa and Khan (2005)	Offline	100% inspection	x	x			x			Aerospace
Finkelshtein et al. (2005)	Offline	Sampling	x	x				x		
Anily and Grosfeld-Nir (2006)	Offline	Sampling and 100% inspection		x			x	x		
Elshafei et al. (2006)	Offline	100% inspection	x	x				x		

(continue)

Authors (year)	Inspection procedures									
	General characteristics		Modeling structure							Application field
	Type	*Strategy*	*Error*	*Cost*	*Human skill*	*Time*	*Defect modeling*	*Simulation*	*Short-run*	
Mandroli et al. (2006)	Online	Sampling and 100% inspection	x	x		x	x	x		
Grosfeld-Nir et al. (2007)	Offline	Sampling and 100% inspection	x	x				x		
Shiau et al. (2007)	Online	Sampling and 100% inspection	x	x		x	x	x		
Van Volsem et al. (2007)	Online	Sampling and 100% inspection		x			x	x		Semiconductor
Wang (2007)	Offline	Sampling	x	x				x		
Yu and Yu (2007)	Online	Sampling	x	x		x	x			Semiconductor
Duffuaa and Khan (2008)	Offline	Sampling and 100% inspection	x	x			x			Aerospace
Wang and Hung (2008)	Offline	Sampling	x	x				x		
Bendavid and Herer (2009)	Offline	Sampling	x	x				x		
Colledani and Tolio (2009)	Offline	Sampling	x				x	x		Manufacturing (generic)

(continue)

Authors (year)	Inspection procedures									
	General characteristics		Modeling structure							Application field
	Type	*Strategy*	*Error*	*Cost*	*Human skill*	*Time*	*Defect modeling*	*Simulation*	*Short-run*	
Duffuaa et al. (2009a)	Offline	100% inspection		x				x		Manufacturing (safety)
Duffuaa et al. (2009b)	Offline	Sampling		x				x		Manufacturing (safety)
Leung (2009)	Online	Sampling		x		x				
Tzimerman and Herer (2009)	Offline	Sampling	x	x				x		
Vaghefi and Sarhangian (2009)	Online	Sampling and 100% inspection	x	x			x	x		
Wang (2009)	Online	Sampling		x		x				Food industry
Wang and Meng (2009)	Offline	Sampling and 100% inspection	x	x			x	x		
Wang et al. (2009)	Offline	Sampling	x	x		x		x		
Yu et al. (2009)	Offline	Sampling and 100% inspection	x	x			x	x		
Azadeh and Sangari (2010)	Online	Sampling		x			x	x		Serial multi-stage production (generic)
Khan et al. (2010)	Offline	100% inspection	x				x	x		

(continue)

Authors (year)	Inspection procedures									
	General characteristics		**Modeling structure**							**Application field**
	Type	***Strategy***	***Error***	***Cost***	***Human skill***	***Time***	***Defect modeling***	***Simulation***	***Short-run***	
Nakagawa et al. (2010)	Online	Sampling		x		x				Information technology
Trovato et al. (2010)	Online	Sampling and 100% inspection	x	x		x			x	Manufacturing (generic)
Khan et al. (2011)	Offline	100% inspection	x	x			x	x		
Korytkowski (2011)	Online	Sampling	x	x				x		Multiproduct multistage production system (generic)
Tsai and Wang (2011)	Offline	Sampling	x	x				x		
Avinadav and Sarne (2012)	Offline	Sampling and 100% inspection	x	x				x		Biometry
Azadeh et al. (2012)	Online	Sampling and 100% inspection		x			x			Serial multi-stage production (generic)
Galindo–Pacheco et al. (2012)	Offline	Sampling and 100% inspection		x			x	x		
Ho and Quinino (2012)	Online	Sampling		x		x				Semiconductor

(continue)

Authors (year)	Inspection procedures									
	General characteristics		Modeling structure							Application field
	Type	*Strategy*	*Error*	*Cost*	*Human skill*	*Time*	*Defect modeling*	*Simulation*	*Short-run*	
Khan et al. (2012)	Offline	100% inspection	x	x			x			
Tirkel and Rabinowitz (2012)	Online	Sampling and 100% inspection		x		x		x		Semiconductor
Avinadav and Perlman (2013)	Offline	Sampling	x	x						Semiconductor
Chen (2013)	Online	Sampling		x		x				Semiconductor
Duffuaa and El-Ga'aly (2013a)	Offline	100% inspection		x						
Duffuaa and El-Ga'aly (2013b)	Offline	Sampling		x						
Huang et al. (2013)	Online	Sampling		x		x	x			
Aslam et al. (2014)	Offline	Sampling	x							Electronic
Bouslah et al. (2014)	Offline	Sampling	x				x	x		
Khan et al. (2014)	Offline	100% inspection	x	x	x		x			Automotive
Liu et al. (2014)	Offline	Sampling	x							Electronic

(continue)

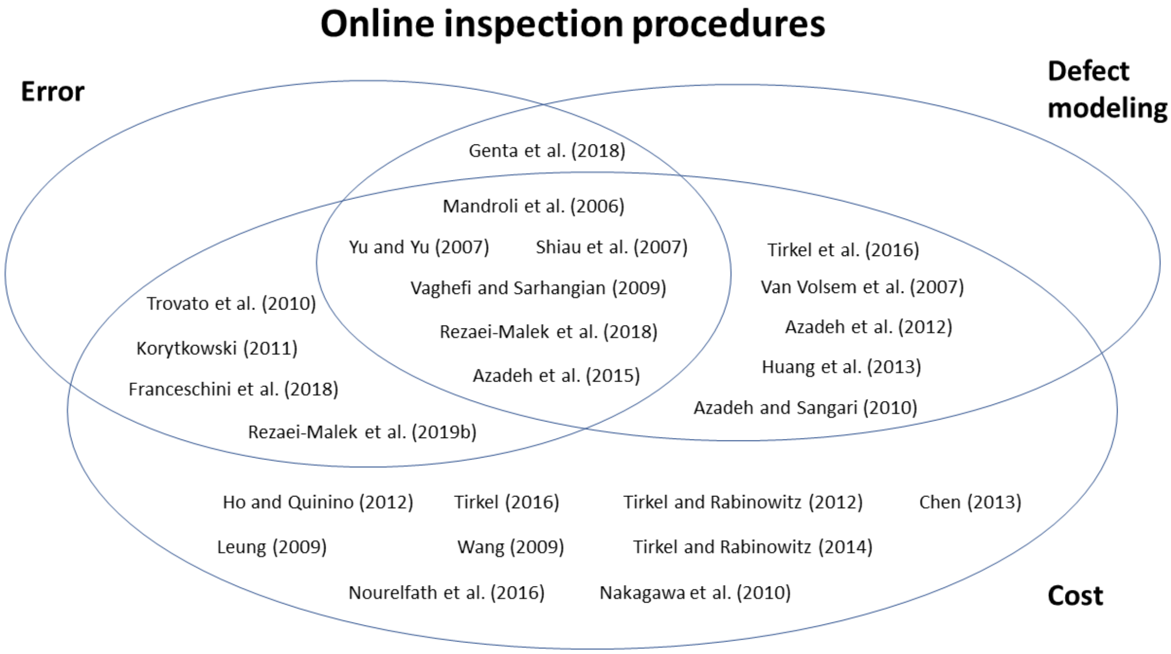
Authors (year)	Inspection procedures									
	General characteristics		**Modeling structure**							**Application field**
	Type	***Strategy***	***Error***	***Cost***	***Human skill***	***Time***	***Defect modeling***	***Simulation***	***Short-run***	
Tirkel and Rabinowitz (2014)	Online	Sampling and 100% inspection		x		x		x		Semiconductor
Yang and Cho (2014)	Offline	100% inspection		x			x			Electronic
Azadeh et al. (2015)	Online	Sampling and 100% inspection	x	x			x	x		Serial multi-stage production (generic)
Duffuaa and El-Ga'aly (2015)	Offline	Sampling	x	x						
Mohammadi et al. (2015)	Offline	Sampling	x	x				x		Machining
Nourelfath et al. (2016)	Online	Sampling		x		x		x		Manufacturing (generic)
Ramzan and Kang (2016)	Offline	Sampling and 100% inspection	x	x	x		x			Textile
Sarkar and Saren (2016)	Offline	Sampling	x	x			x	x		
Tirkel (2016)	Online	Sampling and 100% inspection		x		x				Semiconductor
Tirkel et al. (2016)	Online	Sampling and 100% inspection		x		x	x			Semiconductor

(continue)

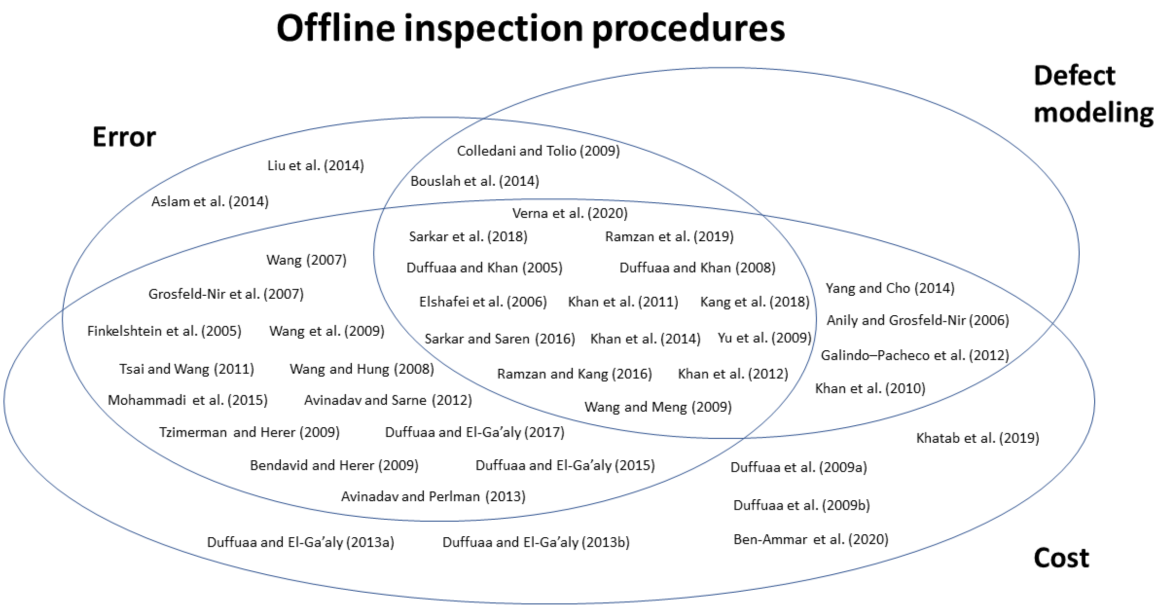
Authors (year)	Inspection procedures									
	General characteristics		Modeling structure							Application field
	Type	*Strategy*	*Error*	*Cost*	*Human skill*	*Time*	*Defect modeling*	*Simulation*	*Short-run*	
Duffuaa and El-Ga'aly (2017)	Offline	100% inspection	x	x						
Franceschini et al. (2018)	Online	Sampling and 100% inspection	x	x					x	Electromechanical
Genta et al. (2018)	Online	Sampling and 100% inspection	x				x		x	Electromechanical
Kang et al. (2018)	Offline	Sampling and 100% inspection	x	x	x	x	x	x		Textile
Rezaei-Malek et al. (2018)	Online	Sampling	x	x			x	x		Automotive
Sarkar et al. (2018)	Offline	Sampling	x	x			x	x		
Khatab et al. (2019)	Offline	Sampling		x				x		
Ramzan et al. (2019)	Offline	Sampling and 100% inspection	x	x	x	x	x			Textile
Rezaei-Malek et al. (2019b)	Online	Sampling	x	x				x		Automotive

(continue)

Ben-Ammar et al. (2020)	Offline	Sampling and 100% inspection		x		x		x		
Verna et al. (2020)	Offline	Sampling and 100% inspection	x	x			x	x	x	Automotive



(a)



(b)

Figure 7. Classification of examined papers by Venn diagrams putting together the features "Error", "Cost" and "Defect modeling" with the attribute “Type”, i.e. “Online” (a) and “Offline” (b).

3.5. Bibliometric snapshot

The survey is concluded with a brief bibliometric analysis by *Scopus* database. Bibliographic details, such as "(Journal) Subject Area" and "Author keywords", may represent attributes for papers classification. The 66 examined papers (see rows in regular style of Table 3) come from 23 journals. These are listed together with the corresponding number of papers in Table 4. According to the "Subject Area" specified in *Scopus*, the majority of examined papers belongs the areas of "Engineering" and/or "Decision Sciences".

Table 4. List of journals examined in the survey with the corresponding number of papers.

Journals	**Number of papers**
International Journal of Production Research	16
Computers and Industrial Engineering	9
European Journal of Operational Research	7
International Journal of Advanced Manufacturing Technology	5
International Journal of Production Economics	5
IIE Transactions	3
Reliability Engineering and System Safety	3
Applied Mathematical Modelling	2
Quality Engineering	2
Computers and Mathematics with Applications	1
Computers and Operations Research	1
Indian Journal of Fibre and Textile Research	1
International Journal of Computer Integrated Manufacturing	1
International Journal of Operational Research	1
International Journal of Productivity and Quality Management	1
International Journal of Simulation and Process Modelling	1
Journal of Industrial and Management Optimization	1
Journal of Manufacturing Systems	1
Journal of the Operations Research Society of Japan	1
Mathematics	1
Naval Research Logistics	1
Omega	1
Operations Research	1

On the other hand, for the 66 examined papers, the most recurring keywords, in decreasing order, are: quality control, inspection(s), offline inspection(s) (or off-line inspection(s)), inspection error(s), optimization, dynamic programming, inspection cost(s), process targeting, and quality.

4. Conclusions and research perspectives

This paper presents a novel survey on the recent studies on inspection procedures for both online and offline inspection paradigms. The objective is to propose a re-reading of the papers developed in the last 15 years in the light of new research paradigms. A total of 66 papers, published on peer-reviewed scientific journals, is considered. Analyses performed in the past surveys are aggregated considering further classification features. The proposed taxonomy, summarized in Figure 1, allows the following actions:

- analysis and classification of inspection procedures, with the aim of identifying elements for improvement and choosing the most appropriate procedure for a given application;
- study and proposal of new inspection procedures, by identifying and analyzing lacks and criticalities of the existing ones.

In addition, Table 3 presents an overall literature classification. The adopted classification attributes and features may be combined through Venn diagrams, thus creating detailed maps showing the research areas which are not adequately covered by the literature. The Venn diagrams illustrated in Figure 7 combine the more considered modeling features of inspection procedures (i.e. "Error", "Cost" and "Defect modeling"), thus highlighting that only a limited proportion of the examined papers consider them simultaneously. A summary coverage map, with reference to the adopted taxonomy, is shown in Table 5. This table enables an overview on research areas not covered or only partially covered by the literature. “Human skill” and “Short-run” appear to be the less studied modeling features of inspection procedures.

These survey results need to be contextualized with respect to modern manufacturing processes. Given the current convergence between the cyber and physical world (“Industry 4.0”), innovative inspection strategies are going to be developed (Schmitt and Voigtmann, 2018; Tao and Qi, 2019). Application of modern information technologies in manufacturing (“smart manufacturing”) drives to the development of novel “smart inspection strategies”. Such digitalization has also increased the use of simulation in the design and operation of manufacturing systems (Mourtzis, 2019). Technological advancements are thus resulting in an explosive growth of the number of devices connected to “Internet of Things (IoT)” (Ahmed et al., 2017).

Table 5. Coverage map of examined literature on inspection procedures, with reference to the adopted taxonomy. Light, medium and dark grayscale levels correspond respectively to proportions lower than one-third, between one-third and two-thirds, and greater than two-thirds of examined literature.

		General characteristics of inspection procedures				
		Type		***Strategy***		
		Online	**Offline**	**Sampling**	**100% inspection**	**Mixed sampling and 100% inspection**
Modeling structure of inspection procedures	**Error**					
	Cost					
	Human skill					
	Time					
	Defect modeling					
	Simulation					
	Short-run					

Grayscale level	***Proportion of examined literature***
	Lower than 1/3
	Between 1/3 and 2/3
	Greater than 2/3

Most IoT applications do not only focus on monitoring discrete events but also on mining the information collected by connected objects. Several cost-effective and flexible IoT solutions are based the deployment of sensors in manufacturing to perform online inspections with real-time data. In order to collect product quality data, sensors are embedded in production equipment and real-time data are used to determine which equipment requires service, repair or replacement.

In this context, “big data” analytics support the overall quality monitoring, early warning of quality defects, and rapid identification of root causes (Ahmed et al., 2017). As a result, two potential scenarios arise for inspection strategies in the Industry 4.0 framework:

- 100% inspection, generally possible by IoT sensors, enabling a continuous quality monitoring, obtained by inspections integrated into manufacturing process and done automatically;
- acceptance sampling, required only in case of technological constraints, as it loses advantages of efficiency and reduced costs, typical of 100% inspection performed with IoT sensors.

On the other hand, models for the feedback of the data with the aim of process control become more precise but at the same time more complex, since more and more process parameters and disturbance variables are considered (Schmitt and Voigtmann, 2018). These parameters must be acquired and made available during the process. In this context, the need of an accurate “Defect modeling” is highlighted, as well as the need for greater attention to “Human skill” of inspectors and “Short-run” productions.

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