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Inventory models for imperfect production and inspection processes with various inspection options under one-time and continuous improvement investment

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ABSTRACT

This study investigates both internal and external effects of defective production and delivery from imperfect production and inspection processes in a stable production and inventory system, and subsequent defective returns and dispositions. We first develop profit-maximizing imperfect-quality inventory models for various inspection options (sampling inspection, entire lot screening, and no inspection) under one-time improvement investment in production and inspection reliability. We then present the models under continuous improvement (CI) investments over multiple periods, which have not been explored before. In a CI environment, we further propose an inspection alternative of changing an inspection option from entire lot screening to no inspection and vice versa. We develop an algorithm for finding the optimal inspection policy yielding a superior profit, among inspection option change between entire lot screening and no inspection and those without option change. Based on the analytical models along with numerical and simulation analyses, we provide important managerial implications to practicing managers and future research directions.

1. Introduction

The imperfect quality of both production and inspection processes results in producing defectives, passing some to customers, and subsequently causing defective returns and dispositions in a closed-loop (forward and reverse) supply chain. Defective production and inspection failure affect a firm's profit negatively in the short and long run through external failure costs related to defective returns, reverse logistics, refund or exchange, resolution of customer complaints and regaining customer loyalty as well as internal failure costs related to rework, salvage and scrap. In practice, the average return rates in apparel and consumer electronics industries amount to 19.44% and 8.46%, of which 49.45% and 35.71% are due to defects, respectively [1]. The annual value of product returns is estimated at $100 billion [2,3], and commercial returns in e-commerce are recorded up to 25% of sales [4]. Thus, to reduce these negative effects by improving reliability in production and inspection processes, the firm can invest in prevention activities to improve process control and capability, workers' skills, inspection and test equipment design, as well as appraisal activities to determine the degree of conformance and screen out defectives [5]. A critical issue here to a manager is to decide *whether to invest in improving the reliability level one time to its optimum or continuously over time given a capital constraint* from the firm's annual budget plan.

Most past studies on imperfect-quality inventory models, however, have focused on cost-minimizing aspects primarily related to internal effects of defective production and its process quality improvement. Those studies dealing with quality investment have mainly focused on finding the global optimal solution without considering continuous improvement, a basic principle of total quality management [6]. Therefore, the main purpose of this study is to *explore both internal and external issues of defective production, inspection failure and related quality improvement investment for a firm in a closed-loop supply chain*. We develop imperfect-quality inventory models for various inspection options such as sampling inspection (SI), entire lot screening (LS) and no inspection (NI) under both one-time and continuous improvement (CI, aka Kaizen) investment settings and analyze the results. The objective of the models is to determine the profit-maximizing production lot size, rework frequency, and defective and inspection failure proportions related to respective capital investment. In solution, we jointly determine these decision variables using differential calculus and nonlinear programming. We also numerically compare the optimal solutions of the models for various inspection options (SI, LS and NI) to discover optimal investment paths between one-time improvement without a

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capital constraint and continuous improvement with the budget constraint. We further investigate the previously unexplored impact of an inspection option change in a continuous improvement environment, between the two economic inspection alternatives (i.e., entire lot screening and no inspection) for a stable process.

The significance of this study lies in building more practical and comprehensive models for a firm in a close-loop supply chain to provide key managerial insights into practices through extensive simulation analyses, thereby extending the extant knowledge on the imperfect-quality inventory and quality management and bridging the gap between practice and academia. The rest of the paper is organized as follows. Following the introduction, Section 2 reviews and analyzes the extant relevant literature. Section 3 develops inventory models for imperfect production and inspection processes with various inspection options (SI, LS and NI) under one-time investment given no budget constraint, and numerically illustrates the optimal solutions. Section 4 presents inventory models for continuous improvement (CI) investment given budget constraints over multiple periods. Section 5 develops further an algorithm for inspection option changes between LS and NI and presents the simulation results of finding the optimal inspection policy for CI. Lastly, in Section 6 we conclude the present study with managerial implications and future research directions.

2. Literature review and analysis

Most previous imperfect-quality inventory studies have focused on cost-minimization models for an imperfect production process, deteriorating or stable, with different inspection methods or process reliability improvement (see Yano and Lee [7] and Yoo [8] for a review). In the studies that examined a production process which deteriorates as run cycles progress, inspection was mostly based on regular intervals [9–24]. These studies dealt with inspection errors [13–15,18,24], delivery of defectives to customers without their subsequent returns [13,14,24], inspection schedule [11–15,17,18] and control chart design [15,18], and investment in production reliability improvement [9].

On the other hand, more directly related to the present study are the ones for *a stable production process*, generally assumed to follow a Bernoulli process generating binomial yields with no deterioration over time. For this process, Deming [25] suggested *kp* rule for entire lot screening and no inspection, arguing them as two most economic inspection alternatives (see also Duncan [26]). Most of the following studies since then examined the inspection option of entire lot screening [27–45] except Zhang and Gerchak [46] for a fractional lot. Among them, some also considered the optimal investment decision on production process reliability [28–30,34,37,38,40,45].

Further, most studies above included only one disposition option, such as instantaneous rework [9–22,24,38], salvage [36], or scrap at no cost [23,27–31,34,37,40,41,43,45,46]. A few exceptions were So and Tang [33] including both rework and salvage and Chiu et al. [44] considering both rework and scrap.

Through the review, we discover the following crucial points that serve as underpinning for our study:

- Most imperfect-quality inventory studies focused on cost-minimization models that mainly reflect internal effects of defective production without considering an imperfect inspection process and external reverse logistics issues of defective returns. In practice, however, an inspection process is also often not perfect, let alone a production process, thereby resulting in an inspection error of falsely not screening out some proportion of defectives even with entire lot screening and thus passing them to customers. This in turn causes customers' return of defectives back to the firm, incurring related costs.
- Those studies dealing with process reliability investment primarily concerned the production process only. In practice, however, planning and control of appraisal processes including inspection and test, training of employees in an inspection line, design of an inspection process and introduction of a better inspection equipment are also crucial prevention activities of quality management in reducing the risk of defectives being delivered to customers, causing subsequent return and loyalty problems [47].
- Many past studies involving quality investment implicitly assumed that the optimal quality level can be achieved with one-time capital investment. In practice, however, quality improvement efforts are typically made continuously over time rather than its optimal level being reached at once, due to various constraints such as limited budget on quality improvement activities, limitation in present technology and so on. Therefore, finding the optimal investment paths of production and inspection process reliability improvement through continuous improvement (CI) over time under the budget constraint would help a manager make an effective decision.
- In the CI practice, it can be more profitable for a firm to change its static optimal inspection option dynamically over time from entire lot screening to no inspection or vice versa. So we also investigate this inspection option change, which has not been explored in the prior research to the best of our knowledge.
- Finally, many previous studies except for a few dealt with only one defective disposition option. In practice, however, firms in consumer electronics, apparels, automotive parts and others use multiple disposition options such as rework, salvage and scrap together.

Therefore, in the present study, we incorporate all of the above important issues in practice into our models.

3. Inventory model with one-time investment given no budget constraint

3.1. Problem description and assumptions

In this section, we first develop a general *sampling inspection* (SI) model, and then derive from it *entire lot screening* (LS) and *no inspection* (NI) models. We investigate a closed-loop supply chain in which a manufacturer's production and inspection processes are stable and non-deteriorating but not perfectly reliable and hence some defectives are delivered to customers, causing subsequent customers' returns and the firm's disposition of defectives. Fig. 1 describes the forward and reverse flow of inventories and transactions, in which the solid lines indicate the actual inventory flows while the dotted lines show how stock or activity influences a net depletion rate (see notation in Table 1 hereafter).

In each cycle, items of lot size Q are produced at a finite production rate M, including defectives from an imperfect production process. Given the assumption that production follows a stable Bernoulli process [25–45] generating binomial yields with defective proportion π following its *pdf*, $f(\pi)$, the process yields defective quantity πQ. Then, a proportion of a lot, θQ, is sampled and inspected with a given sampling proportion θ. Note that when $\theta = 0$, there is no inspection (NI), and when $\theta = 1$, inspection is based on entire lot screening (LS). An inspection rate I is