Int. J. Production Economics 140 (2012) 922–933

Contents lists available at SciVerse ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Lot sizing and quality investment with quality cost analyses for imperfect production and inspection processes with commercial return

Seung Ho Yoo [a], DaeSoo Kim [b,*], Myung-Sub Park [b]

[a] Sun Moon University, Tangjeong-myeon, Asan, Chungnam 336-708, Republic of Korea
[b] Korea University, Business School, Anam-dong, Seongbuk-gu, Seoul 136-701, Republic of Korea

ARTICLE INFO

Article history:
Received 3 September 2010
Accepted 14 June 2012
Available online 27 July 2012

Keywords:
Inventory
Imperfect production
Inspection
Return
Quality cost

ABSTRACT

This study examines an imperfect production and inspection system with customer return and defective disposal. We develop an optimal lot sizing model with production and inspection quality investment, incorporating all the quality costs. We find the optimal lot size, rework frequency, defective proportion, and Type I and Type II inspection error proportions which minimize the total quality cost and maximize the total profit. We further analyze the solutions for no, partial, sequential and joint investment decisions on production and/or inspection processes in terms of quality costs using numerical analyses. The result provides important managerial insights into practice.

1. Introduction

In a closed-loop supply chain, we frequently discover firms producing defective items and passing some to customers due to imperfect quality in both production and inspection processes. This imperfect process reliability then causes customers to return defective items for exchange or refund. For example, the average return rate in the apparel and the consumer electronics industry amounts to 19.44% and 8.46%, of which 49.45% and 35.71% are due to defects, respectively (Reverse Logistics Executive Council, 1999). The annual value of product returns is estimated at $100 billion (Stock et al., 2002; Blackburn et al., 2004) and commercial returns in online retailing and e-commerce are recorded up to 25% of sales (Krikke et al., 2004). In addition, imperfect inspection incurs an opportunity loss by falsely screening out non-defective items and disposing of them as defectives. Thus, it is important for firms to understand both internal and external effects of defective production and inspection failure on lot sizing, inventory, quality costs and profit.

There have been a vast number of studies that deal with imperfect production, inspection and reverse logistics issues. Most studies focused mainly on developing cost-minimizing models for either internal effects of defective production and process quality improvement, or recycling and rework of reusable item returns. The imperfect production and inspection system in practice, however, incurs not only internal failure costs related to rework, salvage and scrap, but also external failure costs from defective item return, reverse logistics, resolution of customer quality problems, and refund or exchange, negatively affecting the firm's profit. Thus, to reduce these negative effects, the firm often invests in prevention activities to improve process capability, worker skills, inspection and test equipment design, as well as appraisal activities to determine the degree of conformance and internally screen out defectives. Consequently, it is imperative for a firm to carefully consider the tradeoff relationships among the internal and external aspects of quality costs (i.e., prevention, appraisal, internal failure and external failure) in the optimal investment decision along with lot sizing (Juran and Gryna, 1988).

In this light, this study explores internal and external issues of defective production, inspection failure (Type I and Type II errors), and related quality improvement investment for a firm in a closed-loop supply chain with commercial return. Specifically, we develop a profit-maximizing model that jointly determines the optimal production lot size, rework frequency, and defective production and inspection error proportions related to respective investment. We solve the model optimally using differential calculus and nonlinear programming. We also analyze our model in terms of four quality cost components to discover their tradeoff relationships in lot sizing and quality investment decision making. Moreover, we investigate the solutions and quality cost structure of different decisions in practice with no, partial, sequential and joint investment in production and inspection process reliability, in order to provide important managerial insights and help managers make well-informed decisions. The significance of this study may lie in building a more practical model, quantifying and analyzing quality costs and comparing

* Corresponding author. Tel.: +82 232 902 817; fax: +82 2922 7220.
E-mail address: kimd@korea.ac.kr (D. Kim).

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http://dx.doi.org/10.1016/j.ijpe.2012.07.014

different investment decision-making situations, thereby extending the current body of knowledge on imperfect-quality inventory and quality management.

The rest of the paper is organized as literature review and analysis, basic imperfect-quality inventory model and solution approach, extended quality investment model and quality cost decomposition, and optimal solution and quality cost analysis for different investment decisions, followed by conclusions.

2. Literature review and analysis

Most previous research of an imperfect production system has focused on developing cost-minimization models for either deteriorating or stable production processes with different inspection methods (see Yoo et al., 2009, 2012 for a review). The studies of a deteriorating process since Porteus (1986) and Rosenblatt and Lee (1986) typically assumed that the production process goes from an in-control state to an out-of-control state as a run cycle progresses, mostly with inspection based on regular intervals and instantaneous rework of defective items (see Yano and Lee, 1995 for a review). Besides the determination of lot size or production cycle, these studies also dealt with investment in production process quality (Porteus, 1986; Ouyang et al., 2002), inspection schedule or policy (Lee and Rosenblatt, 1987, 1989; Lee and Park, 1991; Liou et al., 1994; Rahim, 1994; Kim et al., 2001; Rahim and Ben-Daya, 2001; Wang and Sheu, 2001), inspection errors (Lee and Park, 1991; Liou et al., 1994; Rahim, 1994; Rahim and Ben-Daya, 2001; Wang and Sheu, 2003; Yeh and Chen, 2006), inspection size (Vickson, 1998; Yeh and Chen, 2006), delivery of defective items to customers (Lee and Park, 1991; Liou et al., 1994; Yeh and Chen, 2006), and finite multiple lot sizing (Guu and Zhang, 2003).

More directly related to the present study are the studies of a stable production process since Deming (1982). These studies typically assumed that the production process follows a Bernoulli process generating binomial yields, primarily with inspection by entire lot screening and scrap of defective items at no cost (Schwaller, 1988; Cheng, 1989, 1991a, 1991b; Anily, 1995; Lee et al., 1996; Agnihothri et al., 2000; Otake and Min, 2001; Affisco et al., 2002; Elhafsi, 2002; Tripathy et al., 2003; Grosfeld-Nir, 2005; Grosfeld-Nir et al., 2006; Leung, 2007; Chiu et al., 2007). Some exceptions include Zhang and Gerchak (1990) examining inspection of a fractional lot, Salameh and Jaber (2000) dealing with salvage, and Yoo et al. (2009) investigating two-way inspection errors with rework and salvage of sales returns. Some studies also considered investment in production process reliability with lot sizing (Cheng, 1989, 1991a, 1991b; Lee et al., 1996; Otake and Min, 2001; Affisco et al., 2002; Tripathy et al., 2003; Leung, 2007; Yoo et al., 2012).

In contrast to most of the studies above dealing with internal issues related to defective production, reverse logistics modeling studies have investigated external issues of recycling or reusable item returns with mixed disposal methods of rework and scrap (Schrady, 1967; Richter, 1996a, 1996b; Teunter, 2001; Koh et al., 2002; Dobos and Richter, 2004, 2006). Their focus was primarily on finding cost-minimizing production and recycling (repair or remanufacturing) lot sizes to satisfy market demand, not related to commercial returns (see Stock et al., 2002; Blackburn et al., 2004 for return issues).

Through the literature review, we discover some crucial points which serve as underpinning of the present study. First, most imperfect production system studies focused on developing cost-minimization models that reflect only internal effects of defective production, not considering an imperfect inspection process and external reverse logistics issues of commercial returns of defective items. In practice, however, the inspection process is often not perfect or error-free, let alone the production process, thereby resulting in Type II inspection error of falsely not screening out some proportion of defectives even with entire lot screening and thus passing them to customers. This then subsequently causes customers' defective return for exchange or refund and incurs lost sales and additional costs (Reverse Logistics Executive Council, 1999; Stock et al., 2002; Blackburn et al., 2004). Second, those studies dealing with process reliability investment were mainly concerned with production processes. 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 better inspection equipments are also important prevention activities of quality management in reducing the delivery of defective items to customers and subsequent return and loyalty problems (Juran and Gryna, 1988). Third, besides the external failure issues due to Type II inspection error, an imperfect inspection process also involves Type I inspection error, which falsely screens out some non-defective items and regards them as defectives. Thus, this yields an opportunity loss in practice by not being able to sell those falsely screened non-defective items to customers (Liou et al., 1994; Yoo et al., 2009). Fourth, many previous studies have dealt with only one defective disposal option. In practice, however, firms in consumer electronics, apparel, automotive parts industries, etc. use multiple disposal options of rework, salvage and scrap together (Cyber Atlas, 2000; Yoo et al., 2012). And fifth, previous studies have not examined all the quality cost components comprehensively. In practice, however, identifying and measuring quality costs (i.e., prevention, appraisal, internal failure and external failure costs) are crucial for firms in quantifying the size of the quality problem, thereby helping justify control and improvement efforts, guide their development and track progress in quality management activities (Juran and Godfrey, 1998).

Therefore, to close the gap between practice and academia, we extend extant studies, considering all the above issues previously unexplored. The next two sections develop basic and extended inventory and/or quality investment models.

3. Basic imperfect-quality inventory model and solution approach

3.1. Problem description and assumptions

We investigate a practice in which a manufacturer's production and inspection processes are stable and non-deteriorating but not perfectly reliable. Thus the two imperfect processes result in producing defective items, and not only delivering some defective items to customers leading to the customers' return but also yielding an opportunity loss by falsely screening out some non-defectives as defectives. In modeling, we extend particularly previous two studies, Yoo et al. (2012) dealing with continuous improvement for imperfect production and inspection processes with Type II inspection error and Yoo et al. (2009) considering both Type I and Type II inspection errors without quality investment. Further, different from these studies, the present study focuses on detailed quality cost decomposition analyses in addition to building a more comprehensive practical model. Fig. 1 describes the forward and reverse flow of inventories and transactions (see notations in Table 1 henceforth).

The imperfect production system produces lot size Q in cycle T. Given that the production follows a stable Bernoulli process generating binomial yields with defective proportion π from its probability density function (*pdf*), $f(\pi)$, the process yields defective quantity πQ among Q. Then, the entire lot Q is inspected