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A supply chain coordination mechanism for common items subject to failure in the electronics, defense, and medical industries

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ABSTRACT

Prior research on inventory management for imperfect items assumes that such items can be dealt with through salvage or rework. Increased repair costs and decreased production costs arising from modern production processes (e.g. miniaturization, 3D printing), however, have led suppliers to increasingly eschew such solutions in favor of items and components which are discarded upon failure rather than being reworked or scrapped. In this paper, we first determine optimal supplier and buyer inventory policies for items which fail and which cannot be reworked. We then develop a supply chain coordination mechanism which uses a common replenishment time to coordinate a supply chain consisting of a single supplier and n buyers. Our coordination mechanism yields a global minimum for system-wide costs. Numerical examples are provided to illustrate important conditions under which our model is particularly effective at reducing system-wide costs.

1. Introduction

Miniaturization and other modern production processes have created an increasingly important class of items not subject to rework (i.e. not cost effective to repair or technically irreparable) which are used across a wide range of industries. The electronics industry, for example, utilizes a variety of small transistors, circuits, and other small components which cannot be repaired upon failure due to their method of installation and/or relatively small size (Dumbrowski et al., 2011). Bullets, certain ballistic missile components, and other types of ordnance also exemplify a category of military supplies which are unable to be reworked upon failure (Rossi 1987). Additionally, certain sterile medical supplies (e.g. saline solution, sterile gauze, and other surgical supplies), whether due to feasibility or regulatory requirements, are similarly useless upon failure. These items share both the potential for probabilistic failure during storage and a general lack of feasible conditions for repair or rework upon failure. Medical supplies, for example, can experience failure during storage through loss of sterile conditions for a variety of reasons such as tampering, unexpected storage environment changes, or compromised packaging. Similarly, ordnance and electronic components can fail through exposure to water and extreme environmental conditions, rendering these items irreversibly damaged.

This paper develops a supply chain coordination mechanism for a supply chain consisting of a single supplier and n buyers for items of this type. In order to develop our coordination mechanism, we begin by considering optimal inventory policies for the buyers and seller under the economic order and production quantity (EOQ/EPQ) framework of Harris (1913) and Taft (1918). Having derived optimal inventory policies for individual members of the supply chain, we apply the bisection algorithm in order to coordinate the supply chain using a common replenishment time. System-wide costs are minimized through the use of our coordination mechanism, allowing us to propose potential methods through which cost savings can be shared with buyers in order to induce mutually-beneficial cooperation.

Modeling optimal inventory policies for practically important items which fail and are unusable after failure requires us to ease the basic assumption of perfect item quality within the EOQ/EPQ framework. One way in which these models differ is in their treatment of the rate at which defective items enter the system, Eroglu and Ozdemir (2007) and Papachristos and Konstantaras (2006) assume that the item defect rate is a uniformly distributed random variable. These papers highlight, respectively, the importance of defect rate magnitude and the timing of defective inventory disposal as key drivers of optimal profit and inventory levels. Tsou (2007), in emphasizing the role of product quality in driving optimal order quantities among buyers, assumes imperfect items are normally distributed among lots. Maddah and Jaber (2008) model the proportion of imperfect items in delivered lots as being a

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random fraction of delivered items. Their model identifies manufacturing screening conditions under which slight changes in defective item rates (i.e. yield) lead to relatively large fluctuations in optimal order quantities. Huang (2004) contributes to the literature by modeling process deterioration within a supply chain, whereby defective items are produced a random rate according to a known probability density distribution which fluctuates over the life of the production process. Jaber et al. (2008) and Wahab and Jaber (2010) demonstrate that defect rates decline as a function of learning curve gains in the production process. Jaber et al. (2013) identify hidden inventory costs within an entropic production environment, where input prices and product quality are used to determine the "temperature" of a production system, using a random uniform distribution of imperfect items.

Other researchers model imperfect items as perishable inventory subject to time-dependent deterioration. Wee et al. (2006) allow for defective items to be identified during screening and emphasize the need to account for even relatively small amounts of deterioration. Khanra et al. (2011) model time-dependent item deterioration in the presence of quadratic time-varying demand rates and identify the role of credit policies in helping suppliers coordinate with customers in light of industry-specific demand patterns. Dye (2013) introduces the concept of preservation technology in slowing the rate of item deterioration and derive a model for optimizing supplier investments in preservation technology and inventory replenishment policies. Sana (2010) introduces price-dependent demand and time-varying deterioration for perishable products as more realistic ways to model real-world conditions, highlighting the importance of external validity within the inventory optimization literature.

These models also differ in the methods by which defective items are disposed. Multiple methods for disposing of imperfect items are also proposed, including rework (Porteus 1986), scrap (Lee and Rosenblatt 1987), single-lot disposal (Salameh and Jaber 2000; Konstantaras et al. 2007), and tiered pricing of imperfect items based on the extent of imperfections (Tsou 2007; Tsou et al., 2009). Porteus (1986) and Lee and Rosenblatt (1987) identify manufacturing adjustments that allow for the identification and treatment (either rework or disposal) of defective items during a production run, thereby allowing for longer production runs. Salameh and Jaber (2000), in treating imperfect items as poor quality items to be disposed of as a single lot, demonstrates the sensitivity of holding costs to imperfect item disposal policies (i.e. rework vs. disposal). Tsou (2007) and Tsou et al. (2009) both consider how item quality impacts how suppliers' imperfect item disposal policies impact inventory policies in the presence of item quality differences. The consistent focus on rework and/or discounted disposal of imperfect quality items within these models reflects a singular focus on avoiding materials waste in order to minimize total costs within manufacturing environments. Modern manufacturing environments, however, feature more specialized and costly labor inputs relative to traditional production line-based factories. The combination of items which are smaller and more difficult to repair with more expensive labor inputs makes rework increasingly infeasible for modern suppliers. Discounted disposal of products requiring rework is infeasible given that such products are unlikely to be in demand in sufficient quantities. For example, circuit boards or sterile medical supplies are of little use once they failed. The elimination of rework and discounted disposal in our model, therefore, better reflects the realities of contemporary manufacturing environments.

Sher and Kim (2015) previously considered optimal order policies for items which experience complete probabilistic failure and which cannot be reworked or scrapped in the context of a single buyer. In modern production and distribution environments, however, companies are primarily concerned with the optimization of entire supply chains. Our paper extends Sher and Kim (2015) in several ways. First, we consider the supplier's inventory problem and develop a model and obtain optimal production policies for similar items. We then derive a supply chain coordination mechanism which incorporates optimal inventory policies for a supplier and n buyers. We further derive the Hessian matrix for our coordination mechanism and prove its convexity, thereby demonstrating that our solution represents a global minimum for total system-wide costs. Our result is of significant practical importance to both suppliers and buyers in that it supports a centralized (i.e. coordinated) approach to supply chain coordination. Achieving system-wide minimum costs through our proposed framework not only benefits suppliers through reduced manufacturing costs, but also provides buyers with the opportunity to reduce their total costs below what is achievable under the decentralized (i.e. uncoordinated) approach through the distribution of cost savings achieved through centralized coordination of replenishment times.

Optimal inventory policies inform efforts to coordinate supply chains by providing the preferred inventory levels for both buyers and suppliers (Zimmer 2002; Arshinder and Deshmukh 2008). Relevant papers in the literature demonstrate how centralized approaches to optimizing inventory policies can result in system-wide cost minimization. Banerjee (1986) derives a model through which supply chain costs can be minimized in a mutually beneficial manner through the joint determination of lot sizing. Hill and Omar (2006) similarly rely on an integrated production-inventory model for a supply chain featuring a single supplier and a single buyer. Modak et al. (2015; 2016) highlight the role of centralization in optimizing multi-channel, multi-echelon, single-item supply chains. Sana (2011) models a three-echelon supply chain featuring a single supplier, manufacturer, and retailer and imperfect quality items. Pal et al. (2012) coordinate a supply chain for imperfect items subject to rework consisting of two suppliers and a single buyer and retailer. Lo et al. (2007) develops a single manufacturer, single retailer supply chain for with imperfect production processes and time-dependent deteriorating item quality. Ghiami and Williams (2015) model a single supplier, multiple buyer supply chain for deteriorating items with finite production rate. While prior literature considers supply chain coordination for imperfect quality items, our model consider items which are delivered in perfect condition but which fail completely rather than being subject to time-dependent deterioration. The prevalence of such items in several important industries, coupled with the prospect for such items becoming more ubiquitous as repair costs rise and production costs lower in line with more efficient processes, highlights the practical importance of our model.

The remainder of this paper is organized as follows. The assumptions and notation used to describe our model are given in Section 2, while our EPQ model is developed and optimized in Section 3. Our supply chain coordination mechanism is developed in Section 4, with related numerical examples used to analyze the model in Section 5. Section 6 highlights the main contributions of our proposed model and associated implications for managers.

2. Assumptions and notation

The following assumptions are used in the development of our model:

1. Demand rate, setup/order costs, and inventory holding costs are known and deterministic.
2. Production of items is continuous and at a constant rate during the production run.
3. Inventory is accumulated during the production period, with maximum inventory levels achieved at the end of the production period.
4. A 100% screening is performed when the lot is delivered to separate the defective items.
5. Defective items are replaced at manufacturer's cost.
6. Lots are comprised of items with a failure rate with known probability density function.
7. Items which fail are not subject to rework.