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# Analysis of a two-party supply chain with random disruptions

F. Zeynep Sargut [a], Lian Qi [b,*]

[a] Department of Industrial Systems Engineering, Izmir University of Economics, Balçova, Izmir, Turkey

[b] Department of Supply Chain Management & Marketing Sciences, Rutgers Business School, Rutgers University, Newark, NJ 07102, USA

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ABSTRACT

We study a continuous-review inventory problem of a two-echelon supply chain with random disruptions, identify properties of the optimal cost function, compare the optimal order quantity with the classical economic order quantity, analyze the sensitivity of the optimal solution, and explore the conditions under which zero-inventory ordering policy is preferred.

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## 1. Introduction

We model an inventory problem of a supplier and a retailer that are subject to random disruptions. The retailer orders a single product from the supplier to fulfill the customer demand, which follows a constant arrival rate over time. If the supplier or retailer is disrupted, caused by events such as the web server internal errors, storms, strikes, and workforce reduction, it will go through a recovery period. Customers arriving at the retailer during its recovery period cannot be served and the potential sales will be lost. Similarly, if the retailer orders during the recovery period of the supplier, the order will not be taken. We consider a continuous-review inventory system with Zero-Inventory Ordering (ZIO) policy. We also explore conditions under which ZIO is a better policy than a basic order-up-to level type policy with a positive reorder point.

Our research is motivated by some recent reports. Kindergan et al. [7] depicts the impacts of winter storms in early 2010 that affected Mid-Atlantic and Northeastern regions of the United States. During these storms, many malls and grocery stores shut down but still had inventory expenses to keep the on-hand preserved stocks, such as clothing, electronics, and furniture. In addition, since storms caused power outages and road closures, many stores could not receive their supplies on time.

Supply chain risk management and mitigation strategies have been systematically investigated by several researchers (see, e.g., [8]). This paper is mainly focused on mitigating the disruptions by adjusting the order quantity of the retailer.

We model availabilities of both supplier and retailer using alternating renewal processes, in which the service and recovery periods follow one after another (see, e.g., [2,10,13]). We construct the average annual cost of the retailer utilizing the renewal reward theorem, and aim to identify the optimal order quantity of the retailer. In addition, we compare the optimal order quantity with the classical Economic Order Quantity (EOQ). We also prove some monotonicity and convexity properties of the optimal cost function and order quantity. These results show the great tractability of our cost function and model.

Inventory management with supply uncertainties has been studied by a few researchers. Parlar and Berkin [10] examine an EOQ type inventory model with supply disruptions, ZIO policy and zero lead time. The cost function is corrected and the properties of the cost function is derived in [2]. Weiss and Rose [19] consider an extended EOQ model in which supply (or demand) is interrupted by an event at a known future time and lasts for a random period. Recently, Qi et al. [13] model a continuous-review inventory problem with random supplier and retailer disruptions. The ZIO assumption is relaxed in [11].

Bielecki and Kumar [3] consider the optimality of zero-inventory policies for unreliable manufacturing systems, and identify the optimal production policy with a threshold value. The production is at the maximum rate if the inventory level is less than the threshold value, and is not required for the inventory levels over the threshold value, and otherwise is at the demand rate. The conditions under which optimal threshold value is zero is given. We identify the optimal order level whereas in [3], the optimal threshold value is determined. Moreover, we consider disruptions at the other party that result in delays in the order arrivals.

Some research works also incorporate stochastic demand. Chao [4] formulates a dynamic inventory management model

* Corresponding author.
*E-mail address:* lianqi@business.rutgers.edu (L. Qi).

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based on a continuous-time Markov decision process. Parlar et al. [12], and Song and Zipkin [17] study periodic-review inventory problems with uncertain supply and identify the structures of the corresponding optimal policies. Nurani et al. [9] considers a failure-prone manufacturing system with Poisson demand and a probability of producing defective items. The research states the conditions under which ZIO is optimal.

For problems with multiple suppliers involved, Ramasesh et al. [15] compare sole- and dual-sourcing strategies under $(Q, r)$ policies with uncertain lead times. Anupindi and Akella [1] derive the optimal ordering policy for the supply process between a buyer and two unreliable suppliers. Gürler and Parlar [6] use a $(Q, r)$ model to analyze a problem with two randomly available suppliers. Tomlin [18] proposes a dual-sourcing model, with a cheap but unreliable supplier and a reliable but expensive supplier. Federgruen and Yang [5] study multiple-sourcing in newsvendor settings.

Interested readers may refer to [13,14] for comprehensive surveys of supply chain management problems with supply uncertainties.

Different from the above works (considering one echelon supply uncertainties only), except [13], we consider disruptions at multiple echelons, at both the supplier and the retailer. As pointed out by Qi et al. [13], disruptions at a lower echelon have more significant impacts on the supply chain performance than those at a higher echelon.

In [13] on-hand inventory of the retailer is assumed to be destroyed upon any disruptions at the retailer, whereas in our case the disruptions at the retailer result in lost sales. We believe that this is a more realistic assumption, since most common disruptions at the retailers such as power outages, storms, strikes, and errors in management information systems do not really destroy any stock. When the North Jersey area was hit by a winter storm in early 2010, many shopping malls and groceries were closed temporarily. However, most items in the stores were well kept and could be sold after the storm (see [7]).

In addition, our problem can also be interpreted as a problem that considers random disruptions at the retailer and stochastic lead-times at the supplier, which depend on the availabilities of both the supplier and the retailer.

The rest of this paper is organized as follows. In Section 2, we formulate our model. We explain the analytical results and the managerial insights derived from the computational study in Section 3. We give future research directions in Section 4.

## 2. Two-party supply chain with random disruptions

### 2.1. Assumptions

The demand at the retailer is assumed as deterministic and constant. After a disruption event, the retailer (or the supplier) will go through a *recovery period* before becoming available again (going back to the *service period*). Therefore, the service (ON) and recovery (OFF) periods follow one after another at both the supplier and the retailer (refer to Fig. 1). The durations of the ON and OFF periods at the supplier and the retailer are both independently and exponentially distributed. We believe that the exponential distribution assumption is reasonable in this context, as argued in [11,13].

When the retailer is disrupted, it becomes unavailable (but still keep its on-hand inventory) and cannot serve its customers or receive replenishment from the supplier during the recovery period. We assume that the unserved customer demand is lost. If the retailer places an order during the supplier's recovery period, this order will not be filled until the supplier recovers from its disruption. Hence, the retailer may not have inventory on hand to serve its customers even when it is available itself, because the shipments from the supplier might be delayed due to supplier disruptions. We assume the delivery lead time at the retailer is zero.

We further define a *retailer cycle* to be the time period between two consecutive order arrivals at the retailer. In Fig. 1, we depict two full retailer cycles. In the first retailer cycle, at time $A$, the retailer observes a disruption event. Therefore, customers cannot be served until the OFF period at the retailer ends (indicated by the constant inventory level during the OFF period). At time $B$, the supplier is disrupted. Afterward, the inventory level at the retailer hits zero, so it places an order to the supplier. However, since the supplier is still OFF. The supplier recovers at time $D$, but the retailer is disrupted again before that, at time $C$, and has not recovered yet. Retailer has to wait until time $E$, when both the retailer and the supplier are ON, to complete the delivery to the retailer.

However, during the second retailer cycle, the retailer orders at time $H$, when its inventory level reaches zero, and receives the shipment instantaneously.

### 2.2. Model formulation

We apply the renewal reward theorem to formulate the long run average cost function at the retailer. We denote the annual rate of customer demand at the retailer by $D$. The rate of disruption at the retailer is denoted by $\alpha$ and the rate of recovery at the retailer is denoted by $\beta$. $\lambda$ is the rate of disruption at the supplier, whereas $\varphi$ is the rate of recovery at the supplier. We define $h$ as the unit annual inventory holding cost at the retailer, $c$ as the unit ordering cost at the retailer, $F$ as the fixed ordering cost at the retailer, and $\pi$ as the unit lost sale cost at the retailer, such that $\pi > c$. We define $S$, the vulnerability of the retailer as $\frac{\alpha}{\beta}$ and $S2$, the vulnerability of the supplier as $\frac{\lambda}{\varphi}$.

We define the following random variables to calculate the expected annual cost at the retailer.

- $T$: the length of the retailer cycle
- $m$: the number of times the retailer is disrupted during a retailer cycle
- $R_i$: the length of the $i$th recovery period at the retailer
- $w$: the retailer's waiting time to receive its order if the supplier is OFF
- $C$: the total cost incurred during a retailer cycle.

Our decision variable is the order quantity of the retailer, $Q$. We derive the expected retailer cycle length and cost and then formulate the expected annual cost at the retailer based on the renewal reward theorem.

#### 2.2.1. The expected retailer cycle length

The retailer cycle length $T$ is composed of $t_1$, $t_2$, and $t_3$.

- $t_1$: the total length of ON periods at the retailer during a retailer cycle before its inventory level reaches zero,
- $t_2$: the total length of OFF periods at the retailer during a retailer cycle before its inventory level reaches zero,
- $t_3$: the retailer's waiting time for its placed order, during which the retailer does not have any inventory on hand.

We are now ready to derive the expected retailer cycle length, $E[T]$, with the following two propositions.

**Proposition 2.1.** *$m$ follows the Poisson distribution with rate $\alpha$ and $E[m] = \alpha t_1$.*

**Proof.** Since retailer disruptions only happen when the retailer is ON, we construct a Poisson process for retailer disruptions happening during $t_1$ and the time between two consecutive disruptions are exponentially distributed with rate $\alpha$. This conclusion follows from this constructed Poisson process. □

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