

Effectiveness of policies for mitigating supply disruptions

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Structured Abstract:

Purpose - The purpose of this paper is to examine *supply*-side disruptions in a supply chain, and to analyse the effectiveness of two inventory-based policies for mitigating the impact of supply disruptions: maintaining strategic inventory reserves (the *R*-policy), and using larger orders (the *Q*-policy).

Design/methodology/approach- We assess the effectiveness of two inventory-based mitigating policies implemented at a reseller when end customer demand is stable but supply can be disrupted. An analytical model is provided, and numerical experiments are conducted to evaluate the effectiveness of the policies for mitigating the impact of disruption under different disruption scenarios.

Findings - Results indicate that the *R*-policy performs consistently better than the *Q*-policy in terms of product availability measures, as tested under a wide range of frequency and duration of supply disruptions.

Practical implications – Supply chain trends of lean operations and global sourcing have exposed business organizations to a greater risk and have further raised the need to protect businesses against random supply disruptions.

Originality/value - The paper intends to contribute to the narrowing of the gap in the research of supply-side disruptions. Further, the topic of inventory reserves has been discussed to date in only a very general sense; the paper proposes conditions for practical implementation and provides unique insights into the effectiveness of the use of strategic inventory reserves as a supply disruption mitigation policy.

Keywords:

Supply chain risk management (SCRM), supply disruptions, mitigation policies, simulation, inventory reserves

Article Classification:

Research paper

1. Introduction

For over a decade, we have witnessed dramatic increases in speed, quantity, and complexity of global business transactions. Factors that contributed to these changes are many, and include the revolutionary advancement of information technology (IT) and the gradual realization that collaboration is essential for the long-term sustainability of businesses operating in supply chains. However, under this fast-paced global business setting where responsiveness and coordination among partners are emphasized more than ever, supply chains have become more susceptible to unpredictable events that could lead to supply disruptions and undermine performance. Disruptive events in the supply chain are not only increasing in frequency, but their impact can be costly and can potentially bring portions of the supply chain to a complete halt (Handfield, Blackhurst, Craighead, and Elkins, 2011). Some sources of supply chain disruptions include natural disasters, stricter border security, plant shutdowns, port lockouts, political and labour unrest, IT system failure, industrial accidents, and global economic recession among others (Snyder and Shen, 2006). These events may have a low probability of occurring individually; however, collectively, the probability of occurrence and long-term impact could be quite significant as we have observed in recent events such as plant fires and port lockouts. Without appropriate strategies in place to fundamentally deal with these risks, companies could become vulnerable to even a minor disruption occurring halfway around the world (Chopra and Sodhi, 2004; Sheffi, 2005). Naturally, developing robust supply chains to withstand the negative impact of supply disruptions has become a mandate in businesses today.

Despite the realization of the significance of supply chain risk management (SCRM), the study of supply disruptions and business continuity has only recently gained major attention both in practice and academic research. Two prevailing supply chain trends escalate business awareness of the importance of SCRM in general, and supply disruptions in particular: (i) global sourcing and (ii) lean operations. The common practice of global outsourcing or low cost country sourcing (LCCS) makes individual stakeholders within supply chains increasingly dependent on their business partners located overseas. As organizations source a greater proportion of manufactured products from low-cost countries, they often do not consider the hidden perils of these approaches, especially within the context of SCRM. While benefits of global sourcing are clear, there are also risks associated with the practice (Handfield, 2007). Not only is a business only as strong as the weakest link in its supply chain, but it is also susceptible to disruptions occurring anywhere in the system, as evidenced by the global economic crisis that followed the slowdown of businesses in the US and in China. Another major supply chain trend that raised attention on SCRM is the worldwide use of lean operations that have become a staple in global business practice with many industries using inventory turnover as the main key performance indicator (KPI) as mentioned in the “State of Logistics: The Canadian Report 2008” (Industry Canada, 2008). Generally, lean operations

aiming for higher inventory turnovers are ideal for settings with low levels of uncertainty within the supply chain. While demand-side uncertainty problems are often resolved by keeping safety stock or by increasing capabilities to quickly respond to unexpected events or demographic changes in the market, such measures do not provide sufficient protection for business from the long-term debilitating impact resulting from *supply*-side disruptions.

Our paper will address the significance of supply chain risk management (SCRM) in a setting where demand is steady but supply is subject to random disruptive events. We focus on the impact that supply disruptions have on supply chain performance by proposing two policies for mitigating this impact - using strategic inventory reserves and ordering in larger lots - and assessing their effectiveness through supply chain model analysis and numerical experiments. A regular EOQ-based policy (without the use of any mitigating policies) is used as the base case for our study. In particular, we intend to address the following research questions:

- How effective are the two inventory-based policies – strategic inventory reserves versus larger orders - in mitigating the impact of supply disruptions?
- How do the disruption frequency and the length of disruption, independently and in combination, affect the effectiveness of the policies?
- What are the settings under which the use of strategic inventory reserves in a supply chain would be appropriate as a mitigating policy, where the reserve inventory would be used only in the case of a supply disruption?

The primary contributions of this research are that we assess the effectiveness of two inventory-based mitigating policies through extensive simulation experiments in terms of product availability measures under different scenarios of disruption frequencies and recovery rates, and study the relevance of using strategic inventory reserves under supply disruptions (a concept only previously discussed in general terms, to our knowledge). This research can initiate investigation into other alternative policies to mitigate supply disruption impact and stimulate discussion on the practical use of strategic inventory reserves. Further, our study adds theoretical value by applying an analytical approach of incorporating the operating characteristics of a capacitated queuing system to model random supply disruption durations and frequency.

The remainder of the paper is organized as follows. The next section reviews relevant studies on supply chain risk management and supply disruptions. Following this, we develop analytical models for the inventory-based policies for mitigating supply-side disruptions. In section four, we present and

discuss numerical results from simulation experiments, followed by a discussion of the managerial implications in section five. Finally, conclusions, limitations, and future research directions are presented.

2. Literature review

Existing research on supply disruptions is mainly conducted within the context of SCRM (Chopra and Sodhi, 2004; Tang and Tomlin, 2008). Therefore, we begin our literature review of supply disruptions with a review of research in SCRM, which encompasses a wide scope of research streams. SCRM can be defined as the identification and management of risks through coordination among partners within the supply chain to reduce supply chain vulnerability (Juttner, Peck, and Christopher, 2003). Norrman and Lindroth (2002) further define SCRM as a process where supply chain partners apply risk management tools collaboratively to manage and mitigate risks caused by logistics-related activities. Tang (2006a) provides a comprehensive review on perspectives of SCRM, and addresses the SCRM issues along two dimensions: *supply chain risk* and *mitigation approach*. Ritchie and Brindley (2007) construct an overall SCRM framework with focus towards risk management influencers, and demonstrate the need to develop a set of tools and approaches to address the diversity of issues in SCRM. While the supply chain risks that companies face at both operational and strategic levels appear to be unavoidable and unpredictable, Christopher and Lee (2004) indicate that a supply chain with a high level of risk cannot be efficient.

Worth noting amongst recent empirical research on SCRM and supply disruptions is a study by Kern, Moser, Hartmann, and Moder (2012) which focuses on the process dimensions of upstream SCRM and shows that competent SCRM (including risk identification, assessment, and mitigation) in companies leads to superior performance. Papadakis (2006) investigates vulnerability of supply chains empirically by analyzing and comparing stock performance of firms with make-to-order (MTO) and make-to-forecast (MTF) models facing supply disruptions. While certain empirical results on supply disruptions and associated risk can be industry specific, as in Kilian (2008) and Sodhi and Lee (2007). Wagner and Bode (2006) reveal in a comprehensive study of German companies that supply chain characteristics such as the reliance on specific customers, the degree of single sourcing, and dependence on global sourcing are all relevant for a company's exposure to supply chain risk. Hendricks and Singhal (2005), in an extensive empirical study, report that supply chain disruptions can lead to a company's long-term negative financial performance, especially in terms of shareholder wealth and stock returns when compared to an industry benchmark. Anecdotal business examples are abundant over the last 15 years to support their findings. As an example, Ericsson was slow to react to a supply disruption caused by its supplier's semiconductor plant fire in 2000, losing 400 million Euros in sales (Hopkins, 2005). Similarly, during a supply shortage of computer components resulting from a major earthquake in Taiwan in 1999, Dell and Apple responded

with different pricing strategies, which led to a setback for Apple while improving Dell's earnings by more than 40% over the period of supply crisis (Martha and Subbaprishna, 2002).

Traditionally, studies of supply chain disruptions approach the issue from either demand-side uncertainty or supply-side disruptions. Literature on demand-side uncertainty is vast with decades of classical inventory management research discussing optimal ways to manage an organization's inventory under different settings. Some of the earlier works in the inventory management literature include Minner (2003), Lariviere and Porteus (2001), Corbett and DeGroot (2000), Scheller-Wolf and Tayur (1999), Moynzadeh and Nahmias (1988), and Eppen (1979). Research on supply-side disruptions includes studies of EOQ-based inventory models when suppliers are not reliable and replenishment lead time is instantaneous. These works describe disruptions with on-off periods that follow random distributions with multiple supply sources (Gürler and Parlar, 1997; Parlar and Perry, 1996) as well as with a single supply source (Berk and Arreola-Risa, 1994; Parlar, 1997; Parlar and Berkin, 1991; Snyder and Tomlin, 2008; Weiss and Rosenthal, 1992;). In particular, Parlar and Berkin (1991) model the random supply disruptions with exponentially distributed on and off periods with a constant demand in determining order quantity. That is, the supply, under an EOQ ordering policy, is available over a random interval of length X prior to a disruptive event, and the unavailability of supply lasts for a random duration Y . Our paper is similar to that of Parlar and Berkin (1991) in its basic model setting. The focus of our research, however, is primarily on the assessment of the performance of mitigating policies under various disruption scenarios (defined in terms of disruption frequencies and recovery rates).

More recently, Snyder and Shen (2006) conduct a comprehensive discussion of the relationship between demand-side uncertainty and supply-side disruptions in an unpublished working paper, and demonstrate that the optimal strategies differ under the two types of uncertainty. The paper further shows that the cost of failing to prepare for supply disruptions is greater than that of failing to plan for demand uncertainty. While demand-side uncertainties and measures to counter them have been extensively studied and implemented for years with success, especially with the advancement of information technology and reliable logistics, studies on supply-side disruptions are relatively limited in scope and depth, thus warranting increased attention.

Among papers that study mitigating policies to address potential supply disruptions, Schmitt (2011) analytically models supply disruptions in a multi-echelon supply chain, and numerically demonstrates the effectiveness of combining inventory placement and back-up methods, where the greatest improvement in service level can be achieved by inventory placement to cover short disruptions and back-up methods to help the supply chain recover from long disruptions. In similar streams of research, a range of different supply chain strategies are proposed to mitigate disruption impact, including the use of advance warning of disruptions (Snyder and Tomlin, 2008), strategic inventory (Schmitt, 2011),

contracting and supplier diversification (Babich, Burnetas, and Ritchken, 2007), and dual sourcing and mix-flexibility (Tomlin, 2006; Tomlin and Wang, 2005). Stecke and Kumar (2009) confirm the speculation that both the number of supply disruptions and the size of economic losses are increasing at a fast rate. Based on a statistical study of a vast data set, they propose strategies that can be implemented to decrease the possibility of a disruption, provide advance warning, and cope after a disturbance. Further, at a macro level, Tang (2006a), Sheffi (2005, 2001), Lee (2004), and Rice and Caniato (2003) discuss strategies to design fundamentally resilient supply chains. Others propose different methodologies to show how supply chain resilience could be achieved, such as via multi-agent based modeling (Thadakamalla, Raghavan, Kumara, and Albert, 2004; Swaminathan, Smith, and Sadeh, 1998), supply network modeling (Barabasi, 2009; Barabasi and Bonabeau, 2003; Choi, Dooley, and Rungtusanatham, 2001), and case studies (Allen, Datta, and Christopher, 2006; Apte 2011; Norrman and Jansson, 2004).

The use of strategic inventory reserves we examine in this paper has been proposed in general terms by Chopra and Sodhi (2004) and Sheffi (2001) as a potential means to mitigate the impact of supply disruption. These works point out that strategic inventory reserves should be distinguished from the safety stock that is held to protect against demand-side uncertainty, and would not be used to prevent stockouts during “normal times”. In other words, reserve inventory could be viewed as a measure to cover the front-end of a supply disruption and provide protection until other measures can be implemented (Schmitt, 2011). In this paper, we propose some practical business conditions that would justify the use of reserve inventory as well as demonstrate its’ effectiveness as an inventory-based disruption mitigating policy.

3. Modeling supply disruptions

Typically, supply chain risk can be characterized by both the probability of an event and its severity given that an event occurs (Handfield et al., 2011). We consider a reseller in a supply chain who fills stable and known end customer demand from inventory, which in turn is replenished by orders with an upstream supplier. We assume that supply-side disruptions may occur at any point in time according to a Poisson distribution with an average frequency of λ (per year). Once a supply disruption occurs, the availability of upstream inventory to replenish reseller inventory ceases temporarily (for the duration of the disruption); however, demand can continue to be met from inventory until it is exhausted. Depending on the length of the disruption and on-hand inventory at the time of the beginning of a disruption, the reseller could very likely experience stockouts. The recovery process will be under way as soon as a disruption begins, and subsequent restoration to the normal state of operations will be completed on average in $1/\mu$ time units (years) according to an exponential distribution. Ordering and shipment from the supplier resumes as soon as normal state is restored.

We consider a base case using an economic order quantity, whereby risk of supply disruption is passively accepted by the reseller without any mitigating policies. We then propose two inventory-based policies to mitigate supply disruptions: the placement of orders of larger size, Q (hereafter referred to as the Q -policy) and the use of strategic inventory reserves, R (referred to as the R -policy). The use of extra inventory via placing large order quantities (Gurler and Parlar 1997) and strategic reserves (Chopra and Sodhi 2004; Schmitt 2011; Sheffi 2001; Tomlin 2006;) has been discussed in research as possible mechanisms to mitigate supply disruptions, although the latter only in general terms. We intend to investigate in detail the effectiveness of these mitigating policies through supply chain modeling and simulation experiments.

Notations to be used for the models presented in this paper are as follows:

Notations:

D :	annual demand rate
i :	annual holding cost rate per unit
C :	unit cost of an item
S :	fixed ordering cost
π_L :	lost sales cost per unit
q :	economic order quantity (EOQ)
Q :	a larger order size, where $Q = q + X$
R :	quantity of strategic inventory reserves
λ :	average disruption rate per year ($\therefore 1/\lambda$ is the mean time between disruptions)
μ :	average recovery rate to the normal state ($\therefore 1/\mu$ is the mean span of disruption)
T_1 :	order interval when EOQ(q) is implemented
T_2 :	order interval when larger lot size (Q) is used

Note that, due to the nature of “arrivals” of disruptions, the starting point of a disruption within a replenishment order interval at the retailer (given that a disruption occurs during the order interval) is uniformly distributed between $(0, T)$ where T is the length of a natural order cycle.

We now examine three models - the base case (EOQ policy), the Q -policy, and the R -policy.

3.1 Base case - EOQ implementation

In the base case, we consider an EOQ ordering policy - a natural choice for ordering with steady and known demand. The supply disruption process considered here can be approximated by a single server capacitated queuing system, $M/M/1/K$, where the system capacity K is 1, implying that restoration efforts

are concentrated to fully recover from a disruptive state to a normal state. For practical purposes, any major and concurrently occurring minor disruptions could be considered as one disruptive incident. Operating characteristics for $M/M/1/K$ system are illustrated in Gross and Harris (1985) based on (i) the frequency of disruption and (ii) the rate of recovery to the normal state. Setting the system capacity, K to 1, we obtain state probabilities p_0 (no disruption) and p_1 (disruption) as

$$p_0 = \frac{1 - \rho}{1 - \rho^2} = \frac{\mu}{\lambda + \mu} \quad (1)$$

$$p_1 = \frac{(1 - \rho)\rho}{1 - \rho^2} = \frac{\lambda}{\lambda + \mu} \quad (2)$$

Note that $\rho = \lambda/\mu$ for this finite capacity queuing system. Also, by definition, $\sum_{n=0}^1 p_n = p_0 + p_1 = 1$.

The inventory path for this base case is displayed in Figure 1. A typical “disruption cycle” starts after a restoration to a normal state from a disruptive event (i.e., a regeneration point), followed by a duration of normal operations (average length of $1/\lambda$), a disruptive event, and a recovery process (average length of $1/\mu$) that returns operations to the normal state. Thus, the average length of a typical period which consists of a disruption state and a recovery state is $(\lambda + \mu)/(\lambda\mu)$. Applying these results, we express the expected total cost of EOQ ordering with supply disruption, where unfilled demand is treated as lost sales, as in (3).

$$TC_q = \left[\left(\frac{2 + \lambda T_1}{2\lambda T_1} \right) \cdot \left(\frac{1}{2} q \cdot T_1 \cdot i \cdot C + S \right) + \left(\frac{1}{\mu} - \frac{T_1}{2} \right) \cdot D\pi_L \right] \cdot \left(\frac{\lambda\mu}{\lambda + \mu} \right) \quad (3)$$

(Insert Figure 1 about here)

We assume that the expected demand during a disruption is greater than the average on-hand inventory (i.e., average disruption duration is greater than half of the order interval), to allow for stockout situations during supply disruption; that is, $\frac{1}{\mu} > \frac{T_1}{2}$.

3.2 Mitigating policy 1: Q -policy

As an alternative to the base case, we consider ordering a larger lot size to mitigate the impact of a possible supply disruption. Placing an order quantity (Q) that is larger than the EOQ under a steady and known demand naturally leads to a longer order cycle, which in turn results in higher on-hand inventory at the time of a disruption and thus shorter periods of stockouts, on average, as displayed in Figure 2.

(Insert Figure 2 about here)

Applying steps as in the base case, we determine the expected total costs for the Q -policy as:

$$TC_Q = \left[\left(\frac{2 + \lambda T_2}{2\lambda T_2} \right) \cdot \left(\frac{1}{2} Q \cdot T_2 \cdot i \cdot C + S \right) + \left(\frac{1}{\mu} - \frac{T_2}{2} \right) \cdot D \pi_L \right] \cdot \left(\frac{\lambda \mu}{\lambda + \mu} \right) \quad (4)$$

The convexity of the expected total cost function TC_Q in (4) is shown in the Appendix A. Taking the first derivative of TC_Q with respect to Q , we determine that the optimal order quantity Q^* (where $Q^* > q$) is the value of Q that satisfies the following condition:

$$(\lambda \cdot i \cdot C) \cdot Q^3 + (D \cdot i \cdot C - \lambda \cdot D \cdot \pi_L) \cdot Q^2 = 2D^2 S \quad (5)$$

Theoretically, the larger lot size (Q) is unrestricted and could take on any values greater than the EOQ (or q). However, we set the upper bound for Q (or Q^U) as $Q < \frac{2D}{\mu}$ based on the condition $\frac{1}{\mu} > \frac{T_2}{2}$, as described earlier with the base case.

3.3 Mitigating policy 2: R -policy

Based on the definitions of the term used by Chopra and Sodhi (2004), Schmitt (2011), and Sheffi (2001), reserve inventory is not expected to be accessed during “normal” stockout situations resulting from

demand-side uncertainties. Thus, we propose that inventory reserves be held in a physical location different from regular inventory (and with a lower holding cost rate, as described below), and that a fixed cost (also described below) be incurred to access the reserves during disruptive events; otherwise, it would be impractical not to use reserve inventory in other situations, supply disruption or not, to prevent stockouts.

There are evidences to support different holding cost rate for reserve inventory. Lambert and Mentzer (1982) include variable storage costs as a component of inventory holding costs. Buttimer, Rutherford, and Witten (1997) show that location, market conditions, and physical building characteristics affect warehouse rent to the degree that square foot rental rates in one part of their area of the study were more than double those in another. Further, Mueller and Mueller (2007) discuss that demand for warehouse space is affected by the “path of goods movement”, which would allow for an opportunity to use less expensive warehouse space that is off of this path for storing reserve inventory. In this paper, we propose that reserve inventory be maintained at a centralized location with low warehouse rent and high storage density, which could be shared by a number of users. Thus, we use an annual holding cost rate of i_R for maintaining strategic reserves during non-disruptive time periods where $i_R \leq i$ (i.e., the annual holding cost rate for reserve inventory would be less than that for regular inventory).

We also use a one-time fixed cost, S_R , associated with accessing reserves. This cost could include payment to a third-party storage provider for access (e.g., to cover labour), fixed transportation costs to relocate the inventory reserves, and a fixed cost for subsequent replenishment of reserves at the end of the disruption.

A regular EOQ replenishment policy based on demand stability is used for normal non-disruptive periods while maintaining inventory reserves to prepare for the possibility of disruption. Once disruption occurs and the period of disruption extends long enough to generate stockouts, retailer inventory will be replenished from the inventory reserves to lengthen the in-stock period. An inventory profile for the strategic reserve case is displayed in Figure 3, and the expected total relevant cost over time for the R -policy is written as:

$$TC_R = \left[\left(\frac{2 + \lambda T_1}{2\lambda T_1} \right) \left(\frac{1}{2} q T_i i C + S \right) + \left(\frac{2 + \lambda T_1}{2\lambda} + \frac{R}{2D} \right) R i_R C + S_R + \left(\frac{1}{\mu} - \frac{q}{2D} - \frac{R}{D} \right) \pi_L D \right] \cdot \left(\frac{\lambda \mu}{\lambda + \mu} \right) \quad (6)$$

(Insert Figure 3 about here)

The proof of convexity of TC_R in (6) is straightforward and is shown in the Appendix B. Accordingly, we obtain the optimal values for the strategic reserves, R^* , as follows:

$$R^* = D \cdot \left[\frac{\pi_L}{i_R \cdot C} - \left(\frac{1}{\lambda} + \frac{T_1}{2} \right) \right] \quad (7)$$

The result suggests maintaining a strategic inventory level (R) as determined by the difference between “the quantity to balance the cost ratio $\pi_L/(i_R \cdot C)$ ” and “the average demand over regular stock usage time”.

The size of reserve inventory, R , is unrestricted; however, we set the upper bound for R (or R^U) as $R^U = D \cdot \left(\frac{1}{\mu} - \frac{T_1}{2} \right)$ based on the condition that $\frac{1}{\mu} - \frac{T_1}{2} - \frac{R}{D} > 0$ to allow for the assumption that stockouts tend to occur during a disruption period.

4. Numerical experiments and results

4.1 Simulation model

We develop a discrete-event simulation model for the inventory and replenishment system described above in order to study the performance of the two inventory-based policies for mitigating disruption impact. The simulation is run under varying disruption frequency and duration. The model is developed using Visual Basic for Applications (VBA) programming for managing iterations and tabulating results.

We assume that end demand is deterministic and is met from inventory, which is replenished by supply from upstream. The primary source of uncertainties arises from random disruption frequencies and durations, which allows us to isolate the impact of supply-side disruption. When a supply disruption occurs, end demand is filled from inventory; however, inventory cannot be replenished by way of ordering from upstream in the supply chain. Once remaining inventory or inventory reserves (if applicable) are exhausted during a disruption period, stockouts are considered lost sales. At the end of a disruption, inventory and inventory reserves (if applicable) are replenished. Replenishment of inventory is instantaneous, and in the event of a disruption, any lead time considerations related to replenishment at the end of the disruption can simply be modeled as part of the disruption recovery rate. Our treatment of replenishment under supply uncertainty in our simulation experiments bears similar characteristics to Qi, Shen, and Snyder (2010).

In the base case, an EOQ policy is simulated with passive acceptance of disruptive events with no additional protection for possible disruptions. We then compare the performance of the base case, under simulated disruptions, to the performance of disruption mitigating policies (the Q -policy and the R -policy). Since the long run average total cost is parameter-specific (i.e., it is contingent on different sets

of demand and cost parameters used for numerical experiments), cost considerations will be discussed only in terms of general relations between cost parameters and the relative cost efficiencies of the mitigating policies. Numerical experiments mainly focus on the impact the two mitigating policies have on the performance related to product availability (i.e., fill rates and the percent of disruption cycles without stockouts) as we vary the disruption frequency (λ) and recovery rate (μ). It should be noted that the results in terms of stockouts are not affected by the choice of cost and demand parameters; in other words, it is disruption frequency and recovery rate that affects product availability performance. We experiment with a sufficiently wide range of values for the disruption frequency (λ) and recovery rate (μ) to investigate the dynamics and effectiveness of mitigating policies.

4.2 Parameters for simulation experiments

We fix the following parameters for the exposition of our simulation experiments for the base case, the Q -policy, and the R -policy:

$$D = 625 \text{ units}$$

$$S = \$500/\text{order}$$

$$S_R = \$1,000/\text{usage of reserves}$$

$$i = 0.25/\text{unit/year}$$

$$i_R = 0.20/\text{unit/year}$$

$$C = \$800/\text{unit}$$

$$\pi_L = \$1,000/\text{unit}$$

$$\text{Order quantity in the base case} = \text{EOQ} = 56 \text{ units}$$

In addition, we use the following values for the disruption frequency (λ) and the recovery rate (μ) in terms of occurrences per year for each of the three policies we simulate, resulting in 468 ($= 3 * 3 * 52$) scenarios:

$$\lambda = 1, 4, 12$$

$$\mu = 2, 4, \dots, 104$$

Simulation runs are initialized as being in a state of no disruption, and for each combination of parameters, we simulate 65,000 consecutive demand instances (with the initial 5,000 being treated as a warm-up period) and perform 300 replications to obtain long-run average values for fill rates, percent of disruption cycles without stockouts, average on hand inventory, and inventory related costs.

For the sake of understanding the dynamics of the two mitigating policies relative to each other, we set the average amount of inventory to be equal for the two policies so as to conduct unbiased numerical experiments. Specifically, for the Q -policy, we set the order quantity Q by increasing the EOQ by 60 units (i.e., $X=60$); while for the R -policy, in which reserves are only to be used in the case of disruption, the order quantity will equal the EOQ and the amount of reserves held will equal 30 units (i.e., $X/2=30$). Results are consistent for other combinations of Q and R values (with equal average on-hand inventory). Note, again, that the expected frequency and duration of disruptions (as determined by λ and μ) will be varied so that the comparisons of results of the two mitigating policies are not biased by our choice of values for Q and R . An exemplary inventory profile of these two policies (ignoring disruptions) is provided in Figure 4.

(Insert Figure 4 about here)

4.3 Insights on stockouts

For all combinations of λ and μ that we simulated, the R -policy (in which the EOQ replenishment is used during normal cycles with separate R units of reserve inventory) performs consistently better than the Q -policy in terms of product availability. Figure 5 and Figure 6 display the effectiveness of the R -policy and the Q -policy in terms of the fill rate and the proportion of disruption cycles without any stockouts respectively.

(Insert Figure 5 about here)

(Insert Figure 6 about here)

Further, Table 1 and Table 2 summarize results comparing the base case, the Q -policy, and the R -policy with respect to the fill rate and percent of disruption cycles without stockouts, with $\lambda = 4$ (the use of

different values for λ will be discussed later) and select values for μ . Results for both measures are provided with 95% confidence intervals.

(Insert Table 1 about here)

(Insert Table 2 about here)

General results indicate that the difference in terms of *average percent of disruption cycles without stockouts* displays the more pronounced discrepancy between the two policies, which can be explained as follows. Under the conditions described earlier and depicted in Figure 4, at any given starting point of a supply disruption, the amount of inventory is approximately equal (on average) for the two mitigating policies (although the Q -policy has a wider range of possible values for the amount of inventory as per Figure 4). Thus, it is expected that the probability of stocking out during a disruption cycle would be equal between the two policies if the distribution of disruption duration is symmetric (e.g., uniform or normal). However, with an exponential distribution of disruption durations, the result may not be so straightforward since it displays a skewed distribution. This will inherently favour the use of strategic reserves over the larger order quantity policy (given the same level of average inventory) since shorter disruption durations are more likely than longer ones; if a short disruption occurs when the Q -policy has less inventory on hand than the R -policy, the former may stockout while the latter may not. On the other hand, if a short disruption occurs when the Q -policy has more inventory on hand than the R -policy, it is possible that *neither* will stock out. In other words, the Q -policy gets penalized in terms of product availability when it has significantly low inventory at the commencement of a disruption, but does not always get “credit” when it has high inventory at the beginning of a disruption since some of the inventory may be redundant. This is consistent with the observation in Figures 5 and 6, in which the R -policy outperforms Q -policy both in terms of the fill rate and average percent of disruption cycles without stockouts. In particular, as displayed in Figure 6, the R -policy results in an increased effectiveness over the Q -policy in average percent of disruption cycles without stockouts as the recovery rate (μ) gradually increases; that is, the R -policy becomes more attractive as a mitigating policy when disruption durations are short. On the other hand, the Q -policy exhibits a higher percent improvement over the base case (EOQ policy) for lower values of recovery rate (or for longer disruption durations) for both measures of product availability.

This result is under the assumption that the average inventory of the two policies is equal. It should also be noted, depending on cost parameters used, that comparing the two policies in terms of total costs under this assumption does not allow for a fair comparison. Thereby, the discussion of results on costs that follows will focus primarily on cost settings in which one policy is preferred over the other.

4.4 Cost comparisons

General costs: As previously described, cost parameters include fixed ordering costs per replenishment ($\$/\text{order}$ for cycle stock), an annual holding cost rate ($\$/\text{unit}/\text{year}$ for cycle stock, $\$/i_R/\text{unit}/\text{year}$ for reserve inventory), the cost per item ($\$/C/\text{unit}$), a lost sales cost ($\$/\pi_L/\text{unit}$), and a fixed cost for accessing reserve inventory ($\$/S_R$). Cost coefficients related to reserve inventory are as discussed in section 3.3. The impact of these parameters on the total cost of the two different mitigating policies is quite straightforward. Intuitively, one of the incentives for proposing the Q -policy is that it can help to reduce stockouts during disruptions while at the same time can be leveraged to reduce annual ordering costs. Thus, this policy becomes more attractive, the higher the cost per order (S) is. Similarly, the greater the discrepancy between i_R and i , (where $i_R < i$) and the higher the value of the item (C), the more desirable the R -policy becomes in terms of cost efficiency. Finally, an increase in the cost of lost sales favours the R -policy as it tends to lead to fewer stockouts than the Q -policy.

It is possible to test these hypotheses by way of our simulation results. Specific values for cost parameters affect performance (service level) only to the extent of impacting the relative length of the natural order cycle (Q/D), which will be determined by the EOQ based on cost parameters. However, for a given EOQ result and mitigating policies (the Q -policy and the R -policy), cost parameters do not affect the performance in terms of number of orders, average inventory, and stockouts. It is thus possible to apply different values of cost parameters to the simulation experiment to see which mitigating policy is preferred for different changes to these parameters. Table 3 summarizes how an increase in a given parameter affects the cost difference between mitigating policies in terms of which policy becomes more attractive than it was before the cost parameter changed. Cost dominance of one policy over the other is parameter specific.

(Insert Table 3 about here)

Stockout costs: Product availability can be described in a number of ways. Nahmias (2005) describes two types of service rates related to product availability: a Type I service rate refers to the probability of

not stocking out during replenishment lead time, while a Type II service rate specifies the fill rate. Although it is more common to see stockout costs defined in terms of a variable cost dependent on the number of units short (Type II service), Silver, Pyke, and Peterson (1998) define a “fixed cost per stockout occasion” due to a need to expedite stock. Also, Bock (1964) suggests that in the case of a manufacturer who may have to shut down an assembly line, it seems plausible that a fixed cost would be incurred for any stockout run, regardless of duration. We further surmise that in the case of a retailer, wholesaler, or distributor, there may be a policy whereby any stockout, regardless of size, warrants an investigation of some sort (such as examining root causes, reevaluating suppliers, or analyzing mitigating policies). Thus, the significant difference in service level performance between the two mitigating policies we studied, in terms of the proportion of disruption cycles without stockouts, may be of interest to some businesses. This could be incorporated by introducing a different type of stockout cost, namely π_1 , a penalty cost incurred for any instance of a stockout run during any given disruption cycles, in addition to π_2 , a regular stockout cost for Type II stockouts applied per unit stocked out.

4.5 Disruption frequency (λ) and recovery rate (μ)

In general, the joint effect of varying the disruption frequency (λ) and the recovery rate (μ) reveals that the R -policy consistently outperforms the Q -policy in terms of product availability, a result expected for an exponentially distributed disruption duration as previously discussed. Within each policy, however, the effects of λ (1, 4, 12) on percent of disruptions without stockouts and stockouts per disruption for a given value of μ are not significant, whereas, it is evident that the percent of disruption cycles without stockouts is monotonically increasing in μ (Figure 7 and Figure 8). That is, the occurrence of a stockout during a disruption is contingent on the recovery rate μ , independent of the frequency rate λ , which implies that the impact of proactive measures (e.g., preparing for supply disruptions through increased visibility) that lead to a lower disruption frequency (λ) is not as pronounced in improving the percent of disruption cycles without stockouts as the impact of reactive measures (e.g., using backup supplier sources or spot markets) that result in high recovery rate (μ).

(Insert Figure 7 about here)

(Insert Figure 8 about here)

However, the effect of the changes in disruption frequency (λ) on fill rates are quite apparent, especially with relatively smaller values of μ ; although for larger values of μ , the effect of an increase in

disruption frequency (λ) on fill rates as well as percent of disruption cycles without stockouts is largely suppressed for both mitigating policies as observed in Figure 9 and Figure 10. Further, fill rates display a monotonically increasing pattern in μ . That is, with either mitigating policy, both proactive measures (leading to a lower λ) and reactive measures (resulting in a higher μ) are influential in maintaining desired fill rates. This is also consistent with intuition that if there exist sufficient mechanisms in the supply chain to effectively and quickly resolve supply disruptions (expressed in the form of high μ), the frequency of supply disruptions (λ) becomes a minor issue at best.

(Insert Figure 9 about here)

(Insert Figure 10 about here)

5. Discussion of managerial implications

Supply disruptions and the need for preparation for such are a growing reality for business managers, particularly given the seemingly incompatible trends of increased global sourcing and lean operations. As Kouvelis, Chambers, and Wang (2006) point out, despite the surge in interest in SCRM from the academic and business community, implementation of policies and strategies to mitigate disruption impact still lags in practice. One of the main challenges relates to costs associated with implementation; in the absence of reliable data on the benefits of mitigating policies, the requisite costs of implementing will remain a major concern for companies (Tang 2006b). It is of importance, therefore, for companies to be able to identify appropriate mitigating policies prior to actual implementation. This paper thus intends to provide managers with some insight into the potential practical use and performance of two inventory-based mitigation policies, particularly the use of strategic inventory reserves – stock that is only used to prevent stockouts during supply disruptions.

We show that the use of strategic inventory reserves proves to be a more effective tool for mitigating supply disruption impact than the practice of maintaining larger stocks of cycle inventory via larger orders, particularly in terms of reducing the probability of incurring a stockout during a supply disruption. For managers in supply chain environments where a stockout of any size results in a significant fixed cost being incurred, this result may be of particular interest. This may apply, for example, in situations where the absence of a specific part or component results in a production shut down/restart or where the disruption of a supplied product would necessitate enactment of an expensive backup plan (e.g., expediting stock from another source). In these cases, the use of strategic inventory reserves would

be a preferred mitigation strategy. Further, for managers who have the ability to leverage secondary storage locations for reserves, where lower warehouse rental rates and the opportunity for higher storage density can lead to significantly reduced holding costs for reserve inventory, using inventory reserves as a means to mitigate supply disruption impact would seem very plausible. In fact, there may be an opportunity for a third party to provide such a service – the storage of reserve inventory in low cost conditions (warehouse located off of the primary corridors and in high-density and shared storage configurations) but with the ability to respond to disruption occurrences to prevent stockouts.

Finally, the performance advantage of the reserves policy over the larger order size policy holds for all scenarios of disruption frequency values and duration values tested. It should be noted that the advantage of the reserves policy is most pronounced when expected disruption durations are short (i.e. reactive measures are in place to resolve disruptions quickly). Thus, in cases where a high fixed cost accompanies a shortage of any size, reactive measures to shorten disruption durations (such as using back-up suppliers or adding short-term capacity) would be more likely to exist. Also, when proactive measures (e.g., building flexibility or creating supply chain visibility through supply chain design and information technology) prevail in the supply chain decreasing the probability of disruptions, fill rates improve but the probability of a stockout during a disruption remains unchanged. However, the probability of stocking out during disruption becomes a moot point if disruptions can be prevented altogether.

6. Conclusion, limitations, and future research directions

With the complex and dynamic nature of supply chains, interconnectedness of business entities, and decreasing product life cycles, any level of preparation for supply disruptions may not be sufficient to fully protect businesses from unknown future risks. A number of real supply disruption examples over the last decade have not only raised the significance of the issue of supply chain risk management but also shed light onto how different companies under a variety of settings can prepare for and respond to various threats. This study demonstrates the practical value of implementable inventory-based mitigation policies - in particular, the use of strategic inventory reserves.

Our research proposes that the use of strategic inventory reserves that are separate from traditional safety stock would apply in cases where the reserves would be inventoried at lower holding costs and where the reserves would come with a fixed cost; otherwise, it would be impractical not to access reserves to prevent stockouts during “normal” times. The need for empirical evidence of low cost secondary storage for reserves, in situations where storage is shared by multiple firms, is a potential area for future study.

The results of simulation experiments in our paper offer a better understanding of the effectiveness and benefits of using inventory reserves (the *R*-policy) versus maintaining larger stocks by way of placing larger orders (the *Q*-policy). Results show that for all combinations of disruption frequency and recovery rate, the *R*-policy performs better than the *Q*-policy in terms of product availability in the supply chain. In particular, the *R*-policy offers a considerable advantage in terms of the number of disruption cycles that result in a stockout of any size. Limitations of our methodology include the very nature of the supply chain that we examined (single retailer with single supplier) and the use of deterministic demand. While this study allows further investigation into other mitigating policies appropriate for various settings and disruption patterns, a simulation experiment may not be sufficient to capture collaboration amongst supply chain partners, a critical factor in mitigating supply chain risks (Juttner et. al., 2003; Norrman and Lindroth, 2002). As supply chain decisions on order quantities, replenishment, delivery, and timing are expected to be made in collaboration with other supply chain partners, a study on developing collaborative policies and strategies encompassing the entire supply chain would be highly relevant. An investigation of disruptions and identification of appropriate mitigating policies in a serial supply chain with multiple stakeholders would thus be an interesting research agenda. Further, empirical research on supply disruptions and mitigating policies using industry data sets that complements simulation-based research (and vice versa) under a comparable supply chain setting could lead to some powerful results. In addition, comparative studies on benefits of implementing centralized versus decentralized mechanisms under different patterns of supply disruptions could provide valuable insights on “overcoming supply chain vulnerability” and “building supply chain resiliency”. These are the ultimate challenges and mandates supply chain managers will continue to face in the dynamics of supply disruptions and uncertainties.

Appendix: Proof of convexity of expected total cost functions

A. Convexity of TC_Q for the Q -policy

From equation (4) we have,

$$\begin{aligned} TC_Q &= \left[\left(\frac{2 + \lambda T_2}{2\lambda T_2} \right) \cdot \left(\frac{1}{2} Q \cdot T_2 \cdot i \cdot C + S \right) + \left(\frac{1}{\mu} - \frac{T_2}{2} \right) \cdot D\pi_L \right] \cdot \left(\frac{\lambda\mu}{\lambda + \mu} \right) \\ &= \left[\left(\frac{2D + \lambda Q}{2\lambda Q} \right) \cdot \left(\frac{Q^2}{2D} \cdot i \cdot C + S \right) + \left(\frac{1}{\mu} - \frac{Q}{2D} \right) \cdot D\pi_L \right] \cdot \left(\frac{\lambda\mu}{\lambda + \mu} \right) \end{aligned}$$

Differentiating with respect to Q , we obtain,

$$TC_Q' = \left(\frac{1}{2\lambda} iC + \frac{Q}{2D} iC - \frac{D}{\lambda \cdot Q^2} S - \frac{\pi_L}{2} \right) \cdot \left(\frac{\lambda\mu}{\lambda + \mu} \right)$$

Further,

$$TC_Q'' = \left(\frac{iC}{2D} + \frac{2D}{\lambda Q^3} \right) \cdot \left(\frac{\lambda\mu}{\lambda + \mu} \right) \geq 0$$

Thus, Q^* satisfies $TC_Q' = 0$ or the condition:

$$(\lambda \cdot i \cdot C) \cdot Q^3 + (D \cdot i \cdot C - \lambda \cdot D \cdot \pi_L) \cdot Q^2 = 2D^2 S$$

B. Convexity of TC_R for the R -policy

From the expected total cost equation with reserves in (6), we have

$$TC_R = \left[\left(\frac{2 + \lambda T_1}{2\lambda T_1} \right) \left(\frac{1}{2} q T_1 i C + S \right) + \left(\frac{2 + \lambda T_1}{2\lambda} + \frac{R}{2D} \right) R i_R C + \left(\frac{1}{\mu} - \frac{q}{2D} - \frac{R}{D} \right) \pi_L D \right] \cdot \left(\frac{\lambda \mu}{\lambda + \mu} \right)$$

Differentiating above cost function with respect to R , we get,

$$TC'_R = \left[\frac{1}{\lambda} \cdot i_R \cdot C + \frac{T_1}{2} \cdot i_R \cdot C + \frac{R}{D} \cdot i_R \cdot C - \pi_L \right] \cdot \left(\frac{\lambda \mu}{\lambda + \mu} \right)$$

Further, we have

$$TC''_R = \frac{i_R \cdot C}{D} \cdot \left(\frac{\lambda \mu}{\lambda + \mu} \right) \geq 0$$

The optimal value of inventory reserves (R^*) is obtained by solving for $TC'_R = 0$, or

$$R^* = D \cdot \left[\frac{\pi_L}{i_R \cdot C} - \left(\frac{1}{\lambda} + \frac{T_1}{2} \right) \right]$$

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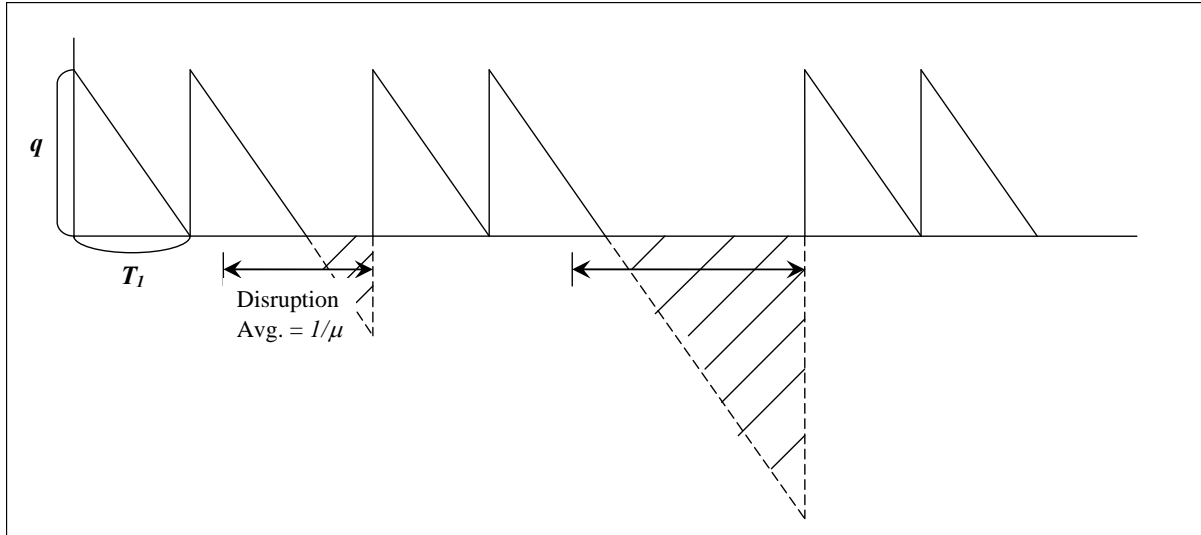


Figure 1. Inventory profile with disruptions when EOQ policy is used

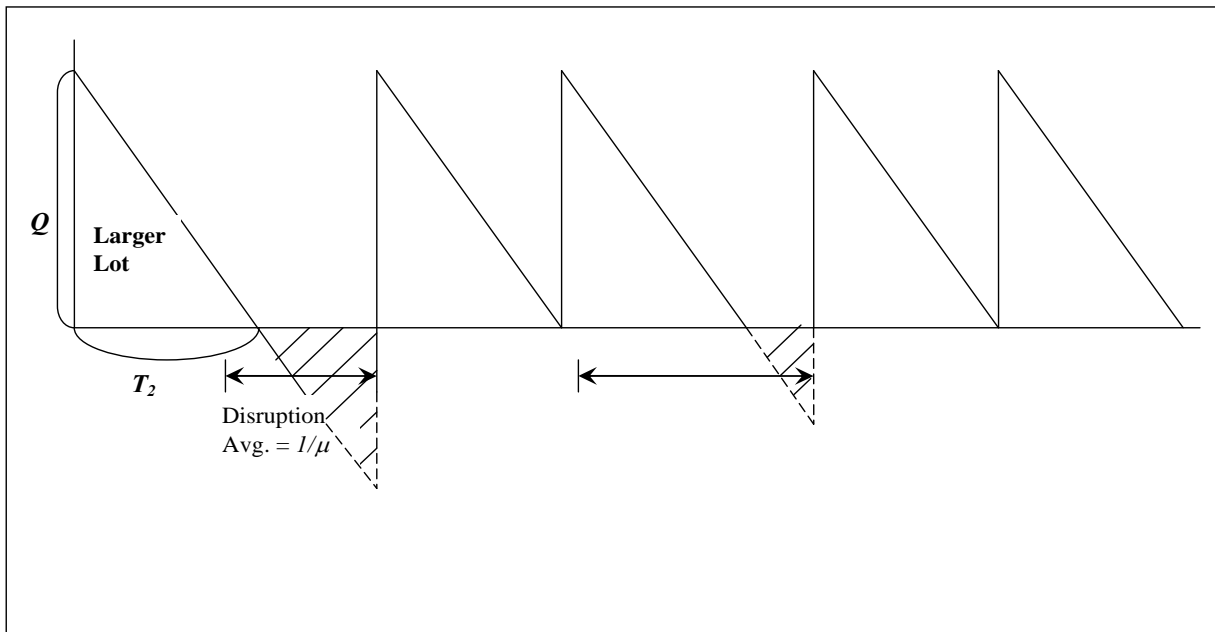


Figure 2. Inventory profile with disruptions when Q -policy is used

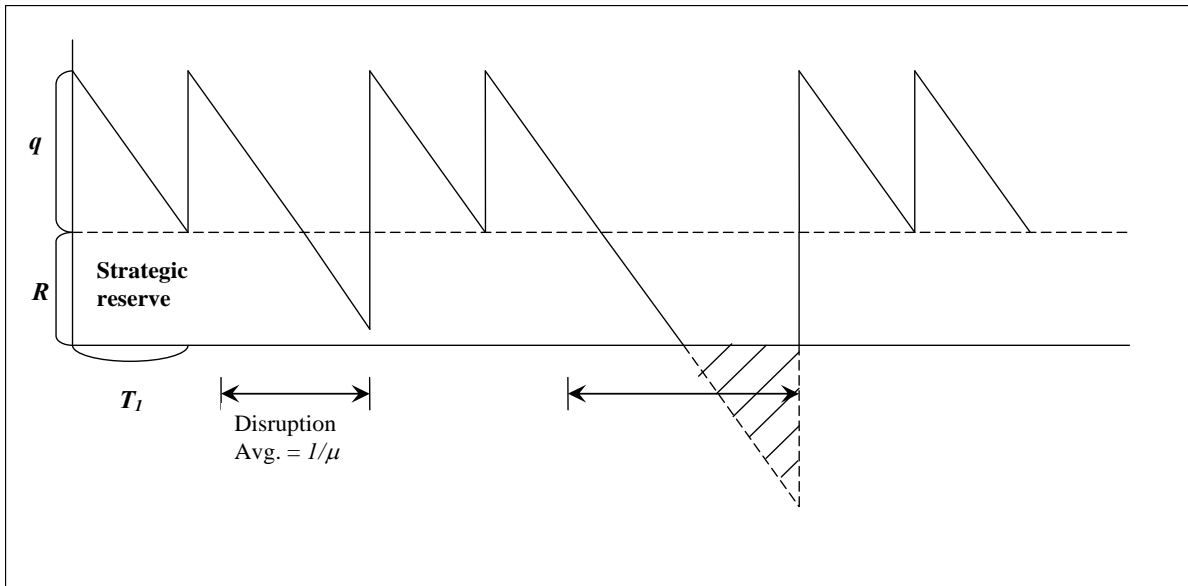


Figure 3. Inventory profile with disruptions when R -policy is used

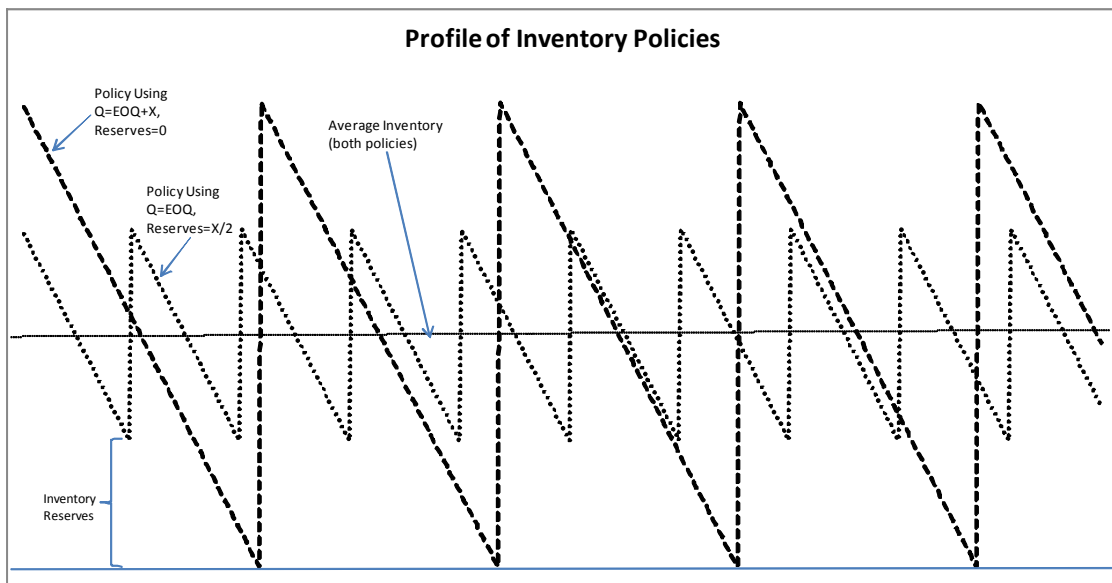


Figure 4 - Inventory profile comparisons with when disruptions did not occur

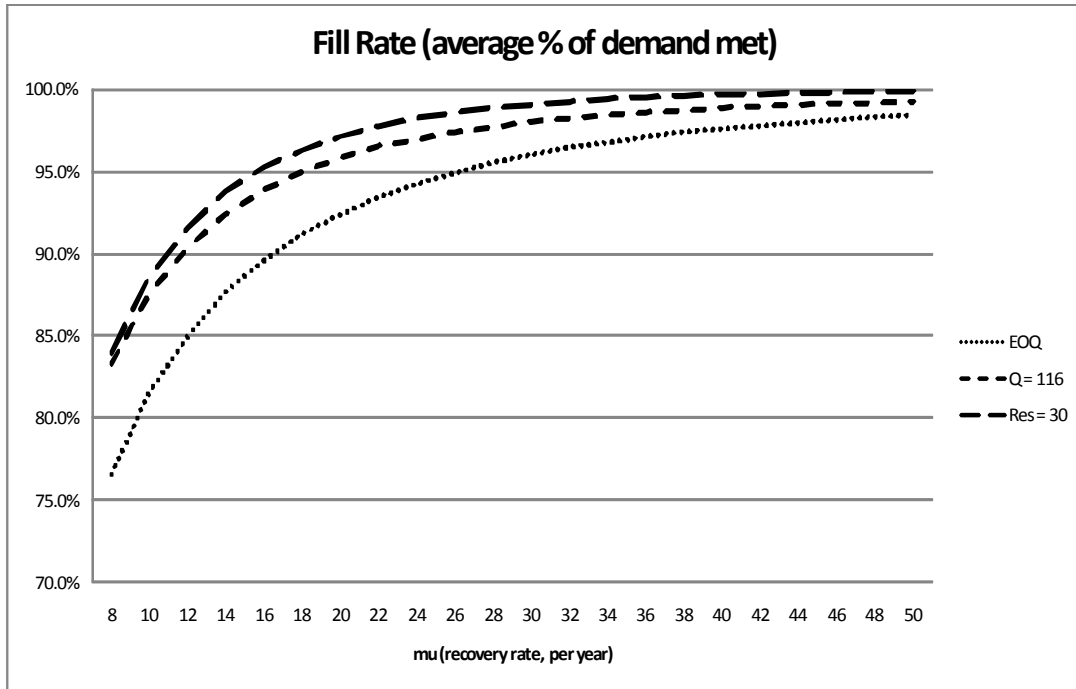


Figure 5. Comparisons of fill rates: $\lambda = 4$, varying μ

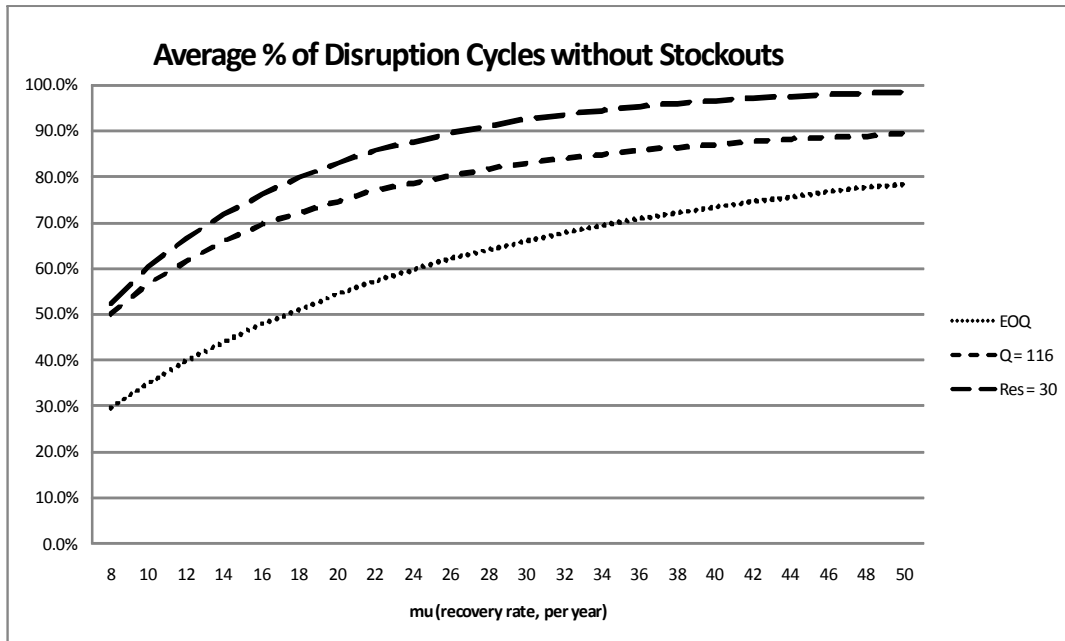


Figure 6. Comparisons of percent of disruption cycles without stockouts: $\lambda = 4$, varying μ

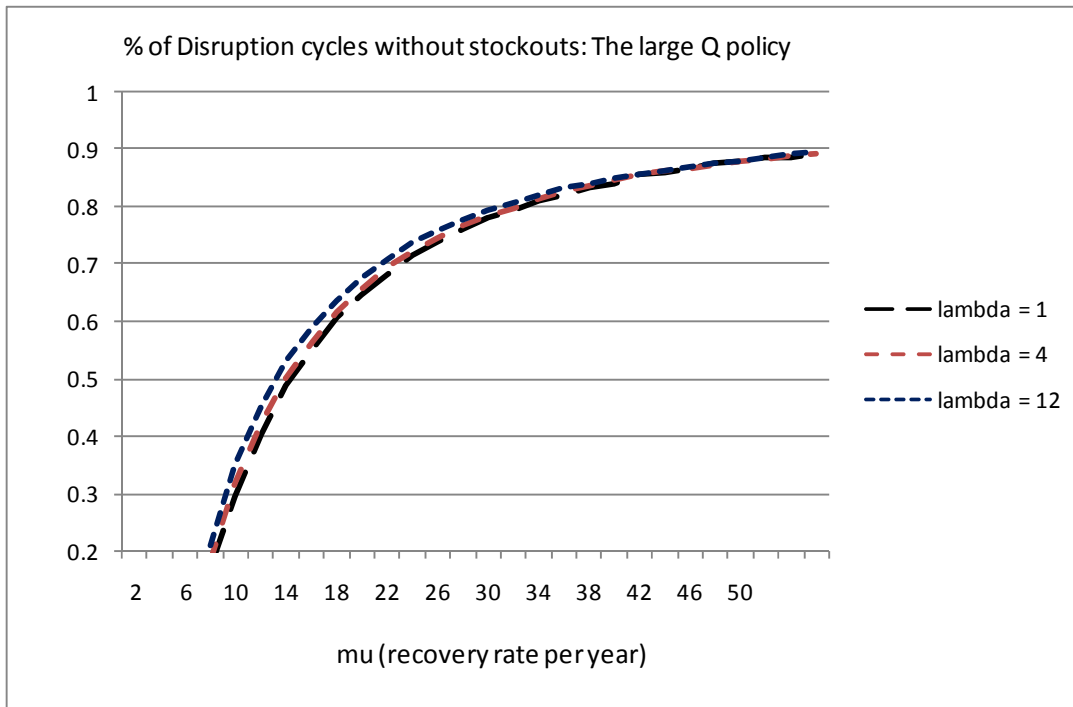


Figure 7. % Disruption Cycles without stockouts with the large Q policy: Effects of λ and μ

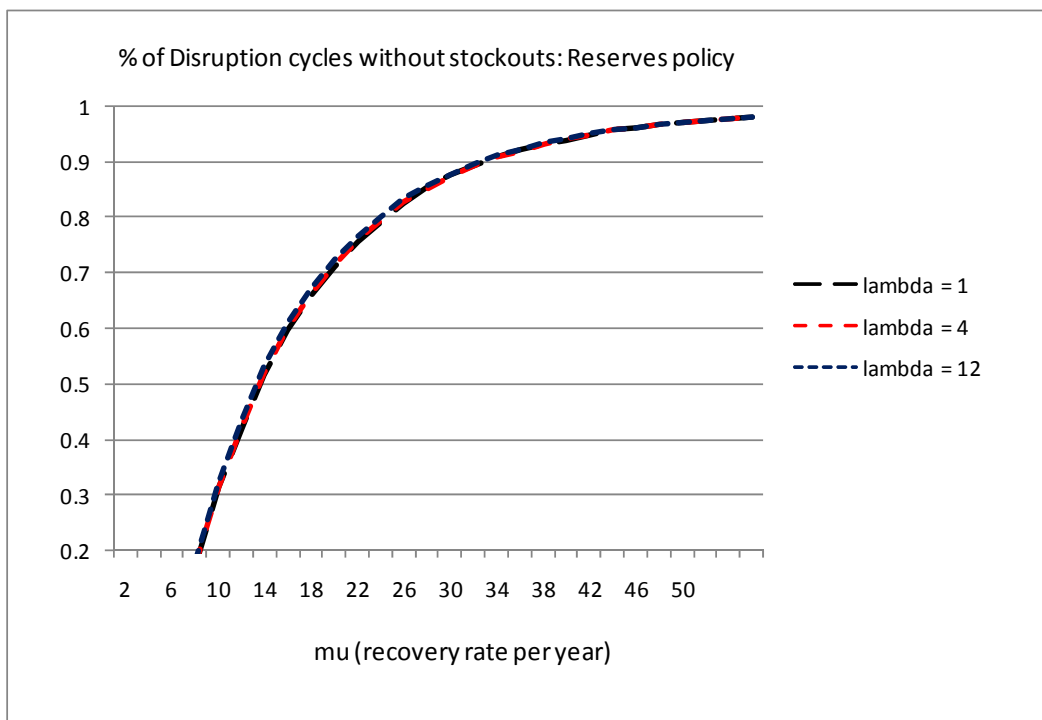


Figure 8. % Disruption Cycles without stockouts with reserves policy: Effects of λ and μ

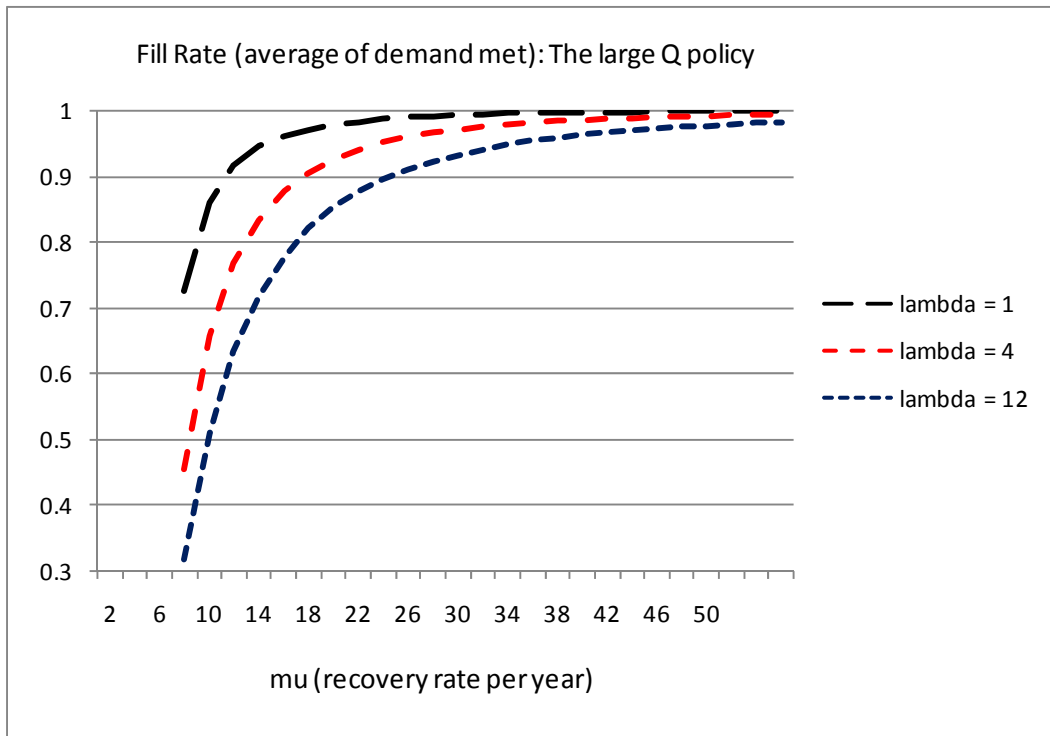


Figure 9. Fill rates with the large Q policy: Effects of λ and μ

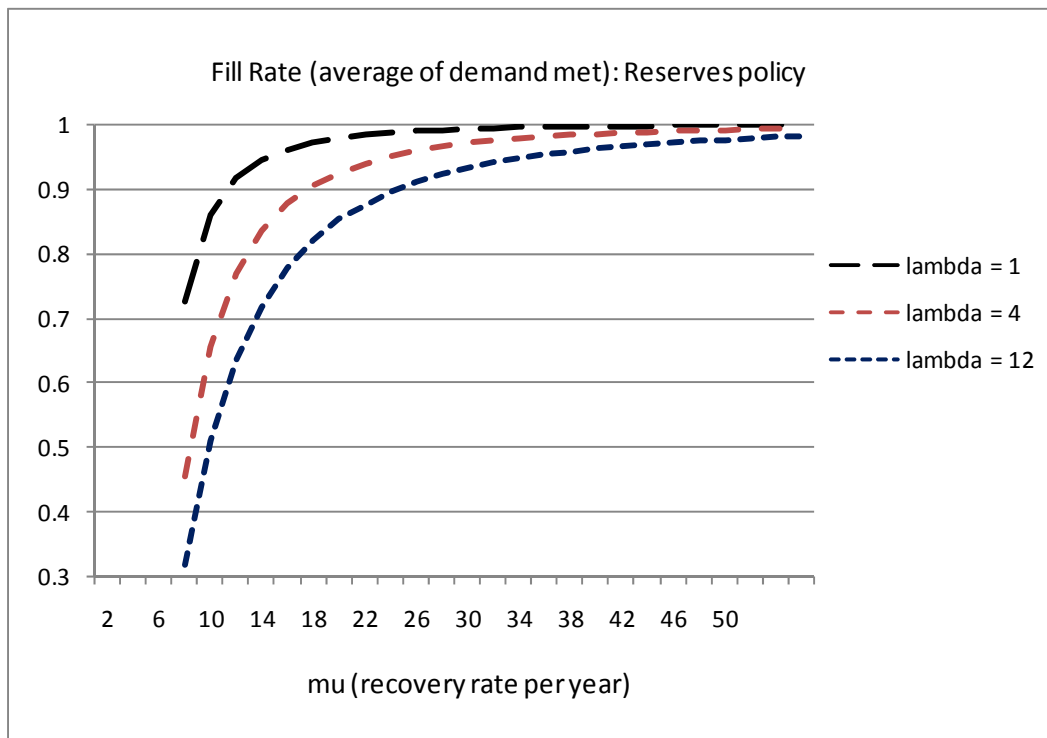


Figure 10. Fill rates with the reserves policy: Effects of λ and μ