Danusantoso, Johannes; Moses, Scott A.

Article

Disruption management in a two-period three-tier electronics supply chain

Cogent Business & Management

Provided in Cooperation with:
Taylor & Francis Group

Suggested Citation: Danusantoso, Johannes; Moses, Scott A. (2016) : Disruption management in a two-period three-tier electronics supply chain, Cogent Business & Management, ISSN 2331-1975, Taylor & Francis, Abingdon, Vol. 3, https://doi.org/10.1080/23311975.2015.1137138

This Version is available at:
https://hdl.handle.net/10419/205849

Danusantoso & Moses, *Cogent Business & Management* (2016), 3: 1137138
http://dx.doi.org/10.1080/23311975.2015.1137138

cogent business & management

OPERATIONS MANAGEMENT | RESEARCH ARTICLE

Disruption management in a two-period three-tier electronics supply chain

Johannes Danusantoso[1]* and Scott A. Moses[1]

Received: 25 September 2015
Accepted: 21 December 2015
Published: 22 January 2016

*Corresponding author: Johannes Danusantoso, School of Industrial & Systems Engineering, University of Oklahoma, 202W. Boyd St., Norman, OK 73019-1022, USA
E-mail: johannes.danu@gmail.com

Reviewing editor:
Shaofeng Liu, University of Plymouth, UK

Additional information is available at the end of the article

Abstract: We study strategies to manage demand disruptions in a three-tier electronics supply chain consisting of an Electronics Manufacturing Services provider, an Original Equipment Manufacturer (OEM), and a Retailer. We model price sensitivity of consumer demand with the two functions commonly used for this purpose, linear and exponential, and introduce disruptions in the demand function. We assume each supply chain member faces an increasing marginal unit cost function. Our decentralized supply chain setting is governed by a wholesale price contract. The OEM possesses greater bargaining power and therefore is the Stackelberg leader. A penalty cost incurred by the Retailer is introduced to capture the cost of deviation from the original plan. We find exact analytical solutions of the effectiveness of managing the disruption when the consumer demand function is linear, and we provide numerical examples as an illustration when the consumer demand function is either linear or exponential. We show that the original production quantity exhibits some robustness under disruptions in both centralized and decentralized supply chains, while the original optimal pricing does not. We show that supply chain managers should not automatically react to an individual disruption, in certain cases it is best to leave the production plan unchanged.

ABOUT THE AUTHORS

Johannes Danusantoso received his PhD in Industrial Engineering from the University of Oklahoma. He is currently working in the Supply Chain area within Alcatel-Lucent, Inc.

Scott A. Moses is an associate professor in the School of Industrial & Systems Engineering at the University of Oklahoma. His current research activity focuses on scalable algorithms for real-time order promising and on high-speed tactical-level planning of production tasks and material flow in large discrete systems. His research has been published in journals such as IIE Transactions, Sloan Management Review, International Journal of Production Research, and Computers & Operations Research.

PUBLIC INTEREST STATEMENT

After a plan to meet demand has been developed, various disruptive events (e.g. counterfeiting and piracy, new technology, an economic downturn) may occur that introduce a disparity between supply and demand. Effective management of demand disruptions is particularly important in the electronics industry where the combination of high demand variability and short product life cycles further increases the risk of a supply chain member being caught holding obsolete goods. In this paper, we study management of demand disruptions in a three-tier electronics supply chain consisting of an Electronics Manufacturing Services (EMS) provider who builds the subassemblies, an Original Equipment Manufacturer (OEM) who integrates the subassemblies into the final product and performs system tests, and a Retailer who sells the product to the consumer. We show that supply chain managers should not automatically react to a single disruption but rather understand the consequences of different recovery strategies.

Subjects: Business & Policy; Production, Operations & Information Management; Supply Chain Management

Keywords: Stackelberg leader; demand disruption; supply chain coordination; wholesale price contact

1. Introduction

CEOs and executives in the electronics industry are striving for global integration to a much greater extent than their peers in other industries (IBM Global Business Services, 2008). Global integration aims to build the supply chain by virtually linking individual providers (nodes) who are the best at executing their particular task. Unlike the days of vertical integration, these nodes do not have to be owned by one firm and can be situated anywhere in the world.

Survival in this fiercely competitive marketplace is made even more difficult by the dynamic nature of the electronics industry. Various unanticipated events may disrupt a laboriously developed demand and supply plan. The combination of unanticipated events and short product life cycles in the electronics industry further increases the risk that a supply chain member will be caught with excess inventory of last generation components and/or finished goods. For example, counterfeit products may significantly reduce the brand owner's market share (i.e. create a demand disruption) which results in excess finished goods inventory. One maker of high-performance audio products estimates that about one third of its branded headphones and audio products sold online in 2013 are fakes (Taylor, 2013). Counterfeit components used unknowingly in manufacturing can lead to lower yield (i.e. create a supply disruption) and to higher manufacturing costs due to increased scrap rates and rework. Natural disasters may cause damage to the manufacturing infrastructure and put people temporarily out of work. The massive flood in Thailand in 2011 forced a top hard drive maker to shut down production, and this supply disruption caused prices for hard drives to increase by as much as 20–40% (Randewich, 2011).

Disruption management is concerned with minimizing the cost impact of the disruption once the disruptive event has occurred. The concept of disruption management was first applied to airline flight and crew scheduling problems that occur when unexpected events, such as inclement weather or aircraft mechanical breakdown, create schedule disruptions (Clausen, Hansen, Larsen, & Larsen, 2001; Yu, 1998; Yu, Argüello, Song, McCowan, & White, 2003; Yu & Qi, 2004). If a manufacturer improves its management of disruptions, which as we will see sometimes means no response is the best response, then it can see an improvement in customer satisfaction, a reduction in inventory, a reduction in obsolescence leading to write-offs, and savings on transportation cost and improved supplier relationships by not expediting and de-expediting the supply stream every time a demand disruption occurs.

Clausen et al. (2001) proposed the application of the disruption management concept to supply chain management. Qi, Bard, and Yu (2004) introduced disruption management into supply chain coordination problems. They examined the cost impact (deviation penalties) on a two-period one-supplier one-retailer supply chain model when the production plan could no longer be executed as originally formulated. Since then, many researchers have extended disruption management and supply chain coordination under various scenarios.

Xu, Qi, Yu, and Zhang (2006) study a similar supply chain coordination model but under production cost disruptions. Xiao and Qi (2008) examine the effects of production cost disruptions and demand disruptions simultaneously on the coordination between one manufacturer and two competing retailers by an all-unit quantity discount scheme and an incremental discount scheme. Lei, Li, and Liu (2012) use linear wholesale price contract menu to analyze the one-supplier one-retailer supply chain under demand and cost disruptions with asymmetric information. Zhang, Fu, Li, and Xu (2012) investigate the coordination between one manufacturer and two competing retailers with demand disruptions with a revenue-sharing contract.

None of the above papers consider how to coordinate a disrupted three-tier supply chain. In fact, there are not many papers on the subject of coordination of a three-tier supply chain. Munson and Rosenblatt (2001) use a quantity discount contract to coordinate a supplier-manufacturer-retailer supply chain with deterministic demand where the manufacturer is the Stackelberg leader. Ding and Chen (2008) show that a flexible buyback contract can be used to coordinate a three-tier supply chain with stochastic demand. Seifert, Zequeira, and Liao (2012) examine the impact of subsupply chain coordination and show that it is more profitable to coordinate between the supplier and the manufacturer than between the manufacturer and the retailer.

In this paper, we study a coordination problem of a two-period three-tier electronics supply chain consisting of an Electronics Manufacturing Services (EMS), a dominant Original Equipment Manufacturer (OEM), and a Retailer with demand disruption. Demand disruption is defined as the difference between the actual consumer demand faced by the Retailer and the initial forecast given to the OEM and EMS. We analyze the effects of the demand disruption on the optimal order quantity, retail price, and the supply chain profit relative to original plan. We find the exact analytical solutions of the effectiveness of managing the disruption (measured by the fraction of the supply chain profit relative to the basic model ignoring the disruption) when the consumer demand function is linear, and we provide numerical examples as an illustration when the consumer demand function is either linear or exponential.

This paper contributes to the literature in the following ways. We consider demand disruption in a three-tier supply chain, whereas most papers to date consider disruption in a two-tier supply chain. Our decentralized model is governed by the commonly used wholesale price contract (Cachon, 2003; Lariviere & Porteus, 2001) with forced compliance, i.e. the supplier is forced to install a given capacity in advance (once he accepts a contract from the manufacturer). This concept was proposed by Cachon and Lariviere (2001). We assume the OEM in the second tier possesses greater bargaining power and makes the first strategic moves and therefore is the Stackelberg leader. We also consider increasing marginal unit cost in our model while others consider fixed unit cost.

The remainder of this paper is organized as follows. Section 2 defines our supply chain model for both the centralized and decentralized cases. In Section 3, we derive the optimal OEM decision and the subsequent EMS and Retailer responses before and after disruption. Section 4 provides numerical examples to illustrate our results. Concluding remarks are provided in Section 5. Secondary data to prove the stability of the proposed model are included in Appendix 1.

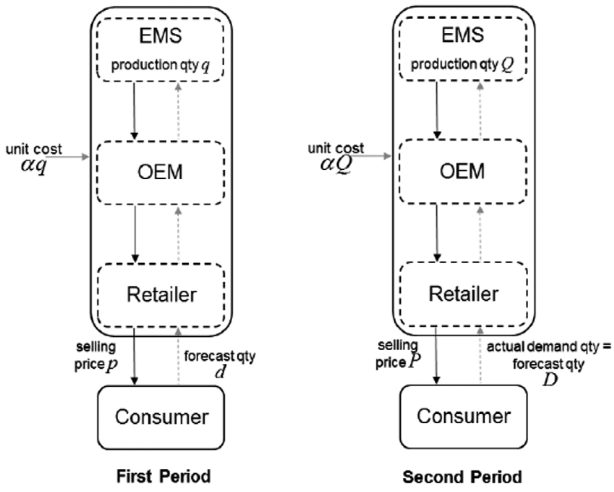
2. Basic model of a supply chain

In our three-tier electronics supply chain, the EMS manufactures a single product and sells to the OEM who adds further value to the product and sells to the Retailer, who sells to the consumer market after incurring some marketing expenses as well as operating costs (rent, utilities, labor, etc.). Due to the volatile nature of the electronics supply chain, we assume that each supply chain member faces an increasing marginal unit cost function. Banker, Datar, and Kekre (1988) and Eliashberg and Steinberg (1987) provide a good discussion on the usage of the increasing marginal cost function.

2.1. Model of a centralized supply chain

As a benchmark, we first consider a model where the EMS, OEM, and the Retailer are under by one firm (Figure 1). The product unit cost is $\alpha\, q(p)$ where α is the marginal cost coefficient. In the first period, a production plan q is created based on a forecast market demand d and is used for purposes such as procurement of raw materials and capacity planning. In the second period, the product is sold in the retail market at retail price p and the actual market demand D is known and matches the initial forecast d. We consider the two most commonly used mathematical functions for representing a downward-sloping price p versus demand d relationship: (1) linear $d(p) = a - bp$ and (2) exponential $d(p) = Ap^{-B}$. In the linear demand function, a is the market scale (i.e. the maximum possible demand), b is the price-sensitive coefficient, and $(a/b) \geq p \geq 0$. In the exponential demand

Figure 1. Centralized supply chain model.



function, A is also the market scale, B is the demand elasticity, and $A, B \geq 0$. While the linear demand function is mathematically convenient, the exponential demand function is a closer estimate of reality.

The centralized firm maximizes the expected profit π_c by setting the retail price p to the value obtained from the following optimization problem:

$$\max \pi_C(p) = p.q(p) - \alpha.q(p)^2 \tag{1}$$

Differentiating with respect to retail price p, we obtain necessary and sufficient conditions for profit maximization:

$$\frac{d\pi_c}{dp} = 0; \frac{d^2\pi_c}{dp^2} = 0 \tag{2}$$

Table 1 lists the principal notation, and Table 2 shows the optimum parameters for the centralized supply chain with linear demand.

Table 1. List of principal notation

	First period	Second period
Actual consumer demand	d	D
Unit retail price charged to the consumers	p	P
Unit wholesale price to the OEM	w_1	W_1
Unit wholesale price to the retailer	w_2	W_2
Quantity produced by the EMS and supplied to the OEM	q_1	Q_1
Quantity ordered by the OEM and supplied to the retailer	q_2	Q_2
Quantity ordered by the Retailer and supplied to the market	q	Q
Profit at the EMS	π_1	Π_1
Profit at the OEM	π_2	Π_2
Profit at the retailer	π_3	Π_3
Total supply chain profit	π_{TOT}	Π_{TOT}

Table 2. Optimum parameters for centralized supply chain with base linear demand

No disruption	With disruption			
	Case 1: $\Delta a > b\lambda_1$	**Case 2: $0 < \Delta a < b\lambda_1$**	**Case 3: $-b\lambda_2 < \Delta a < 0$**	**Case 4: $\Delta a < -b\lambda_2$**
$q^* = \frac{a}{2(1+b\alpha)}$	$Q^* = \varepsilon q^*$	$Q^* = q^*$	$Q^* = q^*$	$Q^* = q^*$
$p^* = \frac{a(1+2b\alpha)}{2b(1+b\alpha)}$	$P^* = \varepsilon p^* + \lambda_1$	$P^* = p^* + \frac{\Delta a}{b}$	$P^* = p^* + \frac{\Delta a}{b}$	$P^* = \kappa p^* - \lambda_2$
$\pi_C^* = \frac{a^2}{4b(1+b\alpha)}$	$\Pi^* = \varepsilon^2 \pi^* + \lambda_1 q^*$	$\Pi^* = \pi^* + \frac{\Delta a}{b} q^*$	$\Pi^* = \pi^* + \frac{\Delta a}{b} q^*$	$\Pi^* = \kappa^2 \pi^* - \lambda_2 q^*$
	where $\varepsilon = 1 + \frac{\Delta a - b\lambda_1}{a}$			where $\kappa = 1 + \frac{\Delta a + b\lambda_2}{a}$

2.2. Model of a decentralized supply chain

In the decentralized supply chain, the Retailer forecasts to OEM in the first period an order quantity q based on the forecast market demand d. The OEM, in turn, informs the EMS the intent to order quantity q_2. Accordingly, the EMS creates a production plan of quantity q_1. The actual market demand is realized in the second period, and in the deterministic case, it equals the forecast d. The Retailer buys the product from the OEM at a certain unit wholesale price w_2 and incurs unit cost (includes advertisement cost, setup and ordering cost, etc.) of $\alpha_3 q$, where α_3 is the marginal unit cost coefficient at the Retailer. The OEM buys the product from the EMS at a certain unit wholesale price w_1 and incurs unit cost (includes setup cost and ordering cost, final assembly and test cost) of $\alpha_2 q_2$, where α_2 is the marginal unit cost coefficient at the OEM. The EMS manufactures the product at unit cost (includes material cost and labor and load) of $\alpha_1 q_1$, where α_1 is the marginal unit cost coefficient at the EMS. Since the contract offered stipulates forced compliance, and assuming there is no leftover quantity in the supply chain at the end of the second period, we have $d = q = q_1 = q_2$.

The objective function of each supply chain member in the decentralized model is to maximize its own profit. By applying the first- and second-order conditions from Equation (2), we obtain the optimal quantity solution of the entire supply chain. We then can calculate the offered wholesale prices

Table 3. Optimum parameters for decentralized supply chain with base linear demand

No disruption	With disruption			
	Case 1: $\Delta a > b\lambda_1$	**Case 2: $0 < \Delta a < b\lambda_1$**	**Case 3: $-b\lambda_2 < \Delta a < 0$**	**Case 4: $\Delta a < -b\lambda_2$**
$q^* = \frac{a}{2(2+b(2\alpha_1+\alpha_2+2\alpha_3))}$	$Q^* = \varepsilon q^*$	$Q^* = q^*$	$Q^* = q^*$	$Q^* = kq^*$
$W_1 = 2\alpha_1 q^*$	$W_1^* = \varepsilon w_1^*$	$W_1^* = w_1^*$	$W_1^* = w_1^*$	$W_1^* = \kappa w_1^*$
$w_2 = \frac{2(1+b(2\alpha_1+\alpha_2+\alpha_3))}{b} q^*$	$W_2^* = \varepsilon w_2^*$	$W_2^* = w_2^*$	$W_2^* = w_2^*$	$W_2^* = \kappa w_2^*$
$p^* = \frac{3+2b(2\alpha_1+\alpha_2+2\alpha_3)}{b} q^*$	$P^* = \varepsilon p^* + \lambda_1$	$P^* = p^* + \frac{\Delta a}{b}$	$P^* = p^* + \frac{\Delta a}{b}$	$P^* = \kappa p^* - \lambda_2$
$\pi_1^* = \alpha_1 (q^*)^2$	$\Pi_1^* = \varepsilon \pi_1^*$	$\Pi_1^* = \pi_1^*$	$\Pi_1^* = \pi_1^*$	$\Pi_1^* = \kappa \pi_1^*$
$\pi_2^* = \frac{2+b(2\alpha_1+\alpha_2+2\alpha_3)}{b} q^{*2}$	$\Pi_2^* = \varepsilon \pi_2^*$	$\Pi_2^* = \pi_2^*$	$\Pi_2^* = \pi_2^*$	$\Pi_2^* = \kappa \pi_2^*$
$\pi_3^* = \frac{1+b\alpha_3}{b} (q^*)^2$	$\Pi_3^* = \varepsilon^2 \pi_3^* + \lambda_1 q^*$	$\Pi_3^* = \pi_3^* + \frac{\Delta a}{b} q^*$	$\prod_3^* = \pi_3^* + \frac{\Delta a}{b} q^*$	$\Pi_3^* = \kappa^2 \pi_3^* - \lambda_2 q^*$
$\pi_{tot}^* = \frac{3+b(3\alpha_1+\alpha_2+3\alpha_3)}{b} q^{*2}$	$\Pi_{TOT}^* = \varepsilon^2 \pi_{TOT}^* + \lambda_1 q^*$	$\Pi_{TOT}^* = \pi_{TOT}^* + \frac{\Delta a}{b} q^*$	$\prod_{TOT}^* = \pi_{TOT}^* + \frac{\Delta a}{b} q^*$	$\Pi_{TOT}^* = \kappa^2 \pi_{TOT}^* - \lambda_2 q^*$
	where $\varepsilon = 1 + \frac{\Delta a - b\lambda_1}{a}$			where $\kappa = 1 + \frac{\Delta a + b\lambda_2}{a}$

Table 4. Optimum parameters for centralized and decentralized supply chain with base exponential demand

$d(p) = Ap^{-B}$, $B = \frac{1-k}{k}$	
Centralized	**Decentralized**
$q^* = A^k\left[\left(\frac{1-2k}{1-k}\right)\frac{1}{2\alpha}\right]^{1-k}$	$q^* = \frac{(2A)^k}{2}\left[\left(\frac{1-2k}{1-k}\right)^2\frac{1}{2\alpha_1+\alpha_2+2\alpha_3}\right]^{1-k}$
	$W_1 = 2\alpha_1 q^*$
	$w_2 = \frac{(1-k)(2\alpha_1+\alpha_2)+\alpha_3}{1-2k}\cdot 2q^*$
$p^* = \frac{2\alpha(1-k)}{1-2k}q^*$	$p^* = 2\left(\frac{1-k}{1-2k}\right)^2(2\alpha_1+\alpha_2+2\alpha_3)q^*$
$\pi^*_{TOT} = \frac{\alpha}{1-2k}q^{*2}$	$\pi^*_1 = \alpha_1(q^*)^2$
	$\pi^*_2 = \frac{2\alpha_1+\alpha_2+2\alpha_3}{1-2k}q^{*2}$
	$\pi^*_3 = \frac{2k(1-k)(2\alpha_1+\alpha_2)+\alpha_3}{(1-2k)^2}q^{*2}$
	$\pi^*_{TOT} = \frac{(3-4k)(\alpha_1+\alpha_3)+(1-2k^2)\alpha_2}{(1-2k)^2}q^{*2}$

and the maximum supply chain profit. Table 3 shows the optimum parameters for the decentralized supply chain with linear demand.

Table 4 shows the optimum parameters for the centralized and the decentralized supply chain with exponential demand.

3. Behavior of a supply chain with demand disruption

We now investigate a supply chain that experiences a demand disruption that results in an inevitable deviation from the initial production plan. We use the two-stage stochastic programming with recourse model. The randomness in demand is price independent and can be modeled in an additive form (Mills, 1959).

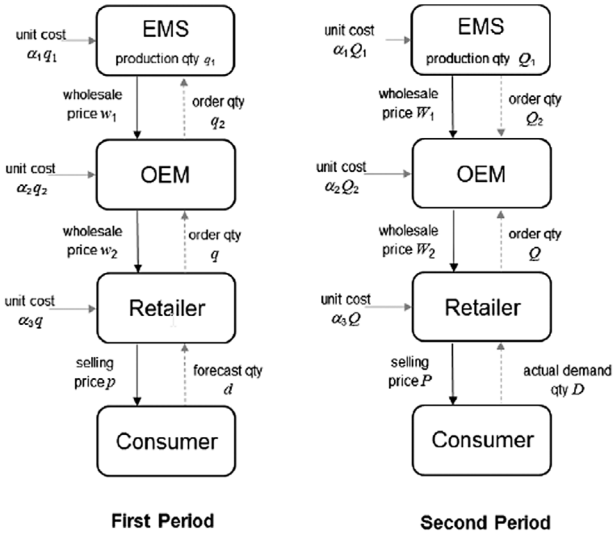


Figure 2. Decentralized supply chain model.

3.1. Disruption in a supply chain with linear demand

The actual demand realized in the second period is Q:

$$D(P) = Q = d(P) + \Delta a = a + \Delta a - bP \tag{3}$$

where Δa is assumed to be a normally distributed random variable. $\Delta a > 0$ represents an increased market demand, and $\Delta a < 0$ represents a decreased market demand. The Retailer purchases from the OEM quantity Q_2 at unit wholesale price W_2, and sells to the consumer at a new retail price P. The EMS produces quantity Q_1 and sells to the OEM at unit wholesale price W_1. Assuming there is no quantity leftover in the supply chain, we have $D = Q_2 = Q_1 = Q$. We introduce $\lambda_1 > 0$ and $\lambda_2 > 0$ as the unit penalty cost of the increase and decrease in production from the original plan (see Figure 2).

The new retail price P from the actual market demand Q in Equation (3) can be written as

$$P = \frac{a + \Delta a - Q}{b} \tag{4}$$

The centralized supply chain optimization problem now becomes

$$\max \Pi = Q\left(\frac{a + \Delta a - Q}{b} - \alpha Q\right) - \lambda_1 (Q - q)^+ - \lambda_2 (q - Q)^- \tag{5}$$

where Π is the new total supply chain profit and $(x)^+ = \max\{x, 0\}$.

We propose two constraints:

- $Q > q$ when $\Delta a > 0$: the production quantity cannot be decreased when the actual demand is more than originally planned.
- $Q < q$ when $\Delta a < 0$: the production quantity cannot be increased when the actual demand is less than originally planned.

Actual demand is more than originally planned ($\Delta a > 0$)

Since $Q > q$ or $Q - q > 0$, the centralized supply chain profit function (5) now becomes

$$\Pi = Q\left(\frac{a + \Delta a - Q}{b} - \alpha Q\right) - \lambda_1 (Q - q) \tag{6}$$

We calculate the new optimum quantity Q^* using the first-order condition as in Equation (2) and compare with the original optimum quantity from Equation (5):

$$Q^* = \frac{a + \Delta a - b\lambda_1}{2(1 + b\alpha)} = q^* + q^* \frac{\Delta a - b\lambda_1}{a} = \epsilon q^*$$

$$\text{where } \varepsilon = 1 + \frac{\Delta a - b\lambda_1}{a} \tag{7}$$

We proposed earlier the constraint $Q > q$ when $\Delta a > 0$, but we see that Q^* will be less than q^* if $0 < \Delta a < b\lambda_1$. We have two cases with regard to the value of in Equation (7):

Case 1: $\Delta a > b\lambda_1$

When this condition is true, Q^* satisfies the constraint $Q > q$ when $\Delta a > 0$, implying that Π is indeed maximized at Q^*. We calculate the new optimum parameters and compare with the optimum solution in the linear demand function in Equation (5):

$$P^* = \varepsilon p^* + \lambda_1, \Pi^* = \varepsilon^2 \pi^* + \lambda_1 q^*$$

$$\text{where } \varepsilon = 1 + \frac{\Delta a - b\lambda_1}{a} \tag{8}$$

The increase in the consumer demand results in the optimum solution that is higher than the original one.

Case 2: $0 < \Delta a < b\lambda_1$

When this condition is true, Q^* does not satisfy the constraint $Q > q$ when $\Delta a > 0$, implying that Π is indeed maximized at Q^*. This implies that the original production plan should not be changed $Q^* = q^*$ unless the magnitude of demand disruption is large enough (greater than $b\lambda_1$). However, the retail price can be increased following the new demand function. We calculate the new optimum parameters and compare with the optimum solution in the linear demand function in Equation (5):

$$Q^* = q^*, P^* = p^* + \frac{\Delta a}{b}, \Pi^* = \pi^* + \frac{\Delta a}{b} q^* \tag{9}$$

Although the quantity sold is the same as the originally planned, the retail price can be increased and hence, the profit will increase as well.

Actual demand is less than originally planned ($\Delta a < 0$)

Since $Q < q$ or $Q - q < 0$, the centralized supply chain profit function (5) now becomes

$$\Pi = Q\left(\frac{a + \Delta a - Q}{b} - \alpha Q\right) - \lambda_2 (q - Q) \tag{10}$$

We calculate the new optimum quantity Q^* using the first-order condition as in Equation (2) and compare with the original optimum quantity from Equation (5):

$$Q^* = \kappa q^* \text{where } \kappa = 1 + \frac{\Delta a + b\lambda_2}{a} \tag{11}$$

We see that the value of Q^* may be greater than q^* if $-b\lambda_2 < \Delta a < 0$. We have two cases with regard to the additive term in Equation (11):

Case 3: $-b\lambda_2 < \Delta a < 0$

When this condition is true, Q^* does not satisfy the constraint $Q < q$ when $\Delta a < 0$. This implies that the original production plan should not be changed $Q^* = q^*$ unless the magnitude of demand disruption is large enough (greater than $b\lambda_2$). The optimum solution of Case 3 is exactly the same as Equation (9) for Case 2. The quantity sold is the same as the originally planned but the retail price should be decreased to achieve maximum profit (which is still less than the optimum profit in the linear demand function).

Case 4: $\Delta a < -b\lambda_2$

When this condition is true, Q^* satisfies the constraint $Q < q$ when $\Delta a < 0$, implying that Π is indeed maximized at Q^*. We calculate the new optimum parameters and compare with the optimum solution in the linear demand function in Equation (5):

$$P^* = \kappa p^* - \lambda_2, \Pi^* = \kappa^2 \pi^* - \lambda_2 q^*$$

$$\text{where } \kappa = 1 + \frac{\Delta a + b\lambda_2}{a} \tag{12}$$

The decrease in the consumer demand results in the optimum solution that is lower than the original one.

For the decentralized supply chain, we apply the actual demand from Equation (3) and the new retail price from Equation (4), the profit maximization problem at the Retailer in Equation (5) now becomes

$$max\Pi_3 = Q\left(\frac{a+\Delta a-Q}{b}\right) - \left(W_2Q + \alpha_3Q^2\right) - \lambda_1(Q-q)^+ - \lambda_2(q-Q)^+ \tag{13}$$

where $(x)^+ = \max\{x, 0\}$

We apply the same two constraints as were given earlier for the centralized supply chain and tabulate the results in Table 3.

3.2. Disruption in a supply chain with exponential demand

Let $\delta \neq 1$ be the demand disruption parameter. The actual demand Q realized in the second period can be expressed in the new deterministic demand function $D(P) = Q = (\delta A)P^{-B}$. The centralized supply chain optimization problem now becomes

$$\max \Phi = (\delta A)^{1/B}Q^{B-1/B} - \alpha Q^2 - \lambda_1(Q-q)^+ - \lambda_2(q-Q)^- \tag{14}$$

where Π is the new total supply chain profit and $(x)^+ = \max\{x, 0\}$.

When actual demand is more than originally planned ($Q > q$), Equation (14) becomes

$$\max \Pi = (\delta A)^{1/B}Q^{B-1/B} - \alpha Q^2 - \lambda_1(Q-q) \tag{15}$$

The optimum quantity Q^* that maximizes the profit can be derived from the first-order condition of Equation (15):

$$\frac{d\Pi}{dQ} = \frac{B-1}{B}(\delta A)^{1/B}Q^{-1/B} - 2\alpha Q - \lambda_1 = 0 \tag{16}$$

Given the formulas above, it can be seen that exact solutions would be very difficult to obtain. We will adopt a numerical analysis approach to find the optimum quantity Q^* when the base demand is exponential. In the remainder of this section and the section following, we will present constraints in a similar fashion as those of the linear demand function in the previous sections.

The root of the nonlinear Equation (16) will give the optimum quantity Q^* that maximizes the centralized supply chain profit. However, Q^* can be of any value and not necessarily satisfy the constraint $Q^* = q^*$. We apply the following property of Limits Function

$$\lim_{x\to a}\left(f(a)+g(x)\right) = \lim_{x\to a}f(x) + \lim_{x\to a}g(x)$$

to investigate.

Suppose the optimum quantity Q^* is infinitely close to the originally planned q^*, or $Q^* \to q^*$. Equation (16) becomes:

$$\lim_{Q^*\to q^*}\left(\frac{B-1}{B}\left(\frac{\delta A}{Q^*}\right)^{1/B} - 2\alpha Q^* - \lambda_1\right) = 0$$

$$\delta^* = \left(1 + \frac{\lambda_1}{2\alpha q^*}\right)^B \tag{17}$$

We apply the similar procedure for the negative disruption and we have

$$\delta^* = \left(1 - \frac{\lambda_2}{2\alpha q^*}\right)^B \tag{18}$$

Similar to the threshold parameter Δa for the linear demand function in Section 2.1, these δ^* will determine whether the disruption is major (Case 1 and 4) or minor (Case 2 and 3).

Using the same procedure, we obtain the following threshold parameters for the decentralized supply chain with base exponential demand when the demand increases

$$\delta^* = \left(1 + \frac{\lambda_1}{2q^*(2\alpha_1 + \alpha_2 + 2\alpha_3}\right)^B \tag{19}$$

and when the demand decreases

$$\delta^* = \left(1 - \frac{\lambda_2}{2q^*(2\alpha_1 + \alpha_2 + 2\alpha_3)}\right)^B \tag{20}$$

4. Numerical analysis and discussion

In each of the four scenarios presented in this section, we consider three reactions to the demand disruption:

(1) Baseline: no action taken. The production plan, the wholesale price, and the retail price in the second period are equal to the first period. We take into account the consequence of not responding to the demand disruption (e.g. some quantities will be left unsold when the actual demand is less than the original plan).

(2) Retail Price Adjustment: the Retailer chooses not to participate in the Stackelberg game by adjusting the retail price independently in order to maximize own profit. The production plan and the wholesale price in the second period are equal to the first period. We show that this scenario works well for the Retailer only when the disruption is positive.

(3) Optimal Disruption Management: methods of handling the demand disruption are used that will generate the optimum profit. In the centralized model, the firm will adjust both production plan and the retail price if the disruption is major (beyond a certain threshold) and otherwise will adjust only the retail price. In the decentralized model, the OEM, being the leader, will make adjustment to the production plan and the wholesale price policies only when the demand disruption is major (beyond a certain threshold). When the demand disruption is minor, the OEM will keep the original production plan and the wholesale price policies and let the Retailer decide on the retail price. We show that the original production plan already has some robustness with disruptions.

4.1. Disruption in a centralized supply chain with linear demand

Let the demand function be characterized by the market scale $a = 1\,0\,0\,0$, the price-sensitive coefficient $b = 1$, and the positive coefficient of the product marginal cost in the centralized supply chain $\alpha = 1$. The unit penalty cost for changing the production plan is $\lambda_1 = \$300$ due to the demand increase and $\lambda_2 = \$60$ due to the demand decrease. From Table 2, we find the optimal demand quantity is $q^* = 250$, the optimal retail price is $p^* = 750$, and the supply chain profit will be $\pi^* = \$125,000$.

Case 1: Demand Increase $\left(\Delta a > b\lambda_1\right)$

Suppose the market scale is higher than anticipated, $\Delta a = 4\,0\,0$. In the baseline scenario, the demand increase is completely ignored. There are no changes in the production quantity, the retail

price, and the profit. However, from Equations (4) and (3), we can see that there is an opportunity to increase the retail price to $1,100.

$$P = \frac{(a + \Delta a) - q}{b} = (1000+400) - 250 = \$1150$$

The profit now becomes

$$\Pi = qP - \alpha q^2 = 250 \times 1150 - 1 \times 250^2 = \$225,000.$$

This is an increase of 80% compared to the profit from the original production plan.

Also from Equations (4) and (3), we see that the firm has the option to sell a larger quantity with the original retail price. However, the firm will lose money due to the penalty cost λ_1 when the production plan is increased. With the numbers above, the firm profit goes to zero when the production quantity is increased to 450 units.

From Section 3.1 Equation (7), we obtain the new optimal retail price $P^* = \$1,125$ and the new production quantity $Q^* = \$275$. The new supply chain profit is $\Pi^* = \$226,250$. By acting upon the demand disruption, a larger quantity will be sold at a higher retail price and the profit will increase by 81%.

From the results above, we see that Optimal Disruption Management in case 1 will generate more profit than the baseline. The difference in the profit increase between a Retail Price Adjustment and Optimal Disruption Management is small (1%) when the market scale increases by 40%, but it grows larger with the larger market scale increase. For example, Optimal Disruption Management will result in 49% incremental profit compare to a Retail Price Adjustment when the market scale increases by 100%.

Case 2: Demand Increase $(\Delta a < b\lambda_1)$

Suppose the market scale increase is 100, which corresponds to case 2 in Section 3.1. This demand increase is ignored in the baseline scenario. Applying Optimal Disruption Management, the owner retains the original production plan of 250 units but increases the retail price to $850. This results in a profit of $150,000, an increase of 20% from the baseline. Optimal Disruption Management is in fact the same as a Retail Price Adjustment in this case.

Case 3: Demand Decrease $\left(\Delta a < -b\lambda_2\right)$

The market scale decreases by 50, which corresponds to case 3 in Section 3.1. When the demand decrease is ignored (baseline), only 200 units can be sold at $750 unit price. The profit will be $84,500 after $3,000 penalty cost for disposing 50 leftover units.

Applying Optimal Disruption Management, the firm keeps the original production plan of 250 units but has to reduce the retail price to $700 to avoid any leftover. This results in $112,500 profit, an increase of 33% from the baseline. Similar with case 2, Optimal Disruption Management in case 3 is in fact the same as a Retail Price Adjustment.

Case 4: Demand Decrease $\left(\Delta a < 0, \Delta a < b\lambda_2\right)$

Suppose the market scale now is lower than anticipated, $\Delta a = -1\ 0\ 0$. As the baseline, we consider the firm continues to product 250 units and to sell at the $750 retail price. At the end of the second period, there are 100 units leftover. The profit is $44,000 after incurring a $6,000 penalty cost for disposal of 100 excess units.

If the firm chooses to sell all 250 units per the original production plan and to lower the unit retail price to \$650 per Equation (4), the maximum profit will be \$100,000, which is a 127% increase compared to the baseline.

Within the demand disruption context, this situation corresponds to case 4 in Section 3.1. Applying Optimal Disruption Management, we have the optimal retail price $P^* = \$660$, the new production quantity $Q^* = 240$, and the new supply chain profit Π^* = \$100,200. By acting upon the demand disruption, the owner eliminates the potential excess inventory and increases the profit by 128% compared to the baseline.

Similar to the demand increase in case 1, the difference in the profit increase between a Retail Price Adjustment and Optimal Disruption Management is small (1%) in the analysis above, but it grows larger as the market scale further decreases. For example, Optimal Disruption Management will result in \$24,200 profit compare to zero profit in a Retail Price Adjustment when the market scale decreases by 50%.

We summarize our results of the effectiveness of demand disruption management in Table 5. Additional results can be found in Table 9 in Appendix 1.

Table 5 Effectiveness of demand disruption management in the centralized supply chain with when the base demand is linear

$a = 1,000; b = 1; \alpha = 1; \lambda_1 = 300; \lambda_2 = 60$

Market scale change (%)	Demand disruption		Quantity		Retail price ($)	Supply chain profit	Supply chain profit Relative to none (Baseline) (%)
	Case	Reaction	Produced	Sold			
+100	1	None (Baseline)	250	250	750	\$125,000	
+100	1	Ret. Price Adj.	250	250	1,750	\$375,000	+200
+100	1	Opt. Disr. Mgmt.	425	425	1,575	\$436,250	+249
+40	1	None (Baseline)	250	250	750	\$125,000	
+40	1	Ret. Price Adj.	250	250	1,150	\$225,000	+80
+40	1	Opt. Disr. Mgmt.	275	275	1,125	\$226,250	+81
+10	2	None (Baseline)	250	250	750	\$125,000	
+10	2	Ret. Price Adj.	250	250	850	\$150,000	+20
+10	2	Opt. Disr. Mgmt.	250	250	850	\$150,000	+20
−5	3	None (Baseline)	250	200	750	\$84,500	
−5	3	Ret. Price Adj.	250	250	700	\$112,500	+33
−5	3	Opt. Disr. Mgmt.	250	250	700	\$112,500	+33
−10	4	None (Baseline)	250	150	750	\$44,000	
−10	4	Ret. Price Adj.	250	250	650	\$100,000	+127
−10	4	Opt. Disr. Mgmt.	240	240	660	\$100,200	+128
−50	4	None (Baseline)	250	–	750	N/A	
−50	4	Ret. Price Adj.	250	250	250	N/A	
−50	4	Opt. Disr. Mgmt.	140	140	360	\$24,200	

4.2. Disruption in a decentralized supply chain with linear demand

We allocate 50% of the product cost to the EMS, 35% to the OEM, and 15% to the Retailer, or $\alpha_1 = 0.5, \alpha_2 = 0.35$, and $\alpha_3 = 0.15$. When there is no disruption, we can calculate using the formulas in Table 3 the supply chain total optimum profit of \$99,456 from selling 136 units with a retail price of \$863. The wholesale price from the EMS to the OEM is \$137 and from the OEM to the Retailer is \$685. The OEM, being the Stackelberg leader, realizes most of the profit (69%) followed by the Retailer (22%) and the CM (9%).

Suppose the market scale is higher than anticipated, Δa = 4 0 0. In the baseline scenario, the demand increase is completely ignored. There are no changes in the production quantity, the retail price, and the profit. However, from Equations (4) and (3), we can see that there is an opportunity to increase the retail price to \$1,264.

$$P = \frac{(a + \Delta a) - q}{b} = \left(1000{+}400\right) - 136 = \$1264$$

In the case of a Retail Price Adjustment, we assume there are no changes in the wholesale prices within the supply chain. The profit increase, just like the penalty cost, will be at the Retailer only.

When we apply Optimal Disruption Management as in the previous section, the quantity sold increases to 150 at a \$1,249 retail price. The new total optimum profit is \$160,697, a 62% increase from the baseline and an 8% higher than the Retail Price Adjustment above. The OEM still realizes most of the profit, but its share now reduces to 51%, while the Retailer's share increases to 42%.

We apply the same logic on the four cases similar to the previous section and we tabulate the impact of managing the demand disruption in Table 6. Additional results can be found in Table 10 in Appendix 1.

When the demand increases but is ignored, the supply chain profits for each member remain the same as if there was no disruption. However, the Retailer will have to dispose of the excess inventory at the end of the second period if no action is taken in response to the demand decreases.

Applying a Retail Price Adjustment when the disruption is positive will result in an increase only to the Retailer's profit because the wholesale price policies remain the same. We see in our numerical example that this works well when the disruption is positive. The Retailer may still earn some profit when the negative disruption is close to the threshold $-b\lambda_2$ (−10% in our numerical example). As the negative disruption grows larger, the Retailer profit quickly goes away (no profit when the market scale decreases by 50% in our numerical example). A Retail Price Adjustment works best when the disruption is within the threshold $0 \leq \Delta a \leq b\lambda_1$ for positive disruption and $-b\lambda_2 \leq \Delta a \leq 0$ for negative disruption. In fact, Optimal Disruption Management formulated in case 2 and case 3 in Section 3.1 is a Retail Price Adjustment.

Optimal Disruption Management results in the optimum solution in case 1 and case 4 (demand disruption exceeding the threshold). In Case 1, the Retailer earns a larger share of the total supply chain profit (an increase from 22 to 42%) when the positive disruption is relatively small (40% in our example) and is acted upon. The OEM, being the Stackelberg leader, still retains most of the total supply chain profit (>50%). As the positive disruption becomes larger, the Retailer's profit portion will shrink, as the Retailer will incur a higher penalty cost due to the additional quantity needed to produce the original production plan. In our analysis, the Retailer's portion shrinks from 42 to 31% of the total profit when the market scale increases from +40 to +100%. The Retailer's profit portion behaves similarly when the disruption is negative. When the market scale reduces by 50%, the Retailer still earns some profit under Optimal Disruption Management compare to none under a Retail Price Adjustment.

In summary, we can see that the supply chain profit in both the centralized and decentralized models with linear demand equals the baseline if the demand disruption is positive but ignored.

Table 6. Effectiveness of demand disruption management in the decentralized supply chain with when the base demand is linear

$a = 1,000; b = 1; \alpha_1 = 0.5; \alpha_2 = 0.35; \alpha_3 = 0.15; \lambda_1 = 300; \lambda_2 = 60$

Market scale change (%)	Demand disruption		Quantity		Wholesale price to CEM	Wholesale price to retailer ($)	Retail price ($)	Supply chain profit				
	Case	Reaction	Produced	Sold				EMS (%)	OEM (%)	Retailer (%)	Total ($)	Rel. to none (Baseline) (%)
+100	1	None (Baseline)	136	136	$137	685	863	9	69	22	99,456	
+100	1	Ret. Price Adj.	136	136	$137	685	1,864	4	29	67	235,008	+136
+100	1	Opt. Disr. Mgmt.	232	232	$233	1,164	1,767	8	60	31	327,349	+229
+40	1	None (Baseline)	136	136	$137	685	863	9	69	22	99,456	
+40	1	Ret. Price Adj.	136	136	$137	685	1,264	6	44	50	153,408	+54
+40	1	Opt. Disr. Mgmt.	150	150	$151	753	1,249	7	51	42	160,697	+62
+10	2	None (Baseline)	136	136	$137	685	863	9	69	22	99,456	
+10	2	Ret. Price Adj.	136	136	$137	685	964	8	61	31	113,055	+14
+10	2	Opt. Disr. Mgmt.	136	136	$137	685	964	8	61	31	113,055	+14
−5	3	None (Baseline)	136	87	$137	685	863	+	+	−	53,754	
−5	3	Ret. Price Adj.	136	136	$137	685	863	10	74	16	92,655	+14
−5	3	Opt. Disr. Mgmt.	136	136	$137	685	863	10	74	16	92,655	+14
−10	4	None (Baseline)	136	37	$137	685	863	+	+	−	N/A	
−10	4	Ret. Price Adj.	136	136	$137	685	764	11	80	9	85,408	
−10	4	Opt. Disr. Mgmt.	136	131	$132	658	768	10	76	14	83,432	
−50	4	None (Baseline)	136	0	$137	685	863	+	+	−	N/A	
−50	4	Ret. Price Adj.	136	136	$137	685	364	+	+	−	N/A	
−50	4	Opt. Disr. Mgmt.	76	76	$77	384	423	11	81	8	26,629	

Applying Optimal Disruption Management will maximize the supply chain profit. When the positive disruption is major, the production plan and the wholesale price policies will be adjusted, and the retail price will be increased. When the demand disruption is positive but minor, the supply chain will sell the same quantity but at a higher retail price. In our numerical example, the management of the positive demand disruption in the centralized model results in a higher profit increase relative to the decentralized model.

When the demand disruption is negative and ignored, the supply chain will experience higher financial damage in the decentralized model. In our numerical example, the profit decrease in the major negative disruption case is twice the decrease in the minor negative case for both the centralized and decentralized models. In the decentralized model, the Retailer enjoys the least benefit from managing the demand decrease because it is burdened with the financial risk of demand planning.

4.3. Disruption in a centralized supply chain with exponential demand

Suppose the base exponential demand function is characterized by market scale $A = 1.05 \times 10^{11}$, demand elasticity $B = 3$, and marginal cost coefficient $\alpha = 1$. The unit penalty cost for changing the production plan is $\lambda_1 = \$300$ due to the demand increase and $\lambda_2 = \$60$ due to the demand

Table 7. Effectiveness of demand disruption management in the centralized supply chain with when the base demand is exponential

$A = 1.05 \times 10^{11}$; $B = 3$; $\alpha = 1$; $\lambda_1 = 300$; $\lambda_2 = 60$

Market scale change (%)	Demand disruption		Quantity		Retail price ($)	Supply chain profit ($)	Supply chain profit relative to none (Baseline) (%)
	Case	Reaction	Produced	Sold			
+900	1	None (Baseline)	250	250	750	125,000	
+900	1	Ret. Price Adj.	250	250	1,616	341,457	+173
+900	1	Opt. Disr. Mgmt.	337	337	1,463	353,272	+183
+400	1	None (Baseline)	250	250	750	125,000	
+400	1	Ret. Price Adj.	250	250	1,282	258,120	+106
+400	1	Opt. Disr. Mgmt.	267	267	1,255	258,606	+107
+100	2	None (Baseline)	250	250	750	125,000	
+100	2	Ret. Price Adj.	250	250	945	173,375	+39
+100	2	Opt. Disr. Mgmt.	250	250	945	173,375	+39
−20	3	None (Baseline)	250	200	750	84,500	
−20	3	Ret. Price Adj.	250	250	696	111,560	+32
−20	3	Opt. Disr. Mgmt.	250	250	696	111,560	+32
−40	4	None (Baseline)	250	150	750	44,000	
−40	4	Ret. Price Adj.	250	250	633	95,644	+117
−40	4	Opt. Disr. Mgmt.	242	242	639	95,708	+118
−90	4	None (Baseline)	250	25	750	N/A	
−90	4	Ret. Price Adj.	250	250	348	24,530	
−90	4	Opt. Disr. Mgmt.	163	163	401	33,649	

decrease. From Table 4, we calculate the optimal centralized supply chain profit of $125,000, which is obtained by selling 250 units at a retail price of $750.

Suppose the market scale increases by 400% (disruption parameter $\delta = 5$). From Equation (17), we know that this disruption belongs to case 1. We use numerical analysis of the Newton Method to find the roots of Equation (16). We calculate Q_j^* using the formula:

$$Q_j = Q_{j-1} - \frac{f\left(Q_{j-1}\right)}{f'\left(Q_{j-1}\right)} \quad \text{until} \quad \left|\frac{f\left(Q_{j-1}\right)}{f'\left(Q_{j-1}\right)}\right| \leq 0.5$$

where $j = 1, 2, 3, 4, \ldots$, and from Equation (16):

$$f(Q) = \frac{B-1}{B}\left(\frac{\delta A}{Q}\right)^{1/B} - 2\alpha Q - \lambda_1 f'(Q) = \frac{1-B}{B^2}\left(\frac{\delta A}{Q^{1+B}}\right)^{1/B} - 2\alpha$$

For the initial value Q_0, we use the optimum quantity of the base demand 250. After two iterations, we obtain $Q \cong 267$.

We use a similar procedure to calculate the optimum quantity for the different constraint cases. As in Section 4.1, we calculate the retail price and the firm's profit for Optimal Disruption Management and a Retail Price Adjustment and tabulated the results in Table 7. Additional results can be found in Table 11 in Appendix 1.

In general, we have similar results from the disruption when the base demand is linear in Section 4.1. Total profit is higher when the demand disruption is managed, using Optimal Disruption Management as well as a Retail Price Adjustment. The profit difference between a Retail Price Adjustment and Optimal Disruption Management is not significant when the disruption is small relative to the threshold. However, Optimal Disruption Management results in a higher profit as the demand disruption becomes larger. When the demand decreases by 90% (disruption parameter $\delta = 0.1$), the Retailer will still earn a profit of $33,649 under Optimal Disruption Management compared to $24,530 under a Retail Price Adjustment.

4.4. Disruption in a decentralized supply chain with exponential demand

We use the same cost allocation as for the decentralized supply chain with linear demand. When there is no demand disruption (baseline), profit is maximized by selling 126 units at a retail price of $942. The OEM, being the Stackelberg leader, has the largest share of the profit (51%) followed by the Retailer (41%) and the EMS (8%). We apply the same logic for the different cases of the demand disruption as in the previous sections. The results are tabulated in Table 8. Additional results can be found in Table 12 in Appendix 1.

We find in our example that when the demand is exponential, the initial production plan in the decentralized model is more robust to a demand disruption than the centralized model. Using the Newton Method as in the previous section, we find that the initial production plan in the decentralized model should not be changed unless the market scale increases more than 406% or decreases more than 37% compared to 310% or 32% in the centralized model.

Similar to the results from the previous sections, the profit is higher when the demand disruption is managed. The supply chain profit is maximized under Optimal Disruption Management when the disruption is relatively large compared to the threshold. However, we see that the OEM's share of the profit under Optimal Disruption Management becomes lower than the Retailer's when the disruption is positive. This suggests that the wholesale price contract does not work very well for the Stackelberg leader and another coordination mechanism such as a revenue-sharing contract should be considered.

Table 8. Effectiveness of demand disruption management in the decentralized supply chain with when the base demand is exponential

$A = 1.05 \times 10^{11}$; $B = 3$; $\alpha_1 = 0.5$; $\alpha_2 = 0.35$; $\alpha_3 = 0.15$; $\lambda_1 = 300$; $\lambda_2 = 60$

Market scale change (%)	Demand disruption		Quantity		Wholesale price to EMS ($)	Wholesale price to retailer ($)	Retail price ($)	Supply Chain profit				
	Case	Reaction	Produced	Sold				EMS (%)	OEM (%)	Retailer (%)	Total ($)	Rel. to none (Baseline) (%)
+1,000	1	None (Baseline)	126	126	127	589	942	8	51	41	102,871	
+1,000	1	Ret. Price Adj.	126	126	127	589	2,096	3	21	76	248,214	+141
+1,000	1	Opt. Disr. Mgmt.	166	166	166	925	1,912	5	42	53	277,823	+170
+500	1	None (Baseline)	126	126	127	589	942	8	51	41	102,871	
+500	1	Ret. Price Adj.	126	126	127	589	1,713	4	26	70	199,901	+94
+500	1	Opt. Disr. Mgmt.	134	134	134	778	1,678	4	39	57	204,461	+99
+100	2	None (Baseline)	126	126	127	589	942	8	51	41	102,871	
+100	2	Ret. Price Adj.	126	126	127	589	1,187	6	39	55	133,735	+30
+100	2	Opt. Disr. Mgmt.	126	126	127	589	1,187	6	39	55	133,735	+30
−20	3	None (Baseline)	126	100	127	589	942	9	56	36	93,949	
−20	3	Ret. Price Adj.	126	126	127	589	875	9	56	36	94,359	+0
−20	3	Opt. Disr. Mgmt.	126	126	127	589	875	9	56	36	94,359	+0
−50	3	None (Baseline)	126	63	127	589	942	10	69	21	76,483	
−50	3	Ret. Price Adj.	126	126	127	561	748	10	63	27	78,373	+2
−50	3	Opt. Disr. Mgmt.	126	126	127	561	748	10	63	27	78,373	+2
−85	4	None (Baseline)	126	19	127	589	942	+	+	−	N/A	
−85	4	Ret. Price Adj.	126	126	127	396	501	+	+	−	N/A	
−85	4	Opt. Disr. Mgmt.	92	92	92	443	556	10	72	17	40,656	

5. Conclusion

We have investigated disruption management in a two-period three-tier decentralized electronics supply chain consisting of an EMS, an OEM, and a Retailer. We began our study with a centralized model where the EMS, OEM, and Retailer are all within one firm. We then extended these results to a decentralized model governed by a wholesale price contract. Our modeling and analysis approaches are applicable to both linear and exponential demand functions.

A penalty cost is incurred when a demand disruption necessitates an increase or decrease in production from the original plan. Additional production requires more expensive resources such as overtime labor, and in this case we show that the supply chain can generate more profit if the demand increase is properly managed. In the case when actual demand is less than the initial plan, the supply chain may have to dispose or sell the leftover inventory to a secondary market, and disruption management can minimize the reduction in supply chain profit. We also show the robustness of the original production quantity. When the disruption is within a certain threshold, it is more profitable for the supply chain to adhere to its original production plan, especially when the demand function is exponential.

When the demand disruption occurs in the decentralized model with linear demand and is managed using Optimal Disruption Management, the OEM as the Stackelberg leader retains the larger share of the supply chain profit. However, this is not always true when the demand disruption occurs in the decentralized model with exponential demand. Further study is required to determine if the wholesale price contract indeed does not work in favor of the Stackelberg leader in the case of disruptions with exponential demand.

Several managerial insights can be gained from the results of this paper. First, supply chain managers should not automatically react to an individual disruption but rather understand the consequences of different recovery strategies. When circumstances correspond to case 2 and case 3 we see that it is better to leave the production plan unchanged. With a good pricing scheme, the retailer will not end up with obsolete finished goods inventory. Second, retailers have the opportunity to maximize their profit (by increasing their retail price) if the actual demand exceeds the plan and the powerful OEM does not react. Third, contingency plans (e.g. extra inventory, extra manufacturing capacity, alternative suppliers) should be readily available to ensure business continuity and avoid long-term impact. Fourth, supply chain managers also need to understand the power structure and the coordination mechanism of the decentralized supply chain. A simple pure wholesale price contract may not be ideal and may need to be coupled with other coordinating contracts such as a profit sharing and return policy.

Our work can be extended in several directions. We have assumed that there is only one leader in the supply chain. One extension to our model would be where there are several competing players in each supply chain tiers and multiple leaders. A second direction would be to consider an extension to the wholesale price contract, such as a revenue-sharing contract, buy-back contract, etc. Finally, it would be interesting to apply robust optimization techniques in the model. Closed-form expressions of key parameters can be derived and will provide a deeper insight into the effect of leadership in the supply chain when the demand function is exponential and stochastic.

Funding
The authors received no direct funding for this research.

Author details
Johannes Danusantoso[1]
E-mail: johannes.danu@gmail.com
ORCID ID: http://orcid.org/0000-0002-1595-681X
Scott A. Moses[1]
E-mail: moses@ou.edu
[1] School of Industrial & Systems Engineering, University of Oklahoma, 202W. Boyd St., Norman, OK 73019-1022, USA.

Citation information
Cite this article as: Disruption management in a two-period three-tier electronics supply chain, Johannes Danusantoso & Scott A. Moses, *Cogent Business & Management* (2016), 3: 1137138.

References

Banker, R. D., Datar, S. M., & Kekre, S. (1988). Relevant costs, congestion and stochasticity in production environments. *Journal of Accounting and Economics, 10*, 171–197. http://dx.doi.org/10.1016/0165-4101(88)90002-X

Cachon, G. P. (2003). Supply chain coordination with contracts. in A. G. de Kok & S. C. Graves (Eds.), *Handbooks in operations research and management science Volume 11: Supply chain management: Design, coordination and operation* (pp. 229–232). Amsterdam: Elsevier B.V.

Cachon, G. P., & Lariviere, M. A. (2001). Contracting to assure supply: How to share demand forecasts in a supply chain. *Management Science, 47*, 629–646. http://dx.doi.org/10.1287/mnsc.47.5.629.10486

Clausen, J., Hansen, J., Larsen, J., & Larsen, A. (2001). Disruption management. *OR/MS Today, 28*, 40–43.

Ding, D., & Chen, J. (2008). Coordinating a three level supply chain with flexible return policies. *Omega, 36*, 865–876. http://dx.doi.org/10.1016/j.omega.2006.04.004

Eliashberg, J., & Steinberg, R. (1987). Marketing-production decisions in an industrial channel of distribution. *Management Science, 33*, 981–1000. http://dx.doi.org/10.1287/mnsc.33.8.981

IBM Global Business Services. (2008, May 5). *The enterprise of the future: The global CEO study 2008* (Electronics Industry Edition). Retrieved April 25, 2009, from IBM Global Business Services Website: http://www-935.ibm.com/services/us/gbs/bus/pdf/gbe03105-usen-ceo-electronics.pdf

Lariviere, M. A., & Porteus, E. L. (2001). Selling to the newsvendor: An analysis of price-only contracts. *Manufacturing & Service Operations Management, 3*, 293–305.

Lei, D., Li, J., & Liu, Z. (2012). Supply chain contracts under demand and cost disruptions with asymmetric information. *International Journal of Production Economics, 139*, 116–126. http://dx.doi.org/10.1016/j.ijpe.2011.11.031

Mills, E. S. (1959). Uncertainty and price theory. *The Quarterly Journal of Economics, 73*, 116–130. http://dx.doi.org/10.2307/1883828

Munson, C. L., & Rosenblatt, M. J. (2001). Coordinating a three-level supply chain with quantity discounts. *IIE Transactions, 33*, 371–384.

Qi, X., Bard, J. F., & Yu, G. (2004). Supply chain coordination with demand disruptions. *Omega, 32*, 301–312. http://dx.doi.org/10.1016/j.omega.2003.12.002

Randewich, N. (2011, Oct 28). Thai Floods Boost PC Hard Drive Prices. (US). San Fransisco: Reuters. Retrieved from http://www.reuters.com/article/us-thai-floods-drives-idUSTRE79R66220111028

Seifert, R. W., Zequeira, R. I., & Liao, S. (2012). A three-echelon supply chain with price-only contracts and sub-supply chain coordination. *International Journal of Production Economics, 138*, 345–353. http://dx.doi.org/10.1016/j.ijpe.2012.04.006

Taylor, P. (2013, May 12). Sennheiser Fight Fake Electronic Goods. *Financial Times,* New York. Retrieved from http://www.ft.com/intl/cms/s/0/6454afe8-b9a7-11e2-9a9f-00144feabdc0.html#axzz3uZu4MlDG .

Xiao, T., & Qi, X. (2008). Price competition, cost and demand disruptions and coordination of a supply chain with one manufacturer and two competing retailers. *Omega, 36*, 741–753. http://dx.doi.org/10.1016/j.omega.2006.02.008

Xu, M., Qi, X., Yu, G., & Zhang, H. (2006). Coordinating dyadic supply chains when production costs are disrupted. *IIE Transactions, 38*, 767–775.

Yu, G. (Ed.). (1998). *Operations research in the airline industry*. Norwell, MA: Kluwer Academic.

Yu, G., Argüello, M., Song, G., McCowan, S., & White, A. (2003). A new era for crew recovery at continental airlines. *Interfaces, 33*, 5–22. http://dx.doi.org/10.1287/inte.33.1.5.12720

Yu, G., & Qi, X. (2004). *Disruption management*. Singapore: World Scientific. http://dx.doi.org/10.1142/5632

Zhang, W.-G., Fu, J., Li, H., & Xu, W. (2012). Coordination of supply chain with a revenue-sharing contract under demand disruptions when retailers compete. *International Journal of Production Economics, 138*, 68–75. http://dx.doi.org/10.1016/j.ijpe.2012.03.001

Appendix 1

Table 9. Effectiveness of demand disruption management in the centralized supply chain with when the base demand is linear

$a = 2,000; b = 0.9; \alpha = 0.8; \lambda_1 = 100; \lambda_2 = 60$

Market scale change (%)	Demand disruption		Quantity		Retail price ($)	Supply chain profit ($)	Supply chain profit relative to none (Baseline) (%)
	Case	Reaction	Produced	Sold			
+100	1	None (Baseline)	581	581	1,576	645,995	
+100	1	Ret. Price Adj.	581	581	3,798	1,937,984	+200
+100	1	Opt. Disr. Mgmt.	1,137	1,137	3,182	2,527,148	+291
+40	1	None (Baseline)	581	581	1,576	645,995	
+40	1	Ret. Price Adj.	581	581	2,465	1,162,791	+80
+40	1	Opt. Disr. Mgmt.	788	788	2,236	1,244,202	+93
+10	2	None (Baseline)	581	581	1,576	645,995	
+10	2	Ret. Price Adj.	581	581	1,798	775,194	+20
+10	2	Opt. Disr. Mgmt.	581	581	1,798	775,194	+20
−5	3	None (Baseline)	581	481	1,576	482,372	
−5	3	Ret. Price Adj.	581	581	1,465	581,395	+21
−5	3	Opt. Disr. Mgmt.	581	581	1,465	581,395	+21
−10	4	None (Baseline)	581	381	1,576	318,749	
−10	4	Ret. Price Adj.	581	581	1,354	516,796	+62
−10	4	Opt. Disr. Mgmt.	539	539	1,401	520,238	+63
−50	4	None (Baseline)	581	–	1,576	N/A	
−50	4	Ret. Price Adj.	581	581	465	N/A	
−50	4	Opt. Disr. Mgmt.	306	306	771	144,528	

Table 10. Effectiveness of demand disruption management in the decentralized supply chain with when the base demand is linear

$a = 1,500$; $b = 0.75$; $\alpha_1 = 0.4$; $\alpha_2 = 0.55$; $\alpha_3 = 0.05$; $\lambda_1 = 300$; $\lambda_2 = 150$

Market scale change (%)	Demand disruption		Quantity		Wholesale price to CEM ($)	Wholesale price to retailer ($)	Retail price ($)	Supply chain profit				
	Case	Reaction	Produced	Sold				EMS (%)	OEM (%)	Retailer (%)	Total ($)	Rel. to none (Baseline) (%)
+100	1	None (Baseline)	243	243	194	1,328	1,676	7	70	23	348,145	
+100	1	Ret. Price Adj.	243	243	194	1,328	3,676	3	29	68	833,975	+140
+100	1	Opt. Disr. Mgmt.	449	449	360	2,457	3,401	6	63	31	1,326,345	+281
+40	1	None (Baseline)	243	243	194	1,328	1,676	7	70	23	348,145	
+40	1	Ret. Price Adj.	243	243	194	1,328	2,209	4	45	51	542,477	+56
+40	1	Opt. Disr. Mgmt.	303	303	243	1,660	2,395	6	60	34	635,070	+82
+10	2	None (Baseline)	243	243	194	1,328	1,676	7	70	23	348,145	
+10	2	Ret. Price Adj.	243	243	194	1,328	1,876	6	61	33	396,728	+14
+10	2	Opt. Disr. Mgmt.	243	243	194	1,328	1,876	6	61	33	396,728	+14
−5	3	None (Baseline)	243	168	194	1,328	1,676	10	75	15	232,999	
−5	3	Ret. Price Adj.	243	243	194	1,328	1,576	7	75	18	323,854	+39
−5	3	Opt. Disr. Mgmt.	243	243	194	1,328	1,576	7	75	18	323,854	+39
−10	4	None (Baseline)	243	93	194	1,328	1,676	+	+	−	N/A	
−10	4	Ret. Price Adj.	243	243	194	1,328	1,476	8	81	11	299,562	
−10	4	Opt. Disr. Mgmt.	236	236	189	1,295	1,484	8	78	14	295,429	
−50	4	None (Baseline)	243	0	194	1,328	1,676	+	0	−	N/A	
−50	4	Ret. Price Adj.	243	243	194	1,328	676	+	+	−	N/A	
−50	4	Opt. Disr. Mgmt.	139	139	112	764	814	8	85	6	94,154	

Table 11. Effectiveness of demand disruption management in the centralized supply chain with when the base demand is exponential

$A = 5 \times 10^{14}$; $B = 4$; $\alpha = 1$; $\lambda_1 = 300$; $\lambda_2 = 60$

Market scale change (%)	Demand disruption		Quantity		Retail price ($)	Supply chain profit ($)	Supply chain profit relative to none (Baseline) (%)
	Case	Reaction	Produced	Sold			
+900	1	None (Baseline)	397	397	1,059	262,282	
+900	1	Ret. Price Adj.	397	397	1,884	590,277	+125
+900	1	Opt. Disr. Mgmt.	589	589	1,707	639,256	+143
+400	1	None (Baseline)	397	397	1,059	262,282	
+400	1	Ret. Price Adj.	397	249	1,584	332,444	+27
+400	1	Opt. Disr. Mgmt.	508	508	1,489	487,465	+86
+100	2	None (Baseline)	397	397	1,059	262,282	
+100	2	Ret. Price Adj.	397	397	1,172	307,825	+17
+100	2	Opt. Disr. Mgmt.	397	397	1,172	307,825	+17
−20	3	None (Baseline)	397	317	1,059	173,188	
−20	3	Ret. Price Adj.	397	397	1,002	240,139	+39
−20	3	Opt. Disr. Mgmt.	397	397	1,002	240,139	+39
−40	3	None (Baseline)	397	238	1,059	84,814	
−40	3	Ret. Price Adj.	397	397	932	212,537	+151
−40	3	Opt. Disr. Mgmt.	382	382	941	212,783	+151
−90	4	None (Baseline)	397	–	896	N/A	
−90	4	Ret. Price Adj.	397	397	596	78,833	
−90	4	Opt. Disr. Mgmt.	275	275	653	96,568	

Table 12. Effectiveness of demand disruption management in the decentralized supply chain with when the base demand is exponential

$A = 5 \times 10^{13}$; $B = 4$;$\alpha_1 = 0.6$; $\alpha_2 = 0.35$; $\alpha_3 = 0.05$; $\lambda_1 = 250$; $\lambda_2 = 50$

Market scale change (%)	Demand disruption		Quantity		Wholesale price to EMS ($)	Wholesale price to retailer ($)	Retail price ($)	Supply chain profit				
	Case	Reaction	Produced	Sold				EMS (%)	OEM (%)	Retailer (%)	Total ($)	Rel. to none (Baseline) (%)
+1,000	1	None (Baseline)	133	133	160	574	782	12	57	31	85,575	
+1,000	1	Ret. Price Adj.	133	133	160	574	1,425	6	29	65	172,275	+99
+1,000	1	Opt. Disr. Mgmt.	215	215	258	627	1,265	14	31	56	277,823	+137
+600	1	None (Baseline)	133	133	160	574	782	12	57	31	85,575	
+600	1	Ret. Price Adj.	133	133	160	574	1,273	7	32	61	151,968	+76
+600	1	Opt. Disr. Mgmt.	197	197	236	546	1,155	13	28	59	172,688	+99
+100	2	None (Baseline)	133	133	160	574	782	12	57	31	85,575	
+100	2	Ret. Price Adj.	133	133	160	574	930	7	49	43	107,723	+24
+100	2	Opt. Disr. Mgmt.	133	133	160	574	930	7	49	43	107,723	+24
−20	3	None (Baseline)	133	107	160	574	782	14	57	29	70,773	
−20	3	Ret. Price Adj.	133	133	160	574	740	13	60	27	80,913	+14
−20	3	Opt. Disr. Mgmt.	133	133	160	574	740	13	60	27	80,913	+14
−50	3	None (Baseline)	133	66	160	574	782	18	59	23	44,401	
−50	3	Ret. Price Adj.	133	133	160	574	657	15	70	15	69,970	+58
−50	3	Opt. Disr. Mgmt.	133	133	160	574	657	15	70	15	69,970	+58
−80	4	None (Baseline)	133	26	160	574	782	26	73	1	14,826	
−80	4	Ret. Price Adj.	133	133	160	574	523	+	+	−	N/A	
−80	4	Opt. Disr. Mgmt.	96	96	116	416	567	12	57	31	45,478	+206

Cogent Business & Management **(ISSN: 2331-1975) is published by Cogent OA, part of Taylor & Francis Group.**