An Integrated Vendor-Buyer Model Subject to Supply Disruption with Transportation Cost

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ABSTRACT

A combined proactive and reactive approach to deal with disruption in the supply chain (SC) is presented in this paper, where an optimization model that is capable of determining the optimal safety stock level and optimal recovery schedule for a serial two-stage SC system was developed. The system considered in the study consists of a single vendor and a single buyer, subject to random supply disruption. The vendor keeps extra inventory as safety stock to be used at the time of disruption as to minimize stock-outs. In addition, the effect of transportation cost to the recovery model is investigated. The developed problem is solved using the branch-and-bound algorithm and numerical analysis is conducted to show the applicability of the model. The

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results indicate that the optimal safety stock level is not significantly influenced by short disruption time and primarily affected by holding cost value. It can be emphasized that within the same number of recovery cycles, the increase of setup cost and ordering cost will increase the optimal safety stock quantity. On the other hand, an increase in holding cost will decrease the optimal safety stock quantity. This paper contributes to the literature on supply disruption recovery and safety stock inventory decisions.

Keywords: *Supply chain; Supply disruption; Safety stock; Transportation cost; Vendor-Buyer Model.*

Introduction

The capability of an organization's supply chain will be challenged when disruption occurs, as the SC manager need to act fast and optimize the necessary resources to respond accordingly. Without an effective action plan, the uncertainty and unpredictability that could occur in the daily operations might lead to poor SC performance and major loss. Furthermore, major disruptions have occurred that caused long-term negative impacts. The 2011 tsunami in Japan and flood in Thailand are examples for the devastating effects that major disruptions could have on the supply chain and subsequently led to research work that studied the appropriate mitigation and recovery strategies in order to prepare the SC against such catastrophes.

In the literature, mitigation strategies to face disruptions have been proposed, which include avoiding extra leanness, adding redundancy, and modularizing process and product design [1]. It was also suggested that SC strategies against disruption can be grouped into a general framework of prevention, response, protection, and recovery policies [2]. Moreover, it was highlighted that a firm can respond better to external disruptions by strengthening its relationship with suppliers. From the operational research and management science (OR/MS) approach, [3] proposed several mitigation strategies for disruption through inventory management, sourcing and demand flexibility, facility location, and interaction with external stakeholders. In addition, [4] proposed in their study that an alternative strategy for supply chain disruption mitigation can be achieved by designing simple processes.

Mitigation strategies to prepare the SC against supply disruption could be in the form of inventory management, sourcing strategy, supply chain network design and several others. These proactive approaches are taken before the disruptions occur. Reactive strategies, on the other hand, are action measures that take place after the disruption occurs, such as the use of backup suppliers, backup transportation or possibly different coordination of SC operations. In the literature review by [5], the authors studied the quantitative methods of supply chain design with a focus on reactive approaches to face disruption. Two disruption considerations commonly considered are whether there is a measure for recovery or without any. In addition, three basic risks to be considered are production, supply and transportation disruptions. The authors proposed future studies that integrate recovery elements into proactive models. [6] reviewed the literature on risk and disruption management in production-inventory and SC systems. In the study, the modelling work was categorized into four classes, including modelling for the imperfect production process, with disruption, supply chain risk, and modelling for disruption recovery. Solution approaches were classified into traditional optimization approaches, heuristic approaches, search algorithm approaches, and simulation approaches. This review emphasized the lack of study that considers a series of multiple disruptions and also the lack of quantitative disruption and risk management models. In addition, implementation of the model on real-life supply chain has been very limited.

In quantitative studies on supply chain disruptions, common objectives among the studies were to seek optimal ordering quantity and cost optimization. Research work includes studies by [7], which presented a real-time recovery mechanism for a two-stage serial supply chain system. Another study by the same authors [8] was on the economic lot-sizing problem of a two-stage SC subject to transportation disruption. [9] studied a multi-layer supply chain model while supply disruption, machine breakdown, safety stock, and maintenance breakdown that occur simultaneously. Their model calculated the integrated total expected cost for the supplier, manufacturer 's warehouse, manufacturer and retailer. [10] proposed a recovery plan for disruptions in a two-stage and single item batch production inventory system. In another study, [11] proposed a recovery plan for managing disruptions in a three-stage production system using an efficient heuristic to manage both single and multiple disruptions.

In the practice of holding extra inventory, there will be a trade-off between the cost resulting from disruptions and the cost resulting from the inventory protection [12]. The authors presented an economic order quantity with disruption (EOQD) model with different ordering policies. [13] studied the effectiveness of two inventory-based policies for mitigating the impact of supply disruptions. R-policy uses strategic inventory reserves while Q-policy uses larger orders. Using analytical model methods, the result showed that R-policy is better. Furthermore, this paper proposed several practical business conditions that would justify the use of reserve inventory. In addition, [14] studied the determination of safety stocks based on a policy of linear order release rules. The cost efficiency of various safety stocks approaches was investigated through a simulation study. These studies indicated that while inventory is a common mitigation strategy, the optimal inventory policy under disruption and in a complex setting does not have a clear-cut solution.

Other research works on safety stock optimization include assembly-to-order system [15] with the order service level objective or constraint. Two problems were considered which include maximizing order service level and minimizing the investment for achieving the service level target. The study employed a greedy algorithm that uses the item-level information only which can be applied when a detailed bill of materials is not available. In addition, [16] studied optimal safety stock for a serial two-stage SC, under guaranteed-service safety stock model assumptions. In this study, the safety stock decision was determined by the cost and lead time of the SC. Besides, [17] proposed a stock control model to optimize the production, the inventory quantity and the backorder level simultaneously for a tire manufacturing company. [18] studied a dynamic inventory hedging problem in a single product, one-supplier-one-buyer supply chain. His study presented an improved strategy from the traditional inventory management approach using advanced supply signals, lost sales, and a fixed transportation cost.

Within the scope of inventory management strategy combined with disruption management, the objective of this study is to develop an inventory model of a supply disruption recovery plan that integrates the mitigation strategy of keeping extra inventory. In addition, transportation cost is incorporated into the model to analyze its effect on disruption process.

The paper is organized as follows. Section II analyzes the relevant past literature of this study. Section III addresses the mathematical model development of the problem under study. Section IV lists the results for numerical analysis together with the discussion. Section V ends the paper with a conclusion and possible areas of future research.

Methodology

Model Development

In this section, an optimal disruption recovery plan is formulated for a two-stage supply chain system consisting of a single vendor and a single buyer. The vendor has both production and inventory system and follows the Economic Production Quantity model (EPQ). On the other hand, the buyer only has inventory and follows the Economic Order Quantity Model (EOQ). The products are produced in batches where the demand rate is assumed to be deterministic and constant. During a normal production cycle at the vendor, the production system can face an unexpected supply disruption. During the disruption, there is no production and the unsatisfied demand becomes backorders or lost sales. After the disruption ends, the recovery process will take place in the recovery window. Safety stock will be used to minimize backorders and lost sales in the first cycle of the recovery window. Figure 1 shows the inventory curve of the problem.

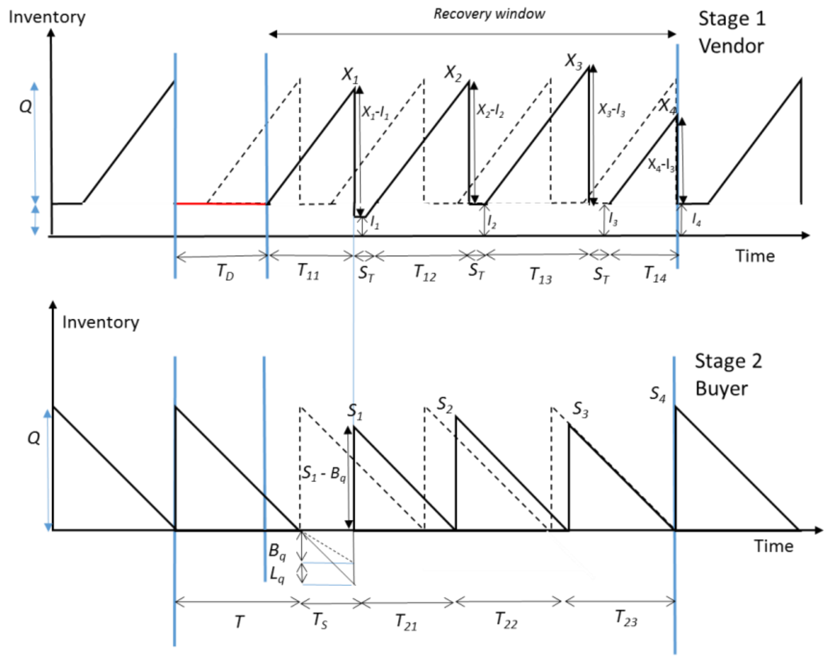


Figure 1: Inventory curve for a two-stage supply chain system under disruption with safety stocks

The recovery model proposed in this study is based on the model by Hishamuddin et al. (2014) with the extension to include excess inventory in the form of safety stock. The cost elements included in the model are setup cost, inventory holding cost, back order cost, lost sales cost, transportation cost and penalty cost. The objectives of the model are to determine the expected total cost of the recovery process, the optimal number of production cycles required to recover from the disruption, the new recovery schedule, consisting of the optimal ordering quantities for buyer and production quantities for the vendor, and the optimal level for safety stock

The following are additional assumptions of the model:

1. The production rate is greater than the demand rate
2. Backorder and lost sales only occur in the first cycle
4. The second stage follows the zero-order inventory policy
5. The safety stock inventory level is replenished at the end of the recovery cycles
6. Disruption time is less than the interval of one production cycle time
7. Shipment of the product during normal production and ordering cycle will take one round trip of the transport truck

8. The truck can accommodate up to an additional 20% capacity than regular quantity for normal ordering cycle

The notations used in developing the mathematical model are as follows:

Decision variables

X_i	production lot size of cycle *i* in the recovery schedule for stage 1 (units)
S_i	order lot size of cycle *i* in the recovery schedule for stage 2 (units)
n	number of cycles in the recovery window
X_s	safety stock quantity (units)

Parameters and notations

A_1	setup cost for the first stage ($/setup)
A_2	ordering cost for the second stage ($/order)
D	demand rate for the system (units/year)
H_1, H_2	annual inventory cost for stages 1 and 2 ($/unit/year)
P	production rate (units/year)
Q_1	production lot size for stage 1 in the original schedule (units)
Q_2	ordering lot size for stage 2 in the original schedule (units)
B_q	back order quantity for stage 2
L_q	lost sales quantity for stage 2
T_D	disruption period
T	production cycle time for a normal cycle *(Q/D)*
S_T	production setup time for each production cycle
B_1, B_2	unit back order cost per unit time for stages 1 and 2 ($/unit/time)
L_1, L_2	unit lost sales cost for stages 1 and 2 ($/unit)
T_{1i}	production time for cycle *i* in the recovery window for stage 1
T_{2i}	production time for cycle *j* in the recovery window for stage 2
I_i	inventory level at the end of cycle i in the recovery window
T_S	shortage of product during the shortage time
C_T	unit transportation cost for each delivery ($/shipment)
q_t	truck capacity
f_1	the penalty function for the delay in recovering the original schedule in the first stage
f_2	the penalty function for the delay in recovering the original schedule of the second stage handled by the first stage
f_3	the penalty function for the delay in recovering the original schedule in the second stage

The total setup cost for stage 1, is formulated by multiplying the set up cost for stage 1 with the number of setups or the number of cycles in the recovery period : A_1 * (Number of setup) $= A_1 * n$ (1)

For this model, the inventory at the end of each cycle *i* is defined as
$I_i = I_{i-1} + X_i - S_i$ for $i=1, 2, \ldots, n$ (2)

Based on Figure 1, the inventory holding cost for stage 1 is obtained by calculating the area under the curve during the recovery cycle:

$$= H_1 * \left[\left(Io * T_{11} + \frac{1}{2}(X_1 - Io) * T_{11} \right) + \left(I_1 * S_T + I_1 * T_{12} + \frac{1}{2}(X_2 - I_1) * T_{12} \right) + \left(I_2 * S_T + I_2 * T_{13} + \frac{1}{2}(X_3 - I_2) * T_{13} \right) + \left(I_3 * S_T + I_3 * T_{14} + \frac{1}{2}(X_4 - I_3) * T_{14} \right) + \ldots \right]$$

$$= H_1 * \left(\sum_{i=1}^{n} \left(\frac{1}{2} (X_i + I_{i-1}) * \frac{X_i}{P} \right) + S_T * \sum_{i=1}^{n-1} I_i \right) \quad (3)$$

For the backorder quantity for stage 1, the number is calculated by the shortage of product during the shortage time, T_S as indicated below:

$$B_q = T_S * D - L_q \quad (4)$$

$$T_S = T_D + \frac{X_1}{P} - \frac{Q}{D} \quad (5)$$

Therefore the backorder cost for stage 1 is

$$= B_1 * \frac{1}{2} * (T_S * D - L_q) * \left(T_D + \frac{X_1}{P} - \frac{Q}{D} \right) \quad (6)$$

While the lost sales cost for Stage 1 is

$$= L_1 * \left(n * Q - \sum_{i=1}^{n-1} S_i \right) \quad (7)$$

As for the transportation cost, the value is obtained by multiplying the unit transportation cost per delivery with the number of deliveries in the recovery cycle.

n-1

$$= C_T \sum_{i=1} S_i/q_t \qquad (8)$$

For the penalty cost, the calculation is as below

$$= f_1(n^2) + f_2(n^2) \qquad (9)$$

Finally, the total recovery cost for stage 1 is the combination of all the cost elements for stage 1:

$$TC_1(X_i, n) = \left[\frac{A_1 * n + H_1 * \left(\sum_{i=1}^{n}\left(\frac{1}{2}(X_i + I_{i-1}) * \frac{X_i}{P}\right) + S_t * \sum_{i=1}^{n} I_i\right) + C_T * \sum_{i=1}^{n-1}\frac{S_i}{q_t} + f_1(n^2) + f_2(n^2)}{nT}\right] + \left(B_1 * (T_S * D - L_q)\left(T_D + \frac{X_1}{P} - \frac{Q}{D}\right)\right) + \left(L_1 * (n * Q - \sum_{i=1}^{n-1} S_i)\right) \qquad (10)$$

Subsequently, for stage 2, the total recovery cost for stage 2 consists of ordering cost, inventory holding cost, backorder cost lost sales cost and penalty cost.

First, the ordering cost for stage 2 is computed by multiplying the ordering cost with the number of orders in the recovery window;

$$= A_2 * (n-1) \qquad (11)$$

Then, the inventory holding cost for stage 2 is obtained by calculating the area under the curve during the recovery cycle:

$$= \frac{H_2}{2D} * \left[(S_1 - B_q)^2 + \sum_{i=2}^{n-1} S_i^{\,2}\right] \qquad (12)$$

As for the backorder cost for stage 2, the value is formulated as

$$= B_2 * \frac{1}{2} * (B_q * T_S)$$

$$= B_2 * \frac{1}{2} * (T_S * D - L_q) * \left(T_D + \frac{X_1}{P} - \frac{Q}{D}\right) \qquad (13)$$

While the lost sales quantity $L_q = \left(n * Q - X_S - \sum_{i=1}^{n-1} S_i\right)$ and lost sales cost is calculated as

$$= L_2 * L_q \qquad (14)$$

The last cost element is the penalty cost for stage 2 which is defined as

$$= f_3(n^2) \qquad (15)$$

Similar to stage 1, total recovery cost for stage 2 can be formulated by combining all the cost elements:

$$TC_2(S_i, n) = \left[\frac{\left(A_2 * (n-1)\right) + \left(\frac{H_2}{2D} * \left[(S_1 - B_q)^2 + \sum_{i=2}^{n-1} S_i^{\,2} \right] \right) + f_3(n^2)}{n * T} \right] +$$

$$\left(B_2 * \frac{1}{2} * (T_S * D - L_q) * \left(T_D + \frac{X_1}{P} - \frac{Q}{D} \right) \right) \qquad (16)$$

$$+ \left(L_2 * \left(n * Q - \sum_{i=1}^{n-1} S_i \right) \right)$$

The total cost function, which is the objective function is obtained by adding TC_1 and TC_2, subject to system constraints (18) – (24).

$$= Min\left[TC_1(X_i, i = 1,2,..n) + TC_2(S_i, i = 1,2,..n) \right] \qquad (17)$$

Subject to the following constraints (17)-(24):

$X_i \geq Q$	(to meet delivery requirements)	(18)
$S_i < qt$	(truck capacity constraint)	(19)
$I_O = X_S = I_n$	(initial inventory is equal to safety stock)	(20)
$\sum_{i=1}^{n} X_i \leq nPT$	(production capacity constraint.)	(21)
$S_n = Q$	(final ordering quantity is resumed to original quantity in normal cycle	(22)
$T_i \leq T - S_t$	(disruption time constraint)	(23)

$$\sum_{i=1}^{n} X_i \geq nTD - L_q + X_S \quad \text{(to meet demand and safety stock replenishment)} \tag{24}$$

Results and Discussions

Numerical Analysis

The recovery model is a complex constrained mixed integer program, thus needs a specialized software to solve the model. Therefore, the developed model was solved using the Branch-and-Bound algorithm, which was coded in LINGO 15.0. This optimization software was selected due to its ability to seek global optimal solutions for NP-hard problems and has relatively easy application. In the analysis, numerical studies were conducted for five test problems. Table 1 lists the parameters used in the numerical computation. Parameters in test 1 are designated as the base parameters for the analysis. In test 2, the disruption time is longer. Meanwhile, in test 3, the unit lost sales costs are changed to be higher than the unit back order costs. For test 4, the unit holding cost values are higher and in test 5, setup cost and ordering cost values are doubled. Table 2 lists the results for each test problem. Subsequently, Table 3 shows the optimal recovery schedule for each test problem, consisting of production and shipment quantities. Values for production rate, P = 250 000, demand rate, D=200 000, and unit transportation cost C_T=200 were used in the analysis.

Table 1: Parameters for the test problem

Test No.	A_1	A_2	H_1	H_2	B_1	B_2	L_1	L_2	T_D
1	200	50	1.5	2	4	4	8	8	0.01
2	200	50	1.5	2	4	4	8	8	0.015
3	200	50	1.5	2	8	8	4	4	0.01
4	200	50	2.5	3	4	4	8	8	0.01
5	400	100	1.5	2	4	4	8	8	0.01

Table 2: Results for the test problems

Test no.	n	TC	TC_1	TC_2	X_s	L_q	B_q
1	4	47141.2	33733.6	13407.6	2236	0	1776
2	4	46667.3	33495.7	13171.6	2236	0	2229
3	4	47200.7	33677.8	13523.0	2236	0	1618
4	4	58681.4	42426.0	16255.4	1788	0	1593
5	4	63354.7	43893.6	19461.1	3162	0	1683

Table 3: Production quantity and ordering quantity in the recovery cycles for the test no. 1 to 5

Test no.	n	Cycle	Production quantity in each cycle	Shipment quantity in each cycle	Inventory
1	4	1	6708	6708	2236
		2	5590	6708	1118
		3	5590	6708	0
		4	7826	5590	2236
2	4	1	6024	6708	1552
		2	5590	6708	434
		3	6274	6708	0
		4	7826	5590	2236
3	4	1	6510	6708	2038
		2	5590	6708	920
		3	5788	6708	0
		4	7826	5590	2236
4	4	1	5083	5367	1505
		2	4472	5367	611
		3	4756	5367	0
		4	6261	4472	1789
5	4	1	9487	9487	3162
		2	7906	9487	1581
		3	7906	9487	0
		4	11068	7906	3162

From Table 1, it can be seen that the optimal recovery plan for test 1 to test 5 was obtained when there were zero lost sales. In addition, the optimal recovery cycles for all test problems were similar at four recovery cycles. Comparison of the results between test 1 and test 2 showed that total recovery cost, *TC* was a bit lower for test problem 2 even though the disruption time is longer. This is due to the lower inventory holding cost. The backorder quantity was higher for longer disruption time but optimal safety stock quantity was similar to test 1.

In test 3, the backorder cost B_1, B_2 and lost sales cost L_1, L_2 were changed so that the backorder cost is higher than lost sales cost. The results showed less number of backorder quantity and higher *TC* from test 1 which is as expected from the model. For test 4, the holding cost H_1 and H_2 were higher than the values in test 1 and the results showed that the optimal safety stock quantity and backorder quantity were smaller than Test 1. For test 5, the setup cost A_1, and ordering cost A_2 were higher than test 1 and the results showed a higher optimal safety stock level and lower backorder quantity compared to test 1.

Table 3 shows the production quantity and shipment quantity for each recovery cycle. It can be observed that the production quantity is the highest for the first cycle in order to minimize stockouts. In addition, it can be seen from the table that the inventory quantity at the end of the recovery cycle is resumed to the quantity of optimal safety stock.

The values for safety stock quantity X_S were the same for test 1, test 2, and test 3. Changes in disruption time, backorder cost, and lost sales cost did not make a difference in the optimal results for safety stock. However, different optimal safety stock quantity was obtained for test 4 when the holding costs were changed. Similarly, the optimal safety stock quantity changed in test 5 when setup cost and ordering cost were changed. Therefore, it can be established that inventory holding cost, setup cost, and ordering cost have a substantial effect on the safety stock level.

Sensitivity Analysis

A sensitivity analysis was performed to investigate the effect of the critical parameters of the model. Parameters for test problem 1 were used as the base for the analysis. Figure 3 shows the changes in the model for different values of disruption time, T_D. Figure 4 shows the analysis for different setup and ordering cost, while Figure 5 shows the values of total recovery cost and safety stock as holding cost changes. Figure 6 shows the effect of different transportation cost to the model.

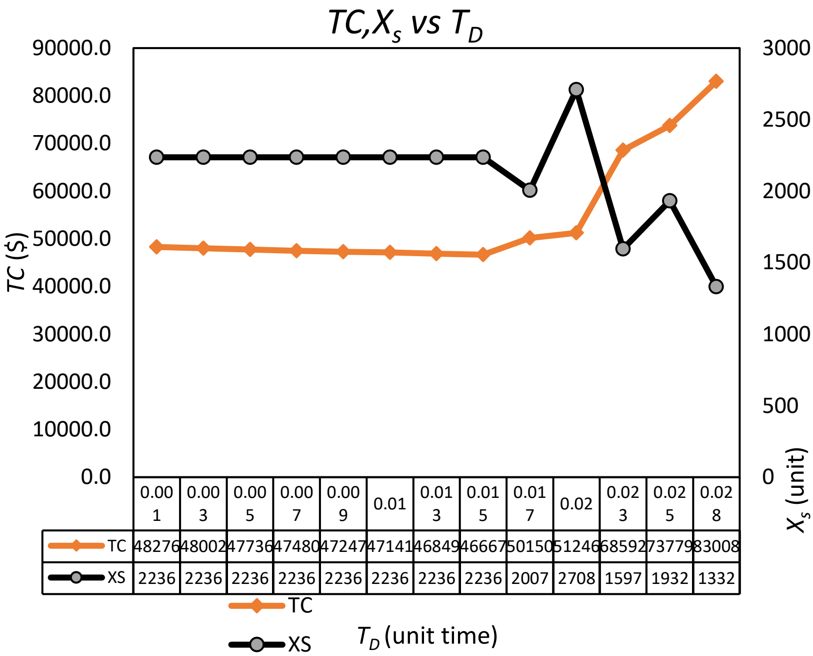


Figure 3: TC, X_S vs disruption time, T_D

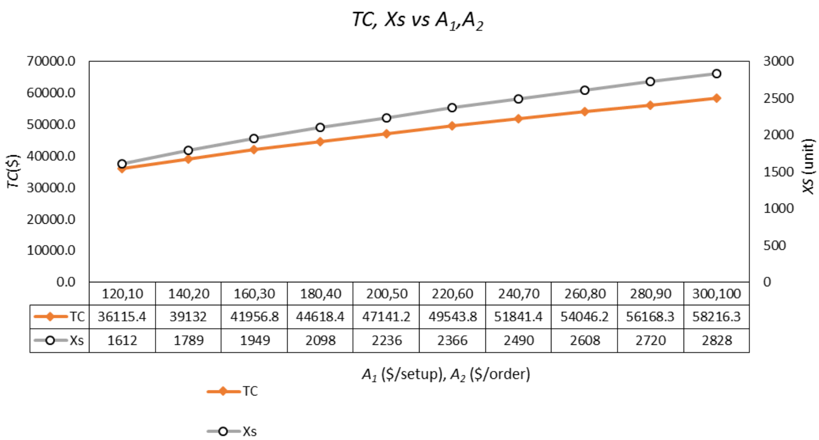
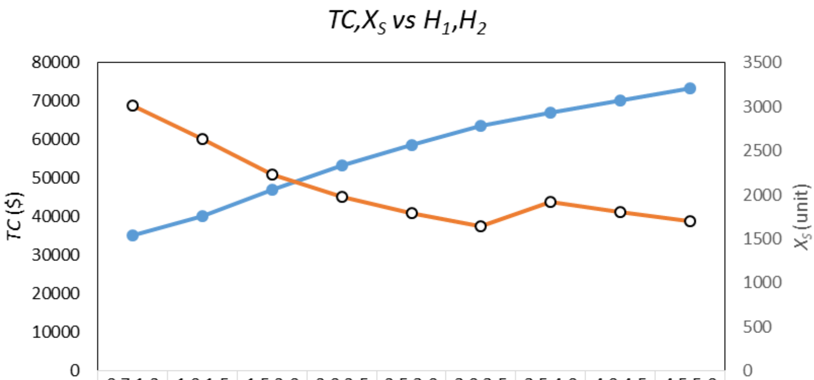
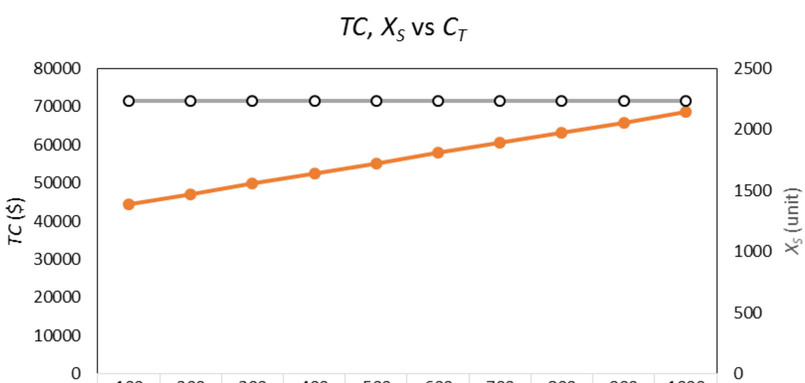


Figure 4: TC, X_S vs setup cost A_1 and ordering cost A_2



	0.7,1.2	1.0,1.5	1.5,2.0	2.0,2.5	2.5,3.0	3.0,3.5	3.5,4.0	4.0,4.5	4.5,5.0
TC	35076.2	40052.6	47141.2	53248.2	58681.4	63617.9	66917.4	70280.7	73472.2
Xs	3015	2638	2236	1975	1789	1647	1917.4	1802	1705

Figure 5: *TC* vs holding cost H_1 and H_2



	100	200	300	400	500	600	700	800	900	1000
TC	44457	47141	49824	52507	55191	57874	60557	63240	65924	68607
Xs	2236	2236	2236	2236	2236	2236	2236	2236	2236	2236

Figure 6: *TC* vs transportation cost C_T

From Figure 3, the total recovery cost *TC* slightly decreased in the beginning but started to increase when disruption time T_D is longer than 0.015. Within the disruption period range of 0.001 to 0.015, the result for optimal recovery cycle was obtained at four cycles with zero lost sales. However, the production quantity and shipment quantity were different because of the different quantity of product shortage during the affected time. Within the same number of recovery cycles, the solution for optimal production and shipment quantity affected the inventory holding costs, thus explaining the slight decrease of *TC*. As for optimal safety stock (X_S) level, all results were similar within this T_D range. At T_D=0.017, the optimal solution was also attained at four recovery cycles but with some quantity of lost sales. Thus, the value of *TC* increased. When T_D was larger than 0.017, the solution was acquired with less number of optimal recovery cycles, a higher number of lost sales, lower value of optimal safety stock quantity and higher *TC*.

From Figure 4, the result indicated that *TC* increased with a higher setup cost A_1 and ordering cost A_2. On the other hand, the optimal X_S decreased. The optimal recovery cycles for this set of data were the same at four recovery cycles. Subsequently from Figure 5, from the range of H_1, H_2=0.7, 1.2 to 3.0, 3.5, the values of *TC* increased with higher holding costs but the quantity of X_S decreased. The optimal recovery cycles for this set of data were the same at four cycles with zero lost sales. When H_1, H_2 was increased to higher values, the optimal recovery cycles was reduced to three cycles with some quantity of lost sales. In addition, the values of *TC* increased while the optimal safety stock quantity decreased. In Figure 6, it can be seen that *TC* increased as the transportation cost C_T increased while the optimal safety stock level remained the same value.

From the sensitivity analysis of this model, it can be highlighted that within the same number of recovery cycles, an increase of setup cost and ordering cost will cause the optimal safety stock to increase as well. The reason would be that with high safety stock level, backorders and lost sales quantity can be minimized without the need for a high number of recovery cycles due to high setup and ordering costs. On the other hand, an increase in holding cost will decrease the optimal safety stock quantity. This is because, with a high level of safety stock and high inventory holding cost per unit, total inventory holding costs for the system will be a large value.

Analysis of fixed safety stock policy

In this section, a scenario where a company owns a stock policy was illustrated. For this scenario, the safety stock X_s was a user input instead of a decision variable. This situation could represent a company with certain safety stock policy due to limitations such as storage space. Four values of X_S and two T_D values were used to investigate the effects of low level, medium level, and high-level safety stocks to the optimal recovery schedule. Other parameter values are similar to test 1 in the previous section. From the results in Table 4, the lowest *TC* value when T_D=0.01 was obtained at X_S = 2000 with four optimal recovery cycles. Low level and medium level safety stocks did not change the number of optimal recovery cycles. At high-level safety stock, the optimal recovery cycle can be reduced. Meanwhile, for T_D=0.02, the lowest *TC* value was obtained at X_S = 2500 with three recovery cycles. The low, medium and high safety stocks level did not change the number of recovery cycles, only the lost sales and backorder quantity. There is a trade-off between the safety stocks level and the backorder and lost sales quantity in the optimal recovery plan.

Table 4: Results of analysis with fixed safety stock policy

T_D	X_s	n	TC	TC_1	TC_2	L_q	B_q
0.01	500	4	74925.1	47376.4	27548.8	1736	1382
	1000	4	66907.3	43450.0	23457.2	1236	1527
	2000	4	50910.0	35583.6	15326.5	236	1729
	2500	3	55835.5	36975.4	18860.1	854	1817
0.02	500	3	86541.0	51644.6	34896.4	2854	1817
	1000	3	78509.2	47874.5	30634.7	2354	2139
	2000	3	62510.0	39969.4	22540.6	1354	2236
	2500	3	54551.6	36022.2	18529.5	854	2236

Conclusion

In this paper, an inventory recovery model of a two-stage serial supply chain consisting of a vendor and a buyer subject to supply disruption was developed. Mitigation strategy by keeping extra inventory or safety stock was considered as the response to the supply disruption. The developed model is a nonlinear constrained model that is capable of providing the total recovery cost, the optimal number of recovery cycles, production and order quantity for the vendor and the buyer, and the optimal safety stocks quantity. In the numerical examples, five test problems were used to examine the result of the model. A sensitivity analysis was conducted to examine the effect of the critical parameters of the model. In addition, a scenario where safety stock level is a fixed quantity was provided to illustrate the situation where the SC may have constraints in the amount of safety stock that can be kept.

The results showed that the optimal amount of safety stock was not significantly influenced by short disruption time. When disruption time was large and resulted in high lost sales, less number of optimal recovery cycle was obtained in the result. In addition, the result of optimal safety stock was also reduced. From the results, it can be emphasized that within the same number of recovery cycles, an increase of setup cost and ordering cost will affect the optimal safety stock quantity to increase as well. On the other hand, an increase in holding cost will decrease the optimal safety stock quantity. Small increases in transportation cost do not affect the number of optimal recovery cycles and optimal safety stock level. The model in this study can be used for SC managers to make better decisions in terms of inventory management to prepare and respond to supply disruption. For future research, this study can be extended to multiple buyers or three echelon system setting. Furthermore, the duration of disruption can be assumed to be longer than one production cycle or consideration can be made for multiple disruptions. Introducing the effect of other constraints that might reflect real life SC operations would be another interesting extension.

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