Disruption recovery of two-stage serial supply chain with consideration of carbon emission cost

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Abstract—The consequences of disruption to a supply chain can be damaging and costly. A firm’s management needs to utilize its resources effectively to minimize the economic, and possibly environmental impact. This paper proposes the recovery model of a two stage serial supply chain subject to supply disruption. The system consists of a single manufacturer and a single retailer, subject to random supply disruption. The manufacturer keeps extra inventory as safety stock to be used at the time of disruption. In addition, the system may have stockouts in the form of partial backorders and lost sales. This study will incorporate the environmental effect consideration in the recovery model by including the carbon dioxide emission caused by the transportation activities during the recovery cycle. The objective of the optimization model is to determine (1) the new recovery schedule of the manufacturer and retailer, (2) the optimal quantity for safety stock, and (3) the carbon emission cost impact during recovery. The model developed is solved using LINGO, where numerical examples and sensitivity analysis are provided to test the feasibility of the model. The result of this study is an introduction of a recovery model that incorporates environmental consideration in the disruption recovery decision-making process.

Keywords— Supply disruption, recovery model, supply chain, safety stock, carbon emission

I. INTRODUCTION

The complexity of the operation and the interdependence between different entities in the supply chain means that there will be challenges and issues to be addressed. As organizations embark on globalization, outsourcing and offshoring to manage their supply chain, they are also exposing themselves to supply chain disruption risks. Thus, the focus of many researches in the supply chain disruption field is to find optimal strategies to deal with these disruptions.

As the environmental problem throughout the world becomes serious issues, several regulations and policies have taken place in order to drive the corporation to become environmentally responsible. Among the objectives are to minimize waste, reduce energy consumption, and minimize greenhouse gas (GHG) emission. Ideally, the design and operation of the supply chain should cause minimal negative impacts to the environment.

Literature in the environmentally responsible supply chain is part of a broader subject field of sustainable supply chain management (SSCM). Under SSCM, there are three dimensions of sustainability that need to be addressed which are economic, environmental, and social consideration, also commonly referred as triple bottom line (TBL). However, the interest of this paper is the work that focuses on the environmental aspects of SSCM.

This paper is organized as follows. Section II analyzes the relevant past literature to this study. Section III addresses the mathematical model development of the system under study. Section IV lists the results for numerical analysis together with the discussion. Section V ends the paper with the conclusion.

II. LITERATURE REVIEW

A. Supply disruption recovery

When facing supply disruption, firms will react by mitigation and recovery actions. Among the mitigation strategy proposed are by building reserves in the form of inventory, capacity, supplier redundancy and responsiveness (Chopra, Sodhi...
Carbon dioxide (CO2) emission is the common consideration in the supply chain design study. Paksoy (2010) proposed a weighted average of all objective functions. To incorporate environmental issues into classic supply chain network design model is to express the objective function as a sustainable supply chain management (SSCM). According to SSCM review by Eskandarpour et al. (2015), 3 most common function of the EOQ was referred to as Sustainable Order Quantity (SOQ). To address the sustainability factor, there are fixed model extended from classical economic order quantity (EOQ) to include sustainable development criteria. The multi-objective costs and CO2 emissions.

Safety stock have been discussed in the literature as additional inventory that is being kept to manage demand uncertainty and also for yield randomness. Customer service level and service factor are commonly considered in determining the size of the safety stock. Keskin et. al (2015) proposed a stock control model to optimize the production, the inventory quantity and the backorderer simultaneously for tire manufacturing company. Mixed integer linear programming model (MILP) was used to model the safety stock problem. The optimization model was solved using mathematical modelling, genetic algorithm, and greedy algorithm. Gao (2015) studied a dynamic inventory hedging problem in a single product, one-supplier-one-buyer supply chain. According to the research, conventional safety stock or inventory hedging is less effective due to compromise in efficiency and resiliency. His study presented resilience-driven, adaptive hedging strategy as an improvement from traditional inventory management approach. The model featured advance supply signals, lost sales, and fixed transportation cost. The strategy was developed by combining contract coordination and collaborative forecasting.

The aim of a recovery plan is to preserve, as much as possible, the original plan that was set before disruption (Hopp et al. 2012). The subject of interest is the cost analysis when an organization deviated from a predetermined plan or schedule. The paper by Qi et al. (2004) was among the early literature on disruption management.

Studies on supply chain disruptions began with single-stage inventory system and later a growing number of researches had been conducted to include two or more stages (Xia et al. (2004), Hishamuddin et al. (2012,2013), B. Pal et al. (2014), Paul et al. (2014). Atan and Snyder (2012) analyzed two multi-echelon inventory systems subject to disruptions including the serial and distribution network topologies system. The objective of these studies are optimal ordering quantity and cost optimization. The most commonly used mathematical model in inventory management is the Economic Order Quantity (EOQ) which provides a formula to calculate the optimal order quantity with minimum total cost. In order to address the scenario where supply disruption occurs, Parlar and Berkin (1991) introduced the EOQD model before later been corrected by Berk and Arreola-Risa (1994). To model EOQ with supply disruptions, the most common way is to assume that the supply process has two states, one in which it functions normally and one in which it is disrupted. Atan and Snyder (2014) summarizes the studies on EOQ models with supply disruptions (EOQD). The models discussed are on EOQD with internal disruption, EOQD with internal and external disruption, and EOQD with disruption in manufacturing. Additional assumptions for the EOQD are stock out will occur on customer demands.

B. Environmental consideration in supply disruption management

From the literature review, the incorporation of environmental effect in the decision making process are mainly related to sustainable supply chain management (SSCM). According to SSCM review by Eskandarpour et al. (2015), 3 most common factors in environmental considerations are facilities, transport and product design. The authors suggested that the easiest way to incorporate environmental issues into classic supply chain network design model is to express the objective function as a weighted average of all objective functions.

Carbon dioxide (CO2) emission is the common consideration in the supply chain design study. Paksoy (2010) proposed a model for supply chain system that incorporates constraint of CO2 emission quota as an environmental impact. In this paper, emission trading factor is considered in designing the supply chain network. The two objectives of the model are to minimize all transportation cost between two echelons and to minimize the emission of CO2 in manufacturing process. Chaabane et al. (2012) presented a study of supply chain design with consideration of carbon emission cost and total logistics cost. Environmental regulations in the form of GHG emissions limits (caps) were used for this study. The two objective functions are to minimize the total logistics cost and to minimize the total emission quantity of CO2 caused by production and transportation activities. The solution methodology uses multi-integer linear programming (MILP) to relate the economic and the environmental dimensions together.

Tseng, Hung (2014) proposed a decision making model for planning a sustainable supply chain for apparel manufacturing. The objective is to minimize the total costs by considering both operational costs and social costs of CO2 emissions. Operational costs include those costs associated with materials purchasing, production, and transportation. CO2 emissions include the emissions resulting from the production process and transportation. For the scenario in the study which considers multinational enterprises that own many manufacturing plants located in different countries, the authors developed a mixed integer, nonlinear optimization model. The results shows that total CO2 emissions decrease as the social costs rates of CO2 emissions increase. It is suggested that enterprises will be driven to reduce their CO2 emission if they are forced to pay for the social costs of CO2 emissions. The decision makers will make optimal strategies to make tradeoffs between the operational costs and CO2 emissions.

The environmental impact has been studied in the classical inventory models as well. Bouchery et al. (2012) presented the model extended from classical economic order quantity (EOQ) to include sustainable development criteria. The multi-objective function of the EOQ was referred to as Sustainable Order Quantity (SOQ). To address the sustainability factor, there are fixed
amount of carbon emissions associated for each order and also per unit storage. The decision will affect ordering and warehousing operation. The result showed that carbon emission reduction can be achieved by low cost operational adjustments e.g. changing batch size. This paper also studied a multi-echelon extension of the SOQ model.

To the best of our knowledge, there is no specific study that focuses on incorporating the environmental impact in the disruption recovery management. Thus, this paper aims to include environmental effect into the disruption recovery models by considering the carbon dioxide emission caused by transportation activities during the recovery cycle. The social carbon cost approach will be used to calculate the cost of carbon emission. The recovery model proposed in this study is based on the work by Hishamuddin et al. (2014).

III. RECOVERY MODEL DEVELOPMENT

A. System Description

In this study, an optimal disruption recovery plan will be formulated for a two stage supply chain consisting of a manufacturer and one retailer. The manufacturer has production and inventory, and follows the Economic Production Quantity model (EPQ). The retailer only has inventory and follows the Economic Order Quantity Model (EOQ). A single batch production product is considered. Demand rate is deterministic and constant. During a normal production cycle at the manufacturer, the production system may be disrupted and will take time to restore the system to the working condition. The manufacturer keeps extra inventory as safety stock to be used at the time of disruption.

During disruption, when the inventory at retailer reaches zero, the safety stock at manufacturer will be delivered to satisfy the retailer’s order. When safety stock that have been delivered to retailer reaches zero, the unsatisfied demand becomes backorders. After the disruption lasts, the recovery process will take place in the recovery window. There will be extra costs incurred in order to recover the system from the disruption, including backorder costs, lost sales costs and penalty costs for both the manufacturer and the retailer. During recovery, the production will be increased to satisfy backorders and build up the inventory level to the safety stock level.

In order to determine total recovery cost, six types of costs will be considered which are setup cost, inventory holding cost, back order cost, lost sales cost, and penalty cost. The objectives of the model are to determine:

1) The expected total cost of the recovery process
2) The number of production cycle required to recover from the disruption
3) The new recovery schedule, consisting of ordering quantity and production quantities for manufacturer
4) The optimal quantity for safety stock

The following are additional assumptions of the proposed model:

1. The demand rate is less than the production rate, i.e. D<P.
2. No shortages are allowed during the subsequent cycles following the disruption.
3. The second stage follows the zero-order inventory policy, where an order is made only when the on-hand inventory reaches zero.
4. The first stage completes the buildup of safety stock inventory level at the end of the cycles in the recovery window

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

Decision variables

\[ X_i \] \quad \text{production lot size of cycle } i \text{ in the recovery schedule for stage 1 (units)}

\[ S_i \] \quad \text{order lot size of cycle } i \text{ in the recovery schedule for stage 2 (units)}

\[ n \] \quad \text{number of cycles in the recovery window}

\[ X_s \] \quad \text{safety stock quantity (units)}

Other parameters and notation

\[ A_1 \] \quad \text{setup cost for the first stage ($/setup)}

\[ A_2 \] \quad \text{ordering cost for the second stage ($/order)}

\[ D \] \quad \text{demand rate for the system (units/year)}

\[ H_{1}, H_{2} \] \quad \text{annual inventory cost for stages 1 and 2 ($/unit/year)}

\[ P \] \quad \text{production rate (units/year)}

\[ Q_1 \] \quad \text{production lot size for stage 1 in the original schedule (units)}

\[ Q_2 \] \quad \text{ordering lot size for stage 2 in the original schedule (units)}

\[ B_q \] \quad \text{back order quantity for stage 2}

\[ L_q \] \quad \text{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 ($/\text{unit/time}$)
$L_1, L_2$ unit lost sales cost for stages 1 and 2 ($/\text{unit}$)
$T_{1i}$ production time for cycle $i$ in the recovery window for stage 1
$T_{2j}$ 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
$f_1$ the penalty function for delay in recovering the original schedule in the first stage
$f_2$ the penalty function for delay in recovering the original schedule of the second stage handled by the first stage
$f_3$ the penalty function for delay in recovering the original schedule in the second stage
$CO_2$ amount of carbon dioxide (CO$_2$) emission from the truck (gr/km)
$d$ distance from manufacturer to retailer
$SC$ social cost of carbon

Figure 1: Inventory Curve of the Two Stage Supply Chain with Safety Stocks
B. Mathematical Formulation

The total recovery cost for stage 1 will be the sum of setup cost, inventory holding cost, backorder cost, lost sales cost, and penalty cost.

- \( TC \): Total recovery cost for Stage 1, Stage 2 and carbon dioxide emission cost
- \( TC_1 \): Total recovery cost for Stage 1
- \( TC_2 \): Total recovery cost for Stage 2
- \( TC_3 \): Total carbon emission cost during recovery period

**Recovery cost for stage 1, \( TC_1 \)**

Setup cost for Stage 1 is the amount of number of setup multiplied by the setup cost.
\[
\text{Setup cost} = A_1 \times \text{(Number of setup)} = A_1 \times n \quad (1)
\]

Total holding cost for stage 1 is the amount of inventory during recovery process multiplied by the annual holding cost for Stage 1 (\( H_1 \)). The amount of inventory during recovery was obtained by calculating the area under the curve in the inventory model (within recovery period). Based on Hishamudin et al. (2013), inventory at end of each cycle \( i \) can be defined as
\[
I_i = I_{i-1} + X_i - S_i \quad \text{for} \ i = 1, 2, \ldots, n
\]

Inventory Holding cost for Stage 1
\[
H_1 = \left[ I_0 \times T_{11} + \frac{1}{2} X_1 \times T_{11} \right] + \left[ I_1 \times S_{T} + I_1 \times T_{12} + \frac{1}{2} X_2 \times T_{12} \right] + \left[ I_2 \times S_{T} + I_2 \times T_{13} + \frac{1}{2} X_3 \times T_{13} \right] + \\
\left[ I_3 \times S_{T} + I_3 \times T_{14} + \frac{1}{2} X_4 \times T_{14} \right] + \ldots
\]
\[
= H_1 \left[ I_0 + \frac{1}{2} X_1 \right] \times T_{11} + I_1 + \frac{1}{2} X_2 \right] \times T_{12} + I_2 + \frac{1}{2} X_3 \right] \times T_{13} + I_3 + \frac{1}{2} X_4 \right] \times T_{14} + \\
S_r(I_1 + I_2 + I_3 + I_4 + I_n)
\]
\[
= H_1 \left[ \sum_{i=1}^{n} \left( I_{i-1} + \frac{1}{2} X_i \right) \times \frac{X_i}{P} + S_r \sum_{i=1}^{n} I_i \right] \quad (2)
\]

Backorder cost for Stage 1 was determined by multiplying the backorder cost with the quantity of backorder
\[
B_q = T_{D} \times D - L_q
\]
\[
= B_1 \times \frac{1}{2} \times B_q \times T_{21b}
\]
\[
= B_1 \times \frac{1}{2} \times (T_{D} \times D - L_q) \times \left( \frac{S_2 - B_q}{D} - S_1 \right) \quad (3)
\]
Lost sales cost for Stage 1 was computed using below formula:

\[ L_1 \ast \left( n \ast Q - \sum_{i=1}^{n} S_i \right) \]  

Penalty cost for Stage 1 was calculated as below:

\[ f_1(n^2) + f_2(n^2) \]  

The total recovery cost for stage 1 will be the sum of setup cost, inventory holding cost, backorder cost, lost sales cost, and penalty cost.

\[
TC_1(X_i, n) = \left[ A_1 \ast n + H_1 \ast \left( \sum_{i=1}^{n} \left( I_{i-1} + \frac{1}{2} X_i \right) \ast \frac{X_i}{P} + S_i \ast \sum_{i=1}^{n} I_i \right) \right. \\
\left. + \left( B_1 \ast \frac{1}{2} \ast (T_D \ast D - L_q) \ast \left( \frac{S_2 - B_q}{D} - \frac{S_1}{D} \right) \right) + \left( L_1 \ast \left( n \ast Q - \sum_{i=1}^{n} S_i \right) \right) \right) \\
\left. + f_1(n^2) + f_2(n^2) \right]
\]

Recovery Cost For Stage 2, TC_2

For stage 2, total recovery cost for stage 2 will be the sum of ordering cost, inventory holding cost, backorder cost, lost sales cost, and penalty cost.

The ordering cost is the rate for ordering cost multiplied by the number of ordering cycle.

\[ A_2 \ast n \]  

Inventory holding cost for Stage 2 was calculated as below:

\[
H_2 \left[ \frac{1}{2} \ast S_1 \ast T_{21a} \right] + \left( \frac{1}{2} \ast (S_2 - B_q) \ast T_{22} \right) + \left( \frac{1}{2} \ast S_3 \ast T_{23} \right) + ...
\]

\[
= \frac{1}{2} \ast H_2 \left[ S_1 \ast \frac{S_1}{D} \right] + \left( S_2 - B_q \right) \ast \left( \frac{S_2 - B_q}{D} \right) + \left( S_3 \ast \frac{S_3}{D} \right) + ...
\]

\[
= \frac{H_2}{2} \left[ S_1^2 + \left( S_2 - B_q \right)^2 + \sum_{i=3}^{n} S_i^2 \right]
\]

The backorder cost for Stage 2 can be derived as follows:

\[ B_2 \ast \frac{1}{2} \ast (Bq \ast T_{21b}) \]

\[ = B_2 \ast \frac{1}{2} \ast (T_D \ast D - L_q) \ast \left( \frac{S_2 - B_q}{D} - \frac{S_1}{D} \right) \]
The lost sales cost for Stage 2 was derived as below:

\[ L_2 * \left( n * Q - \sum_{i=1}^{n} S_i \right) \]  \hspace{1cm} (10)

Penalty Cost for Stage 2 was calculated using the formula below:

\[ f_3(n^2) \]  \hspace{1cm} (11)

The total recovery cost for stage 2 will be the sum of ordering cost, inventory holding cost, backorder cost, lost sales cost, and penalty cost.

\[
TC_2(Si, n) = \left[ (A_2 * n) + \left( \frac{H_2}{2D} * \left( S_1^2 + S_3^2 + \sum_{i=3}^{n} S_i^2 \right) \right) + \left( B_2 * \frac{1}{2} * (T_D * D - L_q) * \left( \frac{S_2 - B_q}{D} - \frac{S_1}{D} \right) \right) + \left( L_2 * \left( n * Q - \sum_{i=1}^{n} S_i \right) \right) + f_3(n^2) \right]
\]  \hspace{1cm} (12)

**Total Emission cost during recovery period, TC_3**

In order to quantify the cost impact of carbon dioxide emission, this study will adopt the concept of social carbon cost (SCC). It is a cost of marginal damage caused by an additional ton of carbon dioxide emission. Total CO₂ emission in the recovery cycle is the amount of total distance travelled multiplied by the number of CO₂ emission per kilometer.

Total distance travelled during recovery cycle is the value of number of recovery cycle (n) multiplied by distance from manufacturer to retailer (collection and delivery).

\[ = n * 2 * d \]

Total cost of CO2 emission during recovery cycle is the value of total distance travelled multiplied by amount of CO₂ emission from the truck per unit kilometer and social cost of carbon, SC.

\[ TC_3(n) = n * 2 * d * CO_2 * SC \]  \hspace{1cm} (13)

**Optimal Recovery Plan for Stage 1 and Stage 2**

The minimal recovery cost for the two-stage system would give the optimal recovery plan for the system under disruption. By solving the objective function below, the value for decision variables \( X_i, S_i, n, \) and \( X_s \) can be obtained.

\[ = Min \left[ TC_1(X_i, i = 1, 2, .., n) + TC_2(S_i, i = 1, 2, .., n) + TC_3(n) \right] \]  \hspace{1cm} (14)

Subject to the following constraints:

\[ X_i \geq Q \]  \hspace{1cm} (15)
\[ 0 < X_s < Q \]  \hspace{1cm} (16)
\[ I_o = X_s = I_n \]  \hspace{1cm} (17)
\[ \sum_{i=1}^{n} X_i \leq nPT \]  \hspace{1cm} (18)
\[ S_n = Q \]  \hspace{1cm} (19)
\[ T_s \leq T - S_i \]  \hspace{1cm} (20)
\[ \sum_{i=1}^{n} X_i \geq nTD - L_q + X_s \]  \hspace{1cm} (21)
All decision variables are nonnegative.

The total cost function (14) consists of the total cost for Stage 1 and Stage 2. Equation (15) ensures that the production size in recovery schedule is larger than the original schedule in order to satisfy safety stock requirement. Equation (16) ensures that the safety stock quantity, \( X_S \), is less than \( Q \). Equation (17) ensures that the initial inventory is equal to the amount of safety stock. Equation (18) represents the production capacity constraint. Equation (19) ensures that the ordering quantity is resumed to \( Q \) at the end of the recovery cycle. Equation (20) limits the disruption time to be less than \( T - S_r \). Equation (21) ensures that all demand during recovery are met and safety stock level is resumed.

IV. RESULTS AND DISCUSSIONS

The above problem was solved using Lingo 15.0 solver and the optimum solution found were listed in table below. The parameters for the system were changed in each test problem to investigate the effect to the number of recovery cycle, total recovery cost and safety stock quantity. The results showed the number of cycle that give the optimal total recovery cost. Table 1 listed the parameters used in the numerical computation. Table 2 showed the number of optimal recovery cycle (\( n \)), total cost for Stage 1 (\( TC_1 \)), total cost for Stage 2 (\( TC_2 \)), total emission cost (\( TC_3 \)), and total recovery cost for Stage 1 and Stage 2 (\( TC \)).

A. Numerical Analysis

<table>
<thead>
<tr>
<th>Table 1: Parameters for the test problem</th>
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<td>Test Parameters</td>
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<tr>
<th>Table 3: Production quantity and ordering quantity in the recovery cycles for test no. 2 and test no. 4</th>
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Fixed value of social carbon cost, $SC$ ($40 /$\text{metric-tonne}$) was used for each test. The reason for this is because social carbon cost ($SC$) value is usually determined annually, which means that the amount will stay the same for a certain period of time. Similarly, fixed values are used for distance between manufacturer and retailer ($30\text{km}$) and carbon dioxide emission ($255.38\text{g/km}$) to simulate the existing supply chain system with existing truck arrangement rather than new location or transportation consideration.

A similar number of optimal recovery cycles ($n=3$) were obtained for all the test problems. Thus, carbon emissions cost ($TC_3$) had the same values. For each test problem, total cost from stage 1 ($TC_1$) contributed the most to the total recovery cost ($TC$). Table 3 showed the production quantity and ordering quantity in the optimal recovery plan for test no. 2 and test no. 4.

**B. Sensitivity Analysis**

A sensitivity analysis was conducted to show the effect of different system parameters to the developed model. These values were used in the analysis; $P=1.5\times10^5$, $D=1\times10^5$, $A_f=200$, $A_f=20$, $H_f=1.2$, $H_f=1.8$, $B_f=2$, $B_f=2$, $L_f=20$, $L_f=20$, $S_f=0.0001$, $X_S=0$. The range of $T_D$ is changed from 0.005 to 0.025. In Table 4, safety stocks quantity were changed from 0 to 1000.

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<th>$T_D$</th>
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<td>2627.85</td>
</tr>
<tr>
<td>100</td>
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Figure 2: Total recovery cost vs. disruption time

Figure 3: Total recovery cost vs. safety stock level

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Table 4 showed the changes in total recovery cost, \( TC \) towards disruption time. From the results, total costs were observed to decrease with the increase of disruption time. This result is counter intuitive with the initial assumption that total recovery cost will increase for longer disruption time. Another analysis was conducted to show the changes in total recovery cost, \( TC \) towards safety stock quantity. Table 5 showed that total recovery cost \( TC \) increased with increase in safety stocks. The reason behind this could be because as the safety stock quantity increases, the inventory holding cost will increase, resulting in higher recovery total recovery cost. Table 6 showed the changes in total recovery cost, \( TC \) towards \( d \), distance between manufacturer and retailer. \( TC \) increased as the distance between manufacturer and retailer increased. Figure 2 showed the graphical representation between total recovery cost, \( TC \) with disruption time \( T_d \), while figure 3 showed the relationship between \( TC \) and safety stock, \( X_s \).

V. Conclusion

A disruption recovery model of two-stage serial chain with incorporated carbon emission cost was developed in this paper. Safety stock was considered as the mitigation strategy to proactively respond to the supply disruption. The objectives of the optimization model is to provide the optimal recovery cost, production and ordering quantity, level of safety stocks, and carbon emission cost impact during the recovery cycle. The model was solved using LINGO software for 5 test problems. The results showed that even though safety stock will reduce the amount of backorder and lost sales, the total recovery cost will increase in order to resume the safety stock inventory level. The carbon emission cost is dependent on the number of recovery cycle, the distance between manufacturer and retailer, and the carbon market price at the time of evaluation. By incorporating environmental factor in the form of carbon emission, the total recovery cost will increase.

The environmental consideration for the supply disruption management in this study is limited to carbon emission cost from transportation only. More complex system should be considered for future study in order to reflect real life supply chain environment and operation. Similarly, the supply chain system can be extended to multiple retailers or three echelon system setting.

REFERENCES

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