Three-Echelon Green Supply Chain Inventory Decision for Imperfect Quality Deteriorating Items

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ABSTRACT
This paper presents an integrated supply chain inventory model for deteriorating items with an imperfect quality considering its environmental impact, particularly the supply chain carbon footprint. An imperfect production system produces a certain number of defective items. Therefore, in our model, the manufacturer conducts a 100% quality check to prevent the delivery of defective items. A third-party logistics (3PL) company supports the logistics between the manufacturer and the buyer, by transporting the products from the manufacturer to a warehouse and then delivering the products in a smaller quantity to the buyer. The proposed solution procedure determines the number of deliveries per cycle, delivery interval, and delivery quantity between the 3PL and the buyer simultaneously. It also determines the production quantity of the manufacturer and the delivery quantity from the manufacturer to the 3PL. The objective is to minimize the expected total cost and to reduce total carbon emissions.

Keywords: carbon emission, imperfect quality, deteriorating items, supply chain inventory

1. INTRODUCTION
The reduction of supply chain environmental effects has received massive attention. Researchers and practitioners consider sustainable supply chain management practices to reduce the environmental effect (e.g., total carbon emissions) without forfeiting the primary objective of minimizing cost or maximizing financial profit. Anderson et al. (2020) identified a positive correlation between the supply chain’s environmental and socially responsible activities with the financial performance although the effects are different for each supply chain. Supply chain inventory control can be combined with a green growth perspective to support companies’ sustainable operations (Wang et al., 2019). However, the implementation of carbon pricing does not guarantee a reduction in global emission (Fang et al., 2020); this call for wise and innovative supply chain decision.

Carbon emissions come from various supply chain activities, including freight transport, material handling, and storage (McKinnon, 2018). Hua et al. (2016) considered carbon emissions from order shipment, inventory holding, and item deterioration in an order quantity model. Dwicahyani et al. (2017) considered emission and energy usage from production, remanufacturing, and transportation activities in a closed-loop supply chain. Wangsa (2017) incorporated emissions from production and transportation. Daryanto & Wee (2018) considered emissions from fuel combustion during transportation, from electricity consumption in inventory holding, and emissions from disposing of deteriorated items.

Other research extended the low-carbon supply chain inventory model, incorporating the existence of imperfect quality items. Wahab et al. (2011) and Jauhari et al. (2014) considered the return of defective products from the buyer to the vendor and incorporated tracking carbon emissions. Jauhari & Laksono (2017) extended the model, assuming that the manufacturer provides a warranty for defective products. Further, the model considered a fuzzy demand rate and an adjustable production rate. Recently, Tiwari et al. (2018) and Daryanto et al. (2019b) incorporated the effect of defective products and carbon emissions for deteriorating items in an integrated two-echelon supply chain.

This study extends previous research by simultaneously considering the effect of a carbon emission tax, imperfect quality, and item deterioration in a three-echelon supply chain. Specifically, this paper extends Daryanto et al.’s (2019a) three-echelon supply chain model, which consists of a manufacturer, third-party logistics (3PL) service provider, and buyer. The present paper also considers the effect of imperfect quality products. Quality inspection is carried out by the manufacturer to prevent the delivery of defective products. This inspection is performed just after production, similar to Sarkar et al. (2017). Also, this paper assumes that the 3PL performs all transportation activities. The model also considers carbon emissions from energy consumption in production, fuel consumption in transportation, energy consumption in warehousing, and disposal activities.

This research contributes to the theoretical knowledge of low-carbon supply chain models to reduce supply chain carbon emissions. Practically, this model can help managers decide the number of deliveries per cycle, delivery interval, and delivery quantity between the 3PL and buyer...
simultaneously when carbon tax regulation exists. This model can also determine the manufacturer’s production quantity and the delivery quantity from the manufacturer to the 3PL.

2. LITERATURE REVIEW

Integration and coordination among supply chain members is an essential practice in supply chain management. In an integrated supply chain, members jointly make decisions through communication and information sharing. Previous research has shown the advantage of supply chain integration in reducing total cost and optimizing profit. Khan & Wisner (2019) identified a significant correlation between supply chain integration and organizational learning that will affect supply chain responsiveness and flexibility, and which will ultimately impact firm performance.

Recently, research on green supply chain management has also shown the benefit of supply chain integration in terms of enhancing environmental performance (Tseng et al., 2019). A green supply chain management (GSCM) integrates environmental concerns such as waste, pollution, and emissions into supply chain management practices (Sarkis, 2012). Mishra et al. (2020) investigated carbon emissions and solid waste from end-of-life goods, while Das et al. (2020) considered water footprint and supplier’s social risk, and developed a holistic sustainable supply chain. In literature, many quantitative and qualitative management tools can be used in modelling and developing a green supply chain (Tundys, 2018). Research and publication on GSCM have emerged since the 1990s and have had exponential growth since 2010 until the present (Tseng et al., 2019). GSCM includes the application of environmental management principles, reverse logistics, recycling and remanufacturing, closed-loop supply chains, and low carbon supply chain management (LCSCM). Currently, LCSCM is gaining widespread attention because supply chain activities such as sourcing, production, warehousing, and distribution are massive sources of greenhouse gas emissions, including carbon dioxide. The aim is to reduce the overall carbon emissions of supply chains (Das & Jharkharia, 2018). LCSCM research includes studies of supply chain inventory management. In these studies, the optimization model has been reformulated, for which the objective function is to maximize total profit or minimize the total cost and total carbon emissions.

Wahab et al. (2011) and Chen & Hao (2015) examined the total cost of a two-echelon supply chain with and without carbon emissions consideration. Other researchers have studied supply chain inventory models for different carbon pricing systems such as incorporating a carbon tax, emission cap, and emission trading (Jaber et al., 2013; Benjaafar et al., 2013; Hammami et al., 2015). A carbon tax system penalizes the number of carbon emissions emitted by a firm based on a local/national/regional tax rate. An emission cap system strictly limits the emitted carbon emissions by a firm. In contrast, carbon emission trading allows a firm to exceed their predetermined cap by buying an excess quota from other firms. The effect of different coordination mechanisms such as vendor-managed inventory on LCSCM has been incorporated by Zanoni et al. (2014), Bazan et al. (2015), Bazan et al. (2017), Marchi et al. (2019), and Bai et al. (2019). Hariga et al. (2017) and Shamayleh et al. (2019) studied LCSCM for cold product supply chains, which require specialized equipment to maintain reduced temperatures, which consume a considerable amount of electricity. Aljazzar et al. (2018) and Sarkar et al. (2018) studied the impact of a trade credit scenario on carbon emissions reduction. Alhaj et al. (2016) and Gosh et al. (2018) developed the LSCM model with uncertain customer demand. The effect of defective items on LCSCM has been studied by Jauhari et al. (2014), Sarkar et al. (2016b), and Sarkar et al. (2018). Daryanto & Wee (2018) considered the effect of deterioration rate on total cost and emissions in a two-echelon low-carbon supply chain. The study considered indirect carbon emissions from warehouse energy usage and direct carbon emissions from fuel combustion during order deliveries and disposal of deteriorated items. Tiwari et al. (2018) added the impact of imperfect quality. Further, Daryanto et al. (2019a) extended the study to a three-echelon low-carbon supply chain.

In many cases, a company produces a percentage of imperfect quality products during out-of-control production processes or due to imperfect materials and inappropriate handling. The effect of imperfect quality on supply chain inventory model has been studied by many researchers such as Huang (2002, 2004), Goyal et al. (2003), Wee et al. (2006), Giri & Chakraborty (2011), Wahab et al. (2011), Jauhari et al. (2014), Lee & Kim (2014), Sarkar et al. (2016a), and Yu & Hsu (2017), assuming that the buyer performs the quality inspection. Khouja (2003), Bazan et al. (2014), Sarkar et al. (2017), and Marchi et al. (2019) incorporated quality screening by the manufacturer to prevent the delivery of imperfect quality products. Recently, Daryanto et al. (2019b) examined carbon emissions reduction when an inspection is performed by the manufacturer instead of the buyer, although, a trade-off between carbon emissions reduction and cost-saving may occur. In this situation, management’s willingness and commitment to reducing total carbon emissions are needed. The contribution of previous authors and this paper is presented in Table 1.

Table 1 Contribution of selected literature and the proposed model

| Authors | Two-echelon supply chain | Three-echelon supply chain | Inspection | Deteriorating items | Carbon emissions |
|---------|--------------------------|---------------------------|------------|---------------------|-----------------|
| Huang (2002) | Yes | | Yes | | |
| Goyal et al. (2003) | Yes | | Yes | | |
| Wee et al. (2006) | Yes | | Yes | Yes | |
| Giri & Chakraborty (2011) | Yes | | Yes | Yes | |
| Wahab et al. (2011) | Yes | | Yes | Yes | |
3. MODEL DEVELOPMENT

This model begins with the following scenario. Suppose a supply chain consisting of a manufacturer, a 3PL, and a buyer. The 3PL company supports the buyer’s logistics activities by ordering, holding, and then delivering the items periodically. The manufacturer starts the production based on the 3PL’s order $Q_d$. The manufacturer’s production is imperfect and produces a certain rate of defective products with a known probability $\beta$. The manufacturer carries out a quality inspection to prevent the delivery of defective products. The 3PL performs the transportation of $Q_d$ from the manufacturer in one shipment. Then, the 3PL delivers the products to the buyer, $n$ times per cycle $(T)$ in a constant quantity $Q_d$, and constant time interval $(T_d)$. The supply chain member works together to minimize the negative impacts of their activities as well as their total cost. The study considers the following assumptions:

(1) A single type of product is considered in which the demand rate $(D)$ is known and constant,
(2) The manufacturer’s production rate $(R)$ is known, constant, and larger than the demand rate,
(3) The deterioration rate $(\theta)$ of the inventory is constant per unit time,
(4) The deteriorated items will be disposed at the end of the cycle,
(5) The 3PL performs all the transportation by truck,
(6) The defective products will be stored until the end of the production period and then be sold to a secondary market,
(7) Demand shortage is not allowed.

Other notations used in the proposed model are as follows:

- $TC_m$, $TC_p$, $TC_b$: The total cost of the manufacturer, 3PL, and buyer respectively ($\$/$cycle)
- $I_{at}(t)$, $I_{pt}(t)$, $I_{bt}(t)$: On hand inventory of the supply chain members at time $t$ (manufacturer, 3PL, and buyer respectively) (units)
- $Q_d$: Manufacturer’s production quantity per cycle (units)
- $T_p$: Manufacturer’s production period (year)
- $S_a$: Setup cost ($/cycle$)
- $P_a$: Production cost ($/unit$)
- $P_e$: Carbon emissions from production activities (tonCO$_2$/unit)
- $q_o$: Quality inspection cost ($/unit$)
- $a_p$, $a_b$: Ordering cost of the 3PL and buyer respectively ($/cycle$)
- $h_{a}$, $h_p$, $h_b$: Holding cost of the supply chain members ($/unit/year$)
- $d_{cm}$, $d_{cp}$: Deterioration cost of the supply chain members ($/unit$)
- $W_{cm}$, $W_{cp}$: Energy consumption from the inventory holding of the supply chain members (kWh/unit/year)

### Table 2: Contribution of selected literature and the proposed model (cont’)

| Authors                  | Two-echelon supply chain | Three-echelon supply chain | Inspection Buyer | Deteriorating items | Carbon emissions |
|--------------------------|--------------------------|-----------------------------|------------------|---------------------|-----------------|
| Wang et al. (2011)       | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Jauhari et al. (2014)    | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Zanoni et al. (2014)     | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Lee & Kim (2014)         | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Bazan et al. (2014)      | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Hammami et al. (2015)    | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Yu & Hsu (2016)          | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Sarkar et al. (2016a)    | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Sarkar et al. (2016b)    | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Sarkar et al. (2017)     | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Wangsa (2017)            | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Hariga et al. (2017)     | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Sarkar et al. (2018)     | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Daryanto & Wee (2018)    | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Tiwari et al. (2018)     | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Bai et al. (2019)        | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Daryanto et al. (2019a)  | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Daryanto et al. (2019b)  | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| Marchi et al. (2019)     | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
| This paper               | Yes                      | Yes                         | Yes              | Yes                 | Yes             |
The supply chain members’ emission from waste disposal (ton CO₂/unit): 

\[f_1\]

Fixed transportation cost per delivery of \(Q_1\) ($/delivery): 

\[c_1\]

Fuel consumption of an empty truck to deliver \(Q_1\) (liter/km): 

\[c_{1a}\]

Fuel consumption per ton of \(Q_1\) (liter/km/ton): 

\[d_1\]

Distance from manufacturer to 3PL (km): 

\[f_2\]

Fixed transportation cost per delivery of \(Q_2\) ($/delivery): 

\[c_2\]

Fuel consumption of an empty truck to deliver \(Q_2\) (liter/km): 

\[c_{2a}\]

Fuel consumption per ton of \(Q_2\) (liter/km/ton): 

\[d_2\]

Distance from 3PL to the buyer (km): 

\[v_c\]

Fuel price ($/liter): 

\[b\]

Product weight (kg): 

\[E[\beta]\]

The expected value of defective products probability: 

\[Ee\]

Emission from electricity consumption (ton CO₂/kWh): 

\[Fe\]

Emission from vehicle’s fuel consumption (ton CO₂/liter): 

\[T_x\]

Carbon tax rate ($/ton CO₂): 

\[n\]

3PL’s delivery frequencies per cycle: 

\[T_d\]

Delivery cycle time from the 3PL to the buyer (year); 

\[T_d = T_b\]

The total carbon emissions of the buyer are: 

\[T_E_b = (w_{eb}E_e) \left( \frac{D}{\theta} \right) \left( e^{\theta T_b} - 1 \right) - DT_b \left( \frac{D}{\theta} \right) + D_{eb} \left( e^{\theta T_b} - 1 \right) - DT_b \left( \frac{D}{\theta} \right) \]  

\[3.2 \quad T_E_p and T_E_p Development\]

\[TC_p = C_{op} + C_{tp} + C_{hp} + C_{dp}\]  

\[TC_p\] consists of the ordering, transportation, inventory holding, and deterioration costs, respectively considering the emission. For a single order per cycle, 

\[C_{op} = \frac{q_p}{nT_b}\]
The 3PL takes responsibility for transporting $Q_1$ from the manufacturer to the 3PL’s warehouse and transporting $nQ_2$ from the 3PL’s warehouse to the buyer. The transportation cost depends on the fixed cost per delivery, the variable cost of the load and carbon emissions cost from the truck (Bonney & Jaber, 2011; Wahab et al., 2011).

Therefore,

$$C_{TP} = \frac{1}{nT_b} \left( f_1 + (2d_1c_1v_c + d_1c_{1a}bQ_1v_c) + (2d_1c_1F_zT_x + d_1c_{1a}bQ_1F_zT_x) \right) + \frac{1}{T_b} \left( f_2 + (2d_2c_2v_c + d_2c_{2a}bQ_2v_c) + (2d_2c_2F_cT_x + d_2c_{2a}bQ_2F_cT_x) \right)$$

From Figure 2, by implementing a cross docking, $I_p(0) = Q_1 - Q_2$. Further, at $t = (n-1)T_b$, the 3PL’s inventory is 0.

$$Q_1 = I_p(0) + Q_2 = Q_2e^{\theta \tau_d} \left( \frac{1 - e^{(n-1)(\theta \tau_d)}}{1 - e^{\theta \tau_d}} \right) + Q_2$$

Therefore,

$$Q_1 = \frac{D}{\theta} \left(e^{\theta \tau_b n} - 1 \right)$$

Figure 2 The 3PL’s inventory level (Daryanto et al., 2019a)

The $C_{DP}$ can be derived as

$$C_{DP} = \frac{(d_{cp} + D_{cp}T_z)}{nT_b} \left( \frac{D}{\theta} \left(e^{\theta \tau_b n} - 1 \right) - n \left( \frac{D}{\theta} \left(e^{\theta \tau_b} - 1 \right) \right) \right)$$

and

$$C_{HP} = \frac{(h_p + w_{ep}E_Tz)}{nT_b} \left( \frac{D}{\theta} \left(e^{\theta \tau_b n} - 1 \right) - n \left( \frac{D}{\theta} \left(e^{\theta \tau_b} - 1 \right) \right) \right)$$

The total carbon emissions of the 3PL are

$$TE_p = \frac{1}{T} \left( 2d_1c_1F_c + d_1c_{1a}bQ_1F_c \right) + \frac{1}{T_b} \left( 2d_2c_2F_c + d_2c_{2a}bQ_2F_c \right)$$

$$+ w_{ep}E_Tz \left( \frac{D}{\theta} \left(e^{\theta \tau_b n} - 1 \right) - n \left( \frac{D}{\theta} \left(e^{\theta \tau_b} - 1 \right) \right) \right)$$

$$+ \frac{D_{cp}}{nT_b} \left( \frac{D}{\theta} \left(e^{\theta \tau_b} - 1 \right) \right)$$

$$+ \frac{D_{cp}}{nT_b} \left( \frac{D}{\theta} \left(e^{\theta \tau_b} - 1 \right) \right)$$

3.3 $TC_m$ and $TE_m$ Development

$$TC_m = C_{sm} + C_{pm} + C_{qm} + C_{hm} + C_{dm}$$

$TC_m$ consists of the setup, production, quality inspection, inventory holding, and deterioration costs, respectively, considering the emission. For a single setup per cycle,
\[ C_{Sm} = \frac{s_m}{nT_b} \quad \text{(16)} \]

\[ C_{pm} = \frac{1}{nT_b} (p_m + P_eT_x)T_pR \quad \text{(17)} \]

The emission from production activity is a function of its production rate (Bazan et al., 2017; Aljazzar et al., 2018) and has the following equation, \( P_e = a_pR^2 - b_p + c_p \) where \( a_p \), \( b_p \), and \( c_p \) are emissions parameters.

For a 100% quality inspection,

\[ C_{qm} = \frac{1}{nT_b} q_mT_pR \quad \text{(18)} \]

Due to the imperfect production system, the effective production rate of the manufacturer becomes \( (1 - E[\beta])R \). From Figure 1, and for the boundary conditions \( I_m(0) = 0; I_m(T_p) = Q_1 \)

\[ I_m(t) = \frac{(1 - E[\beta])R}{\theta} (1 - e^{-\theta t}), \text{ for } 0 \leq t \leq T_p \]

\[ I_m(T_p) = Q_1 = \frac{(1 - E[\beta])R}{\theta} (1 - e^{-\theta T_p}) \quad \text{(19)} \]

Besides, for defective products

\[ I_{md}(t) = \frac{E[\beta]R}{\theta} (1 - e^{-\theta t}), \text{ for } 0 \leq t \leq T_p \]

Therefore, the expected inventory cost for both the good and defective products per unit time is

\[ C_{itm} = \frac{(h_m + w_{em}E_eT_x)}{T} \left( \int_0^{T_p} I_m(t) dt + \int_0^{T_p} I_{md}(t) dt \right) \]

\[ \quad = \frac{(h_m + w_{em}E_eT_x)}{nT_b} \left( \frac{(1 - E[\beta])R}{\theta^2} (\theta T_p + e^{-\theta T_p} - 1) + \frac{E[\beta]R}{\theta^2} (\theta T_p + e^{-\theta T_p} - 1) \right) \quad \text{(21)} \]

The deterioration cost per year is

\[ C_{Dm} = \frac{(d_{cm} + D_{em}T_p)}{T} \left( (1 - E[\beta])RT_p - Q_1 \right) + \left( E[\beta]RT_p - \frac{E[\beta]R}{\theta} (1 - e^{\theta T_p}) \right) \quad \text{(22)} \]

From Eq. (11) and (19),

\[ T_p = - \frac{\ln \left( \frac{D + (1 - E[\beta])R - De^{\theta T_p}}{(1 - E[\beta])R} \right)}{\theta} \quad \text{(23)} \]

The expected total carbon emissions of the manufacturer are

\[ TE_{em} = \frac{w_{em}E_e}{T} \left( \frac{(1 - E[\beta])R}{\theta^2} (\theta T_p + e^{-\theta T_p} - 1) + \frac{E[\beta]R}{\theta} T_p + \frac{E[\beta]R}{\theta^2} (e^{-\theta T_p} - 1) \right) \]

\[ \quad + \frac{D_{em}}{T} \left( (1 - E[\beta])RT_p - Q_1 \right) + \left( E[\beta]RT_p - \frac{E[\beta]R}{\theta} (1 - e^{\theta T_p}) \right) + \frac{P_e}{T} T_pR \quad \text{(24)} \]

### 3.4 Solution Procedure

The total cost of the supply chain for an integrated decision is

\[ TC = TC_b + TC_p + TC_m \quad \text{(25)} \]

The convexity of the cost function in \( n \) and \( T_b \) is proved empirically using the illustrative data in section 4, as shown in Figure 3.
A solution procedure is developed to determine the optimal n and T_b that will minimize the above total cost, adapted from Wang et al. (2011) and Daryanto et al. (2019a), as follows:

Step 1. Substitute Eq. (23) into TC.
Step 2. Set n = 1. Input n and other parameters into TC.
Step 3. Derive the partial derivative of TC with respect to T_b and set it equal to zero.
Step 4. Solve the equation to find T_b.
Step 5. Use the available n and T_b to calculate TC(n,T_b).
Step 6. Check for minimal TC.
If TC(n,T_b) < TC(n-1,T_b(n-1)), repeat Step 3 with new n = n + 1, otherwise go to Step 7.
Step 7. Define n-1 as n* (optimal n). From Eq. (23), (11) and (4) derive the optimal T_p, Q_1, and Q_2. Calculate Q_0 = T_pR.

4. ILLUSTRATIVE EXAMPLE AND DISCUSSION

For illustration, a numerical example is presented. Suppose a supply chain of corrugated box product among one packaging manufacturer, a 3PL company, and one consumer goods manufacturer as the buyer, with the following data adapted from Wang et al. (2011), Jaber et al. (2013), and Hariga et al. (2017).

\[
\begin{align*}
\theta &= 0.1 \\
E/\beta &= 0.01 \\
b &= 4 \text{ kg} \\
T_x &= $61.8/\text{tonCO}_2 \\
F_r &= 2.6 \times 10^{-3} \text{ tonCO}_2/\text{liter} \\
E_r &= 0.5 \times 10^{-3} \text{ tonCO}_2/\text{kWh} \\
D &= 10,000 \text{ units/year} \\
o_p &= $300/\text{cycle} \\
h_p &= $3/\text{unit/year} \\
d_{p2} &= $200/\text{unit}
\end{align*}
\]

\[D_{ph} = 1.2 \times 10^{-3} \text{ tonCO}_2/\text{unit}\]
\[w_{ep} = 14.4 \text{ kWh/unit/year}\]
\[o_p = $600/\text{cycle}\]
\[h_p = $1.5/\text{unit/year}\]
\[d_{p2} = $100/\text{unit}\]
\[D_{op} = 1.2 \times 10^{-3} \text{ tonCO}_2/\text{unit}\]
\[f_1 = $200/\text{delivery}\]
\[c_1 = 30 \text{ liter/100 km}\]
\[c_{1a} = 0.5 \text{ liter/100 km/ton}\]
\[d_1 = 500 \text{ km}\]
\[f_2 = $100/\text{delivery}\]
\[c_2 = 25 \text{ liter/100 km}\]
\[c_{2a} = 0.36 \text{ liter/100 km/ton}\]
\[d_2 = 25 \text{ km}\]
\[v_c = $0.75/\text{litter}\]
\[w_{ep} = 14.4 \text{ kWh/unit/year}\]
\[R = 20,000 \text{ units/year}\]
\[s_m = $2,000/\text{cycle}\]
\[p_m = $10/\text{unit}\]
\[q_m = $0.1/\text{unit}\]
\[h_m = $0.5/\text{unit/year}\]
\[d_{sm} = $30/\text{unit}\]
\[D_{om} = 1.2 \times 10^{-3} \text{ tonCO}_2/\text{unit}\]
\[w_{om} = 14.4 \text{ kWh/unit/year}\]
\[a_p = 0.12 \times 10^{-3} \text{ tonCO}_2/\text{year}^2/\text{unit}^2\]
\[b_p = 1.2 \times 10^{-6} \text{ tonCO}_2/\text{year}/\text{unit}^2\]
\[c_p = 1.4 \times 10^{-3} \text{ tonCO}_2/\text{unit}\]

Maple 15 software was used to perform the derivation and calculation following the proposed solution procedure. It was conducted on a PC with AMD 3.20 GHz processor and 4 GB RAM. Solving the above problem using the proposed solution procedure, results in an optimal value of n as \(n^* = 2\) with \(T_b^* = 0.0944\) and \(TC^* = $159,054.7\). From Eq. (23), (11), and (4) the production period \(T_p\), manufacturer’s production quantity \(Q_0\), delivery size from the manufacturer \(Q_1\), and delivery size from the 3PL \(Q_2\) are 0.0968 years, 1,935.7 units, 1,907.1 units, and 949.1 units respectively. Therefore, the \(nQ_2^* < Q_1^* < Q_0^*\) due to deterioration. The complete results are provided in Table 2. Further, from Eq. (7), (14), and (24) the expected total emissions \(TE\) from the supply chain are 275.58 ton CO2/year.

Table 2 also shows that the manufacturer’s total cost decreases for more delivery frequencies per cycle. An opposite situation is faced by the 3PL while the buyer has the optimal \(n^* = 5\) with the lowest \(TC_b = $119,899.5/\text{year}\). If the decision is made solely by the retailer, the \(ETC = $161,225.8\) which is 1.35% higher than the \(ETC\) for \(n^*\). The \(ETE\) is 278.71 tonCO2 per year. These results show the advantage of supply chain integration in reducing total cost and carbon emissions. Table 3 presents the cost and emission of the manufacturer, 3PL, and buyer. In this example, emissions from production activities account for the largest share of the total supply chain emissions.

Table 3 Result of the illustrative example

| n  | \(T_d = T_s\) | \(T_p\) | \(Q_0\) | \(Q_1\) | \(Q_2\) | \(TC_m\) | \(TC_p\) | \(TC_b\) | \(TC\) |
|----|-------------|--------|--------|--------|--------|---------|---------|--------|------|
| 1  | 0.1588      | 0.0812 | 1,623.9| 1,601.2| 1,601.2| 133,526.7| 7,552.4  | 20,614.3| 161,693.5|
| 2* | 0.0944      | 0.0968 | 1,935.7| 1,907.1| 949.1  | 132,113.3| 12,653.9| 14,287.5| 159,054.7*|
| 3  | 0.0693      | 0.1067 | 2,133.5| 2,100.9| 695.5  | 131,521.0| 12,224.6| 12,474.5| 159,220.1|
| 4  | 0.0557      | 0.1145 | 2,290.3| 2,254.5| 558.9  | 131,170.4| 16,993.8| 11,930.0| 160,094.1|
| 5  | 0.0472      | 0.1213 | 2,426.3| 2,387.6| 473.0  | 130,934.3| 18,391.9| 11,899.5| 161,225.8|
| 6  | 0.0413      | 0.1275 | 2,549.4| 2,507.9| 413.7  | 130,766.3| 19,581.8| 12,114.3| 162,462.4|
Table 4 Cost and emission of the manufacturer, 3PL, and buyer

|                  | Cost ($) | Emissions (tonCO₂) |
|------------------|----------|--------------------|
| Manufacturer     |          |                    |
| Setup            | 10,586.5 |                    |
| Production       | 118,548.6| 260.26             |
| Inspection       | 1,024.6  |                    |
| Inventory holding| 467.1    | 3.56               |
| Deterioration    | 1,486.5  | 0.06               |
| Total            | 132,113.3| 263.88             |

| 3PL              |          |                    |
| Ordering         | 3,176.0  |                    |
| Transportation   | 3,779.2  | 4.74               |
| Inventory holding| 927.3    | 3.43               |
| Deterioration    | 4,771.4  | 0.06               |
| Total            | 12,653.9 | 8.23               |

| Buyer            |          |                    |
| Ordering         | 3,176.0  |                    |
| Inventory holding| 1,632.2  | 3.41               |
| Deterioration    | 9,479.3  | 0.06               |
| Total            | 14,287.5 | 3.47               |

Expected total cost (TC) per year: 159,054.7
Expected total emissions (TE) per year: 275.58

Table 5 Comparison of results with and without carbon emission cost

|                  | Integrated decision considering emissions (a) | Buyer’s individual decision with emissions (b) | Integrated decision without emissions (c) | Saving ((l-b)/b) x100% |
|------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------|------------------------|
| n                | 2                                             | 5                                             | 2                                         | -                      |
| T₀               | 0.0944                                        | 0.0472                                        | -                                         | 0.0959                 |
| TC               | $159,054.7/year                               | $161,225.8/year                               | $159,059.3/year                           | 1.35%                  |
| TE               | 275.58 tonCO₂/year                           | 278.71 tonCO₂/year                           | 275.73 tonCO₂/year                        | 0.06%                  |

When the model does not consider carbon emissions costs, the optimal n = 2 with T₀ = 0.0959. The Q₀, Q₁, and Q₂ are higher than the result for the model with carbon emissions. Substituting these results into the model with carbon emissions cost, one has TC = $159,059.3 and TE = 275.73 tonCO₂/year. These results are 0.003% and 0.056% higher than the result of the proposed model with carbon emissions. Table 4 provides a comparison of results with and without carbon emissions cost.

Table 5 Comparison of results with and without carbon emission cost

|                  | Integrated decision considering emissions (a) | Buyer’s individual decision with emissions (b) | Integrated decision without emissions (c) | Saving ((l-b)/b) x100% |
|------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------|------------------------|
| n                | 2                                             | 5                                             | 2                                         | -                      |
| T₀               | 0.0944                                        | 0.0472                                        | -                                         | 0.0959                 |
| TC               | $159,054.7/year                               | $161,225.8/year                               | $159,059.3/year                           | 1.35%                  |
| TE               | 275.58 tonCO₂/year                           | 278.71 tonCO₂/year                           | 275.73 tonCO₂/year                        | 0.06%                  |

A sensitivity analysis was performed by changing the value of one parameter by ±10% and ±20%, as presented in Table 5. The percentage change in expected total cost is calculated as follow:

\[
\% CTC = \frac{TC - TC^*}{TC^*} \times 100\%
\] (26)

The following insights can be identified from the above study:

1. For all parameters, when the values increase, the total cost also increases. However, the rates on how the \% CTC increase vary.
2. The change in demand rate (D) and production cost (p₀) have a significant influence on the total cost. The increase in these parameters results in an increase in the total cost for more than 50% of the parameter’s value increase. The result provides a supply chain manager or decision-maker managerial insights to carefully control the production cost to reduce the total cost.
3. The total cost is also sensitive to the changes in production rate (R), carbon emission tax (Tₐ), deterioration rate (θ), setup and ordering cost (sₘ, qₘ, oₘ), and deterioration cost (dₘ, dₚ, dₚ). These results mean that the setup cost, the ordering cost, and the deterioration cost reduction are also significant in reducing the total cost. The manager needs to monitor the production rate to synchronize with the demand rate, thereby keeping the inventory level as low as possible. Investing in preservation technology to reduce the deterioration rate is another option to decrease the cost.
4. The change in the expected value of defective products probability (E[β]), quality inspection cost (qₘ), fixed transportation cost (f₁, f₂), fuel price (v), holding cost (hₘ, hₚ, hₚ), the fuel consumption of an empty truck (c₁, c₂), and delivery distance (d₁, d₂) are less significant.
5. The change in the fuel consumption per ton payload (C₁a, C₂b), product weight (b), and warehouse energy consumption (wₑ, wₑ, wₑ) are not significant as well. An increase of 20% from these parameters only increase the \% CTC by less than 0.1%
| Parameter | Change | n* | $T_b$ | $T_p$ | $Q_1$ | $Q_2$ | $TC$ | %CTC |
|----------|--------|----|------|------|------|------|------|------|
| $D$      | -20%   | 2  | 0.1069 | 0.0877 | 1,728.4 | 859.6 | 130,680.9 | -21.7 |
|          | -10%   | 2  | 0.1002 | 0.0924 | 1,821.1 | 906.0 | 144,915.0 | -9.76 |
|          | {8000} | 2  | 0.0944 | 0.0968 | 1,907.1 | 949.1 | 159,054.7 | 0     |
|          | +10%   | 2  | 0.0895 | 0.1009 | 1,987.4 | 989.3 | 173,115.2 | 8.12  |
|          | +20%   | 2  | 0.0852 | 0.1047 | 2,062.8 | 1,027.0 | 187,108.6 | 15.0  |
| $R$      | -20%   | 2  | 0.0933 | 0.1196 | 1,882.8 | 937.0 | 151,776.5 | -4.79 |
|          | -10%   | 2  | 0.0939 | 0.1070 | 1,896.6 | 943.9 | 155,079.6 | -2.56 |
|          | {20000} | 2  | 0.0944 | 0.0968 | 1,907.1 | 949.1 | 159,054.7 | 0     |
|          | +10%   | 2  | 0.0948 | 0.0883 | 1,915.1 | 953.0 | 163,684.0 | 2.83  |
|          | +20%   | 2  | 0.0951 | 0.0812 | 1,921.1 | 956.0 | 168,955.4 | 5.86  |
| $\theta$ | -20%   | 2  | 0.1038 | 0.1062 | 2,093.5 | 1,042.4 | 155,372.6 | -2.37 |
|          | -10%   | 2  | 0.0988 | 0.1011 | 1,993.8 | 992.5 | 157,255.9 | -1.14 |
|          | {0.1}  | 2  | 0.0944 | 0.0968 | 1,907.1 | 949.1 | 159,054.7 | 0     |
|          | +10%   | 2  | 0.0906 | 0.0929 | 1,830.9 | 910.9 | 160,778.6 | 1.07  |
|          | +20%   | 2  | 0.0872 | 0.0895 | 1,763.2 | 877.0 | 162,436.6 | 2.08  |
| $s_m$, $q_s$, $q_b$ | -20% | 2  | 0.0864 | 0.0884 | 1,743.2 | 867.8 | 155,516.1 | -2.27 |
|          | -10%   | 2  | 0.0905 | 0.0927 | 1,827.0 | 909.4 | 157,324.4 | -1.10 |
|          | {2000, 600, 300} | 2  | 0.0944 | 0.0968 | 1,907.1 | 949.1 | 159,054.7 | 0     |
|          | +10%   | 2  | 0.0982 | 0.1007 | 1,984.0 | 987.1 | 160,715.2 | 1.03  |
|          | +20%   | 2  | 0.1019 | 0.1045 | 2,058.1 | 1,023.8 | 162,314.7 | 2.01  |
| $\rho_m$ | -20%   | 2  | 0.0951 | 0.0975 | 1,920.9 | 955.9 | 138,560.5 | -14.8 |
|          | -10%   | 2  | 0.0948 | 0.0971 | 1,914.0 | 952.5 | 148,807.8 | -6.88 |
|          | {10}   | 2  | 0.0944 | 0.0968 | 1,907.1 | 949.1 | 159,054.7 | 0     |
|          | +10%   | 2  | 0.0941 | 0.0964 | 1,900.4 | 945.7 | 169,300.7 | 6.05  |
|          | +20%   | 2  | 0.0938 | 0.0961 | 1,893.6 | 942.4 | 179,546.4 | 11.4  |
| $E[\beta]$ | -20% | 2  | 0.0945 | 0.0966 | 1,907.7 | 949.4 | 158,804.5 | -0.16 |
|          | -10%   | 2  | 0.0945 | 0.0967 | 1,907.4 | 949.2 | 158,929.4 | -0.08 |
|          | {0.01} | 2  | 0.0944 | 0.0968 | 1,907.1 | 949.1 | 159,054.7 | 0     |
|          | +10%   | 2  | 0.0944 | 0.0969 | 1,906.8 | 948.9 | 159,180.3 | 0.08  |
|          | +20%   | 2  | 0.0944 | 0.0970 | 1,906.5 | 948.8 | 159,305.5 | 0.16  |
| $q_m$    | -20%   | 2  | 0.0945 | 0.0968 | 1,907.3 | 949.1 | 158,849.3 | -0.13 |
|          | -10%   | 2  | 0.0945 | 0.0968 | 1,907.2 | 949.1 | 158,952.3 | -0.06 |
|          | {0.1}  | 2  | 0.0944 | 0.0968 | 1,907.1 | 949.1 | 159,054.7 | 0     |
|          | +10%   | 2  | 0.0944 | 0.0968 | 1,907.1 | 949.0 | 159,157.1 | 0.06  |
|          | +20%   | 2  | 0.0944 | 0.0968 | 1,907.0 | 949.0 | 159,259.5 | 0.13  |
| Parameter | Change     | n*  | $T_0$  | $T_p$   | $Q_1$  | $Q_2$   | TC      | %CTC   |
|-----------|------------|-----|--------|---------|--------|---------|---------|--------|
| $f_1, f_2$| -20%       | 2   | 0.0935 | 0.0958  | 1,887.4| 939.3   | 158,628.9| -0.27  |
|           | -10%       | 2   | 0.0940 | 0.0963  | 1,897.3| 944.2   | 158,842.3| -0.13  |
|           | (200, 100) | 2   | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,054.7| 0      |
|           | +10%       | 2   | 0.0949 | 0.0973  | 1,916.9| 953.9   | 159,265.9| 0.13   |
|           | +20%       | 2   | 0.0954 | 0.0978  | 1,926.7| 958.7   | 159,476.0| 0.26   |
| $v_c$     | -20%       | 2   | 0.0939 | 0.0962  | 1,895.2| 943.1   | 158,780.0| -0.17  |
|           | -10%       | 2   | 0.0942 | 0.0965  | 1,901.2| 946.1   | 158,917.5| -0.09  |
|           | (0.75)     | 2   | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,054.7| 0      |
|           | +10%       | 2   | 0.0947 | 0.0971  | 1,913.1| 952.0   | 159,191.3| 0.08   |
|           | +20%       | 2   | 0.0950 | 0.0974  | 1,919.0| 955.0   | 159,327.7| 0.17   |
| $h_m, h_p, h_b$ | -20%       | 2   | 0.0956 | 0.0979  | 1,929.8| 960.3   | 158,575.0| -0.30  |
|           | -10%       | 2   | 0.0950 | 0.0973  | 1,918.4| 954.6   | 158,815.7| -0.15  |
|           | (0.5, 1.5, 3) | 2 | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,054.7| 0      |
|           | +10%       | 2   | 0.0939 | 0.0962  | 1,896.1| 943.6   | 159,292.3| 0.15   |
|           | +20%       | 2   | 0.0934 | 0.0957  | 1,885.3| 938.2   | 159,528.6| 0.30   |
| $d_{cm}, d_{cp}, d_{cb}$ | -20%       | 2   | 0.1026 | 0.1053  | 2,073.3| 1,031.3| 155,778.3| -2.10  |
|           | -10%       | 2   | 0.0983 | 0.1007  | 1,985.0| 987.6   | 157,450.5| -1.02  |
|           | (30, 100, 200) | 2 | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,054.7| 0      |
|           | +10%       | 2   | 0.0910 | 0.0932  | 1,837.8| 914.7   | 160,598.2| 0.96   |
|           | +20%       | 2   | 0.0880 | 0.0901  | 1,775.4| 883.8   | 162,087.1| 1.877  |
| $c_1, c_2$ | -20%       | 2   | 0.0937 | 0.0960  | 1,892.6| 941.8   | 158,740.0| -0.20  |
|           | -10%       | 2   | 0.0941 | 0.0964  | 1,899.9| 945.5   | 158,897.5| -0.10  |
|           | (0.30, 0.25) | 2 | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,054.7| 0      |
|           | +10%       | 2   | 0.0948 | 0.0971  | 1,914.4| 952.6   | 159,210.9| 0.10   |
|           | +20%       | 2   | 0.0952 | 0.0975  | 1,921.6| 956.2   | 159,366.9| 0.19   |
| $c_{1a}, c_{2a}$ | -20%       | 2   | 0.0945 | 0.0968  | 1,907.1| 949.1   | 159,035.7| -0.12  |
|           | -10%       | 2   | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,045.0| -0.006 |
|           | (0.005, 0.0036) | 2 | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,054.7| 0      |
|           | +10%       | 2   | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,064.2| 0.006  |
|           | +20%       | 2   | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,073.6| 0.012  |
| $d_1, d_2$ | -20%       | 2   | 0.0937 | 0.0960  | 1,892.6| 941.9   | 158,721.2| -0.21  |
|           | -10%       | 2   | 0.0941 | 0.0964  | 1,899.9| 945.5   | 158,888.1| -0.10  |
|           | (500, 25)  | 2   | 0.0944 | 0.0968  | 1,907.1| 949.1   | 159,054.7| 0      |
|           | +10%       | 2   | 0.0948 | 0.0971  | 1,914.4| 952.6   | 159,220.7| 0.10   |
|           | +20%       | 2   | 0.0952 | 0.0975  | 1,921.6| 956.2   | 159,385.7| 0.21   |
Table 8: Sensitivity analysis of different parameters (cont’t)

| Parameter | Change | \( n^* \) | \( T_b \) | \( T_p \) | \( Q_1 \) | \( Q_2 \) | TC | %CTC |
|-----------|--------|--------|--------|--------|--------|--------|------|--------|
| \( T_s \) | -20%   | 2      | 0.0947 | 0.0971 | 1,912.9 | 951.9  | 155,648.4 | -2.19 |
|          | -10%   | 2      | 0.0946 | 0.0969 | 1,910.0 | 950.5  | 157,351.6 | -1.08 |
|          | +10%   | 2      | 0.0943 | 0.0966 | 1,904.3 | 947.7  | 160,757.7 | 1.06  |
|          | +20%   | 2      | 0.0942 | 0.0965 | 1,901.5 | 946.3  | 162,460.7 | 2.10  |
| \( w_{em}, w_{rep}, \) | -20%   | 2      | 0.0947 | 0.0971 | 1,913.2 | 952.1  | 158,925.8 | -0.08 |
|          | -10%   | 2      | 0.0946 | 0.0969 | 1,910.2 | 950.6  | 158,990.3 | -0.04 |
|          | +10%   | 2      | 0.0943 | 0.0966 | 1,904.1 | 947.6  | 159,118.7 | 0.04  |
|          | +20%   | 2      | 0.0942 | 0.0965 | 1,901.1 | 946.1  | 159,183.1 | 0.08  |
| \( b \) | -20%   | 2      | 0.0945 | 0.0968 | 1,907.1 | 949.1  | 159,035.7 | 0.012 |
|          | -10%   | 2      | 0.0944 | 0.0968 | 1,907.1 | 949.1  | 159,045.0 | 0.006 |
|          | +10%   | 2      | 0.0944 | 0.0968 | 1,907.1 | 949.1  | 159,054.7 | 0     |
|          | +20%   | 2      | 0.0944 | 0.0968 | 1,907.1 | 949.1  | 159,073.6 | 0.012 |

Note: [-] Base value

5. CONCLUSION

In this paper, we proposed an integrated three-echelon green supply chain inventory model considering carbon emissions for imperfect quality deteriorating items. The study considers emissions from production, transportation, warehousing, and waste disposal. A simple procedure was suggested to obtain a solution. This model enables the supply chain managers to optimize the number of deliveries per cycle, delivery interval, delivery quantity of the 3PL, and the lot size of the buyer simultaneously. It also determines the production quantity of the manufacturer and delivery quantity from the manufacturer to the 3PL. The example incorporates and reduces the total carbon emissions cost of the supply chain model. This study also shows the advantage of supply chain integration in reducing carbon emissions. The sensitivity analysis shows that the supply chain manager or decision-maker must give more attention to reducing the production cost, setup cost, ordering cost, and deteriorating cost.

One of the limitations of this study is the assumption of a deterministic demand without considering price-dependent demand or advertisement. However, in real situations, customer demand is probabilistic and is dependent on factors such as price and advertisement. Therefore, future research can consider stochastic demand as well as price and advertisement dependent demand. We can also extend the proposed model with a different carbon tariff system such as a carbon cap or a cap and trade system which have also been applied in several countries.

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