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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 warehousing 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
			Buyer	Vendor		
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

Table 2 Contribution of selected literature and the proposed model (cont')

Authors	**Two-echelon supply chain**	**Three-echelon supply chain**	**Inspection**		**Deteriorating items**	**Carbon emissions**
			Buyer	**Vendor**		
Wang *et al.* (2011)		Yes			Yes	
Jauhari *et al.* (2014)	Yes		Yes			Yes
Zanoni *et al.* (2014)	Yes					Yes
Lee & Kim (2014)	Yes		Yes		Yes	
Bazan *et al.* (2014)	Yes			Yes		
Hammami *et al.* (2015)	Yes					Yes
Yu & Hsu (2016)	Yes		Yes			
Sarkar *et al.* (2016a)		Yes				Yes
Sarkar *et al.* (2016b)		Yes	Yes			Yes
Sarkar *et al.* (2017)	Yes			Yes		
Wangsa (2017)	Yes					Yes
Hariga *et al.* (2017)	Yes					Yes
Sarkar *et al.* (2018)		Yes				Yes
Daryanto & Wee (2018)	Yes				Yes	Yes
Tiwari *et al.* (2018)	Yes		Yes		Yes	Yes
Bai *et al.* (2019)	Yes				Yes	Yes
Daryanto *et al.* (2019a)		Yes			Yes	Yes
Daryanto *et al.* (2019b)	Yes		Yes	Yes	Yes	Yes
Marchi *et al.* (2019)	Yes		Yes			Yes
This paper		Yes		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_1). The manufacturer's production is imperfect and produces a certain rate of defective products with a known probability (β). The manufacturer carries out a quality inspection to prevent the delivery of defective products. The 3PL performs the transportation of Q_1 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_2), 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 (θ) 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 (\$)
$I_m(t)$, $I_p(t)$, $I_b(t)$	On hand inventory of the supply chain members at time t (manufacturer, 3PL, and buyer respectively) (units)
Q_0	Manufacturer's production quantity per cycle (units)
T_p	Manufacturer's production period (year)
s_m	Setup cost (\$/cycle)
p_m	Production cost (\$/unit)
P_e	Carbon emissions from production activities (tonCO$_2$/unit)
q_m	Quality inspection cost (\$/unit)
o_p, o_b	Ordering cost of the 3PL and buyer respectively (\$/cycle)
h_m, h_p, h_b	Holding cost of the supply chain members (\$/unit/year)
d_{cm}, d_{cp}, d_{cb}	Deterioration cost of the supply chain members (\$/unit)
W_{em}, W_{ep}, W_{eb}	Energy consumption from the inventory holding of the supply chain members (kWh/unit/year)

D_{em}, D_{ep}, D_{eb}	The supply chain members' emission from waste disposal (tonCO$_2$/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 (tonCO$_2$/kWh)
Fe	Emission from vehicle's fuel consumption (tonCO$_2$/liter)
Tx	Carbon tax rate ($/tonCO$_2$)
n	3PL's delivery frequencies per cycle
T_d	Delivery cycle time from the 3PL to the buyer (year); $T_d = T_b$

3.1 TC_b and TE_b Development

$$TC_b = C_{Ob} + C_{Hb} + C_{Db} \tag{1}$$

The TC_b consists of the order receiving, inventory holding, and deterioration costs, respectively considering the emission.

$$C_{Ob} = \frac{o_b}{T_b} \tag{2}$$

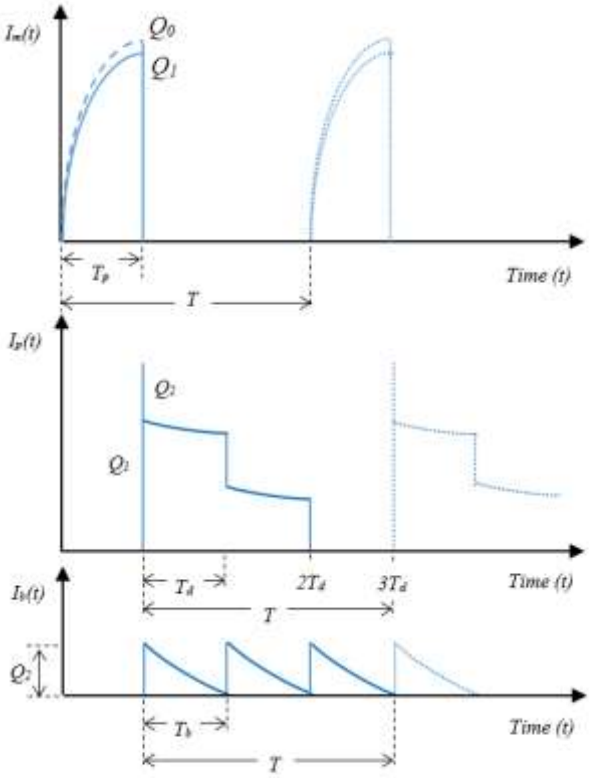

Figure 1 The manufacturer, 3PL, and buyer's inventory

From **Figure 1**, and for the boundary conditions $I_b(0) = Q_2; I_b(T_b) = 0$

$$I_b(t) = \frac{D}{\theta}\left(e^{\theta(T_b - t)} - 1\right), \quad \text{for } 0 \leq t \leq T_b \tag{3}$$

$$Q_2 = \frac{D}{\theta}\left(e^{\theta T_b} - 1\right) \tag{4}$$

Therefore,

$$C_{Hb} = (h_b + w_{eb}E_eT_x)\frac{1}{T_b}\left(\int_0^{T_b} I_b(t)dT\right) = (h_b + w_{eb}E_eT_x)\frac{1}{T_b}\left(\frac{D}{\theta^2}e^{\theta T_b} - \frac{DT_b}{\theta} - \frac{D}{\theta^2}\right) \tag{5}$$

and

$$C_{Db} = (d_{cb} + D_{eb}T_x)\frac{1}{T_b}(Q_2 - DT_b) \tag{6}$$

The total carbon emissions of the buyer are

$$TE_b = (w_{eb}E_e)\frac{1}{T_b}\left(\frac{D}{\theta^2}e^{\theta T_b} - \frac{DT_b}{\theta} - \frac{D}{\theta^2}\right) + (D_{eb})\frac{1}{T_b}\left(\frac{D}{\theta}\left(e^{\theta T_b} - 1\right) - DT_b\right) \tag{7}$$

3.2 TC_p and TE_p Development

$$TC_p = C_{Op} + C_{Tp} + C_{Hp} + C_{Dp} \tag{8}$$

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

$$C_{Op} = \frac{o_p}{nT_b} \tag{9}$$

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,

$$\begin{aligned} C_{Tp} = &\frac{1}{nT_b}\left(f_1 + (2d_1c_1v_c + d_1c_{1a}bQ_1v_c) + (2d_1c_1F_eT_x + d_1c_{1a}bQ_1F_eT_x)\right) \\ &+ \frac{1}{T_b}\left(f_2 + (2d_2c_2v_c + d_2c_{2a}bQ_2v_c) + (2d_2c_2F_eT_x + d_2c_{2a}bQ_2F_eT_x)\right) \end{aligned} \tag{10}$$

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

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

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

Therefore,

$$Q_1 = \frac{D}{\theta}\left(e^{\theta T_b n} - 1\right) \tag{11}$$

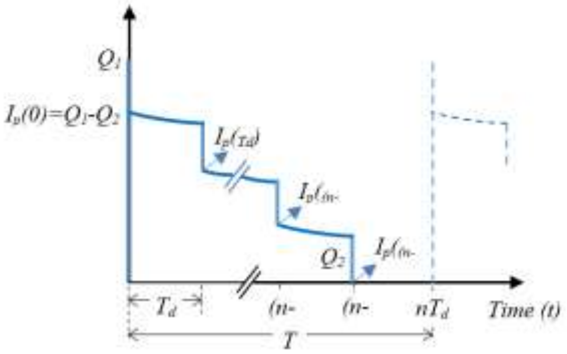

Figure 2 The 3PL's inventory level (Daryanto *et al.*, 2019a)

The C_{Dp} can be derived as

$$C_{Dp} = \frac{(d_{cp} + D_{ep}T_x)}{nT_b}\left(\frac{D}{\theta}\left(e^{\theta T_b n} - 1\right) - n\left(\frac{D}{\theta}\left(e^{\theta T_b} - 1\right)\right)\right) \tag{12}$$

and

$$C_{Hp} = \frac{(h_p + w_{ep}E_eT_x)}{nT_b}\,\frac{\left(\frac{D}{\theta}\left(e^{\theta T_b n} - 1\right) - n\left(\frac{D}{\theta}\left(e^{\theta T_b} - 1\right)\right)\right)}{\theta} \tag{13}$$

The total carbon emissions of the 3PL are

$$\begin{aligned} TE_p = &\frac{1}{T}(2d_1c_1F_e + d_1c_{1a}bQ_1F_e) + \frac{1}{T_b}(2d_2c_2F_e + d_2c_{2a}bQ_2F_e) \\ &+ \frac{w_{ep}E_e}{nT_b}\,\frac{\left(\frac{D}{\theta}\left(e^{\theta T_b n} - 1\right) - n\left(\frac{D}{\theta}\left(e^{\theta T_b} - 1\right)\right)\right)}{\theta} \\ &+ \frac{D_{ep}}{nT_b}\left(\frac{D}{\theta}\left(e^{\theta T_b n} - 1\right) - n\left(\frac{D}{\theta}\left(e^{\theta T_b} - 1\right)\right)\right) \end{aligned} \tag{14}$$

3.3 TC_m and TE_m Development

$$TC_m = C_{Sm} + C_{Pm} + C_{Qm} + C_{Hm} + C_{Dm} \tag{15}$$

TC_m consists of the setup, production, quality inspection, inventory holding, and deterioration costs, respectively, considering the emission. For a single setup per cycle,

$$C_{Sm}=\frac{S_m}{nT_b} \tag{16}$$

$$C_{Pm}=\frac{1}{nT_b}(p_m+P_eT_x)T_pR \tag{17}$$

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 $P_e = a_pR^2 - b_pR + c_p$ where a_p, b_p, and c_p are emissions parameters.

For a 100% quality inspection,

$$C_{Qm}=\frac{1}{nT_b}q_mT_pR \tag{18}$$

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 $I_m(0)=0; I_m(T_p)=Q_1$

$$\begin{gathered} I_m(t)=\frac{(1-E[\beta])R}{\theta}\left(1-e^{-\theta\, t}\right), for\ \ 0\leq\ t\ \leq T_p \\ I_m\left(T_p\right)=Q_1=\frac{(1-E[\beta])R}{\theta}(1-e^{-\theta\, T_p}) \end{gathered} \tag{19}$$

Besides, for defective products

$$I_{md}(t)=\frac{E[\beta]R}{\theta}\left(1-e^{-\theta\, t}\right), \text{for } \ 0\leq\ t\ \leq T_p \tag{20}$$

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

$$\begin{aligned} C_{Hm}&=\frac{(h_m+w_{em}E_eT_x)}{T}\left(\int_0^{T_p}I_m(t)dt+\int_0^{T_p}I_{md}(t)dt\right) \\ &=\frac{(h_m+w_{em}E_eT_x)}{nT_b}\left(\frac{(1-E[\beta])R}{\theta^2}\left(\theta T_p+e^{-\theta T_p}-1\right)+\frac{E[\beta]R}{\theta^2}\left(\theta T_p+e^{-\theta T_p}-1\right)\right) \end{aligned} \tag{21}$$

The deterioration cost per year is

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

From Eq. (11) and (19),

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

The expected total carbon emissions of the manufacturer are

$$\begin{aligned} TE_m=\frac{w_{em}E_e}{T}&\left(\frac{(1-E[\beta])R}{\theta^2}\left(\theta T_p+e^{-\theta T_p}-1\right)+\frac{E[\beta]R}{\theta}T_p+\frac{E[\beta]R}{\theta^2}\left(e^{-\theta T_p}-1\right)\right) \\ &+\frac{D_{em}}{T}\left(\left((1-E[\beta])RT_p-Q_1\right)+\left(E[\beta]RT_p-\frac{E[\beta]R}{\theta}(1-e^{\theta T_p})\right)\right)+\frac{P_e}{T}T_pR \end{aligned} \tag{24}$$

3.4 Solution Procedure

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

$$TC=TC_b+TC_p+TC_m \tag{25}$$

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**.

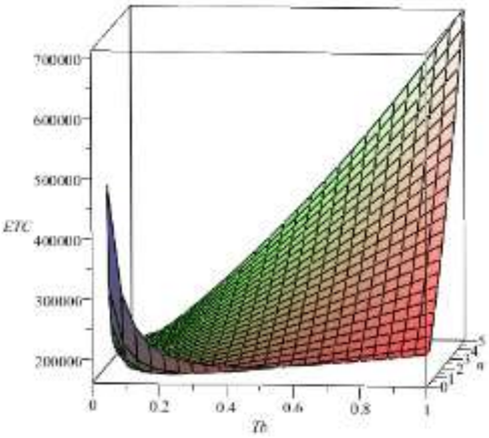

Figure 3 Convexity of *ETC* function in *n* and T_b

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).

θ = 0.1
$E[\beta]$ = 0.01
b = 4 kg
Tx = \$61.8//tonCO$_2$
F_e = 2.6 x 10^{-3} tonCO$_2$/liter
E_e = 0.5 x 10^{-3} tonCO$_2$/kWh
D = 10,000 units/year
o_b = \$300/cycle
h_b = \$3/unit/year
d_{cb} = \$200/unit
D_{eb} = 1.2 x 10^{-3} tonCO$_2$/unit
w_{eb} = 14.4 kWh/unit/year
o_p = \$600/cycle
h_p = \$1.5/unit/year
d_{cp} = \$100/unit
D_{ep} = 1.2 x 10^{-3} tonCO$_2$/unit
f_1 = \$ 200/delivery
c_1 = 30 liter/100 km
c_{1a} = 0.5 liter/100 km/ton
d_1 = 500 km
f_2 = \$ 100/delivery
c_2 = 25 liter/100 km
c_{2a} = 0.36 liter/100 km/ton
d_2 = 25 km
v_c = \$0.75/liter
w_{ep} = 14.4 kWh/unit/year
R = 20,000 units/year,
s_m = \$2,000/cycle
p_m = \$10/unit
q_m = \$0.1/unit
h_m = \$0.5/unit/year
d_{cm} = \$30/unit
D_{em} = 1.2 x 10^{-3} tonCO$_2$/unit
w_{em} = 14.4 kWh/unit/year
a_p = 0.12 x 10^{-9} tonCO$_2$. year^2/unit^3
b_p = 1.2 x 10^{-6} tonCO$_2$.year/ unit^2
c_p = 1.4 x 10^{-3} tonCO$_2$/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 CO$_2$/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 = \$11,899.5/year. If the decision is made solely by the retailer, the *ETC* is \$161,225.8 which is 1.35% higher than the *ETC* for *n**. The *ETE* is 278.71 tonCO$_2$ 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	$T_b = T_d$	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	15,224.6	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 ($)	Emissions (tonCO$_2$)
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

When the model does not consider carbon emissions costs, the optimal $n = 2$ with $T_b = 0.0959$. The Q_0, Q_1, and Q_2 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 tonCO$_2$/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*)	Saving ((*b*-*a*)/*b*) x100%	Integrated decision without emissions (*c*)	Saving ((*c*-*a*)/*c*) x 100%
n	2	5	-	2	-
T_b	0.0944	0.0472	-	0.0959	-
TC	\$ 159,054.7 /year	\$ 161,225.8 /year	1.35%	\$ 159,059.3 /year	0.003%
TE	275.58 tonCO$_2$/year	278.71 tonCO$_2$/year	1.12%	275.73 tonCO$_2$/year	0.056%

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:

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

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 (p_m) 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 (T_x), deterioration rate (θ), setup and ordering cost (s_m, o_p, o_b), and deterioration cost (d_{cm}, d_{cp}, d_{cb}). 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, thus 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 ($E[\beta]$), quality inspection cost (q_m), fixed transportation cost (f_1, f_2), fuel price (v_c), holding cost (h_m, h_p, h_b), the fuel consumption of an empty truck (c_1, c_2), and delivery distance (d_1, d_2) are less significant.

(5) The change in the fuel consumption per ton payload (c_{1a}, c_{2a}), product weight (b), and warehouse energy consumption (w_{em}, w_{ep}, w_{eb}) are not significant as well. An increase of 20% from these parameters only increase the %*CTC* by less than 0.1%

Table 6 Sensitivity analysis of different parameters

Parameter	*Change*	n^*	T_b	T_p	Q_1	Q_2	*TC*	*%CTC*
	-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
D	{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
	-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
R	{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
	-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
θ	{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
	-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
s_m, o_p, o_b	{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
	-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
p_m	{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
	-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
$E[\beta]$	{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
	-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
q_m	{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

Table 7 Sensitivity analysis of different parameters (cont')

Parameter	Change	n^*	T_b	T_p	Q_1	Q_2	TC	%CTC
	-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
f_1, f_2	{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
	-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
v_c	{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
	-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
h_m, h_p, h_b	{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
	-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
d_{cm}, d_{cp}, d_{cb}	{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.	1.877
	-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
c_1, c_2	{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
	-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
c_{1a}, c_{2a}	{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
	-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
d_1, d_2	{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')

Parameter	*Change*	*n**	T_b	T_p	Q_1	Q_2	*TC*	*%CTC*
T_x	-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
	{61.8}	2	0.0944	0.0968	1,907.1	949.1	159,054.7	0
	+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_{ep}, w_{eb}	-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
	{14.4}	2	0.0944	0.0968	1,907.1	949.1	159,054.7	0
	+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
	{4}	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

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 dependant 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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