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Low Carbon Supply Chain Coordination for Imperfect Quality Deteriorating Items

Yosef Daryanto [1,2], Hui Ming Wee [1,*] and Gede Agus Widyadana [3]

1 Department of Industrial and Systems Engineering, Chung Yuan Christian University, 200 Chung-Pei Rd., 32023 Chung-li, Taoyuan, Taiwan; yosef.daryanto@uajy.ac.id
2 Department of Industrial Engineering, Universitas Atma Jaya Yogyakarta, Jl. Babarsari 43, 55281 Yogyakarta, Indonesia
3 Department of Industrial Engineering, Petra Christian University, Surabaya, East Java 60236, Indonesia; gede@peter.petra.ac.id
* Correspondence: weehm@cycu.edu.tw

Received: 19 January 2019; Accepted: 20 February 2019; Published: 5 March 2019

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Abstract: Nowadays, many countries have implemented carbon pricing policies. Hence, the industry adapts to this policy while striving for its main goal of maximizing financial benefits. Here, we study a single manufacturer–retailer inventory decision considering carbon emission cost and item deterioration for an imperfect production system. This study examines two models considering two cases of quality inspection. The first is when the buyer performs the quality inspection, and the second is when the quality inspection becomes the vendor's responsibility so that no defective products are passed to the buyer. Carbon emission costs are incorporated under a carbon tax policy, and we consider the carbon footprint from transporting and warehousing the items. The objective is to jointly optimize the delivery quantity and number of deliveries per production cycle that minimize the total cost and reduce the total carbon emissions. This study provides solution procedures to solve the models, as well as two numerical examples.

Keywords: supply chain inventory; imperfect quality; inspection; carbon emission; deteriorating items

1. Introduction

Supply chain coordination has a favorable effect on inventory replenishment decisions. Supply chain coordination can be realized through information sharing and joint decision-making. Coordination brings many advantages such as lower inventory-related costs and quality improvement [1]. This study considers supply chain management coordination and examines its effect on both economic and environmental performance. This study proposes supply chain inventory models that consider carbon emission costs and the existence of defective items under different inspection coordination mechanisms. Further, the models also consider the effect of item deterioration. In real life, many inventory items deteriorate over time due to spoilage, physical depletion, or obsolescence.

Due to increasing pressure from legislation, customers, and other organizations, business and industry are striving for more eco-friendly operation. The production, distribution, consumption, and other post-consumption processes of a product are sources of carbon emission. Therefore, the concept of a low-carbon supply chain has gained massive interest among researchers and industry practitioners [2,3]. The objective is to control and reduce CO_2 emissions (the major part of greenhouse gas emission) from the supply chain. Recently, Kazemi et al. [4] considered the effect of carbon emissions on several economic order quantity (EOQ) models. Sarkar et al. [5] considered warehouse emissions in the EOQ model with a rework for the defective items. The model also considered partial backorder and multi-trade-credit-period. Taleizadeh et al. [6] proposed economic production quantity (EPQ) models that considered carbon emissions. Recently, Sarkar et al. [7,8] and Daryanto and Wee [9] incorporated a carbon tax in a supply chain total cost model. Wahab et al. [10], Jauhari et al. [11], Sarkar et al. [12], Jauhari [13], Gautam and Khanna [14], and Tiwari et al. [15] incorporated both carbon emissions and imperfect quality in a low-carbon supply chain model. The quality inspection is performed by the buyer, and the defective products are sent back to the vendor or sold into the secondary market at a discounted price.

Table 1 illustrates the research gap by comparing this paper with the existing literature. This study focuses on supply chain inventory models for a system that contains imperfect quality items. The decisions of the supply chain dealing with the defective items in the imperfect production processes affect carbon emissions, because defective item processing also adds to the total emissions. Moreover, the loss due to imperfect quality and deterioration also forces the manufacturer to produce more products to satisfy customer demand per period, resulting in the increase in carbon emission from production, holding, and distribution. The objectives of these studies are to simultaneously minimize the total cost and reduce carbon emissions. This paper also contributes to low-carbon supply chain models by considering two cases of quality inspection. In the first case, the buyer performs the quality inspection, and in the second case, the quality inspection becomes the vendor's responsibility. The first model extends the studies of Wahab et al. [10], Jauhari et al. [11], Sarkar et al. [12], Jauhari [13], and Gautam and Khanna [14] to consider the effect of deterioration. In addition to the fixed and variable inspection costs, the model also extends Tiwari et al.'s [15] model by introducing weight and distance-dependent transportation cost and emission variables. The second model extends the first model by introducing an inspection option to prevent defective products from being shipped to the buyer. This model reduces the expected total costs and emission costs of the supply chain.

Table 1. Gap analysis with existing literature.

Authors	Imperfect Quality		Deteriorating Item	Variable Transportation Cost	Carbon Emission
	Vendor's Inspection	Buyer's Inspection			
Huang (2002)		√			
Goyal et al. (2003)		√			
Wee et al. (2006)		√	√		
Wahab et al. (2011)		√			√
Benjaafar et al. (2013)					√
Lee and Kim (2014)		√	√		
Bazan et al. (2014)	√				
Bozorgi et al. (2014)					√
Jauhari et al. (2014)		√			√
Bozorgi (2016)					√
Ghosh et al. (2016)					√
Sarkar et al. (2016b)		√		√	√
Yu and Hsu (2017)		√			
Sarkar et al. (2017)	√			√	
Toptal and Çetinkaya (2017)					√
Bouchery et al. (2017)					√
Dwicahyani et al. (2017)					√
Wangsa (2017)					√
Li et al. (2017)					√
Anvar et al. (2018)					√
Hariga et al. (2018)					√
Ji et al. (2018)					√
Wang and Ye (2018)					√
Gosh et al. (2018)					√
Ma et al. (2018)					√
Darom et al. (2018)					√
Jauhari (2018)		√			√
Gautam and Khanna (2018)		√			√
Wangsa and Wee (2018)				√	
Tiwari et al. (2018)		√	√		√
Kundu and Chakrabarti (2019)					√
This paper	√	√	√	√	√

This study incorporates carbon emissions, item deterioration, and defective percentage to guide the supply chain managers to make the inventory decisions on the delivery size and the number of deliveries per cycle. This introduction section is followed by reviews of previous related studies in Section 2. Then, Section 3 defines the problem, assumptions, and notations in this study. Section 4 presents two mathematical models. Section 5 provides two numerical examples and the sensitivity analysis to find some insights from the proposed models. In the end, Section 6 summarizes the findings and discusses some opportunities for further research.

2. Literature Review

This study incorporates both economic and emission costs in a two-echelon supply chain production–inventory model assuming that defective products exist in each delivered lot. This section presents the existing literature that supports this study.

2.1. Imperfect Quality Inventory Model

In many industries, production systems are imperfect, producing a certain percentage of defective products. Rosenblatt and Lee [16] and Porteus [17] studied the relationship between the optimal lot size and quality performance. Rosenblatt and Lee [16] studied the optimal production cycle through considering the proportion of defective items, while Porteus [17] related the model to the opportunity for quality improvement and setup cost reduction through investment. Salameh and Jaber [18] incorporated defective items into the EPQ model and considered the screening time and cost. Many other researchers have continued the research on the EOQ and EPQ models with imperfect quality. Those researchers assume that at the end of the screening period, or the end of the cycle, the defective products will be sold at a lower price.

Other researchers bring the effect of imperfect quality items into the integrated vendor–buyer or multi-echelon inventory model. Huang [19] considered imperfect quality and assumed that the vendor provides a product warranty for the defective items. The buyer conducts a 100% inspection, and at the end, the vendor treats the faulty items. Goyal et al. [20] extended the previous model with a single production and multiple deliveries containing defective products. They assumed that the buyer sells the defective items at a discounted price. Figure 1 illustrates the scenario. Wee et al. [21] considered imperfect quality, shortage backorder, and item deterioration in an integrated production–inventory model. Lee and Kim [22] also developed an integrated production–inventory model of imperfect quality deteriorating items.

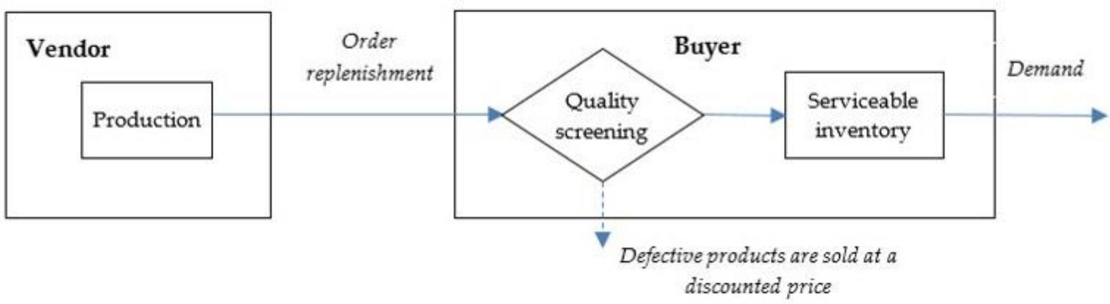

Figure 1. Illustration of an integrated inventory model for imperfect quality items where defective products are sold at a discounted price.

Bazan et al. [23] studied the effect of imperfect quality in different vendor–buyer inventory models. In their study, the vendor performs the inspection and considers one of three possible decisions regarding the defective items: (1) scrap off, (2) salvage at a discounted price, and (3) rework. Figure 2 illustrates the scenario when the vendor performs the inspection. Sarkar et al. [24] studied the integrated inventory model with two-stage inspection by the vendor considering the rework process and variable transportation cost. Yu and Hsu [25] developed a production–inventory model in which the defective items are returned to the vendor immediately for rework.

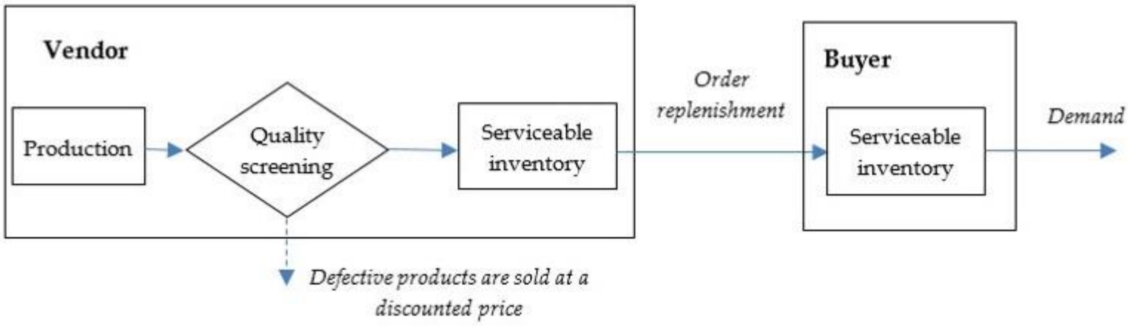

Figure 2. Illustration of an integrated inventory model for imperfect quality items with vendor's inspection.

2.2. Low-Carbon Supply Chain Management

Research on low-carbon supply chain management has increased rapidly in recent years and has been marked by a surge in the amount of literature in this area. Much of this research revealed that supply chain collaboration and the adjustment on operational decisions could reduce carbon emissions without significantly increasing their costs. Wahab et al. [10] studied the optimal shipment size and number of shipments for a two-echelon supply chain with carbon emission cost from transporting the inventory. The emissions are affected by the distance traveled, vehicle fuel efficiency, and the actual shipment weight. Benjaafar et al. [26] modified the traditional supply chain model by associating the carbon footprint from placing an order to the supplier, production setup, production process, and inventory holding. Fahimnia et al. [27] studied the impact of carbon pricing on a closed-loop supply chain through a case study.

Bozorgi et al. [28] considered carbon emissions from transporting and storing cold items that require temperature-controlled trucks and freezers. Bozorgi [29] extended the previous model considering multi-product cold items under limited capacity. Hariga et al. [30] incorporated carbon emissions from transporting and storing the cold items in a three-echelon supply chain. Ghosh et al. [31] considered carbon emissions from production, inventory holding, and transportation in a vendor–buyer supply chain under a single setup and multiple deliveries policy. Toptal and Çetinkaya [32] studied the effect of supply chain coordination and carbon emissions on vendor–buyer order quantity under lot-for-lot delivery. Bouchery et al. [33] examined different supply chain coordination configurations considering carbon emissions under limited vehicle capacity. Dwicahyani et al. [34] incorporated carbon emission costs, energy cost, and waste disposal for a two-echelon supply chain with remanufacturing. Li et al. [35] considered joint carbon tax and cap-and-trade policies for a two-echelon supply chain production–distribution model with transportation outsourcing. Wangsa [36] incorporated the government's penalties and incentive policies to reduce carbon emissions.

Anvar et al. [37] considered emissions from transportation and inventory-holding activities in a one-supplier multi-retailer supply chain. Hariga et al. [38] considered carbon tax and carbon cap policies for a two-echelon supply chain with vendor-managed consignment inventory partnership. The model incorporated emissions from the ordering process, production setup, and holding the inventory. Ji et al. [39] considered a carbon reduction investment from the supplier to get higher customer demand. Wang and Ye [40] compared the effect of considering carbon emissions on just-in-time and economic order quantity decisions for two-echelon supply chain inventory models. Ghosh et al. [41] considered a carbon tax regulation to minimize the total expected cost of a supply chain under stochastic demand and shortage backorder. Ma et al. [42] considered the effect of the carbon tax scheme between suppliers and buyer for production, procurement, and pricing decisions. Darom et al. [43] developed a manufacturer–retailer inventory model considering disruption risks and recovery with safety stock and the effect of carbon emission costs. The model considered carbon emissions from the transportation activities for a better recovery plan. Huang et al. [44] studied inventory and pricing decisions considering carbon emission, production disruption, and controllable deterioration using preservation technology. Recently, Daryanto et al. [45] proposed a low-carbon three-echelon supply chain inventory model considering item deterioration. Kundu and Chakrabarti [46] developed a low-carbon supply chain inventory model taking into account the effect of inflation and the time-value of money. Other researchers incorporated carbon emissions in supplier selection and order allocation [47–49].

3. Problem Definition, Assumption, and Notations

3.1. Problem Definition

This study considers a manufacturer–retailer supply chain that produces one type of item sold solely through one channel. The retailer orders n deliveries of equal lot size (Q) per cycle. The manufacturer implements single-setup multiple-deliveries (SSMD). Hence, it produces nQ units of item per production cycle. This study develops two models considering two cases of quality inspection. (1) In the first, the buyer performs a complete quality inspection process. (2) In the second, the vendor performs the quality inspection so that no defective products are passed to the buyer. The defective items are sold at a discounted price with no additional cost in both scenarios. Both the vendor and the buyer consider the carbon emission costs in their decision to comply with the carbon tax regulation. Model 1 is an extension of Tiwari et al.'s [15] model by introducing weight and distance-dependent transportation costs in addition to the fixed and variable inspection costs. Later, the second model extends the first model by studying another inspection option to reduce the expected total costs and emissions.

3.2. Assumption and Notation

This study explores real-life problems of cost minimization and carbon emission reduction under certain assumptions of a controlled situation. The assumptions are listed below, while the notations are presented in Table 2.

1. The retailer's demand rate and the manufacturer's production rate are known and constant.
2. The manufacturer implements a single-setup multiple-deliveries (SSMD) policy. Based on the retailer's order, the manufacturer produces nQ units of item per production cycle to reduce the setup time and cost. Then, it delivers the item in an equal lot sizes and constant time intervals [50].
3. The replenishment is instantaneous.
4. The items deteriorate in the manufacturer and retailer's inventory. The deterioration rate for both the manufacturer and retailer are equal and constant.
5. The defective percentage, u, has a uniform distribution where $0 \leq \alpha < \beta < 1$.
6. Good products are always available during the quality inspection as $x > D$.
7. The retailer (in Model 1) and the manufacturer (in Model 2) perform a 100% quality inspection to ensure an excellent service.
8. The fixed inspection cost per cycle is constant, whether performed by the buyer or the manufacturer.
9. Carbon emissions come from the fuel and electricity consumption during transporting and holding the inventory.
10. Shortage is not considered.
11. The additional fuel consumption is a linear function of truckloads. Figure 3 illustrates the linear fuel consumption model, which is similar to that of Hariga et al. [30] with an example of the dataset from Volvo Corporation [51].

Table 2. List of notations.

Symbol	Definition
D	demand rate (unit/year);
P	production rate (unit/year);
R	production quantity; $R = PT_1$;
θ	deterioration rate; $(0 \leq \theta < 1)$;
u	the probability of defective products per delivery lot size;
x	quality screening rate (unit/year);
i_c	fixed quality inspection cost (\$/cycle);
u_c	unit inspection cost (\$/unit);
c	retailer's ordering cost (\$/order);
h_d	retailer's holding cost (\$/unit/year);
d_d	retailer's deteriorating cost (\$/unit);
s	manufacturer's setup cost (\$/order);
h_p	manufacturer's holding cost (\$/unit/year);
d_p	manufacturer's deteriorating cost (\$/unit);
t_f	manufacturer's fixed transportation cost per delivery (\$/delivery);
t_v	fuel price for manufacturer's variable transportation cost (\$/liter);
d	distance traveled from vendor to buyer (km);
w	product weight (ton/unit);
c_1	average vehicle fuel consumption when empty (liter/km);
c_2	average additional fuel consumption per ton of load (liter/km/ton);
T_x	carbon emission tax (\$/tonCO_2);
F_e	average emissions from fuel combustion (tonCO_2/liter);
E_e	average emissions from electricity generation (tonCO_2/kWh);
e_1	transportation emission cost (\$/km); $e_1 = c_1 F_e T_x$;
e_2	average additional transportation emission cost per unit product (\$/unit/km); $e_2 = c_2 w F_e T_x$;
e_c	average warehouse energy consumption per unit product (kWh/unit/year);
w_e	warehouse emissions cost per unit product (\$/unit/year); $w_e = e_c E_e T_x$;
T	cycle length;
T_1	production period for the manufacturer in each cycle;
T_2	nonproduction period for the manufacturer in each cycle;
T_i	inspection time per delivery for the retailer;
T_b	inventory cycle length per delivery for the retailer; $T_b = T/n$;
$I_p(t)$	manufacturer's inventory level at time t;
$I_{pd}(t)$	manufacturer's inventory for defective products at time t;
$I_d(t)$	retailer's inventory level at time t;
ETC_d	retailer's expected total cost per year (\$/year);
ETC_p	manufacturer's expected total cost per year (\$/year);
ETC	joint expected total cost per year (\$/year);
ETE_d	retailer's expected total carbon emissions per year (tonCO_2/year);
ETE_p	manufacturer's expected total carbon emissions per year (tonCO_2/year);
ETE	joint expected total carbon emissions per year (tonCO_2/year);
Decision variables	
Q	delivery lot size (unit);
n	number of deliveries per order (positive integer).
*	indicates optimal solution

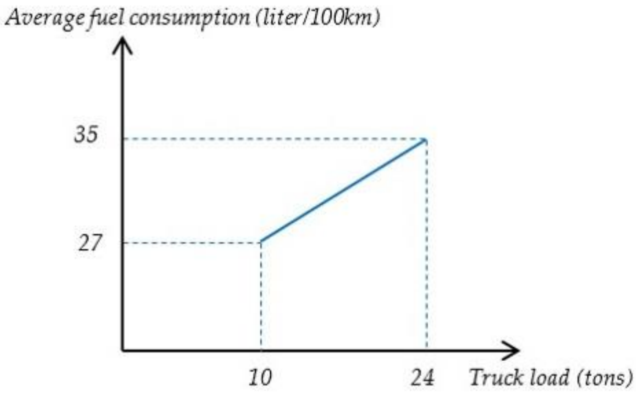

Figure 3. Linear function of average fuel consumption vs. total weight for regional traffic (Data source: Volvo Corporation, 2018).

4. Model Development

This section provides model development for two inspection cases.

4.1. Model Development with Retailer Inspection

This sub-section presents model development when quality inspection becomes the retailer's responsibility. The model is adapted from Tiwari et al. [15]. However, this study considers weight and distance-dependent transportation cost.

The inventory level of the manufacturer and the retailer is illustrated in Figure 4. In one production cycle, the manufacturer produces PT_1 units of the item, and delivers all the produced items to the retailer n times with a constant lot size Q. Right after receiving each lot, the retailer starts the quality inspection that ends at T_i. At T_i, uQ units of defective products will be removed from the inventory. During the period [0, T/n], the retailer's inventory decreases due to demand.

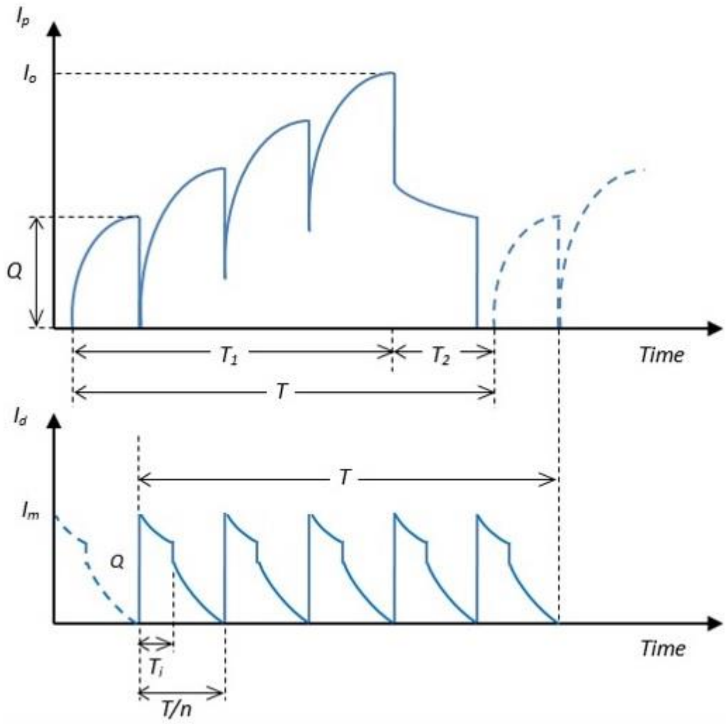

Figure 4. Manufacturer's and retailer's inventory model for constantly deteriorating items with retailer's inspection for n = 5.

4.1.1. Retailer Cost and Emission

As c is the retailer's ordering cost, the ordering cost per year is given by c/T (Lee and Kim [22], Yang and Wee [52]). After a lot arrived, the 100% quality inspection starts and then finishes at T_i. As there are fixed inspection costs per delivery, i_c, and unit inspection costs, u_c (Sarkar et al. [12]), the inspection cost per year is given by:

$$i_c\frac{n}{T} + u_cQ\frac{n}{T} = \frac{n}{T}(i_c + u_cQ) \quad (1)$$

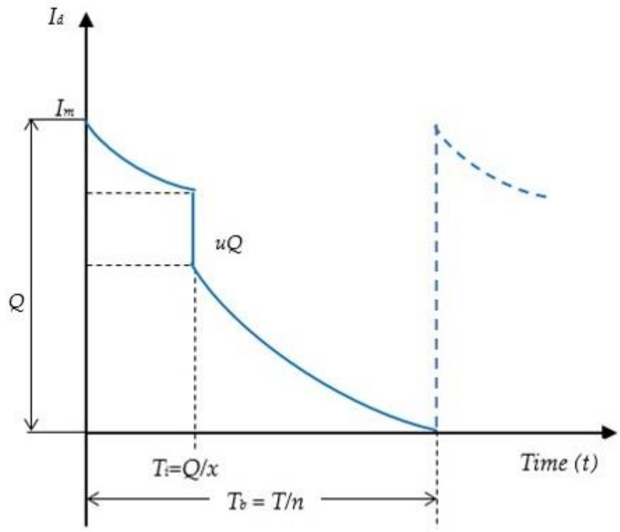

Figure 5. Retailer's inventory model with imperfect quality per delivery cycle.

Figure 5 illustrates the retailer's on-hand inventory per delivery cycle. The inventory level, considering deterioration and imperfect quality, has been studied by researchers such as Jaggi et al. [53] and results in the following equations:

$$I_d(t) = Qe^{-\theta\, t} + \frac{D}{\theta}\left(e^{-\theta\, t} - 1\right),\ 0 \leq\ t\ \leq Q/x \quad (2)$$

$$I_d(t) = Qe^{-\theta\, t} + \frac{D}{\theta}\left(e^{-\theta\, t} - 1\right) - uQ\,, Q/x \leq\ t\ \leq T/n \quad (3)$$

At $t = T/n$, $I_d(T/n) = 0$, therefore equation (3) becomes:

$$Qe^{-\theta T/n} + \frac{D}{\theta}\left(e^{-\theta T/n} - 1\right) - uQ = 0$$

Solving the equation for Q, one has:

$$Q = -\frac{D\left(e^{-\theta T/n} - 1\right)}{\theta\left(e^{-\theta T/n} - u\right)} = \frac{D\left(e^{-\theta T/n} - 1\right)}{\theta\left(u - e^{-\theta T/n}\right)} \text{ which is } = \frac{D\left(e^{\theta T/n} - 1\right)}{\theta\left(1 - ue^{\theta T/n}\right)} \text{ (Jaggi et al. [53])}$$

Hence:

$$Q = I_d(0) = \frac{D\left(e^{\theta T/n} - 1\right)}{\theta\left(1 - ue^{\theta T/n}\right)} \quad (4)$$

Further, the on-hand inventory per year for the retailer is:

$$\frac{n}{T}\left[\int_0^{Q/x} I_d(t)dt + \int_{Q/x}^{T/n} I_d(t)dt\right]$$

$$\frac{n}{T}\left[\frac{Q}{\theta}\left(1-e^{-\frac{\theta Q}{x}}\right)-\frac{D}{\theta^2}\left(\frac{Q\theta}{x}+e^{-\frac{\theta Q}{x}}-1\right)-\frac{1}{\theta}\left(e^{-\frac{\theta T}{n}}-e^{-\frac{\theta Q}{x}}\right)\left(Q+\frac{D}{\theta}\right)-\left(\frac{T}{n}-\frac{Q}{x}\right)\left(uQ+\frac{D}{\theta}\right)\right] \quad (5)$$

We assumed that storing the items requires electrical energy with a certain amount of carbon footprint. Therefore, substituting Equations (4) with (5) and considering the retailer's holding costs and emissions, the inventory holding and emission cost per year becomes:

$$\begin{array}{c}(h_d+w_e)\frac{n}{T}[\frac{D}{\theta^2\left(ue^{\frac{\theta T}{n}}-1\right)^2}\left(\frac{uD}{x}\left(1+e^{\frac{2\theta T}{n}}-2e^{\frac{\theta T}{n}}\right)\right.\\ \left.+u\left(1-e^{\frac{2\theta T}{n}}+ue^{\frac{2\theta T}{n}}-ue^{\frac{\theta T}{n}}\right)+\frac{\theta T}{n}\left(u-1+ue^{\frac{\theta T}{n}}-u^2e^{\frac{\theta T}{n}}\right)+e^{\frac{\theta T}{n}}-1\right)]\end{array} \quad (6)$$

Considering the expected probability value of the defective products ($E[u]$), the average warehouse energy consumption per unit product (e_c), and the average emission from electricity generation (Ee), from Equation (6), the retailer's expected carbon footprint (ETE_d) per year of holding the inventory is:

$$\begin{aligned}ETE_d &= (e_cE_e)\frac{n}{T}[\frac{D}{\theta^2\left(E[u]e^{\frac{\theta T}{n}}-1\right)^2}\left(\frac{E[u]D}{x}\left(1+e^{\frac{2\theta T}{n}}-2e^{\frac{\theta T}{n}}\right)\right.\\ &+E[u]\left(1-e^{\frac{2\theta T}{n}}+E[u]e^{\frac{2\theta T}{n}}-E[u]e^{\frac{\theta T}{n}}\right)\\ &\left.+\frac{\theta T}{n}\left(E[u]-1+E[u]e^{\frac{\theta T}{n}}-E[u]^2e^{\frac{\theta T}{n}}\right)+e^{\frac{\theta T}{n}}-1\right)]\end{aligned} \quad (7)$$

The retailer's deteriorating cost per year is:

$$\frac{d_dn}{T}\left(Q-uQ-\frac{DT}{n}\right)=d_d\left(\frac{(1-u)n}{T}\frac{D\left(e^{\theta T/n}-1\right)}{\theta\left(1-ue^{\theta T/n}\right)}-D\right) \quad (8)$$

The retailer's total cost is the sum of the ordering, inspection, deteriorating, inventory holding, and emission costs. Therefore, considering the probability of the defective products, the expected total cost per year is:

$$\begin{aligned}ETC_d &= \frac{c}{T}+\frac{n}{T}\left(i_c+u_c\frac{D\left(e^{\frac{\theta T}{n}}-1\right)}{\theta\left(1-E[u]e^{\frac{\theta T}{n}}\right)}\right)+d_d\left(\frac{(1-E[u])n}{T}\frac{D\left(e^{\theta T/n}-1\right)}{\theta\left(1-E[u]e^{\theta T/n}\right)}-D\right)\\ &+(h_d+w_e)\frac{nD}{T\theta^2\left(E[u]e^{\frac{\theta T}{n}}-1\right)^2}\left(\frac{E[u]D}{x}\left(1+e^{\frac{2\theta T}{n}}-2e^{\frac{\theta T}{n}}\right)\right.\\ &+E[u]\left(1-e^{\frac{2\theta T}{n}}+E[u]e^{\frac{2\theta T}{n}}-E[u]e^{\frac{\theta T}{n}}\right)\\ &\left.+\frac{\theta T}{n}\left(E[u]-1+E[u]e^{\frac{\theta T}{n}}-E[u]^2e^{\frac{\theta T}{n}}\right)+e^{\frac{\theta T}{n}}-1\right)\end{aligned} \quad (9)$$

4.1.2. Manufacturer Cost and Emission

After the arrival of the retailer's order, the manufacturer starts the production of nQ units of the item at a production rate P. Since s is the setup cost per production cycle, the manufacturer's setup cost per year is s/T.

The first delivery occurs as soon as the quantity is met. The following deliveries occur at T/n intervals. The transportation cost belongs to the manufacturer and consist of fixed and variable costs. Swenseth and Godfrey [54], Nie et al. [55], Rahman et al. [56], and Wangsa and Wee [57] incorporated the variable transportation cost, which is affected by the shipping distance and truckloads. The manufacturer's transportation cost per delivery is given by:

$$t_f+2dc_1t_v+dQwc_2t_v \quad (10)$$

The first element is the fixed transportation setup cost. The second element calculates the transportation cost of an empty truck. As the truck goes from the manufacturer to the retailer and then goes back, the distance is multiplied by two. Then, the transportation cost for the truckload is calculated, which depends on the delivery distance and quantity, product weight, additional fuel consumption per ton per km, and the fuel price. Substituting Equation (4) to (10), the manufacturer's transportation cost per year is given by:

$$\frac{n}{T}\left(t_f + 2dc_1t_v + d\frac{D\left(e^{\theta T/n}-1\right)}{\theta\left(1-ue^{\theta T/n}\right)}wc_2t_v\right) \tag{11}$$

Wahab et al. [10] identified that the emissions from transportation were affected by the delivery distance, actual shipment weight, fuel consumption per km, and CO_2 emissions per liter of fuel. Therefore, the amount of the manufacturer's carbon emission per year as the result of transportation activity can be derived as follows:

$$\frac{n}{T}(2dc_1 + dQwc_2)F_e = \frac{n}{T}\left(2dc_1 + d\frac{D\left(e^{\theta T/n}-1\right)}{\theta\left(1-ue^{\theta T/n}\right)}wc_2\right)F_e \tag{12}$$

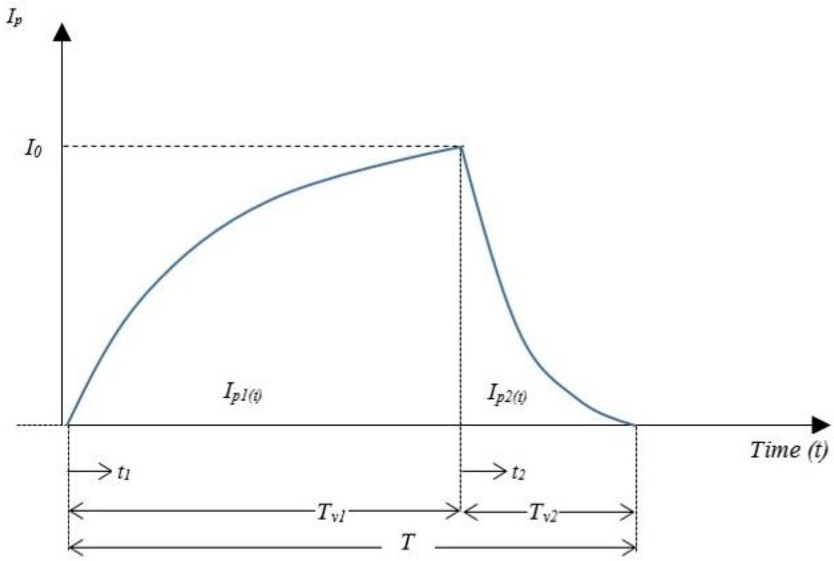

Figure 6. $I_{p1}(t_1)$ and $I_{p2}(t_2)$ vs. time.

As depicted in Figure 6, Lee and Kim [22] studied a similar inventory model for the manufacturer using Yang and Wee's [52] approach. Both production and consumption occur during T_1, while only consumption occurs during T_2. Hsu [58] suggested some revision considering the effect of defective products. Due to defective products and the retailer's quality inspection, the effective demand rate for the manufacturer becomes $D/(1\text{-}u)$. Therefore, the inventory functions are as follows:

$$I_{p1}(t_1) = \frac{P-(D/(1-u))}{\theta}\left(1-e^{-\theta\, t_1}\right),\ 0 \le\ t_1\ \le T_1 \tag{13}$$

$$I_{p2}(t_2) = \frac{(D/(1-u))}{\theta}\left(e^{\theta\ (T_2-t_2)}-1\right), 0\ \ t_2\ \le T_2 \tag{14}$$

From the boundary condition $I_{p1}(T_1) = I_{p2}(0)$ and following Misra's [59] approximation:

$$\left(P-\frac{D}{1-u}\right)T_1\left(1-\frac{1}{2}\theta T_1\right) = \left(\frac{D}{1-u}\right)T_2\left(1+\frac{1}{2}\theta T_2\right)$$

Hence, one has:

$$T_1 \approx \frac{D}{(1-u)P-D} T_2 \left(1 + \frac{1}{2}\theta T_2\right) \tag{15}$$

$$T \approx \frac{T_2}{(1-u)P-D} \left((1-u)P + \frac{1}{2}D\theta T_2\right) \tag{16}$$

From Yang and Wee [52], the manufacturer's inventory per cycle is:

$$\int_0^{T_1} I_{p1}(t_1)dt_1 + \int_0^{T_2} I_{p2}(t_2)dt_2 - n\int_0^{T/n} I_d(t)dt \tag{17}$$

Hence, the manufacturer's holding cost per year is:

$$\begin{gathered}\frac{h_p}{T}\left[\frac{P-(D/(1-u))}{\theta}T_1 + \frac{P-(D/(1-u))}{\theta^2}\left(e^{-\theta\,T_1}-1\right) - \frac{(D/(1-u))T_2}{\theta} - \frac{(D/(1-u))}{\theta^2}\left(1-e^{\theta\,T_2}\right)\right.\\ -n\left(\frac{D}{\theta^2\left(ue^{\frac{\theta T}{n}}-1\right)^2}\left(\frac{uD}{x}\left(1+e^{\frac{2\theta T}{n}}-2e^{\frac{\theta T}{n}}\right)+u\left(1-e^{\frac{2\theta T}{n}}+ue^{\frac{2\theta T}{n}}-ue^{\frac{\theta T}{n}}\right)\right.\right.\\ \left.\left.\left.+\frac{\theta T}{n}\left(u-1+ue^{\frac{\theta T}{n}}-u^2e^{\frac{\theta T}{n}}\right)+e^{\frac{\theta T}{n}}-1\right)\right)\right]\end{gathered} \tag{18}$$

The amount of a manufacturer's carbon emissions per year as the result of warehousing activity can be derived as follows:

$$\begin{gathered}\frac{e_cE_e}{T}\left[\frac{P-(D/(1-u))}{\theta}T_1 + \frac{P-(D/(1-u))}{\theta^2}\left(e^{-\theta\,T_1}-1\right) - \frac{(D/(1-u))T_2}{\theta} - \frac{(D/(1-u))}{\theta^2}\left(1-e^{\theta\,T_2}\right)\right.\\ -n\left(\frac{D}{\theta^2\left(ue^{\frac{\theta T}{n}}-1\right)^2}\left(\frac{uD}{x}\left(1+e^{\frac{2\theta T}{n}}-2e^{\frac{\theta T}{n}}\right)+u\left(1-e^{\frac{2\theta T}{n}}+ue^{\frac{2\theta T}{n}}-ue^{\frac{\theta T}{n}}\right)\right.\right.\\ \left.\left.\left.+\frac{\theta T}{n}\left(u-1+ue^{\frac{\theta T}{n}}-u^2e^{\frac{\theta T}{n}}\right)+e^{\frac{\theta T}{n}}-1\right)\right)\right]\end{gathered} \tag{19}$$

The manufacturer's carbon emissions per year come from Equations (12) and (19). Therefore, the manufacturer's carbon emission cost is:

$$\begin{gathered}\frac{n}{T}\left(2de_1 + d\frac{D\left(e^{\theta T/n}-1\right)}{\theta\left(1-ue^{\theta T/n}\right)}e_2\right)\\ +\frac{w_e}{T}\left[\frac{P-(D/(1-u))}{\theta}T_1 + \frac{P-(D/(1-u))}{\theta^2}\left(e^{-\theta\,T_1}-1\right) - \frac{(D/(1-u))T_2}{\theta} - \frac{(D/(1-u))}{\theta^2}\left(1-e^{\theta\,T_2}\right)\right.\\ -n\left(\frac{D}{\theta^2\left(ue^{\frac{\theta T}{n}}-1\right)^2}\left(\frac{uD}{x}\left(1+e^{\frac{2\theta T}{n}}-2e^{\frac{\theta T}{n}}\right)+u\left(1-e^{\frac{2\theta T}{n}}+ue^{\frac{2\theta T}{n}}-ue^{\frac{\theta T}{n}}\right)\right.\right.\\ \left.\left.\left.+\frac{\theta T}{n}\left(u-1+ue^{\frac{\theta T}{n}}-u^2e^{\frac{\theta T}{n}}\right)+e^{\frac{\theta T}{n}}-1\right)\right)\right]\end{gathered} \tag{20}$$

The loss due to deterioration in the manufacturer's inventory is the total production during the period T_1, minus the total delivered products to the retailer's inventory. Therefore, the manufacturer's deteriorating cost per year is:

$$\frac{d_p}{T}\left(PT_1 - n\left(\frac{D\left(e^{\theta T/n}-1\right)}{\theta\left(1-ue^{\theta T/n}\right)}\right)\right) \tag{21}$$

From Equations (11), (18), (20), and (21), as well as the setup cost, and considering the probability of the defective products, the manufacturer's expected total cost per year is:

$$\begin{aligned} ETC_p \quad &= \tfrac{s}{T} + \tfrac{n}{T}\left(t_f + 2dc_1t_v + d\frac{D\left(e^{\theta T/n}-1\right)}{\theta\left(1-E[u]e^{\theta T/n}\right)}wc_2t_v\right) \\ &+ \tfrac{(h_p+w_e)}{T}\Bigg[\tfrac{P-(D/(1-E[u]))}{\theta}T_1 + \tfrac{P-(D/(1-E[u]))}{\theta^2}\left(e^{-\theta\ \mathrm{T}_1} - 1\right) \\ &- \tfrac{(D/(1-E[u]))T_2}{\theta} - \tfrac{(D/(1-E[u]))}{\theta^2}\left(1 - e^{\theta\ \mathrm{T}_2}\right) \\ &-n\left(\frac{D}{\theta^2\left(E[u]e^{\frac{\theta T}{n}}-1\right)^2}\left(e^{\frac{\theta T}{n}} - 1 + \tfrac{E[u]D}{x}\left(1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}}\right)\right.\right. \\ &+E[u]\left(1 - e^{\frac{2\theta T}{n}} + E[u]e^{\frac{2\theta T}{n}} - E[u]e^{\frac{\theta T}{n}}\right) \\ &\left.\left.+\tfrac{\theta T}{n}\left(E[u] - 1 + E[u]e^{\frac{\theta T}{n}} - E[u]^2e^{\frac{\theta T}{n}}\right)\right)\right)\Bigg] \\ &+\tfrac{n}{T}\left(2de_1 + d\frac{D\left(e^{\theta T/n}-1\right)}{\theta\left(1-E[u]e^{\theta T/n}\right)}e_2\right) + \tfrac{d_p}{T}\left(PT_1 - n\left(\frac{D\left(e^{\theta T/n}-1\right)}{\theta\left(1-ue^{\theta T/n}\right)}\right)\right) \end{aligned} \tag{22}$$

4.1.3. The Integrated Manufacturer and Retailer Cost Function

In an integrated decision, the manufacturer and the retailer jointly specify n, which minimizes the expected total cost (ETC). The ETC is the sum of ETC_d and ETC_p in Equations (9) and (22).

Using Taylor's series expansion for a small value of $\theta T/n$, θT_1, and θT_2, we can solve the cost function by assuming e^x as $1 + x + x^2/2 + x^3/6$. Furthermore, the expected total emissions (ETE) per year from the manufacturer and the retailer can be derived from Equations (7), (12), and (19).

4.1.4. Methodology and Solution Search

The objective is to determine the optimal number of deliveries (n^*) that minimize the expected total cost function (ETC). The value of n^* and the respective T, T_1, and T_2 will lead us to the optimal delivery quantity Q^* and production quantity R. The proposed procedure to derive the positive integer decision variable n is adapted from Tiwari et al. [15] and Yang and Wee [52] as follows:

Step 1. Substitute the T_1 and T functions in Equations (15) and (16) into ETC;
Step 2. Input all the known parameters;
Step 3. Set $n = 1$;
Step 4. Derive the partial derivative of ETC with respect to T_2 and set it to zero. Solve the equation to find the value of T_2;
Step 5. Use the known n and T_2 to find the value of T_1 and T using Equations (15) and (16).
Step 6. Derive the corresponding ETC;
Step 7. If $ETC(n) > ETC(n-1)$, then $n^* = n - 1$ and go to Step 8; otherwise, set $n = n + 1$ and go back to Step 4;
Step 8. Use n^* and the corresponding T^* to find Q^* from Equation (4) and calculate $R = PT_1{}^*$.

4.2. Model Development with Manufacturer Inspection

This sub-section presents the model development when quality inspection becomes the manufacturer's responsibility. The purpose of such a policy is to prevent transporting defective products. The manufacturer performs a quality inspection of all the produced products and keeps the defective products separately until the end of the production period T_1. The defective products will be sold at a discounted price to the secondary market. The inventory level for both the manufacturer (I_p) and the retailer (I_d), including the manufacturer's inventory of the defective products (I_{pd}), is illustrated in Figure 7. In this model, the I_{pd} is accumulated during the T_1 period. Besides, I_d decreases solely due to demand.

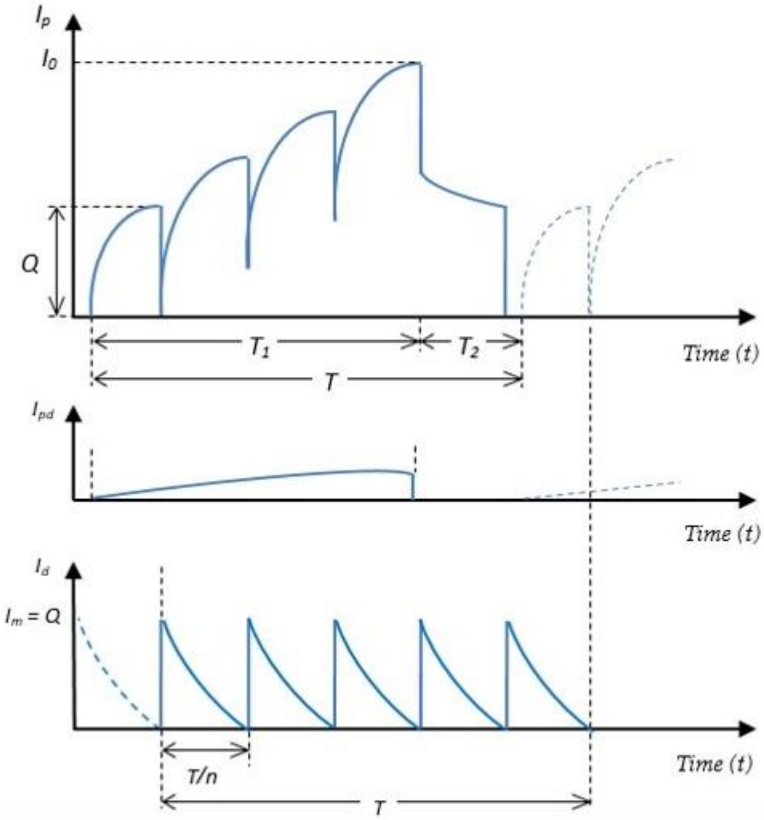

Figure 7. Manufacturer's and retailer's inventory model for constant deteriorating items with manufacturer's inspection for n = 5.

4.2.1. Retailer Cost and Emission

The retailer's total cost is the sum of the ordering, inventory holding, deteriorating, and emission costs. The ordering cost per year is given by *c/T*, which is similar to Model 1 (Section 4.1.1). During the *T/n* period, I_d decreases due to demand and deterioration. From Yang and Wee [52], the inventory function is as follows:

$$I_d(t) = \frac{D}{\theta}\left(e^{\theta\left(\frac{T}{n} - t\right)} - \right), 0 \;\; t \;\; \leq T/n \tag{23}$$

and

$$Q = I_d(0) = \frac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) \tag{24}$$

and the holding cost per year is:

$$h_d \frac{n}{T}\left(\int_0^{T/n} I_d(t)dt\right) = h_d \frac{n}{T}\left(\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) - \frac{T}{n}\right)\right) \tag{25}$$

Further, the deteriorating cost per year is:

$$d_d \frac{n}{T}\left(Q - D\frac{T}{n}\right) = d_d \frac{n}{T}\left(\frac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) - \frac{DT}{n}\right) \tag{26}$$

$$ETE_d = e_c E_e\left(\frac{n}{T}\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) - \frac{T}{n}\right)\right) \tag{27}$$

Equation (27) shows the retailer's carbon emission (ETE_d) from holding the inventory. Therefore, the retailer's carbon emission cost per year is:

$$w_e\left(\frac{n}{T}\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right) \tag{28}$$

The retailer's expected total cost per year (ETC_d) becomes:

$$ETC_d=\frac{c}{T}+(h_d+w_e)\frac{n}{T}\left(\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right)+d_d\frac{n}{T}\left(\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{DT}{n}\right) \tag{29}$$

4.2.2. Manufacturer Cost and Emission

Due to some percentage of defective products, the production rate of the perfect product is $(1-u)P$. The manufacturer's setup cost per year is s/T. In this model, the manufacturer will have an additional inspection cost. Since the total number of products being produced per production cycle is PT_1, considering a fixed inspection cost per cycle (i_c) and unit inspection cost (u_c), the manufacturer's inspection cost per year is:

$$\frac{i_c}{T}+\frac{u_cPT_1}{T} \tag{30}$$

The manufacturer's transportation function is similar to Equation (10); therefore, the transportation cost and emissions per year become:

$$\frac{n}{T}\left(t_f+2dc_1t_v+d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)wc_2t_v\right) \tag{31}$$

$$\frac{n}{T}\left(2dc_1+d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)wc_2\right)F_e \tag{32}$$

From Figure 6, the inventory differential equations are:

$$dI_{p1}(t_1)=((1-u)P-D)dt_1-\theta I_{p1}(t_1)dt_1,\ 0\le\ t_1\ \le T_1$$

$$dI_{p2}(t_2)=-Ddt_2-\theta I_{p2}(t_2)dt_2,\ 0\le\ t_2\ \le T_2$$

For the boundary condition for $t_1 = 0$, $I_1(0) = 0$ and for $t_2 = 0$, $I_2(0) = I_o$ and for $t_2 = T_2$, $I_2(T_2) = 0$, the manufacturer's inventory functions for the good products are:

$$I_{p1}(t_1)=\frac{(1-u)P-D}{\theta}\left(1-e^{-\theta\ t_1}\right),\ 0\le\ t_1\ \le T_1 \tag{33}$$

$$I_{p2}(t_2)=\frac{D}{\theta}\left(e^{\theta\ (T_2-t_2)}-1\right),0\ \ t_2\ \le T_2 \tag{34}$$

From the boundary condition $I_{p1}(T_1) = I_{p2}(0)$, we have the following equation:

$$\frac{((1-u)P-D)}{\theta}\left(1-e^{-\theta\ T_1}\right)=\frac{D}{\theta}\left(e^{\theta T_2}-1\right) \tag{35}$$

From Taylor's series expansion and the assumption of $\theta T << 1$, following Misra's [59] approximation, one has:

$$((1-u)P-D)T_1\left(1-\frac{1}{2}\theta T_1\right)=DT_2\left(1+\frac{1}{2}\theta T_2\right)$$

$$T_1 \approx \frac{D}{(1-u)P-D} T_2 \left(1+\frac{1}{2}\theta T_2\right) \tag{36}$$

$$T \approx \frac{T_2}{(1-u)P-D} \left((1-u)P+\frac{1}{2}D\theta T_2\right) \tag{37}$$

Therefore, the manufacturer's inventory for good products becomes:

$$\int_0^{T_1} \frac{(1-u)P-D}{\theta}\left(1-e^{-\theta\, t_1}\right)dt_1 + \int_0^{T_2} \frac{D}{\theta}\left(e^{\theta\,(T_2-t_2)}-1\right)dt_2 - n\left[\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right] \tag{38}$$

Besides, there is an inventory of defective products. From Figure 6, the inventory differential equation for the defective products is:

$$dI_{pd}(t_1) = uPdt_1 - \theta I_{pd}(t_1)dt_1,\ 0 \le\ t_1\ \le T_1$$

For the boundary condition for t_1 = 0, I_1(0) = 0, the manufacturer's inventory function for the defective products is:

$$I_{pd}(t_1) = \frac{uP}{\theta}\left(1-e^{-\theta\, t_1}\right),\ 0 \le\ t_1\ \le T_1$$

Therefore, the manufacturer's inventory of the defective products becomes:

$$\int_0^{T_1} \frac{uP}{\theta}\left(1-e^{-\theta\, t_1}\right)dt_1 \tag{39}$$

Hence, the manufacturer's holding cost per year is:

$$\begin{array}{l} \frac{h_p}{T}\left(\frac{(1-u)P-D}{\theta}T_1 + \frac{(1-u)P-D}{\theta^2}\left(e^{-\theta T_1}-1\right) - \frac{DT_2}{\theta} - \frac{D}{\theta^2}\left(1-e^{\theta T_2}\right)\right. \\ \left. -n\left(\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right) + \frac{uPT_1}{\theta} + \frac{uP}{\theta^2}\left(e^{-\theta T_1}-1\right)\right) \end{array} \tag{40}$$

Therefore, based on Equations (32) and (40), the manufacturer's carbon emission cost and the total expected carbon emissions per year can be calculated as follows:

$$\begin{array}{l} \frac{n}{T}\left(2de_1 + d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)e_2\right) \\ \quad + \frac{w_e}{T}\left(\frac{(1-u)P-D}{\theta}T_1 + \frac{(1-u)P-D}{\theta^2}\left(e^{-\theta T_1}-1\right) - \frac{DT_2}{\theta}\right. \\ \quad -\frac{D}{\theta^2}\left(1-e^{\theta T_2}\right) - n\left(\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right) + \frac{uPT_1}{\theta} \\ \quad \left. + \frac{uP}{\theta^2}\left(e^{-\theta T_1}-1\right)\right) \end{array} \tag{41}$$

$$\begin{array}{rl} ETE_p & = \frac{n}{T}\left(2dc_1 + d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)wc_2\right)F_e \\ & +\frac{e_cE_e}{T}\left(\frac{(1-u)P-D}{\theta}T_1 + \frac{(1-u)P-D}{\theta^2}\left(e^{-\theta T_1}-1\right) - \frac{DT_2}{\theta}\right. \\ & -\frac{D}{\theta^2}\left(1-e^{\theta T_2}\right) - n\left(\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right) + \frac{uPT_1}{\theta} \\ & \left. +\frac{uP}{\theta^2}\left(e^{-\theta T_1}-1\right)\right) \end{array} \tag{42}$$

The number of deteriorated items in the manufacturer's inventory is the total production during the period T_1, minus the total products delivered to the buyer and the inventory of the defective products. Therefore, the manufacturer's deteriorating cost per year is:

$$\frac{d_p}{T}\left((1-u)PT_1 - n\left(\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)\right) + \left(uPT_1 - \frac{uP}{\theta}\left(1-e^{-\theta\,\mathrm{T}_1}\right)\right)\right) \tag{43}$$

Considering the additional inspection cost and the probability of the defective products, the manufacturer's expected total cost per year is:

$$\begin{aligned} ETC_p \; &= \tfrac{s}{T} + \tfrac{i_c}{T} + \tfrac{u_c P T_1}{T} + \tfrac{n}{T}\left(t_f + 2dc_1 t_v + d\tfrac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) wc_2 t_v\right) \\ &+ \tfrac{n}{T}\left(2de_1 + d\tfrac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) e_2\right) \\ &+ \tfrac{(h_p + w_e}{T}\left(\tfrac{(1-E[u])P-D}{\theta} T_1 + \tfrac{(1-E[u])P-D}{\theta^2}\left(e^{-\theta T_1} - 1\right)\right. \\ &- \tfrac{DT_2}{\theta} - \tfrac{D}{\theta^2}\left(1 - e^{\theta T_2}\right) - n\left(\tfrac{D}{\theta}\left(\tfrac{1}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) - \tfrac{T}{n}\right)\right) + \tfrac{E[u]PT_1}{\theta} \\ &\left. + \tfrac{E[u]P}{\theta^2}\left(e^{-\theta T_1} - 1\right)\right) \\ &+ \tfrac{d_p}{T}\left((1 - E[u])PT_1 - n\left(\tfrac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right)\right)\right. \\ &\left. + \left(E[u]PT_1 - \tfrac{E[u]P}{\theta}\left(1 - e^{-\theta T_1}\right)\right)\right) \end{aligned} \tag{44}$$

4.2.3. The Integrated Manufacturer and Retailer Cost Function

The *ETC* of the integrated system is the sum of Equations (29) and (44). Using Taylor's series expansion for a small value of $\theta T/n$, θT_1, and θT_2, we can solve the cost function by assuming e^x as $1 + x + x^2/2 + x^3/6$. Furthermore, the *ETE* can be derived from Equation (27) and Equation (42).

4.2.4. Methodology and Solution Search

Similar to Model 1, the objective is to determine the optimal number of deliveries (n*) that minimize the expected total cost function *ETC*. The proposed procedure to search for the optimum solution is as follows:

Step 1. Substitute the T_1 and T functions in Equations (36) and (37) into *ETC*;
Step 2. Input all the known parameters;
Step 3. Set $n = 1$;
Step 4. Derive the partial derivative of *ETC* with respect to T_2 and set it to zero. Solve the equation to find the value of T_2;
Step 5. Use the known n and T_2 to find the value of T_1 and T using Equations (36) and (37).
Step 6. Derive the corresponding *ETC*;
Step 7. If $ETC(n) > ETC(n\text{-}1)$ then $n^* = n - 1$ and go to step 8, otherwise set $n = n + 1$ and back to Step 4;
Step 8. Use n^* and the corresponding T^* to find Q^* from Equation (24) and calculate $R = PT_1{}^*$.

5. Numerical Example and Management Insights

5.1. Numerical Example 1

The values of the parameters are considered by adopting data from Yang and Wee [52], Hariga et al. [30], and Tiwari et al. [15] as P = 2,000,000 units/year, D = 500,000 units/year, x = 1,725,000 unit/year, i_c = \$500/delivery, u_c = \$0.5/unit, c = \$2,000/order, s = \$100,000/setup, h_d = \$60/unit/year, h_p = \$40/unit/year, d_d = \$600/unit, d_p = \$400/unit, θ = 0.1, d = 100 km, t_f = \$1000/delivery, t_v = \$0.75/liter, w = 0.01 ton/unit, c_1 = 27 L/100 km, c_2 = 0.57 L/100 km/ton truckload, e_c = 1.44 kWh/unit/year, T_x = \$75/tonCO_2, $F_e = 2.6 \times 10^{-3}$ tonCO_2/L (US. EPA [60]), $E_e = 0.5 \times 10^{-3}$ tonCO_2/kWh (McCarthy [61]), and u is uniformly distributed in which α = 0 and β = 0.04, with $E[u]$ = 0.02.

The minimum value of joint expected total cost can be obtained at n^* = 7 with T_2 = 0.0651856, T_1 = 0.0223966, and T = 0.0875822, as shown in Table 3. The *ETC* is \$2,834,922/year, which is from Equation (4), the optimum Q is 6,387.7 units. The optimum R is 44,793.2 units, and the *ETE* is 30.598 tonCO_2/year. If the supply chain solely minimizes the total amount of carbon footprint, the decision is to perform a single-setup single-delivery (SSSD) as n = 1 with *ETE* = 18.460 tonCO_2/year (saving

39.7%). However, this situation increases the *ETC* into \$3,366,391 (18.7%). Figure 8 shows the convexity of *ETC* when $n = 7$.

Table 3. Expected total cost for different n in Model 1.

n	$T_2(10^{-5})$	$T_1\ (10^{-5})$	$T\ (10^{-5})$	ETC_d	ETC_p	ETC	ETE
1	4960	1703	6663	2,348,991	1,017,400	3,366,391	18.460
2	5641	1937	7578	1,463,323	1,568,493	3,031,816	21.333
3	5961	2048	8009	1,122,012	1,799,193	2,921,205	23.501
4	6161	2117	8278	941,509	1,930,509	2,872,018	25.422
5	6306	2167	8473	830,673	2,017,748	2,848,421	27.216
6	6422	2206	8628	756,370	2,081,526	2,837,896	28.935
7 *	6518	2240	8758	703,611	2,131,311	2,834,922	30.598
8	6603	2269	8872	664,620	2,172,067	2,836,687	32.218
9	6680	2295	8976	634,952	2,206,651	2,841,603	33.805
10	6751	2320	9071	611,889	2,236,823	2,848,712	35.360

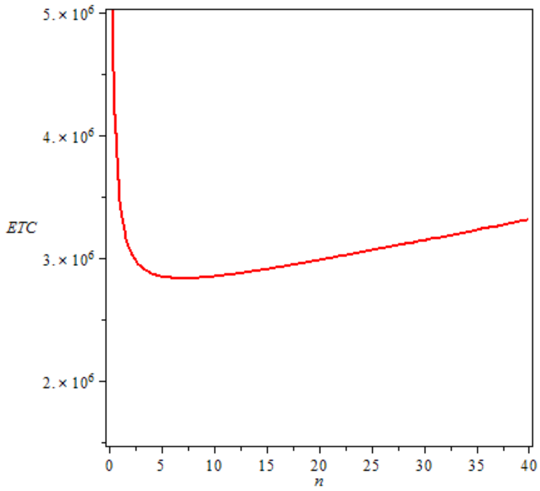

Figure 8. Graphical representation of expected total cost (*ETC*) for a fixed n in Model 1.

When the probability of defective products, unit inspection costs, carbon tax, and variable transport cost are equal to zero ($E[u] = u_c = T_x = t_v = 0$), the results are $n = 7$, $T = 0.08791$, and $ETC =$ \$2,559,246 which are similar to the results of Yang and Wee [52].

5.2. Numerical Example 2

We consider the parameters in numerical example one and solve it using the Model 2 results of the following values. The minimum value of joint expected total cost can be obtained at $n^* = 9$ and $T = 0.08869$, as shown in Table 4. The Q, R, and ETC are 4,929.6 units, 45,360.7 units, and \$2,782,396/year, respectively. The ETE is 33.52 $tonCO_2$/year.

Table 4. Expected total cost for different n in Model 2.

n	$T_2(10^{-5})$	$T_1(10^{-5})$	$T\ (10^{-5})$	ETC_d	ETC_p	ETC	ETE
1	4977	1709	6686	2,041,005	1,312,795	3,353,800	18.22
2	5653	1941	7595	1,167,506	1,844,193	3,011,699	21.07
3	5963	2048	8011	827,178	2,067,759	2,894,937	23.21
4	6151	2113	8264	644,684	2,195,273	2,839,957	25.12
5	6282	2158	8441	530,652	2,280,088	2,810,741	26.91
6	6384	2193	8577	425,568	2,342,142	2,794,711	28.63
7	6467	2222	8689	395,714	2,390,607	2,786,322	30.29
8	6538	2246	8784	352,240	2,430,297	2,782,747	31.92
9 *	6601	2268	8869	318,411	2,463,985	2,782,396	33.52
10	6658	2288	8945	290,923	2,493,378	2,784,301	35.11

Table 5 provides the cost comparison between the two models for the result of examples one and two. The number of deliveries per cycle (n) is higher in Model 2 (when the manufacturer performs the quality inspection), while the delivery lot size (Q) is lower. All the retailer's cost components decrease, while all the manufacturer's cost components increase, except for the setup cost. In total, the ETC of Model 2 is 1.85% lower than the ETC in Model 1. However, the retailer's total costs were reduced by 54.7%, while the manufacturer's total costs increased by 15.6%. Considering this situation, cost-saving compensation from the retailer to the manufacturer is an alternative solution so that both parties take advantage of the implementation of the second inspection policy. Based on Goyal [62]:

$$z = \frac{ETC_{d-case1}}{ETC_{case1}}$$

z is the retailer's cost coefficient. Therefore, ETC_d and $ETCp$ after cost-saving compensation are

$$ETC_d{}^a = zETC_{case2}$$

$$ETC_p{}^a = (1-z)ETC_{case2}$$

Table 5. Comparison between Model 1 and Model 2.

Decision Variables and Cost Items	Model 1	Model 2	Saving (%)
Number of deliveries per cycle (n*)	7	9	
Cycle time (T)	0.08758	0.08869	
Delivery lot size (Q); units	6387.7	4929.6	
Ordering cost ($)	22,835.7	22,550.7	1.25
Inspection cost ($)	295,230.7	0	100
Inventory holding cost ($)	190,027.5	147,863.7	22.2
Deteriorating cost ($)	195,346.3	147,863.7	24.3
Emission cost ($)	171.0	133.1	22.2
Total retailer's cost per year ($)	703,611.2	318,909.1	54.7
Total retailer's cost per year after compensation ($)		*690,574.4*	*1.85*
Setup cost ($)	1,141,784.6	1,127,534.2	1.25
Inspection cost ($)	0	261,366.3	−100
Transportation cost ($)	85,289.5	107,690.0	−26.3
Inventory holding cost ($)	539,976.9	567,658.3	−5.13
Deteriorating cost ($)	362,122.2	397,345.0	−9.73
Emission cost ($)	2,138.0	2390.9	−11.8
Total manufacturer's cost per year ($)	2,131,311.2	2,463,984.8	−15.6
Total manufacturer's cost per year after compensation ($)		*2,091,821.6*	*1.85*
Expected total cost ($)	2,834,922.4	2,782,396.0	1.85
Expected total emission (tonCO_2/year)	30.598	33.523	−9.56

Hence, the retailer and manufacturer total cost per year become $690,574.4 and $2,091,821.6, respectively. Finally, by using this compensation policy, the cost decreases $13,036.7 for the retailer and $39,489.6 for the vendor, or 1.85% for both parties. Table 5 also shows that the *ETE* of Model 2 is 33.52 tonCO_2/year, which is 9.55% higher than the *ETE* in Model 1. We can obtain both the cost-saving and emissions-reducing objectives from Table 4, as there is a chance to reduce the *ETE* of Model 2. For $n = 7$, the *ETE* is 30.292, and the *ETC* is $2,781,779 in which now the *ETE* and the *ETC* are 1.0% and 1.87% lower than those of Model 1, respectively. Thus, the objectives of cost efficiency and carbon footprint level reduction can be obtained simultaneously. The new comparison between the two models is presented in Table 6. It is also observed that the total delivered products to the retailer in Model 2 after adjustment (Model 2 ^{adj}) is less than those in Model 1.

Table 6. Comparison between Model 1 and the adjusted Model 2.

Decision Variables and Cost Items	Model 1	Model 2 ^{adj}	Saving (%)
Number of deliveries per cycle (n^*)	7	7	
Cycle time (T)	0.08758	0.08704	
Delivery lot size (Q); units	6,387.7	6221.2	
Ordering cost ($)	22,835.7	22,977.4	−0.62
Inspection cost ($)	295,230.7	0	100
Inventory holding cost ($)	190,027.5	186,596.1	1.80
Deteriorating cost ($)	195,346.3	186,596.1	4.48
Emission cost ($)	171.0	167.9	1.81
Total retailer's cost per year ($)	703,611.2	396,337.5	43.7
Total retailer's cost per year after compensation ($)		*690,428.8*	*1.87*
Setup cost ($)	1,141,784.6	1,148,869.4	−0.62
Inspection cost ($)	0	261,461.4	−100
Transportation cost ($)	85,289.5	85,764.5	−0.55
Inventory holding cost ($)	539,976.9	529,446.7	1.95
Deteriorating cost ($)	362,122.2	357,812.1	1.20
Emission cost ($)	2,138.0	2117.7	0.95
Total manufacturer's cost per year ($)	2,131,311.2	2,385,471.8	−11.9
Total manufacturer's cost per year after compensation ($)		*2,091,380.5*	*1.87*
Expected total cost ($)	2,834,922.4	2,781,809.3	1.87
Expected total emission (tonCO_2/year)	30.598	30.292	1.00

Sensitivity analysis is performed by increasing or decreasing the value of the parameter by ±25% and ±50% from the original values, as shown in Table 7. The results confirm that the second model is superior to the first model in terms of total cost. The number of deliveries per cycle (n) is sensitive to changes in parameters P, D, s, h_d, h_p, d_d, d_p, and t_f. As the values of parameters P, h_p, d_p, and t_f increase, the smaller the value of n. Contradictory conditions occur for parameters D, s, h_d, and d_d. The expected total cost is highly sensitive to the changes in parameters P, D, θ, s, u_c, h_d, h_p, d_d, d_p, and t_f, and almost insensitive to the changes in other parameters.

It is observed that when the deterioration rate (θ) increases, the expected total cost and the number of deliveries increase, but the delivery quantity decreases. When the probability of defective products (u) increases, the expected total cost increases very slightly, especially when the inspection is performed by the vendor. When the carbon tax (T_x) increases, the number of deliveries remains stable. Otherwise, the delivery quantity and expected total cost increase are very small.

Table 7. Sensitivity analysis of the two models.

Parameter	Value Change	Model 1					Model 2				
		n^*	T	Q^a	ETC	$\%CTC$	n^*	T	Q^b	ETC	$\%CTC$
$P = 2{,}000{,}000$	+50%	7	0.0816	5949.3	3,024,249	6.68	8	0.0819	5120.3	2,966,117.1	6.60
	+25%	7	0.0839	6117.1	2,948,615	4.01	8	0.0842	5263.2	2,892,821.2	3.97
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	8	0.0959	6120.6	2,643,862	−6.74	9	0.0957	5322.0	2,596,679.1	−6.67
	−50%	8	0.1147	7321.0	2,253,495	−20.5	11	0.1153	5296.5	2,217,427.4	−20.3
$D = 500{,}000$	+50%	8	0.0816	7811.6	3,190,858	12.5	10	0.0822	6168.2	3,136,392.1	12.7
	+25%	8	0.0841	6705.8	3,044,190	7.38	9	0.0840	5833.6	2,989,178.5	7.43
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0958	5242.7	2,548,150	−10.1	8	0.0962	4510.9	2,499,238.8	−10.2
	−50%	6	0.1100	4683.3	2,151,051	−24.1	8	0.1120	3501.7	2,108,977.7	−24.2
$c = 2000$	+50%	7	0.0880	6415.9	2,846,315	0.40	9	0.0891	4951.6	2,793,646.2	0.40
	+25%	7	0.0878	6401.8	2,840,625	0.20	9	0.0889	4940.6	2,788,027.5	0.20
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0874	6373.5	2,829,207	−0.20	9	0.0885	4918.6	2,776,752.0	−0.20
	−50%	7	0.0872	6359.3	2,823,479	−0.40	9	0.0883	4907.5	2,771,095.4	−0.41
$s = 100{,}000$	+50%	9	0.1074	6090.8	3,348,784	18,1	11	0.1081	4917.3	3,292,159.7	18.3
	+25%	8	0.0979	6250.1	3,104,546	9.51	10	0.0988	4945.1	3,049,823.5	9.61
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	6	0.0760	6464.7	2,529,737	−10.8	8	0.0773	4834.4	2,480,006.3	−10.9
	−50%	5	0.0625	6383.9	2,169,316	−23.5	6	0.0631	5257.7	2,122,805.7	−23.7
$i_c = 500$	+50%	7	0.0883	6437.1	2,854,827	0.70	9	0.0888	4935.1	2,785,213.3	0.10
	+25%	7	0.0879	6412.4	2,844,894	0.35	9	0.0887	4932.4	2,783,805.1	0.05
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0872	6362.9	2,824,912	−0.35	9	0.0886	4926.8	2,780,986.3	−0.05
	−50%	7	0.0869	6338.0	2,814,883	−0.71	9	0.0886	4924.1	2,779,575.6	−0.10
$u_c = 0.5$	+50%	7	0.0876	6387.5	2,962,557	4.50	9	0.0887	4929.0	2,910,260.4	4.60
	+25%	7	0.0876	6387.6	2,898,740	2.25	9	0.0887	4929.3	2,846,328.1	2.30
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0876	6387.8	2,771,105	−2.25	9	0.0887	4929.9	2,718,463.9	−2.30
	−50%	7	0.0876	6387.9	2,707,289	−4.50	9	0.0887	4930.2	2,654,531.7	−4.60
$h_d = 60$	+50%	9	0.0872	4947.9	2,916,253	2,87	11	0.0880	4003.7	2,848,604.1	2.38
	+25%	8	0.0873	5571.5	2,878,457	1.54	10	0.0883	4014.8	2,817,636.9	1.27
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	6	0.0882	7502.8	2,782,702	−1.84	7	0.0885	6327.8	2,739,318.4	−1.55
	−50%	5	0.0893	9119.2	2,716,341	−4.18	5	0.0889	8901.6	2,680,745.8	−3.65
$h_p = 40$	+50%	5	0.0779	7955.9	3,075,129	8.47	5	0.0776	7768.5	3,033,547.3	9.03
	+25%	6	0.0823	7002.8	2,962,650	4.51	7	0.0827	5908.5	2,915,155.6	4.77
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	8	0.0940	5999.5	2,691,834	−5.05	10	0.0951	4758.0	2,634,200.0	−5.33
	−50%	9	0.1020	5786.3	2,531,836	−10.7	13	0.1051	4044.5	2,468,523.7	−11.3
$d_d = 600$	+50%	9	0.0872	49441	2,918,318	2,94	11	0.0880	4003.7	2,848,604.1	2.38
	+25%	8	0.0873	5569.0	2,879,619	1.58	10	0.0883	4416.4	2,817,636.9	1.27
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	6	0.0882	7507.4	2,781,144	−1.90	7	0.0885	6327.8	2,739,318.4	−1.55
	−50%	3	0.0872	14852.7	2,703,928	−4.62	5	0.0889	8901.6	2,680,745.8	−3.65
$d_p = 400$	+50%	7	0.0820	5981.9	3,010,061	6,18	6	0.0806	6721.3	2,957,798.8	6.30
	+25%	7	0.0847	6174.8	2,923,924	3.14	7	0.0839	5999.6	2,875,189.0	3.33
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	8	0.0922	5884.4	2,738,923	−3.39	10	0.0933	4668.1	2,679,457.1	−3.70
	−50%	9	0.0976	5538.2	2,632,492	−7.14	12	0.0997	4155.5	2,566,509.0	−7.76
$\theta = 0.1$	+50%	7	0.0794	5794.4	3,100,001	9.35	9	0.0804	4470.6	3,041,924.7	9.33
	+25%	7	0.0832	6069.2	2,970,737	4.79	9	0.0843	4683.2	2,915,364.1	4.78
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0927	6762.9	2,691,447	−5.06	9	0.0939	5219.8	2,641,938.0	−5.05
	−50%	7	0.0989	7213.9	2,538,850	−10.4	8	0.0992	5516.8	2,492,404.9	−10.4
$t_f = 1000$	+50%	6	0.0874	7440.5	2,872,436	1.32	7	0.0883	6308.3	2,826,288.0	1.58
	+25%	7	0.0883	6437.1	2,854,827	0.70	8	0.0886	5542.6	2,805,413.7	0.83
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	8	0.0879	5612.0	2,814,046	−0.74	10	0.0885	4425.0	2,756,197.9	−0.94
	−50%	9	0.0880	4991.1	2,790,972	−1.55	12	0.0884	3685.7	2,725,660.0	−2.04
$t_v = 0.75$	+50%	7	0.0876	6391.8	2,837,605	0.09	9	0.0888	4933.7	2,785,501.1	0.11
	+25%	7	0.0876	6389.7	2,836,264	0.05	9	0.0887	4931.6	2,783,948.8	0.06
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0876	6385.7	2,833,581	−0.05	9	0.0886	4927.6	2,780,842.7	−0.06
	−50%	7	0.0875	6383.6	2,832,239	−0.09	9	0.0886	4925.5	2,779,289.1	−0.11

Table 7. *Cont.*

Parameter	Value Change	Model 1					Model 2				
		n^*	T	Q^a	ETC	$\%CTC$	n^*	T	Q^b	ETC	$\%CTC$
$d = 100$	+50%	7	0.0877	6392.8	2,838,309	0.12	9	0.0888	4934.7	2,786,313.0	0.14
	+25%	7	0.0876	6390.3	2,836,616	0.06	9	0.0887	4932.2	2,784,355.0	0.07
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0875	6385.1	2,833,229	−0.06	9	0.0886	4927.0	2,780,436.7	−0.07
	−50%	7	0.0875	6382.6	2,831,535	−0.12	9	0.0886	4924.5	2,778,476.4	−0.14
$E[u] = 0.02$	+50%	7	0.0874	6437.8	2,843,908	0.32	9	0.0887	4931.3	2,784,137.7	0.063
	+25%	7	0.0875	6412.6	2,839,414	0.16	9	0.0887	4930.5	2,783,248.6	0.031
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0877	6363.1	2,830,435	−0.16	9	0.0887	4928.7	2,781,579.0	−0.029
	−50%	7	0.0878	6338.7	2,825,951	−0.32	9	0.0887	4927.7	2,780,796.5	−0.058
$w = 0.01$	+50%	7	0.0876	6387.7	2,835,956	0.04	9	0.0887	4929.6	2,783,408.9	0.036
	+25%	7	0.0876	6387.7	2,835.439	0.02	9	0.0887	4929.6	2,782,902.6	0.018
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0876	6387.7	2,834,405	−0.02	9	0.0887	4929.6	2,781,889.5	−0.018
	−50%	7	0.0876	6.387.7	2,833,889	−0.04	9	0.0887	4929.6	2,781,383.0	−0.036
$c_1, c_2 = 0.27, 0.0057$	+50%	7	0.0876	6388.7	2,835,627	0.02	9	0.0887	4930.5	2,783,244.8	0.031
	+25%	7	0.0876	6388.2	2,835,275	0.01	9	0.0887	4930.0	2,782,838.6	0.016
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0876	6387.2	2,834,570	−0.01	9	0.0887	4928.9	2,782,026.3	−0.013
	−50%	7	0.0876	6386.7	2,834,218	−0.02	9	0.0887	4928.4	2,781,620.2	−0.028
$e_c = 1.44$	+50%	7	0.0876	6386.6	2,835,372	0.016	9	0.0887	4928.7	2,782,845.7	0.016
	+25%	7	0.0876	6387.1	2,835,148	0.008	9	0.0887	4929.2	2,782,620.8	0.008
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0876	6388.3	2,834,698	−0.008	9	0.0887	4930.0	2,782,171.2	−0.008
	−50%	7	0.0876	6388.8	2,834,472	−0.016	9	0.0887	4930.5	2,781,946.2	−0.016
$T_x = 75$	+50%	7	0.0876	6387.7	2,836,077	0.04	9	0.0887	4929.8	2,783,658.0	0.045
	+25%	7	0.0876	6387.7	2,835,500	0.02	9	0.0887	4929.7	2,783,027.1	0.023
	0	7	0.0876	6387.7	2,834,922	0	9	0.0887	4929.6	2,782,396.0	0
	−25%	7	0.0876	6387.7	2,834,345	−0.02	9	0.0887	4929.5	2,781,764.9	−0.023
	−50%	7	0.0876	6387.6	2,833,768	−0.04	9	0.0887	4929.4	2,781,134.2	−0.045

6. Conclusions and Future Research

This study considers a two-echelon supply chain consisting of a manufacturer and a retailer where the production activities are resulting in a certain percentage of defective products. The supply chain entities are willing to reduce their environmental impact by coordinating the delivery quantity and number of deliveries per cycle. The effect of carbon emissions, item deterioration, and two choices of inspection are examined. The models are illustrated with two numerical examples, and the results give some insights. This study is an initial exploratory study that attempts to provide a mathematical solution for a controlled situation; it may be applied to handle larger problems of cost minimization and carbon emission reduction in the future.

From the research finding, it is observed that the numbers of delivered products from the manufacturer are less when the inspection is performed by the vendor. As a result, the total cost of the supply chain is less, because the total inventory-holding cost and the total deteriorating cost are decreasing. However, the vendor's total cost becomes higher when it performs the inspection. Therefore, the retailer needs to compensate a certain amount of cost-saving to the manufacturer so that both parties take advantage.

The research finding also revealed that although the total cost is less when the inspection is performed by the vendor, it does not guarantee a reduction in emissions. However, both the cost-saving and emission-reducing objectives can still be obtained simultaneously by reducing the level of cost savings. In this situation, there is a tradeoff between cost savings and reduction in carbon emissions.

Although this study addresses some practical aspects of a supply chain scenario to deal with lower carbon emissions, the scope has a wide opportunity to be extended. Applying the approach in a three-echelon supply chain or more is one opportunity. Future works can consider the possibility of reworking the defective products, the capacity of the vehicle and storage facility, and investment to reduce the carbon emissions. This study assumes a 100% inspection by the manufacturer. Future research may assume a sampling inspection by the manufacturer, as well as incorporate the issue of imperfect quality inspection.

Author Contributions: Conceptualization, Y.D.; Methodology, Y.D.; Software, Y.D.; Validation, G.A.W. and H.M.W.; Formal Analysis, Y.D.; Investigation, Y.D.; Resources, H.M.W.; Writing—Original Draft Preparation, Y.D.; Writing—Review & Editing, H.M.W. and G.A.W.; Visualization, Y.D.; Supervision, H.M.W.

Funding: This research received no external funding.

Acknowledgments: The authors express their gratitude to the editor and the two anonymous reviewers for their comments and valuable suggestions to improve this paper. The first author also thanks to the United Board for Christian Higher Education in Asia for financing his study.

Conflicts of Interest: The authors declare no conflict of interest.

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