Impact of inspection decision

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Impact of inspection decision on a manufacturer-retailer supply chain for deteriorating items considering carbon emission

Abstract: Nowadays, many countries have implemented carbon pricing policies. Hence, the industry adapts to this policy while striving for their main goal of maximizing financial benefits. 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, 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 passed to the buyer. Carbon emission costs are incorporated under carbon tax policy and consider the carbon footprint from transporting and warehousing the items. The objective is to jointly decide the delivery quantity and number of deliveries per production cycle that minimize the total cost and reduce the total carbon emission. This study provides solution procedures to solve the models and two numerical examples.

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

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1. Introduction

Supply chain coordination on inventory replenishment decision has a favorable effect on supply chain performance. Supply chain coordination can be realized through information sharing and joint decision. Coordination brings many advantages such as lower inventory-related costs and quality improvement (Glock, 2012). This study considers supply chain management coordination and examines the effect on both economic and environmental performance. This study proposes supply chain inventory decision models considering carbon emission cost and the existence of defective items under different inspection coordination. 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 obsoleting.

Due to increasing pressure from legislation, customer and other organizations, the industry is striving for a 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 (Luo et al., 2017; Das & Jharkharia, 2018). The objective is to control and reduce CO_2 emission (the major part of greenhouse gas emission) from the supply chain. Recently, Kazemi et al. (2018) considered carbon emission on several economic order quantity (EOQ) models. Taleizadeh et al. (2018) proposed new economic production quantity (EPQ) models considering carbon emission. Sarkar et al. (2016a and 2018), Tiwari et al. (2018), Daryanto & Wee (2018), etc. incorporated carbon tax into supply chain total cost model for inventory replenishment decisions. The objectives of these studies are to minimize the total cost and reduce carbon emission simultaneously.

This study focuses on supply chain inventory models for a system which contains a percentage of imperfect quality items. Defective products exist due to imperfect production processes. This study considers that the decision of the supply chain to deals with the defective items will affect the carbon emissions because processing the defective items also adds the total emissions. The loss due to imperfect quality and deterioration also forces the manufacturer to produce more products for satisfying customer demand per period. Producing more products will increase carbon emission from the production, holding, and distribution. This study examines two models considering two cases of quality inspection, 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 passed to the buyer. This study extends Tiwari et al.'s (2018) model by examining two inspection situation and considering variable transportation cost and emission which depend on the distance between vendor and buyer, the actual shipment weight (truckloads), and vehicle's fuel efficiency.

This study incorporates carbon emissions, item deterioration, and defective percentage to guide the supply chain makes the inventory decisions on the delivery size and 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 the 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 finding 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, hence producing a certain amount of defective products. Rosenblatt & Lee (1986) and Porteus (1986) studied the relationship between optimal lot size and quality performance. Rosenblatt & Lee (1986) studied the optimal production cycle considering the proportion of defective items, while Porteus (1986) related the model to the opportunity for quality improvement and setup cost reduction through some investment. Salameh & Jaber (2000) incorporated defective items into the EPQ model and considered the screening time and cost. Many other researchers have continued the research on EOQ and EPQ model 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 (2002) 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. (2003) 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. (2006) considered imperfect quality, shortage backorder, and item deterioration in an integrated production-inventory model. Lee & Kim (2014) also developed an integrated production-inventory model of imperfect quality deteriorating items.

<Insert Figure 1>

Bazan et al. (2014) 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. (2017) studied the integrated inventory model with two-stage inspection by the vendor considering the rework process and variable transportation cost. Yu & Hsu (2017) developed a production-inventory model in which the defective items are returned to the vendor immediately for rework.

<Insert Figure 2>

2.2. Low carbon supply chain management

Research on low carbon supply chain management has increased rapidly in recent years, marked by a surge in the amount of literature in this area. Many research revealed that supply chain collaboration and adjustment on operational decisions are able to reduce carbon emissions without significantly increase their costs. Wahab et al. (2011) 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's fuel efficiency, and the actual shipment weight. Benjaafar et al. (2013) modified the traditional supply chain model by associating carbon footprint from placing an order to the supplier, production setup, production process, and inventory holding.

Bozorgi et al. (2014) considered carbon emissions from transporting and storing cold items which require temperature-controlled truck and freezer. Bozorgi (2016) extended the previous model considering multi-product cold items under limited capacity. Hariga et al. (2017) incorporated carbon emissions from transporting and storing the cold items in a three-echelon supply chain. Ghosh et al. (2016) considered carbon emission from production, inventory holding, and transportation in vendor-buyer supply chain under the single-setup multiple-deliveries policy. Toptal & Çetinkaya (2017) studied the effect of supply chain coordination and carbon emission on vendor-buyer order quantity under lot-for-lot delivery. Bouchery et al. (2017) examined different supply chain coordination considering carbon emissions under limited vehicle capacity. Dwicahyani et al. (2017) incorporated carbon emission costs, energy cost, and waste disposal for two-echelon supply chain with remanufacturing. Li et al. (2017) considered joint carbon tax and cap-and-trade policies for two-echelon supply chain production-distribution model with transportation outsourcing. Wangsa (2017) incorporated the government's penalties and incentive policies to reduce carbon emission.

Anvar et al. (2018) considered emissions from transportation and inventory holding activities in a one-supplier multi-retailer supply chain. Hariga et al. (2018) considered carbon tax and carbon cap policies for 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. (2018) considered carbon reduction investment from the supplier to get higher customer demand. Wang & Ye (2018) compared the effect of considering carbon emission on just-in-time and economic order quantity decision for two-echelon supply chain inventory models. Ghosh et al. (2018) considered a carbon tax regulation to minimize the total expected cost of a supply chain under stochastic demand and shortage backorder. Ma et al. (2018) considered the effect of carbon tax scheme between suppliers and buyer for production, procurement, and pricing decisions. Darom et al. (2018) developed a manufacturer-retailer inventory model considering disruption risks and recovery with safety stock and the effect of carbon emission cost. The model considered carbon emission from the transportation activities for a better recovery plan. Huang et al. (2018) studied inventory and pricing decisions considering carbon emission, production disruption and controllable deterioration using preservation technology. Recently, Daryanto et al. (2019) proposed a low carbon three-echelon supply chain inventory model considering item deterioration. Kundu & Chakrabarti (2019) developed low carbon supply chain inventory model taken into account the effect of inflation and time-value of money.

This study also considers a percentage of defective products due to imperfect production processes. Several studies incorporated both carbon emission and imperfect quality in a low carbon supply chain model. Jauhari et al. (2014) studied joint economic lot-sizing model considering carbon emission and defective items delivered in an unequal-sized shipment. The quality inspection is performed by the buyer, and the defective products are returned to the vendor. Jauhari (2018) extended the model considering stochastic demand and adjustable production rate. Gautam & Khanna (2018) incorporated carbon emission cost in an integrated supply chain production-inventory model considering imperfect quality and setup cost reduction. Tiwari et al. (2018) proposed an integrated production-inventory model considering imperfect quality and item deterioration. The quality inspection is performed by the buyer, and the defective products are sold into the secondary market at a discounted price.

The summary of the above literature review is presented in Table 1.

<Insert Table 1>

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) it is the buyer that performs a complete quality inspection process, and 2) it is the vendor that performs the quality inspection so that no defective products 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 (2018) model by introducing weight and distance-dependent transportation cost also the fixed and variable inspection costs. Later, the second model extends the first model by studying another inspection option to reduce the expected total cost and emission.

3.2. Assumption and notation

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 single-setup multiple-deliveries (SSMD) policy. The delivery is in n equal lot sizes.
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 fixed inspection cost per cycle is constant whether performed by the buyer or the manufacturer.
8) Carbon emission is from the fuel and electricity consumption during transporting and holding the inventory.
9) Shortage is not considered.

10) The additional fuel consumption is a linear function of truckloads. Figure 3 illustrates the linear fuel consumption model similar to Hariga et al. (2017) with an example of the dataset from Volvo Corporation (2018).

<Insert Figure 3>

<Insert Table 2>

4. Mathematical model

This section provides the model development for two inspection cases.

4.1. Model development with retailer inspection

This sub-section presents the model development when quality inspection becomes retailer's responsibility. The model is adapted from Tiwari et al. (2018). However, this study considers weight and distance-dependent transportation cost. The inventory level of the manufacturer and the retailer is illustrated in Figure 4.

<Insert Figure 4>

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 (Yang & Wee, 2000; Lee & Kim, 2014). After a lot size arrived, the 100% quality inspection starts and then finishes at T_i. At this time uQ units of defective products will be removed from the inventory. As there are fixed inspection cost i_c per delivery and unit inspection cost u_c (Sarkar et al., 2016b), the inspection cost per year is given by

$$i_c \frac{n}{T} + u_c Q \frac{n}{T} = \frac{n}{T}\left(i_c + u_c Q\right) \tag{1}$$

<*Insert Figure 5*>

Figure 5 illustrates the retailer's on-hand inventory per delivery cycle. The inventory level, considering deterioration and imperfect quality, has been studied by researcher such as Jaggi et al. (2011) and results in the following equations:

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

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

At $t = T/n$, $I_d(T/n) = 0$, therefore from Eq. (3) one has

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

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

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

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

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

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

Hence, the retailer's expected carbon footprint (ETE_d) per year becomes

$$ETE_d = e_c E_e\left(\frac{n}{T}\left[\frac{D}{\theta^2\left(E[u]e^{\frac{\theta T}{n}}-1\right)^2}\left(\begin{array}{l}e^{\frac{\theta T}{n}}-1+\frac{E[u]D}{x}\left(1+e^{\frac{2\theta T}{n}}-2e^{\frac{\theta T}{n}}\right)\\+E[u]\left(1-e^{\frac{2\theta T}{n}}+E[u]e^{\frac{2\theta T}{n}}-E[u]e^{\frac{\theta T}{n}}\right)\\+\frac{\theta T}{n}\left(E[u]-1+E[u]e^{\frac{\theta T}{n}}-E[u]^2e^{\frac{\theta T}{n}}\right)\end{array}\right)\right]\right) \quad (7)$$

The retailer's deteriorating cost per year is:

$$\frac{d_d n}{T}\left(Q-uQ-\frac{DT}{n}\right)$$

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

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

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

4.1.2. Manufacturer cost and emission

After the arrival of retailer's order, Manufacturer starts the production of nQ units of the item in 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 interval. The transportation cost belongs to the manufacturer and consist of fixed and variable costs. Swenseth & Godfrey (2002), Nie et al. (2006), Rahman et al. (2016), and Wangsa & Wee (2018) incorporated the variable transportation cost which is affected by the shipping distance and truckloads. The manufacturer's transportation cost per delivery is given by

$$t_f + 2dc_1t_v + dQwc_2t_v \tag{10}$$

The first element is the fix 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 2. Then it calculates the transportation cost for the truckload which depends on the delivery distance and quantity, product weight, additional fuel consumption per ton per km, and the fuel price. Substitutes Eq. (4) to (10), the manufacturer's transportation cost per year is given by

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

Wahab et al. (2011) identified that the emissions from transportation affected by the delivery distance, actual shipment weight, fuel consumption per km, and CO_2 emission 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 follow

$$\frac{n}{T}(2dc_1 + dQwc_2)F_e$$

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

Lee & Kim (2014) studied a similar inventory model for the manufacturer, and then Hsu (2016) suggested some revision. Due to defective products and retailer's quality inspection, the effective demand rate for the manufacturer become *D/(1-u)*. Therefore, the inventory functions are as follows:

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

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

From the boundary condition $I_{p1}(T_1) = I_{p2}(0)$ and following Misra (1975) approximation

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

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

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

From Yang & Wee (2000), the manufacturer's inventory per cycle is

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

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

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

The amount of manufacturer's carbon emission per year as the result of warehousing activity can be derived as follow

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

The manufacturer's carbon emission per year comes from Eq. (12) and (19). Therefore, the manufacturer's carbon emission cost is

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

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:

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

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

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

4.1.3. The integrated manufacturer and retailer cost function

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

$$
\begin{aligned}
ETC = {} & \frac{c}{T} + \frac{n}{T}\left(i_c + u_c \frac{D(e^{\theta T/n}-1)}{\theta(1-E[u]e^{\theta T/n})}\right) + d_d\left(\frac{(1-E[u])n}{T}\frac{D(e^{\theta T/n}-1)}{\theta(1-E[u]e^{\theta T/n})} - D\right) \\
& + (h_d + w_e)\frac{nD}{T\theta^2\left(E[u]e^{\frac{\theta T}{n}}-1\right)^2}\left(\begin{array}{l} e^{\frac{\theta T}{n}} - 1 + \frac{E[u]D}{x}\left(1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}}\right) \\ + E[u]\left(1 - e^{\frac{2\theta T}{n}} + E[u]e^{\frac{2\theta T}{n}} - E[u]e^{\frac{\theta T}{n}}\right) \\ + \frac{\theta T}{n}\left(E[u] - 1 + E[u]e^{\frac{\theta T}{n}} - E[u]^2 e^{\frac{\theta T}{n}}\right) \end{array}\right) \\
& + \frac{s}{T} + \frac{n}{T}\left(t_f + 2dc_1 t_v + d\frac{D(e^{\theta T/n}-1)}{\theta(1-E[u]e^{\theta T/n})} wc_2 t_v\right) \\
& + \frac{(h_p + w_e)}{T}\left[\begin{array}{l} \frac{P-(D/(1-E[u]))}{\theta}T_1 \\ + \frac{P-(D/(1-E[u]))}{\theta^2}\left(e^{-\theta T_1} - 1\right) \\ - \frac{(D/(1-E[u]))T_2}{\theta} - \frac{(D/(1-E[u]))}{\theta^2}(1-e^{\theta T_2}) \\ - n\left[\frac{D}{\theta^2\left(E[u]e^{\frac{\theta T}{n}}-1\right)^2}\left(\begin{array}{l} e^{\frac{\theta T}{n}} - 1 + \frac{E[u]D}{x}\left(1 + e^{\frac{2\theta T}{n}} - 2e^{\frac{\theta T}{n}}\right) \\ + E[u]\left(1 - e^{\frac{2\theta T}{n}} + E[u]e^{\frac{2\theta T}{n}} - E[u]e^{\frac{\theta T}{n}}\right) \\ + \frac{\theta T}{n}\left(E[u] - 1 + E[u]e^{\frac{\theta T}{n}} - E[u]^2 e^{\frac{\theta T}{n}}\right) \end{array}\right)\right] \end{array}\right] \\
& + \frac{n}{T}\left(2de_1 + d\frac{D(e^{\theta T/n}-1)}{\theta(1-E[u]e^{\theta T/n})}e_2\right) + \frac{d_p}{T}\left(PT_1 - n\left(\frac{D(e^{\theta T/n}-1)}{\theta(1-ue^{\theta T/n})}\right)\right)
\end{aligned} \tag{23}
$$

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 $1 + x + x^2/2 + x^3/6$. Further, the expected total emission (*ETE*) per year from the manufacturer and the retailer can be derived from Eq. (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 as follows:

Step 1. Substitute the T_1 and T functions in Eq. (15) and (16) into (23);

Step 2. Set $n = 1$;

Step 3. Derive the partial derivative of ETC with respect to T_2, and then set it to zero to find the value of T_2;

Step 4. Find the value of T_1 and T using Eq. (15) and (16) and derive the corresponding ETC;

Step 5. If $ETC(n^*-1) \geq ETC(n^*) \leq ETC(n^*+1)$ then $n = n^*$ otherwise, set $n = n + 1$ and back to Step 3;

Step 6. Find Q^* from equation (4) and $R = PT_1$.

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 policy is to prevent from transporting defective products. The manufacturer performs a quality inspection to the entire 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 and the retailer including the manufacturer's inventory of the defective products is illustrated in Figure 6.

<Insert Figure 6>

4.2.1. Retailer cost and emission

Retailer's total cost is the sum of the ordering, inventory holding, deteriorating, and emission cost. The ordering cost per year is given by c/T similar to model 1 (section 4.1.1). During T/n period, I_d decreases due to demand and deterioration. From Yang & Wee (2000), the inventory function is as follow

$$I_d(t)=\frac{D}{\theta}\left(e^{\theta(\frac{T}{n}-t)}-1\right),\quad 0\le t\le T/n \tag{24}$$

and $Q=I_d(0)=\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)$ (25)

and the holding cost per year is

$$h_d\frac{n}{T}\left(\int_0^{T/n}I_d(t)dt\right)=h_d\frac{n}{T}\left(\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right) \tag{26}$$

Further, the deteriorating cost per year is

$$d_d\frac{n}{T}\left(Q-D\frac{T}{n}\right)=d_d\frac{n}{T}\left(\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{DT}{n}\right) \tag{27}$$

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

Eq. (28) shows the retailer's carbon emission (ETE_d) from holding the inventory. Therefore, the retailer's carbon emission cost per year is

$$w_e\left(\frac{n}{T}\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right) \tag{29}$$

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

$$ETC_d=\frac{c}{T}+(h_d+w_e)\frac{n}{T}\left(\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right)+d_d\frac{n}{T}\left(\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{DT}{n}\right) \tag{30}$$

4.2.2. Manufacturer cost and emission

Due to some percentage of defective products, the production rate of the perfect product is $(1\text{-}u)P$. The manufacturer's setup cost per year is s/T. In this model, the manufacturer will have an additional inspection cost. Because 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

$$\frac{i_c}{T} + \frac{u_c PT_1}{T} \tag{31}$$

The manufacturer's transportation function is similar to Eq. (10), therefore the transportation cost and emission per year become

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

$$\frac{n}{T}\left(2dc_1 + d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right)wc_2\right)F_e \tag{33}$$

From Figure 6, the inventory differential equations are:

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

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

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

$$I_{p1}(t_1) = \frac{(1-u)P - D}{\theta}\left(1 - e^{-\theta t_1}\right), \quad 0 \le t_1 \le T_1 \tag{34}$$

$$I_{p2}(t_2) = \frac{D}{\theta}\left(e^{\theta(T_2 - t_2)} - 1\right), \quad 0 \le t_2 \le T_2 \tag{35}$$

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

$$\frac{((1-u)P - D)}{\theta}\left(1 - e^{-\theta T_1}\right) = \frac{D}{\theta}\left(e^{\theta T_2} - 1\right) \tag{36}$$

From Taylor's series expansion and the assumption of $\theta T \ll 1$, following Misra (1975) approximation one has

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

$$T_1 \approx \frac{D}{(1-u)P-D}T_2\left(1+\frac{1}{2}\theta T_2\right) \tag{37}$$

$$T \approx \frac{T_2}{(1-u)P-D}\left((1-u)P+\frac{1}{2}D\theta T_2\right) \tag{38}$$

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

$$\int_0^{T_1}\frac{(1-u)P-D}{\theta}\left(1-e^{-\theta t_1}\right)dt_1+\int_0^{T_2}\frac{D}{\theta}\left(e^{\theta(T_2-t_2)}-1\right)dt_2-n\left[\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right] \tag{39}$$

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

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

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

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

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

$$\int_0^{T_1}\frac{uP}{\theta}\left(1-e^{-\theta t_1}\right)dt_1 \tag{40}$$

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

$$\frac{h_p}{T}\left[\begin{array}{l}\frac{(1-u)P-D}{\theta}T_1+\frac{(1-u)P-D}{\theta^2}\left(e^{-\theta T_1}-1\right)-\frac{DT_2}{\theta}-\frac{D}{\theta^2}(1-e^{\theta T_2})\\ -n\left[\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right]+\frac{uPT_1}{\theta}+\frac{uP}{\theta^2}\left(e^{-\theta T_1}-1\right)\end{array}\right] \tag{41}$$

Therefore, based on Eq. (33) and (41), the manufacturer's carbon emission cost and the total expected carbon emission per year can be calculated as follows:

$$\frac{n}{T}\left(2de_1+d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)e_2\right)+\frac{w_e}{T}\left[\begin{array}{l}\frac{(1-u)P-D}{\theta}T_1+\frac{(1-u)P-D}{\theta^2}\left(e^{-\theta T_1}-1\right)-\frac{DT_2}{\theta}-\frac{D}{\theta^2}(1-e^{\theta T_2})\\-n\left[\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right]+\frac{uPT_1}{\theta}+\frac{uP}{\theta^2}\left(e^{-\theta T_1}-1\right)\end{array}\right] \tag{42}$$

$$\begin{aligned}ETE_p=&\frac{n}{T}\left(2dc_1+d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)wc_2\right)F_e\\&+\frac{e_cE_e}{T}\left[\begin{array}{l}\frac{(1-u)P-D}{\theta}T_1+\frac{(1-u)P-D}{\theta^2}\left(e^{-\theta T_1}-1\right)-\frac{DT_2}{\theta}-\frac{D}{\theta^2}(1-e^{\theta T_2})\\-n\left[\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right]+\frac{uPT_1}{\theta}+\frac{uP}{\theta^2}\left(e^{-\theta T_1}-1\right)\end{array}\right]\end{aligned} \tag{43}$$

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:

$$\frac{d_p}{T}\left((1-u)PT_1-n\left(\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)\right)+\left(uPT_1-\frac{uP}{\theta}\left(1-e^{-\theta T_1}\right)\right)\right) \tag{44}$$

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

$$\begin{aligned}ETC_p=&\frac{s}{T}+\frac{i_c}{T}+\frac{u_cPT_1}{T}+\frac{n}{T}\left(t_f+2dc_1t_v+d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)wc_2t_v\right)+\frac{n}{T}\left(2de_1+d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)e_2\right)\\&+\frac{(h_p+w_e)}{T}\left[\begin{array}{l}\frac{(1-E[u])P-D}{\theta}T_1+\frac{(1-E[u])P-D}{\theta^2}\left(e^{-\theta T_1}-1\right)-\frac{DT_2}{\theta}-\frac{D}{\theta^2}(1-e^{\theta T_2})\\-n\left[\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)-\frac{T}{n}\right)\right]+\frac{E[u]PT_1}{\theta}+\frac{E[u]P}{\theta^2}\left(e^{-\theta T_1}-1\right)\end{array}\right]\\&+\frac{d_p}{T}\left((1-E[u])PT_1-n\left(\frac{D}{\theta}\left(e^{\frac{\theta T}{n}}-1\right)\right)+\left(E[u]PT_1-\frac{E[u]P}{\theta}\left(1-e^{-\theta T_1}\right)\right)\right)\end{aligned} \tag{45}$$

4.2.3. *The integrated manufacturer and retailer cost function*

The ETC of the integrated system is the sum of Eq. (30) and (45).

$$
\begin{aligned}
ETC = {} & \frac{c}{T} + (h_d + w_e)\frac{n}{T}\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) - \frac{T}{n}\right) + d_d \frac{n}{T}\left(\frac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) - \frac{DT}{n}\right) \\
& + \frac{s}{T} + \frac{i_c}{T} + \frac{u_c P T_1}{T} + \frac{n}{T}\left(t_f + 2dc_1 t_v + d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) wc_2 t_v\right) + \frac{n}{T}\left(2de_1 + d\frac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right)e_2\right) \\
& + \frac{(h_p + w_e)}{T}\left[\begin{aligned} & \frac{(1 - E[u])P - D}{\theta}T_1 + \frac{(1 - E[u])P - D}{\theta^2}\left(e^{-\theta T_1} - 1\right) - \frac{DT_2}{\theta} - \frac{D}{\theta^2}(1 - e^{\theta T_2}) \\ & - n\left[\frac{D}{\theta}\left(\frac{1}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right) - \frac{T}{n}\right)\right] + \frac{E[u]PT_1}{\theta} + \frac{E[u]P}{\theta^2}\left(e^{-\theta T_1} - 1\right) \end{aligned}\right] \\
& + \frac{d_p}{T}\left((1 - E[u])PT_1 - n\left(\frac{D}{\theta}\left(e^{\frac{\theta T}{n}} - 1\right)\right) + \left(E[u]PT_1 - \frac{E[u]P}{\theta}\left(1 - e^{-\theta T_1}\right)\right)\right)
\end{aligned}
\tag{46}
$$

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 $1 + x + x^2/2 + x^3/6$. Further, the ETE can be derived from Eq. (28) and Eq. (43).

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 the optimum solution is as follows:

Step 1. Substitute the T_1 and T functions in Eq. (37) and (38) into (46);

Step 2. Set $n = 1$;

Step 3. Derive the partial derivative of ETC with respect to T_2, and then set it to zero to find the value of T_2;

Step 4. Find the value of T_1 and T using Eq. (37) and (38) and derive the corresponding ETC;

Step 5. If $ETC(n^*-1) \geq ETC(n^*) \leq ETC(n^*+1)$ then $n = n^*$ otherwise, set $n = n + 1$ and back to Step 3;

Step 6. Find Q^* from equation (25) and $R = PT_1$.

5. Numerical example and management insights

Numerical example 1

The values of the parameters are considered by adopting data from Yang & Wee (2000), Hariga et al. (2017), and Tiwari et al. (2018) 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 liter/100 km, c_2 = 0.57 liter/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/liter (US. EPA, 2005), $E_e = 0.5\times10^{-3}$ tonCO_2/kWh (POST, 2011), and u is uniformly distributed in which $\alpha = 0$ and $\beta = 0.04$, with $E[u] = 0.02$.

The minimum value of joint expected total cost can be obtained at $n^a = 7$ 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 from Eq. (4) the optimum Q is 6,387.7 units. The optimum R is 44,793.2 units, and the ETE is 30.598 ton CO_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 ton CO_2/year (saving 39.7%). However, this situation increases the ETC into \$3,366,391 (18.7%). Figure 7 shows the convexity of ETC when n = 7.

When the probability of defective products, unit inspection cost, 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 & Wee (2000).

<Insert Table 3>

<Insert Figure 7>

Numerical example 2

Consider the parameter in numerical example 1 and solve it using Model 2 results in the following values. The minimum value of joint expected total cost can be obtained at $n^b = 9$ 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 ton CO_2/year.

<Insert Table 4>

From the numerical example 1 and 2, it is clear that performing a quality inspection at the manufacturer site will save a considerable amount of total cost. Table 5 provides the cost comparison between the two models. 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%. Cost-saving compensation from the retailer to the manufacturer is an alternative solution so that both parties take the advantage from the implementation of manufacturer quality inspection. Based on Goyal (1977):

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

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

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

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

Hence, retailer and manufacturer total cost per year becomes \$690,574.4 and \$2,091,821.6 respectively. By using this compensation policy, finally, the cost decreases \$13,036.7 for the retailer and decreases \$39,489.6 for the vendor or 1.85% for both parties.

<Insert Table 5>

Table 5 also shows that the *ETE* of Model 2 is 33.52 ton CO_2/year which is 9.55% higher than the *ETE* in Model 1. We can obtain both the cost saving and emission reducing objectives as from Table 4 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 Model 1 respectively. Thus, the objective of cost efficiency and reducing the level of the carbon footprint 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 are less than in Model 1.

<Insert Table 6>

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 increases, 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.

<*Insert Table 7*>

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 small especially when the inspection is performed by the vendor. When the carbon tax (T_x) increases, the number of deliveries is remaining stable. Besides, the delivery quantity and expected total cost increase very small.

6. Conclusion and future research

This study considered a two-echelon supply chain consists 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 result gives some insights.

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 the 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 an emission reduction. However, both 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 carbon emissions reduction.

Although this study addresses some practical aspects of supply chain scenario to deal with lower carbon emission, the scope has a wide opportunity to be extended. Applying the approach in a three or more echelon supply chain is one opportunity. Future works can consider the possibility of reworking the defective products, the capacity of the vehicle and storage facility, and an investment to reduce the carbon emissions.

Acknowledgments

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Table 1 Literature Review and Gap Analysis Summary

Authors	Scope	Imperfect quality	Deteriorating item	Variable transportation cost	Carbon emission
Huang (2002)	Two-echelon	√			
Goyal et al. (2003)	Two-echelon	√			
Wee et al. (2006)	Two-echelon	√	√		
Wahab et al. (2011)	Two-echelon	√			√
Benjaafar et al. (2013)	Two-echelon				√
Lee & Kim (2014)	Two-echelon	√	√		
Bazan et al. (2014)	Two-echelon	√			
Bozorgi et al. (2014)	Two-echelon				√
Jauhari et al. (2014)	Two-echelon	√			√
Bozorgi (2016)	Two-echelon				√
Ghosh et al. (2016)	Two-echelon				√
Sarkar et al. (2016b)	Two-echelon	√		√	√
Yu & Hsu (2017)	Two-echelon	√			
Sarkar et al. (2017)	Two-echelon	√		√	
Toptal & Çetinkaya (2017)	Two-echelon				√
Bouchery et al. (2017)	Two-echelon				√
Dwicahyani et al. (2017)	Two-echelon				√
Wangsa (2017)	Two-echelon				√
Li et al. (2017)	Two-echelon				√
Anvar et al. (2018)	Two-echelon				√
Hariga et al. (2018)	Two-echelon				√
Ji et al. (2018)	Two-echelon				√
Wang & Ye (2018)	Two-echelon				√
Gosh et al. (2018)	Two-echelon				√
Ma et al. (2018)	Two-echelon				√
Darom et al. (2018)	Two-echelon				√
Jauhari (2018)	Two-echelon	√			
Gautam & Khanna (2018)	Two-echelon	√			√
Wangsa & Wee (2018)	Two-echelon			√	
Tiwari et al. (2018)	Two-echelon	√	√		√
Kundu & Chakrabarti (2019)	Two-echelon				√
Sarkar et al. (2016a)	Three-echelon			√	√
Hariga et al. (2017)	Three-echelon				√
Sarkar et al. (2018)	Three-echelon			√	√
Huang et al. (2018)	Three-echelon		√		√
Daryanto et al. (2019)	Three-echelon		√	√	√
This article	Two-echelon	√	√	√	√

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 (litre/km);
c_2	average additional fuel consumption per ton of load (litre/km/ton);
T_x	carbon emission tax (\$/tonCO_2);
F_e	average emission from fuel combustion (kgCO_2/liter);
E_e	average emission from electricity generation (kgCO_2/kWh);
e_1	transportation emission cost (\$/km); $e_1 = c_1F_eT_x$;
e_2	average additional transportation emission cost per unit product (\$/unit/km); $e_2 = c_2lF_eT_x$;
e_c	average warehouse energy consumption per unit product (kWh/unit/year);
w_e	warehouse emission cost per unit product (\$/unit/year); $w_e = e_cE_eT_x$;
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 emission per year (kgCO_2/year);
ETE_p	manufacturer's expected total carbon emission per year (kgCO_2/year);
ETE	joint expected total carbon emission per year (kgCO_2/year);
Decision variables	
Q	delivery lot size (unit);
n	number of deliveries per order (positive integer).

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[a]	**6518**	**2240**	**8758**	**703,611**	**2,131,311**	**2,834,922**[a]	**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

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[b]	**6601**	**2268**	**8869**	**318,411**	**2,463,985**	**2,782,396**[b]	**33.52**
10	6658	2288	8945	290,923	2,493,378	2,784,301	35.11

Table 5 Comparison between the 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	6,387.7	4,929.6	
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 ($)	2,138.0	2,390.9	-11.8
Total manufacturer's cost per year ($)	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 (ton CO_2/year)	30.598	33.523	-9.56

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	6,221.2	
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 ($)	2,138.0	2,117.7	0.95
Total manufacturer's cost per year ($)	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 (ton CO_2/year)	30.598	30.292	1.00

Table 7 Sensitivity analysis of the two models

Parameter	Value change	Model 1					Model 2				
		n^a	T	Q^a	ETC	$\%CTC$	n^b	T	Q^b	ETC	$\%CTC$
$P =$ 2,000,000	+50%	7	0.0816	5,949.3	3,024,249	6.68	8	0.0819	5,120.3	2,966,117.1	6.60
	+25%	7	0.0839	6,117.1	2,948,615	4.01	8	0.0842	5,263.2	2,892,821.2	3.97
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	8	0.0959	6,120.6	2,643,862	-6.74	9	0.0957	5,322.0	2,596,679.1	-6.67
	-50%	8	0.1147	7,321.0	2,253,495	-20.5	11	0.1153	5,296.5	2,217,427.4	-20.3
$D =$ 500,000	+50%	8	0.0816	7,811.6	3,190,858	12.5	10	0.0822	6,168.2	3,136,392.1	12.7
	+25%	8	0.0841	6,705.8	3,044,190	7.38	9	0.0840	5,833.6	2,989,178.5	7.43
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0958	5,242.7	2,548,150	-10.1	8	0.0962	4,510.9	2,499,238.8	-10.2
	-50%	6	0.1100	4,683.3	2,151,051	-24.1	8	0.1120	3,501.7	2,108,977.7	-24.2
$c = 2{,}000$	+50%	7	0.0880	6,415.9	2,846,315	0.40	9	0.0891	4,951.6	2,793,646.2	0.40
	+25%	7	0.0878	6,401.8	2,840,625	0.20	9	0.0889	4,940.6	2,788,027.5	0.20
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0874	6,373.5	2,829,207	-0.20	9	0.0885	4,918.6	2,776,752.0	-0.20
	-50%	7	0.0872	6,359.3	2,823,479	-0.40	9	0.0883	4,907.5	2,771,095.4	-0.41
$s = 100{,}000$	+50%	9	0.1074	6,090.8	3,348,784	18.1	11	0.1081	4,917.3	3,292,159.7	18.3
	+25%	8	0.0979	6,250.1	3,104,546	9.51	10	0.0988	4,945.1	3,049,823.5	9.61
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	6	0.0760	6,464.7	2,529,737	-10.8	8	0.0773	4,834.4	2,480,006.3	-10.9
	-50%	5	0.0625	6,383.9	2,169,316	-23.5	6	0.0631	5,257.7	2,122,805.7	-23.7
$i_c = 500$	+50%	7	0.0883	6,437.1	2,854,827	0.70	9	0.0888	4,935.1	2,785,213.3	0.10
	+25%	7	0.0879	6,412.4	2,844,894	0.35	9	0.0887	4,932.4	2,783,805.1	0.05
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0872	6,362.9	2,824,912	-0.35	9	0.0886	4,926.8	2,780,986.3	-0.05
	-50%	7	0.0869	6,338.0	2,814,883	-0.71	9	0.0886	4,924.1	2,779,575.6	-0.10
$u_c = 0.5$	+50%	7	0.0876	6,387.5	2,962,557	4.50	9	0.0887	4,929.0	2,910,260.4	4.60
	+25%	7	0.0876	6,387.6	2,898,740	2.25	9	0.0887	4,929.3	2,846,328.1	2.30
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0876	6,387.8	2,771,105	-2.25	9	0.0887	4,929.9	2,718,463.9	-2.30
	-50%	7	0.0876	6,387.9	2,707,289	-4.50	9	0.0887	4,930.2	2,654,531.7	-4.60
$h_d = 60$	+50%	9	0.0872	4,947.9	2,916,253	2.87	11	0.0880	4,003.7	2,848,604.1	2.38
	+25%	8	0.0873	5,571.5	2,878,457	1.54	10	0.0883	4,014.8	2,817,636.9	1.27
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	6	0.0882	7,502.8	2,782,702	-1.84	7	0.0885	6,327.8	2,739,318.4	-1.55
	-50%	5	0.0893	9,119.2	2,716,341	-4.18	5	0.0889	8,901.6	2,680,745.8	-3.65
$h_p = 40$	+50%	5	0.0779	7,955.9	3,075,129	8.47	5	0.0776	7,768.5	3,033,547.3	9.03
	+25%	6	0.0823	7,002.8	2,962,650	4.51	7	0.0827	5,908.5	2,915,155.6	4.77
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	8	0.0940	5,999.5	2,691,834	-5.05	10	0.0951	4,758.0	2,634,200.0	-5.33
	-50%	9	0.1020	5,786.3	2,531,836	-10.7	13	0.1051	4,044.5	2,468,523.7	-11.3
$d_d = 600$	+50%	9	0.0872	4,944.1	2,918,318	2.94	11	0.0880	4,003.7	2,848,604.1	2.38
	+25%	8	0.0873	5,569.0	2,879,619	1.58	10	0.0883	4,416.4	2,817,636.9	1.27
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	6	0.0882	7,507.4	2,781,144	-1.90	7	0.0885	6,327.8	2,739,318.4	-1.55
	-50%	3	0.0872	14,852.7	2,703,928	-4.62	5	0.0889	8,901.6	2,680,745.8	-3.65
$d_p = 400$	+50%	7	0.0820	5,981.9	3,010,061	6.18	6	0.0806	6,721.3	2,957,798.8	6.30
	+25%	7	0.0847	6,174.8	2,923,924	3.14	7	0.0839	5,999.6	2,875,189.0	3.33
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	8	0.0922	5,884.4	2,738,923	-3.39	10	0.0933	4,668.1	2,679,457.1	-3.70
	-50%	9	0.0976	5,538.2	2,632,492	-7.14	12	0.0997	4,155.5	2,566,509.0	-7.76
$\theta = 0.1$	+50%	7	0.0794	5,794.4	3,100,001	9.35	9	0.0804	4,470.6	3,041,924.7	9.33
	+25%	7	0.0832	6,069.2	2,970,737	4.79	9	0.0843	4,683.2	2,915,364.1	4.78
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0927	6,762.9	2,691,447	-5.06	9	0.0939	5,219.8	2,641,938.0	-5.05
	-50%	7	0.0989	7,213.9	2,538,850	-10.4	8	0.0992	5,516.8	2,492,404.9	-10.4
$t_f = 1{,}000$	+50%	6	0.0874	7,440.5	2,872,436	1.32	7	0.0883	6,308.3	2,826,288.0	1.58
	+25%	7	0.0883	6,437.1	2,854,827	0.70	8	0.0886	5,542.6	2,805,413.7	0.83
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	8	0.0879	5,612.0	2,814,046	-0.74	10	0.0885	4,425.0	2,756,197.9	-0.94
	-50%	9	0.0880	4,991.1	2,790,972	-1.55	12	0.0884	3,685.7	2,725,660.0	-2.04
$t_v = 0.75$	+50%	7	0.0876	6,391.8	2,837,605	0.09	9	0.0888	4,933.7	2,785,501.1	0.11
	+25%	7	0.0876	6,389.7	2,836,264	0.05	9	0.0887	4,931.6	2,783,948.8	0.06
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0876	6,385.7	2,833,581	-0.05	9	0.0886	4,927.6	2,780,842.7	-0.06
	-50%	7	0.0875	6,383.6	2,832,239	-0.09	9	0.0886	4,925.5	2,779,289.1	-0.11
$d = 100$	+50%	7	0.0877	6,392.8	2,838,309	0.12	9	0.0888	4,934.7	2,786,313.0	0.14
	+25%	7	0.0876	6,390.3	2,836,616	0.06	9	0.0887	4,932.2	2,784,355.0	0.07
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0875	6,385.1	2,833,229	-0.06	9	0.0886	4,927.0	2,780,436.7	-0.07
	-50%	7	0.0875	6,382.6	2,831,535	-0.12	9	0.0886	4,924.5	2,778,476.4	-0.14

$E[u] = 0.02$	+50%	7	0.0874	6,437.8	2,843,908	0.32	9	0.0887	4,931.3	2,784,137.7	0.063
	+25%	7	0.0875	6,412.6	2,839,414	0.16	9	0.0887	4,930.5	2,783,248.6	0.031
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0877	6,363.1	2,830,435	-0.16	9	0.0887	4,928.7	2,781,579.0	-0.029
	-50%	7	0.0878	6,338.7	2,825,951	-0.32	9	0.0887	4,927.7	2,780,796.5	-0.058
$w = 0.01$	+50%	7	0.0876	6,387.7	2,835,956	0.04	9	0.0887	4,929.6	2,783,408.9	0.036
	+25%	7	0.0876	6,387.7	2,835.439	0.02	9	0.0887	4,929.6	2,782,902.6	0.018
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0876	6,387.7	2,834,405	-0.02	9	0.0887	4,929.6	2,781,889.5	-0.018
	-50%	7	0.0876	6.387.7	2,833,889	-0.04	9	0.0887	4,929.6	2,781,383.0	-0.036
c_1 , c_2 = 0.27 , 0.0057	+50%	7	0.0876	6,388.7	2,835,627	0.02	9	0.0887	4,930.5	2,783,244.8	0.031
	+25%	7	0.0876	6,388.2	2,835,275	0.01	9	0.0887	4,930.0	2,782,838.6	0.016
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0876	6,387.2	2,834,570	-0.01	9	0.0887	4,928.9	2,782,026.3	-0.013
	-50%	7	0.0876	6,386.7	2,834,218	-0.02	9	0.0887	4,928.4	2,781,620.2	-0.028
$e_c = 1.44$	+50%	7	0.0876	6,386.6	2,835,372	0.016	9	0.0887	4,928.7	2,782,845.7	0.016
	+25%	7	0.0876	6,387.1	2,835,148	0.008	9	0.0887	4,929.2	2,782,620.8	0.008
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0876	6,388.3	2,834,698	-0.008	9	0.0887	4,930.0	2,782,171.2	-0.008
	-50%	7	0.0876	6,388.8	2,834,472	-0.016	9	0.0887	4,930.5	2,781,946.2	-0.016
$T_x = 75$	+50%	7	0.0876	6,387.7	2,836,077	0.04	9	0.0887	4,929.8	2,783,658.0	0.045
	+25%	7	0.0876	6,387.7	2,835,500	0.02	9	0.0887	4,929.7	2,783,027.1	0.023
	0	7	0.0876	6,387.7	2,834,922	0	9	0.0887	4,929.6	2,782,396.0	0
	-25%	7	0.0876	6,387.7	2,834,345	-0.02	9	0.0887	4,929.5	2,781,764.9	-0.023
	-50%	7	0.0876	6,387.6	2,833,768	-0.04	9	0.0887	4,929.4	2,781,134.2	-0.045

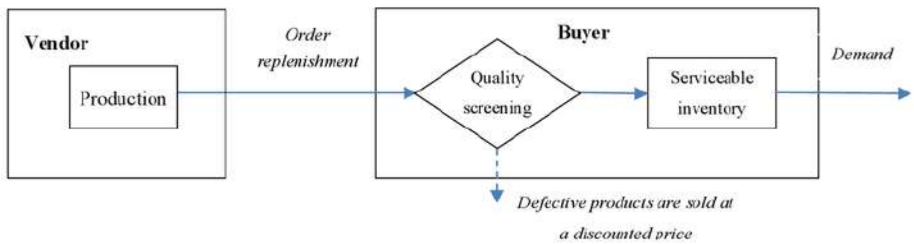

Figure 1 Illustration of an integrated inventory model for imperfect quality items where defective products are sold at a discounted price

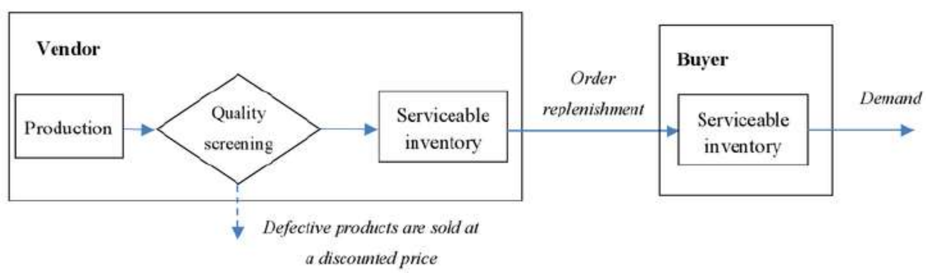

Figure 2 Illustration of an integrated inventory model for imperfect quality items with vendor's inspection

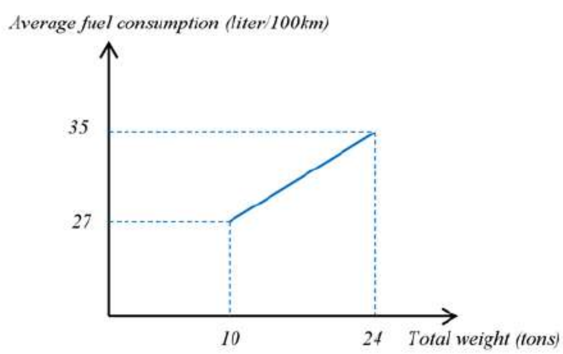

Figure 3 Linear function of average fuel consumption vs. total weight for regional traffic (Data source: Volvo Corporation, 2018)

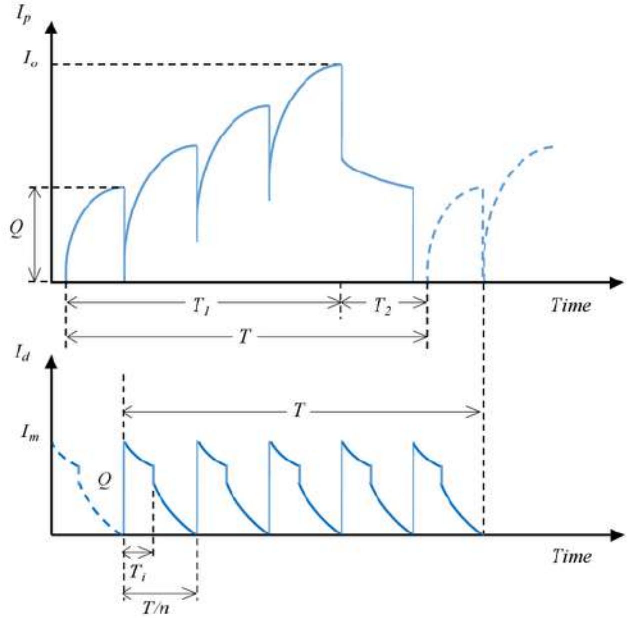

Figure 4 Manufacturer's and retailer's inventory model for constant deteriorating items with retailer's inspection for n = 5

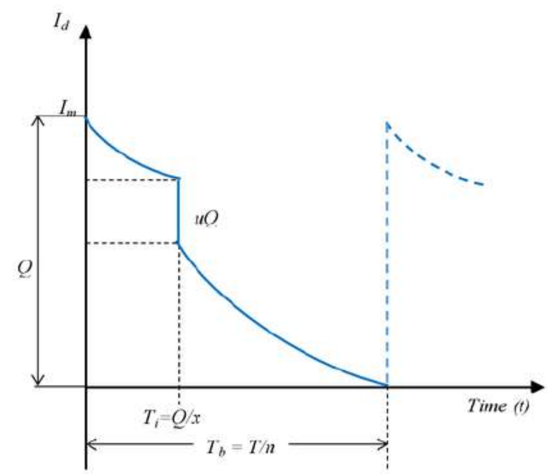

Figure 5 Retailer's inventory model with imperfect quality per delivery cycle

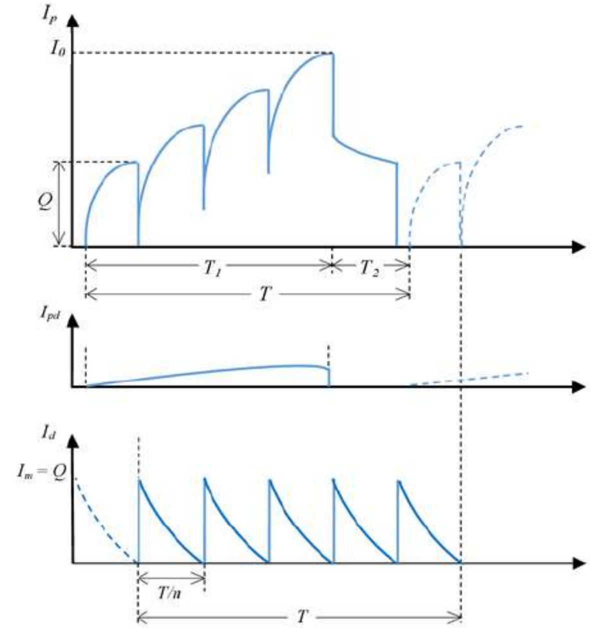

Figure 6 Manufacturer's and retailer's inventory model for constant deteriorating items with manufacturer's inspection for $n = 5$

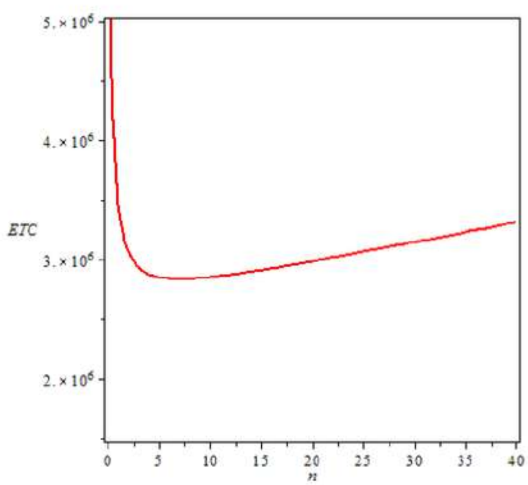

Figure 7 Graphical representation of *ETC* for a fixed n

Impact of inspection decision

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