Sustainable Economic Production Quantity Models: An Approach toward a Cleaner Production

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***Abstract*—Economic production quantity (EPQ) model determines the optimal amount of products to make at one production cycle. This method has been studied for over a century, and is still growing. This paper presents two sustainable or environmentally friendly EPQ models that consider carbon emission in the total cost function. With the increasing challenge to reduce industry's carbon emissions, scholars incorporate sustainability consideration into production decision models. The objective of such approach is to build a cleaner production system that produces less carbon emission. First, this paper presents a basic sustainable EPQ model that considers carbon emission from production, warehousing, and waste disposal activities. Second, we extend the model considering full backorder situation. This paper also illustrates the potential emission reduction from the developed models.**

***Index Terms*—economic production quantity, carbon emission, cleaner production, shortage backorder**

I. INTRODUCTION

Greenhouse gas emissions are believed to be the leading cause of today's climate change, with carbon emissions as the most substantial part. Therefore, efforts towards sustainable development continue to be promoted by governments and non-governmental organizations, as well as by the industrial world. Over 2014-2016, the total global greenhouse gas emissions have shown a slowdown in growth [1]. The 2016 emission increase (about 0.5%) is the slowest since the early 1990s, except for global recession years. Unfortunately, based on preliminary estimation this is likely to change in 2017 with global emissions expected to grow around 2% [2].

Motivated by industry challenges to contribute to carbon emissions reductions, this paper presents two sustainable or environmentally friendly economic production quantity (EPQ) models that consider carbon emissions in the total cost function. First, this paper presents a basic sustainable EPQ model that considers carbon emission from production, warehousing, and waste disposal activities. In the second model, we extended the model by considering the shortage backorder condition. This paper also illustrates the potential carbon emission reduction from the developed models.

The question of how much products to make at one lot has been studied for more than one century [3]. The early model assumed an instantaneous replenishment which is common in economic order quantity (EOQ) study. In a non-instantaneous receipt, such as in an internal production [4], we have an economic production quantity (EPQ) model. The product is both produced and consumed during the period of production. Thus the inventory level will never as large as the production lot size.

Numerous studies have extended EPQ model. Researchers have incorporated the shortage and full backorder situation into EPQ model [5-8]. A full backorder is common when there are only one or a few sources of supply [9]. Besides, companies may plan for shortages when the cost of stocking an item exceeds the profit from selling it [8].

With the increasing awareness of climate change, researchers integrate environmental considerations into production and inventory decision models. For this purpose, researchers can combine economic and environmental measures through a direct accounting approach [10]. Battini et al. [11] incorporated emissions from transportation, storage, and waste disposal into EOQ model. He et al. [12] considered emissions from production and inventory in a production lot-sizing problem based on the EOQ model under cap-and-trade and carbon tax regulations.

Recently, Taleizadeh et al. [13] developed several sustainable EPQ models for different shortage situations. They considered the emissions from production,

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inventory storage, and waste disposal of obsolete inventory. They followed the approach of Pentico et al. [14]. In this paper, we incorporate the solid waste disposal of production scrap and solve the problem using a different approach. Waste disposal is assumed to be a source of air emission. More information on emission from solid waste disposal could be found in Clean Development Mechanism [15]. We also illustrate the potential emissions reduction from the proposed models by providing two numerical examples.

II. Model Development

This study considers a single product with known and constant rates of production and demand. It is assumed that all of the periods are similar and thus, we only need to model the problem in one period or cycle. The production process is considered to be under control. Table I presents the notations in the following model.

A. Basic Sustainable EPQ

We depict the inventory model of the basic EPQ when shortage is not allowed in Fig. 1.

At $t = 0$ the inventory level equal to zero, and increases to the maximum, I_m, at $t = T_1$. At T_1, production stops and inventory level start to decline due to demand. The stock becomes zero at $t = T_2$.

Because the production occurs during T_1, the total production quantity per cycle is

$$Q = PT_1 \tag{1}$$

The total production quantity fulfils the demand in one cycle.

Equation (2) describes the total cost per unit time (TC). Note that we consider carbon emissions from the production, inventory storage, and waste disposal.

$$TC(Q) = C_S + C_{PE} + C_{HE} + C_W \tag{2}$$

- *Setup Cost*

$$C_S = \frac{C_1}{T} = \frac{C_1 D}{Q} \tag{3}$$

- *Production Cost*

The production cost considers the average carbon emission costs generated by energy usage for the machining and handling operations per unit product (C_{2e}).

$$C_{2e} = e_p E_g C_{TX} \tag{4}$$

$$C_{PE} = (C_2 + C_{2e})\frac{Q}{T} = (C_2 + C_{2e})D \tag{5}$$

TABLE I. NOTATIONS.

Symbol	Description
Parameters	
D	Demand rate (units/year)
P	Production rate (units/year)
C_1	Setup cost per cycle ($/cycle)
C_2	Production cost per unit ($/unit)
C_3	Inventory cost per unit product in a time unit ($/unit)
C_4	Waste disposal fixed cost per cycle ($/cycle)
C_5	Backordering cost per unit product in a time unit ($/unit)
e_p	Average production energy consumption per unit (kWh/unit)
e_w	Average energy consumption per warehouse space unit (kWh/m^3)
v	Space occupied by a unit product (m^3/unit)
w	Average weight of solid waste produced per unit product (kg/unit)
E_g	Energy generation standard emission (kgCO_2/kWh)
E_{sw}	Disposal standard emission per ton of solid waste (tonCO_2/ton)
C_{TX}	Carbon price or tax ($/ton$CO_2$)
Dependent variables	
I_m	Maximum inventory level (unit)
I_b	Maximum shortage level (unit)
T_1	Production-consumption period (time unit)
T_3 & T_4	Shortage period (time unit)
C_{2e}	Average production emission cost per unit ($/unit)
C_{3e}	Average inventory emission cost per unit ($/unit)
C_{4e}	Average waste disposal emission cost per unit ($/unit)
C_S	Setup cost
C_{PE}	Production cost
C_{HE}	Inventory holding cost
C_B	Backorder cost
TC	Total cost function
Decision variables	
Q	Optimum order size (unit products) – traditional model
Q^*	Optimum order size (unit products) – sustainable model
T	Cycle length (time unit)
T_2	Consumption period (time unit)

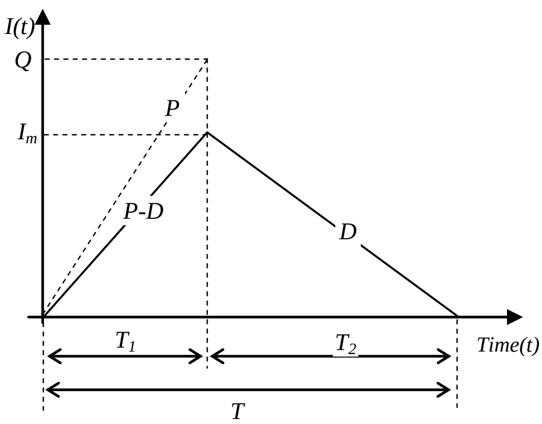

Figure 1. Illustration of basic EPQ model.

- *Inventory Holding Cost*

The inventory costs consider both traditional holding costs and carbon emissions costs generated by warehousing activities.

$$C_{3e} = ve_w E_g C_{TX} \tag{6}$$

From Fig. 1,

$$T_1 = \frac{Q}{P} \text{ and } I_m = (P-D)T_1 = \frac{(P-D)Q}{P} \tag{7}$$

Therefore,

$$C_{HE} = (C_3 + C_{3e})\frac{(P-D)Q}{2P} \tag{8}$$

- *Waste Disposal Cost*

A certain amount of solid wastes are produced and being disposed at the end of the cycle. The waste disposal cost is a function of the fixed costs for disposing of waste into the environment (C_4) and the variable costs of solid waste emission (C_{4e}). Therefore,

$$C_{4e} = wE_{sw}C_{TX} \tag{9}$$

$$C_W = \frac{C_4}{T} + C_{4e}D = C_4\frac{D}{Q} + C_{4e}D \tag{10}$$

By substituting (3), (5), (8), and (10) to (2), we obtain the total cost function per unit time

$$TC(Q) = \frac{C_1 D}{Q} + (C_2 + C_{2e})D + (C_3 + C_{3e})\frac{(P-D)Q}{2P} + C_4\frac{D}{Q} + C_{4e}D \tag{11}$$

By taking the second derivative of TC to Q yields:

$$\frac{\partial^2 TC}{\partial Q^2} = \frac{2C_1 D}{Q^3} + \frac{2C_4 D}{Q^3} \geq 0 \tag{12}$$

Because the second order derivative is always positive, the cost function is strictly convex. By setting the first derivative equal to zero,

$$\frac{\partial TC}{\partial Q} = -\frac{C_1 D}{Q^2} + \frac{(C_3 + C_{3e})(P-D)}{2P} - \frac{C_4 D}{Q^2} = 0 \tag{13}$$

$$Q^* = \sqrt{\frac{2(C_1 + C_4)D}{(C_3 + C_{3e})(1 - D/P)}} \tag{14}$$

If the emission cost (C_{3e}) = 0, (14) becomes

$$Q^* = \sqrt{\frac{2(C_1 + C_4)D}{C_3(1 - D/P)}} \tag{15}$$

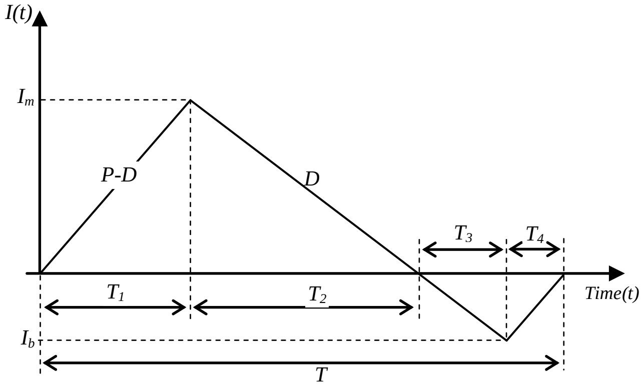

Figure 2. Illustration of EPQ model with a full backorder.

If the emission cost (C_{3e}) and waste disposal cost (C_4) = 0, (14) is similar to the traditional EPQ such as in Fogarty [4] as shown in (16).

$$Q = \sqrt{\frac{2C_1 D}{C_3(1 - D/P)}} \tag{16}$$

B. Sustainable EPQ Model with A Full Backorder

We depict the EPQ inventory model with full backorder in Fig. 2. At t = 0 the inventory level is equal to zero, and increases to the maximum, I_m, at $t = T_1$. At T_1, production stops and inventory levels begin to decline due to demand. The stock becomes zero at $t = T_2$. As demand continues, the shortage occurs and accumulate to I_b at $t = T_3$. Production begins again at $t = T_3$, and the early products are used for backorder. At $t = T$ inventory level becomes zero, and the cycle starts again. Because the production period occurs during T_1 and T_4, the total production quantity Q per cycle is

$$Q = P(T_1 + T_4) \tag{17}$$

This model will be solved by searching the optimum inventory cycle, by defining the time variables T and T_2. From Fig. 2,

$$T = T_1 + T_2 + T_3 + T_4 \tag{18}$$

When I_m,

$$T_1 = \frac{DT_2}{P-D} \tag{19}$$

When I_b,

$$T_4 = \frac{D}{P}(T_3 + T_4) \tag{20}$$

From (18), (19) and (20),

$$T_4 = \frac{D}{P}\left(T - \frac{DT_2}{P-D} - T_2\right) \tag{21}$$

$$T_3 = \frac{P-D}{P}\left(T - \frac{DT_2}{P-D} - T_2\right) = \frac{P-D}{P}T - T_2 \quad (22)$$

Equation (23) describes the total cost per unit time (TC). Note that we will also consider the carbon emissions from the production, warehousing/inventory holding, and waste disposal.

$$TC(T,T_2) = C_S + C_{PE} + C_{HE} + C_W + C_B \quad (23)$$

- *Setup Cost*

$$C_S = \frac{C_1}{T} \quad (24)$$

- *Production Cost*

$$C_{PE} = (C_2 + C_{2e})\frac{Q}{T} = \frac{(C_2 + C_{2e})}{T}P(T_1 + T_4) \quad (25)$$

$$C_{PE} = \frac{(C_2 + C_{2e})}{T}P\left(\frac{DT_2}{P-D} + \frac{D}{P}\left(T - \frac{DT_2}{P-D} - T_2\right)\right) \quad (26)$$

- *Inventory Holding Cost*

C_{HE} is equal to (C_3 + C_{3e}) multiplied by the average amount of inventories per cycle divided by T.

$$C_{HE} = \frac{(C_3 + C_{3e})}{T}\left(\frac{(P-D)T_1^2}{2} + \frac{DT_2^2}{2}\right) \quad (27)$$

$$C_{HE} = \frac{(C_3 + C_{3e})}{T}\frac{DT_2^2}{2}\left(1 + \frac{D}{P-D}\right) \quad (28)$$

- *Waste Disposal Cost*

$$C_W = \frac{C_4}{T} + C_{4e}D \quad (29)$$

- *Backorder Cost*

Fig. 2 shows that shortage occurs during T_3 and T_4. Therefore the backorder cost per unit time is

$$C_B = \frac{C_5}{T}\left(\frac{DT_3^2}{2} + \frac{(P-D)T_4^2}{2}\right) \quad (30)$$

Substituting (21) and (22) to (30), we gain

$$C_B = \frac{C_5}{T}\left(\begin{array}{l}\frac{D}{2}\left(\frac{P-D}{P}\left(T - \frac{DT_2}{P-D} - T_2\right)\right)^2 \\ + \frac{(P-D)}{2}\left(\frac{D}{P}\left(T - \frac{DT_2}{P-D} - T_2\right)\right)^2\end{array}\right) \quad (31)$$

By substituting (24), (26), (28), (29), and (31) to (23), we obtain the total cost function per unit time

$$\begin{aligned} TC(T,T_2) = {} & \frac{C_1}{T} + \frac{(C_2 + C_{2e})}{T}P\left(\frac{DT_2}{P-D} + \frac{D}{P}\left(T - \frac{DT_2}{P-D} - T_2\right)\right) \\ & + \frac{(C_3 + C_{3e})}{T}\frac{DT_2^2}{2}\left(1 + \frac{D}{P-D}\right) + \frac{C_4}{T} + C_{4e}D \\ & + \frac{C_5}{T}\left(\begin{array}{l}\frac{D}{2}\left(\frac{P-D}{P}\left(T - \frac{DT_2}{P-D} - T_2\right)\right)^2 + \\ \frac{(P-D)}{2}\left(\frac{D}{P}\left(T - \frac{DT_2}{P-D} - T_2\right)\right)^2\end{array}\right) \end{aligned} \quad (32)$$

To obtain the optimal value of the decision variable, we must first prove the convexity of the total cost function. For the function to be convex, the following sufficient conditions must be satisfied:

$$\left(\frac{\partial^2 TC}{\partial T_2^2}\right)\left(\frac{\partial^2 TC}{\partial T^2}\right) - \left(\frac{\partial^2 TC}{\partial T_2 \partial T}\right)^2 \geq 0 \quad (33)$$

and one or both

$$\left(\frac{\partial^2 TC}{\partial T_2^2}\right) \geq 0 \quad ; \quad \left(\frac{\partial^2 TC}{\partial T^2}\right) \geq 0 \quad (34)$$

By taking the first and second derivative of TC with respect to T and T_2 yields:

$$\frac{\partial TC}{\partial T_2} = \frac{\left[(C_3 + C_{3e})PT_2 + C_5(DT - PT + PT_2)\right]D}{T(P-D)} \quad (35)$$

$$\frac{\partial^2 TC}{\partial T_2^2} = \frac{(C_3 + C_{3e} + C_5)PD}{T(P-D)} \quad (36)$$

$$\frac{\partial TC}{\partial T} = \frac{\left[\begin{array}{l}2C_1(PD - P^2) - (C_3 + C_{3e})DP^2T_2^2 \\ + 2C_4(PD - P^2) \\ + C_5D(P^2T^2 + D^2T^2 - 2DPT^2 - P^2T_2^2)\end{array}\right]}{2P(P-D)T^2} \quad (37)$$

$$\frac{\partial^2 TC}{\partial T^2} = \frac{\begin{array}{c}2C_1(P-D) + (C_3 + C_{3e})DPT_2^2 \\ + 2C_4(P-D) + C_5DPT_2^2\end{array}}{(P-D)T^3} \quad (38)$$

$$\frac{\partial^2 TC}{\partial T_2 \partial T} = \frac{(C_3 + C_{3e} + C_5)DPT_2}{(D-P)T^2} \quad (39)$$

Substituting (36), (38), and (39) into (33), we gain

$$\left(\frac{\partial^2 TC}{\partial T_2{}^2}\right)\left(\frac{\partial^2 TC}{\partial T^2}\right)-\left(\frac{\partial^2 TC}{\partial T_2 \partial T}\right)^2 = \frac{2(C_1+C4_1)(C_3+C_{3e}+C_5)PD}{(P-D)T^4} \tag{40}$$

As $P > D$ and all the costs are ≥ 0, then (36), (38), and (40) are always ≥ 0. Therefore the cost function is strictly convex. By setting the first derivative equal to zero,

$$T_2 = \frac{C_5(P-D)T}{(C_3+C_{3e}+C_5)P} \tag{41}$$

$$T = \frac{\sqrt{C_5DP(2C_1(P-D)+2C_4(P-D)+(C_3+C_{3e}+C_4)DPT_2{}^2)}}{C_5D(D-P)} \tag{42}$$

Substituting (42) to (41), and for variable T_2, we can get T_2*

$$T_2{}^* = \frac{\sqrt{2DP(C_3+C_{3e})(C_3+C_{3e}+C_5)((C_1+C_4)(P-D))C_5}}{DP(C_3+C_{3e})(C_3+C_{3e}+C_5)} \tag{43}$$

Substituting (43) to (42) and simplify, we can get T*

$$T^* = \frac{1}{C_5D(P-D)}\sqrt{\frac{2DP(P-D)(C_1+C_4)C_5(C_3+C_{3e}+C_5)}{C_3+C_{3e}}} \tag{44}$$

Substituting (43) to (19) and simplify, we can get T_1*

$$T_1{}^* = \frac{\sqrt{2DP(C_3+C_{3e})(C_3+C_{3e}+C_5)((C_1+C_4)(P-D))C_5}}{P(P-D)(C_3+C_{3e})(C_3+C_{3e}+C_5)} \tag{45}$$

Substituting (43) and (44) to (21) and simplify, we can get T_4*

$$T_4{}^* = \sqrt{\frac{2D(C_1+C_4)(C_3+C_{3e})}{P(P-D)C_5(C_3+C_{3e}+C_5)}} \tag{46}$$

From (17), the optimum production quantity is

$$Q^* = P(T_1{}^* + T_4{}^*) \tag{47}$$

Therefore, after simplification

$$Q^* = \sqrt{\frac{2D(C_1+C_4)}{(C_3+C_{3e})\left(1-\frac{D}{P}\right)}}\sqrt{\frac{C_3+C_{3e}+C_5}{C_5}} \tag{48}$$

If the emission cost (C_{3e}) = 0, (48) becomes

$$Q^* = \sqrt{\frac{2D(C_1+C_4)}{C_3\left(1-\frac{D}{P}\right)}}\sqrt{\frac{C_3+C_5}{C_5}} \tag{49}$$

If the emission cost (C_{3e}) and waste disposal cost (C_4) = 0, (48) is similar to the classic EPQ with shortage such as in Cárdenas-Barrón [5].

$$Q = \sqrt{\frac{2DC_1}{C_3\left(1-\frac{D}{P}\right)}}\sqrt{\frac{C_3+C_5}{C_5}} \tag{50}$$

III. Numerical Example

The proposed models can be illustrated using the numerical example from Taleizadeh et al. [13] with some modification. The data was inspired by an Iranian petrochemical company.

Example 1: A production system that does not allow shortages, with the following data

D	=	40 units/year	e_p	=	50 kWh/unit
P	=	100 units/year	e_w	=	5 kWh/m^3
C_1	=	20 \$/cycle	v	=	1.7 m^3/unit
C_2	=	7 \$/unit	w	=	10 kg waste/unit
C_3	=	2.5 \$/unit	E_g	=	0.5 kgCO$_2$/kWh
C_4	=	5 \$/cycle	E_{sw}	=	0.3 tonCO$_2$/ton waste
C_{TX}	=	120 \$/tonCO$_2$			

First, from (4), (6) and (9) we calculate

$$C_{2e} = (50)(0.5/1000)(120) = 3\$/\text{unit}$$
$$C_{3e} = (1.7)(5)(0.5/1000)(120) = 0.51\$/\text{unit}$$
$$C_{4e} = (10/1000)(0.3)(120) = 0.36\$/\text{unit}$$

Therefore,

$$Q^* = \sqrt{\frac{2(20+5)(40)}{(2.5+0.51)(1-40/100)}} = 33.3\,\text{unit}$$

and

$$TC(Q)^* = \frac{(20)(40)}{(33.3)} + (7+3)(40) + (2.5+0.51)\frac{(100-40)(33.3)}{2(100)} + \frac{(5)(40)}{(33.3)} + (0.36)(40) = \$\,474.5$$

If we use the EPQ as shown in (15),

$$Q = \sqrt{\frac{2(20+5)(40)}{(2.5)(1-40/100)}} = 36.5\,\text{unit}$$

With $TC(Q)$ = \$474.8. It is 0.055% larger than $TC(Q^*)$. This result shows that in a business environment with carbon tax system, the industry needs to redefine its production lot size.

In contrast, in an environment without carbon tax system, when Q = 36.5, $TC(Q)$ is \$349.2, and for Q^* = 33.3, $TC(Q^*)$ is \$349.4. It is 0.068% larger than $TC(Q)$. However, in terms of total carbon emissions, we have:

- For Q = 36.5, the total carbon emissions that come from production, inventory holding, and waste disposal is

$$De_pE_g + \left(\frac{(P-D)Q}{2P}\right)e_w vE_g + DwE_{sw}$$
$$= (40)(50)(0.5) + \left(\frac{(100-40)32.7}{2(100)}\right)(5)(1.7)(0.5) +$$
$$(40)(10/1000)(0.3)$$
$$= 1166.6\ \text{kgCO}_2$$

- For Q^* = 33.3, total carbon emissions are 1162.4 kgCO_2, which is 0.35% smaller.

This results show that considering emission cost in EPQ model will reduce the total carbon emissions, although the overall cost will increase. However the percentage of total carbon emissions reduction is higher than the percentage of total cost addition.

Without considering carbon emission and waste disposal as (16), the Q becomes 32.7 unit with $TC(Q)$ equal to \$329. Of course this cost is lowest as it does not consider those two costs.

Example 2: A production system where shortages are allowed with full backorder

We assume that all parameters values are similar to Example 1 with an additional parameter C_5 = 3 \$/unit. Therefore,

$$Q^* = \sqrt{\frac{2(40)(20+5)}{(2.5+0.51)\left(1-\frac{40}{100}\right)}}\sqrt{\frac{2.5+0.51+3}{3}} = 47.1\ \text{unit}$$

with T_2^* = 0.353, T^* = 1.178, and $TC(T,T_2)$ = \$ 456.9

The total carbon emissions become

$$De_pE_g + \left(\frac{DT_2^{\,2}}{2}\left(1+\frac{D}{P-D}\right)\right)e_w vE_g + DwE_{sw}$$
$$= (40)(50)(0.5) + \left(\frac{40(0.364)^2}{2}\left(1+\frac{40}{100-40}\right)\right)(5)(1.7)(0.5)$$
$$+ (40)(10)(0.3)$$
$$= 1138.8\ \text{kgCO}_2$$

Total carbon emissions are 2.03% less than emissions in the system with no shortage and backorder. Compared to the situation where shortages are not allowed, this result indicates that in a full backorder situation the total cost becomes smaller, as confirmed by previous researchers. Further, this study also proves the reduction of carbon emissions in EPQ with full backorder.

IV. Conclusion

This paper presents two sustainable economic production quantity models that consider carbon emission in the total cost function. Carbon emissions are the result of producing and warehousing products, as well as disposing of waste. In this paper, we incorporate the solid waste disposal of production scrap. Waste disposal is assumed to be a source of air emission. We solve the problem using a different approach compared to Taleizadeh et al. [13]. This paper also illustrates the potential emissions reduction from the proposed models by providing two numerical examples.

The results show that in a business environment with carbon tax system, the industry needs to redefine its production lot size. Considering emission cost in the EPQ model will reduce the total cost and total carbon emissions. The numerical example also shows that in a full backorder situation the total cost and total carbon emissions become smaller.

This paper only provides two simple extensions of EPQ models that consider emission cost. With the broader implementation of carbon tax and emission trading system in the future, the models could be extended by considering other aspects such as deterioration rate. In a deteriorating inventory, the total production must consider both demand rate and deterioration rate per unit time. We also need to think the emission from the disposal of the deteriorated items. Further, we can also incorporate partial backorder and quality issue to make the model more realistic.

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