# Low Carbon Economic Production Quantity Model for Imperfect Quality Deteriorating Items

**Y. Daryanto* and H.M. Wee**


## ABSTRACT

This paper presents an economic production quantity (EPQ) model for deteriorating items with a certain percentage of defective products due to an imperfect process. The defective products are sold to a secondary market at a discount price. Due to environmental concern and carbon tax regulation, the manufacturer incorporates the control of carbon emission cost into its decision model. Carbon emission cost is a function of electricity consumption during production and inventory storage; it is also dependent on the carbon tax rate. Since the production process results in work-in-process inventory and carbon emission, the study tries to optimize the throughput time. We also examine the effect of carbon tax regulation on the potential emission reduction from the developed deteriorating item model. A numerical example and sensitivity analysis have been provided, and the result confirms the influence of carbon tax regulation in reducing carbon emission.


**Keywords:** inventory, economic production quantity, carbon emission, deteriorating items, imperfect quality.

**Article Info:** Received March 22, 2019; Revised May 2, 2019; Accepted June 10, 2019.
.

## 1. INTRODUCTION

Sustainable operations and supply chain management are concerned with the objective of keeping the system sustainable (Belvedere and Grando, 2017). The aim is to postulate intergenerational equity on economic, environmental, and social responsibility. The goal is in line with the United Nations' Sustainable Development Goals to achieve a better and more sustainable future for all. The scope includes eco-product design, process improvement, and lean operations, supply chain management including recycling and closed-loop supply chain, etc. (Walker et al., 2014).

As one part of sustainable operations, a greener production system a key concern. The implementation of carbon pricing regulation in many countries and the focus on low carbon operations show the increasing concerns by the government and industries. The concerns include energy consumption, greenhouse gas emissions, waste, noise, and land contamination reduction.

This paper presents an economic production quantity (EPQ) model that considers carbon emissions in decision making. The objective is to plan a production lot size that will minimize the operation and carbon emission costs. The problem is solved by optimizing the total cycle time. By simultaneously considering the impact of carbon emissions, item deterioration, and imperfect quality, this study develops a more general model than the previous studies by Mukhopadhyay & Goswami (2014), Datta (2017), Taleizadeh et al. (2018), Daryanto & Wee (2018), and Sinha & Modak (In press).

## 2. LITERATURE REVIEW

Fogarty et al., (1991) developed an economic production quantity (EPQ) model that considered non-instantaneous replenishment; it assumed both production and consumption occurred during the production period. Other researchers have incorporated the effect of imperfect quality items into the EPQ model. Rosenblatt &

Y. Daryanto* is with the Department of Industrial Engineering, Faculty of Industrial Technology, Universitas Atma Jaya Yogyakarta (email: yosef.daryanto@uajy.ac.id).
H.M. Wee is with the Department of Industrial and System Engineering, Chung Yuan Christian University (email: weehm@cycu.edu.tw).
* Corresponding author

Lee (1986) studied the optimal production cycle considering defective items due to deterioration and defective production processes. Hayek & Salameh (2001) considered the reworking process for all defective products and incorporated holding cost for both the defective and non-defective products. Taleizadeh et al. (2013) proposed an EPQ model with a failure of the reworked items. The model allowed shortages and considered production capacity limit. Al-Salamah (2016) developed an EPQ model with imperfect production and inspection processes, in which two types of inspection errors occur.

Wee (1993) is one of the first researchers who developed an EPQ model for constant deteriorating items allowing partial backorders. Wee & Law (1999) considered the effect of time value of money in an EPQ model for deteriorating items. Widyadana & Wee (2012) proposed an EPQ model for deteriorating items with imperfect quality. They assumed a rework process after several production cycles. Li et al. (2015) considered an EPQ model for deteriorating items with a complete backorder and rework process.

In line with the global awareness on climate change and sustainable development, researchers integrate environmental considerations in the production and inventory decision models. Mukhopadhyay & Goswami (2014) considered pollution as a result of scraps, junks, and sewage from production activities. They incorporated pollution control and treatment costs into the total cost function. Recently, Datta (2017) studied the effect of technology investment for carbon emission reduction in an EPQ model. Carbon emission comes from production setup, production processes, machine operations, product storage, and the disposal of defective products. Taleizadeh et al. (2018) extended the traditional EPQ models for different shortage situations, considering emissions from production, inventory storage, and waste disposal of obsolete inventory. Daryanto & Wee (2018) solved Taleizadeh et al.'s (2018) models using a different approach incorporating solid waste disposal and a carbon tax system. Recently, Sinha & Modak (In press) considered carbon emission cost under an emission trading system.

## 3. MODEL DEVELOPMENT

This study considers a production lot size decision of a manufacturer incorporating the environmental impact of carbon emissions. A carbon tax regulation penalizes the party that emits greenhouse gases. The objective is to minimize total operation and emission cost. Table 1 presents the notations of the model.

Table 1. Notations

| **Symbol** | **Description** |
|---|---|
| Decision variables | |
| $T_2$ | Consumption period (year) |
| $Q_0$ | Total production quantity per cycle (unit) |
| Parameters | |
| $D$ | Demand rate (units/year) |
| $P$ | Production rate (units/year) |
| $u$ | The probability of defective products per cycle; E[$u$] is the expected value of $u$ |
| $\theta$ | Deterioration rate; ($0 \le \theta < 1$) |
| $c_s$ | Setup cost per cycle ($/cycle) |
| $c_p$ | Production cost per unit ($/unit) |
| $c_{pe}$ | Production emission cost per unit ($/unit) |
| $c_i$ | Fixed quality inspection cost per cycle ($/cycle) |
| $c_u$ | Unit inspection cost ($/unit) |
| $c_{h1}$ | Unit holding cost of the good product in a time unit ($/unit) |
| $c_{h2}$ | Unit holding cost of the defective product in a time unit ($/unit) |
| $c_{he}$ | Inventory emission cost per unit ($/unit) |
| $c_d$ | Deteriorating cost per unit ($/unit) |
| $c_w$ | Disposal cost per ton of waste ($/ton) |
| $e_p$ | Average electricity consumption for production (kWh/unit) |
| $e_w$ | Average electricity consumption per warehouse space unit (kWh/m$^3$) |
| $v$ | Space occupied by a unit product (m$^3$/unit) |
| $a$ | Average weight of solid waste produced per unit product (ton/unit) |
| $E_g$ | Standard emission for electricity generation (tonCO$_2$/kWh) |
| $C_{TX}$ | Carbon tax rate ($/tonCO$_2$) |
| $I_p(t)$ | Inventory level of good products at any time $t$ (unit) |
| $I_m$ | Maximum inventory level (unit) |
| $I_{pd}(t)$ | The inventory level of defective products at any time $t$ (unit) |
| $T$ | Cycle length (year) |
| $T_1$ | Production-consumption period (year) |
| $Q$ | Total production of good products per cycle (unit) |
| $ETC$ | Expected total cost ($/year) |
| $ETE$ | Expected total carbon emission (tonCO$_2$/year) |

Further assumptions are listed below:

1. A single type of item is considered with constant demand rate.
2. The item has a constant deterioration rate with no replacement for the deteriorated item.

3. Production rate is constant and higher than the demand rate.
4. The manufacturer conducts a 100% quality inspection. The defective products are stored until $T_1$ and will be sold to a secondary market. Unit holding cost of the defective product ($c_{h2}$) is lower than the good product ($c_{h1}$).
5. Carbon emissions come from production and inventory holding.
6. Production emission cost ($c_{pe}$) is generated by machining operations per unit product (e.g., Wangsa, 2017; Marchi et al., 2019). It is a function of average electricity consumption per unit product ($e_p$), electricity generation standard emission ($E_g$) and carbon tax rate ($C_{TX}$); $c_{pe} = e_p.E_g.C_{TX}$.
7. Inventory emission cost is generated by electricity consumption for warehousing activities (e.g., Hariga et al., 2017; Taleizadeh et al., 2018). The average inventory emission cost per unit product ($c_{he}$) is a function of space occupied by a unit product ($v$), average electricity consumption per warehouse space unit ($e_w$), electricity generation standard emission ($E_g$) and carbon tax rate ($C_{TX}$); $c_{he} = v.e_w.E_g.C_{TX}$.
8. The production process also produces a certain amount of solid waste and will be disposed of (Monte et al., 2009; Soleymanfar et al., 2015; Daryanto & Wee, 2018). Waste disposal cost is a function of disposal cost per ton of waste ($c_w$), the average weight of solid waste produced per unit product ($a$), and total production per cycle.
9. To ensure excellent service and avoid lost sales, a shortage condition is not allowed.

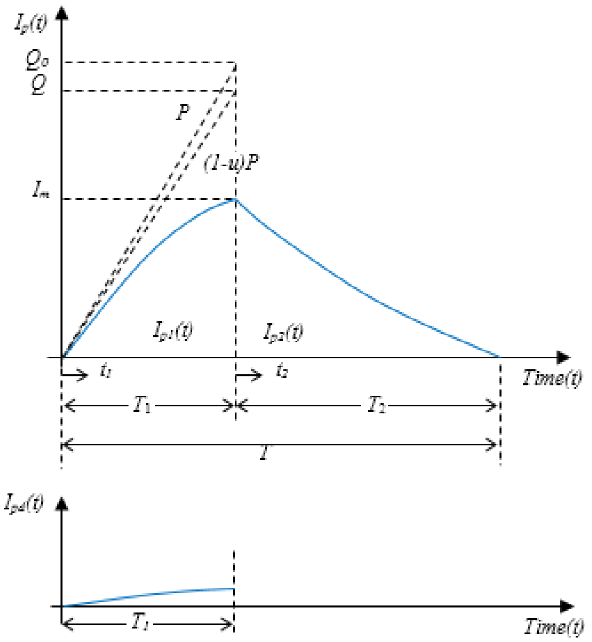


Figure 1. EPQ model with imperfect quality and deterioration

Figure 1 presents the inventory model of EPQ for deteriorating items with a certain percentage of defective products when a shortage is not allowed. The upper and lower parts present the inventory model of good and defective products respectively. At $t = 0$ production starts and the inventory level is still zero. The inventory of good products increases in $(1-u)P-D$ rates. It reaches the maximum level, $I_m$ at $t = T_1$. The inventory of defective products increases in $uP$ rates. At $T_1$, production stops, and inventory level of good products start to decline following demand and deterioration rates. At $T_1$, the defective products are taken out. At the end of the cycle period ($t = T_2$), the inventory is zero.

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

$$Q_0 = PT_1 \tag{1}$$

, and the total production of good products per cycle is

$$Q = (1-u)PT_1 \tag{2}$$

$I_p(t)$ is the inventory level of good products at any time $t$ ($0 < t < T$). At any period, the inventory differential equations are

$$\frac{dI_{p1}(t_1)}{dt_1} = (1-u)P - D - \theta I_P(t_1),\ 0 \le t_1 \le T_1 \tag{3}$$

$$\frac{dI_{p2}(t_2)}{dt_2} = -D - \theta I_p(t_2),\ \ 0 \le t_2 \le T_2 \tag{4}$$

From Figure 1 one has,

$$I_{p1}(0) = 0, I_{p1}(T_1) = I_m = I_{p2}(0), I_{p2}(T_2) = 0 \tag{5}$$

Solving Eq. (3) and (4), we have the inventory level function of good products at any time $t$ as follows

$$I_p(t_1) = \frac{(1-u)P-D}{\theta}(1-e^{-\theta t_1}),\ \ 0 \le t_1 \le T_1 \tag{6}$$

$$I_{p_2(t_2)} = \frac{D}{\theta}(e^{\theta(T_2-t_2)}-1),\ \ 0 \le t_2 \le T_2 \tag{7}$$

At $t = T_1$, from Eq. (5) and (6),

$$I_{p_1(T_1)} = I_m = \frac{(1-u)P-D}{\theta}(1-e^{-\theta T_1}) \tag{8}$$

From Eq. (5) and (7), at $t_2 = 0$

$$I_{p_2}(0_1) = I_m = \frac{D}{\theta}(e^{\theta T_2}-1) \tag{9}$$

Therefore,

$$\frac{(1-u)P-D}{\theta}(1-e^{-\theta T_1}) = \frac{D}{\theta}(e^{\theta T_2}-1) \tag{10}$$

Assuming small $\theta T_1$, from Misra (1975) $T_1$ approximately satisfies

$$T_1 = \frac{D}{(1-u)P-D}T_2(1+\frac{1}{2}\theta T_2) \tag{11}$$

Considering $T = T_1 + T_2$

$$T = \frac{T_2}{(1-u)P-D}\left((1-u)P + \frac{1}{2}D\theta T_2\right) \tag{12}$$

From Figure 1, the inventory of good products per cycle is

$$I_p = \int_0^{T_1} I_{p_1}(t_1)dt_1 + \int_0^{T_2} I_{p_2}(t_2)dt_2 \tag{13}$$

From Eq. (6) and (7)

$$I_p = \int_0^{T_1} \frac{(1-u)P-D}{\theta}(1-e^{-\theta t_1})dt_1 + \int_0^{T_2} \frac{D}{\theta}(e^{\theta(T_2-t_2)}-1)dt_2$$

$$I_p = \frac{(1-u)P-D}{\theta^2}(\theta T_1 + e^{-\theta T_1} - 1) + \frac{D}{\theta^2}(e^{\theta T_2} - \theta T_2 - 1) \quad (14)$$

By using Taylor's series expansion and neglecting the second or higher order of $\theta$ terms, one has,

$$I_p = \frac{(1-u)P-D}{2}\left(1-\frac{\theta T_1}{3}\right)T_1^2 + \frac{D}{2}\left(1+\frac{\theta T_2}{3}\right)T_2^2 \quad (15)$$

$I_{pd}(t)$ is the inventory level of defective products at any time $t$ ($0 < t < T_1$). The inventory differential equation is

$$\frac{dI_{pd}(t_1)}{dt_1} = uP - \theta I_{pd}(t_1), \quad 0 \le t_1 \le T_1 \quad (16)$$

For $I_{pd}(0) = 0$, solving Eq. (16), the inventory level of defective products at any time $t$ is

$$I_{pd}(t_1) = \frac{uP}{\theta}(1-e^{-\theta t_1}), \quad 0 \le t_1 \le T_1 \quad (17)$$

Therefore, the inventory of defective products per cycle is

$$I_{pd} = \int_0^{T_1} I_{pd}(t_1)dt_1 = \int_0^{T_1} \frac{uP}{\theta}(1-e^{-\theta t_1})dt_1$$

$$= \frac{uPT_1}{\theta} + \frac{uP}{\theta^2}(e^{-\theta T_1} - 1) \quad (18)$$

By using Taylor's series expansion and neglecting the second or higher order of $\theta$ terms, one has,

$$I_{pd} = \frac{uPT_1}{\theta} + uPT_1\left(\frac{T_1}{2} - \frac{\theta T_1^2}{6} - \frac{1}{\theta}\right) \quad (19)$$

Figure 1 shows that deterioration occurs during the inventory of good products ([0, $T_1$]; [0, $T_2$]) and defective products ([0, $T_1$]). Therefore, the total deteriorated items per cycle can be formulated as

$$\left((1-u)PT_1 - D(T_1+T_2)\right) + \left(uPT_1 - \frac{uP}{\theta}(1-e^{-\theta T_1})\right)$$

$$= (1-u)PT_1 - D(T_1+T_2) + uPT_1\left(2-\frac{\theta T_1}{2}\right) \quad (20)$$

Equation (21) describes the total cost per unit time ($TC$). It consists of setup cost ($C_1$), production cost ($C_2$), quality inspection cost ($C_3$), holding cost ($C_4$), deteriorating cost ($C_5$), and waste disposal cost ($C_6$) per unit time as follow:

$$TC = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \quad (21)$$

From Eq. (15), (19), and (20), and considering all the cost parameters, we have

$$TC = \frac{c_s}{T} + \frac{c_p + c_{pe}}{T}PT_1 + \frac{c_i + c_u PT_1}{T}$$

$$+ \frac{c_{h1}+c_{he}}{T}\left(\frac{(1-u)P-D}{2}\left(1-\frac{\theta T_1}{3}\right)T_1^2 + \frac{D}{2}\left(1+\frac{\theta T_2}{3}\right)T_2^2\right)$$

$$+ \frac{c_{h2}+c_{he}}{T}\left(\frac{uPT_1}{\theta} + uPT_1\left(\frac{T_1}{2} - \frac{\theta T_1^2}{6} - \frac{1}{\theta}\right)\right)$$

$$+ \frac{c_w aPT_1}{T} \quad (22)$$

Considering the expected value of $u$, Eq. (22) becomes

$$ETC = \frac{c_s}{T} + \frac{c_p + c_{pe}}{T}PT_1 + \frac{c_i + c_u PT_1}{T}$$

$$+ \frac{c_{h_1}+c_{he}}{T}\left(\frac{(1-E[u])P-D}{2}\left(1-\frac{\theta T_1}{3}\right)T_1^2 + \frac{D}{2}\left(1+\frac{\theta T_2}{3}\right)T_2^2\right)$$

$$+ \frac{c_{h_2}+c_{he}}{T}\left(\frac{E[u]PT_1}{2} + E[u]PT_1\left(\frac{T_1}{2} - \frac{\theta T_1^2}{6} - \frac{1}{\theta}\right)\right)$$

$$+ \frac{c_d}{T}\left((1-E[u])PT_1 - D(T_1+T_2) + E[u]PT_1\left(2-\frac{\theta T_1}{2}\right)\right)$$

$$+ \frac{c_w aPT_1}{T} \quad (23)$$

Further, the expected total carbon emission ($ETE$) can be derived from total production and inventory equations as follow:

$$ETE = \frac{e_p E_g}{T}PT_1 + \frac{ve_w E_g}{T}\left(\frac{(1-E[u])P-D}{2}\left(1-\frac{\theta T_1}{3}\right)T_1^2\right.$$

$$\left.+ \frac{ve_w E_g}{T}\left(\frac{E[u]PT_1}{\theta} + E[u]PT_1\left(\frac{T_1}{2} - \frac{\theta T_1^2}{6} - \frac{1}{\theta}\right)\right)\right) \quad (24)$$

For an optimal result, the total cost function must be convex. For the function to be convex, the following sufficient conditions must be satisfied:

$$\frac{\partial^2 ETC}{\partial T_2^2} \ge 0$$

However, the second derivative of Eq. (23) with respect to $T_2$ is a complicated function. Therefore, we provide a numerical experiment to indicate the convexity of Eq. (23).

To solve the total cost equation, we need to express $T$ and $T_1$ in terms of $T_2$. Further, the optimal solution must satisfy the following equation:

$$\frac{\partial^2 ETC}{\partial T_2} = 0$$

Therefore, we developed a procedure to determine the optimal solution as follows:

1. Substitute Eq. (11) and (12) into (23) to express $T$ and $T_1$ in terms of $T_2$;
2. Substitute other parameters into $ETC$;
3. Derive the partial derivative of $ETC$ with respect to $T_2$ and set it to zero. Solve it to find the value of $T_2$;
4. Substitute $T_2$ into Eq. (11) and (12) to gain $T_1$ and $T$.

Use $T_1$ to calculate the optimal production lot size using Eq. (1). Then, calculate the corresponding $ETC$ and $ETE$ using Eq. (23) and (24).

## 4. NUMERICAL EXAMPLE AND DISCUSSION

To illustrate how the proposed model and solution procedure are solving the low carbon EPQ model, we present a numerical example adapted from Taleizadeh et al. (2018). The data illustrate a production and inventory system of a petrochemical company in Iran. New parameters are added to meet the situation in this study. The parameters are presented as follow:

$P$ = 100 units/year,
$D$ = 40 units/year,
$c_s$ = \$20 /setup,
$c_p$ = \$7 /unit,
$c_i$ = \$10 /cycle,
$c_u$ = \$0.1 /unit,
$c_{h1}$ = \$2.5/unit,
$c_{h2}$ = \$0.5/unit,
$c_d$ = \$2/unit,
$c_w$ = \$0.5/ton,
$a$ = 0.02 ton/unit,
$\theta$ = 0.1,
$v$ = 1.7 $m^3$/unit,
$C_{TX}$ = \$75 /ton $CO_2$,
$e_p$ = 80 kWh/unit,
$e_w$ = 8 kWh/$m^3$,
$E_g$ = $0.5 \times 10^{-3}$ ton $CO_2$/kWh,
$E[u]$ = 0.02

First, we calculate the values of $c_{pe}$ and $c_{he}$ as below:

$c_{pe} = e_p.E_g.C_{TX} = (80)(0.0005)(75) = \$3$ /unit

$c_{he} = v.e_w.E_g.C_{TX} = (1.7)(8)(0.0005)(75) = \$0.51$ /unit

Applying the proposed solution procedure, we gain the following results:

$T_2$ = 0.4815 year
$T_1$ = 0.3401 year
$T$ = 0.8216 year
$Q_0 = PT_1$ = 34.0 units
$Q = (1\text{-}u)PT_1$ = 33.3 units

with $ETC$ = \$ 488.95 per year and $ETE$ = 1.72 tons per year. Figure 2 shows the graphical representation of $ETC$ and proves its convexity.

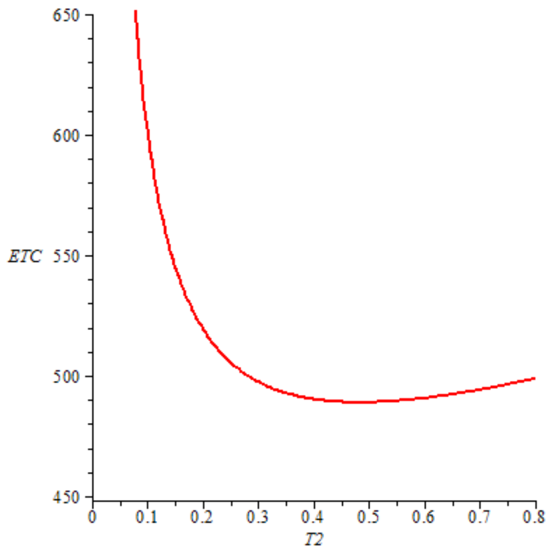


Figure 2. Convexity of the expected total cost function

To get more insight in terms of cost and carbon emission, a sensitivity analysis is done for all parameters ranging from -50% to +50%. Table 2 shows the result. The following insights can be drawn from the sensitivity analysis:

(1) The ETC increases as the value of the parameters increase.
(2) The $ETC$ is highly sensitive to the changes in customer demand ($D$), production cost ($c_p$), production energy consumption ($e_p$), and carbon tax ($C_{TX}$). It is also sensitive to the changes in other parameters except for the waste disposal cost ($c_w$).
(3) The $ETE$ decreases as the value of the carbon tax ($C_{TX}$) increases. This result confirms the benefit of implementing a carbon pricing system. The expected total carbon emission also decreases as the value production cost ($c_p$), unit inspection cot ($c_u$), holding cost ($c_{h1}$ & $c_{h2}$), deteriorating cost ($c_d$), and weight of solid waste produced per unit product ($a$) increase. The expected total carbon emission increases as the value of other parameters increase.
(4) The $ETE$ is highly sensitive to the changes in customer demand ($D$) and production energy consumption ($e_p$). It is also sensitive to the changes of other parameters except for the unit inspection cot ($c_u$), deteriorating cost ($c_d$), waste disposal cost ($c_w$), and weight of solid waste produced per unit product ($a$).

## 5. CONCLUSION

This study examines an economic production quantity problem considering the environmental impact of carbon emission. The objective is to minimize the total operation and carbon emissions costs simultaneously. The manufacturer is charged based on total carbon dioxide it emits. The proposed model incorporates the effect of deterioration, defective products, and waste disposal. Due to deterioration and the existence of some defective products, the total production quantity is more than the total customer demand. Since the production process results in work-in-process inventory and carbon emission, the study tries to optimize the throughput time. We also examine the effect of carbon tax regulation on the potential emission reduction from the deteriorating item model. A numerical example and sensitivity analysis have been provided, and the result confirms the influence of carbon tax regulation in reducing carbon emission.

For future research, this study can be extended by considering an adjustable production rate. Another possible development is to incorporate technology investment to reduce the probability of defective and deteriorating items.

Table 2. Result of sensitivity analysis

| | | Value | | | | | % variation | |
|---|---|---|---|---|---|---|---|---|
| | | $T_2$ | $T_1$ | $Q_0$ | *ETC* | *ETE* | *ETC* | *ETE* |
| *D* (40)* | -50% | 0.7589 | 0.2019 | 20.2 | 274.37 | 0.89 | -43.89 | -48.11 |
| | -25% | 0.5903 | 0.2681 | 26.8 | 381.68 | 1.31 | -21.94 | -23.90 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.3997 | 0.4247 | 42.5 | 592.83 | 2.13 | 21.24 | 23.65 |
| | +50% | 0.3316 | 0.5322 | 53.2 | 693.64 | 2.53 | 41.86 | 47.10 |
| *P* (100)* | -50% | 0.2953 | 1.3320 | 66.6 | 453.47 | 1.68 | -7.26 | -2.51 |
| | -25% | 0.4338 | 0.5292 | 39.7 | 478.42 | 1.71 | -2.15 | -0.78 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.5053 | 0.2517 | 31.5 | 494.96 | 1.73 | 1.22 | 0.45 |
| | +50% | 0.5215 | 0.2000 | 30.0 | 498.86 | 1.74 | 2.03 | 0.76 |
| $c_s$ (20)* | -50% | 0.3938 | 0.2769 | 27.7 | 475.55 | 1.70 | -2.74 | -0.96 |
| | -25% | 0.4399 | 0.3101 | 31.0 | 482.59 | 1.71 | -1.30 | -0.46 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.5197 | 0.3677 | 36.8 | 494.80 | 1.73 | 1.20 | 0.42 |
| | +50% | 0.5552 | 0.3935 | 39.3 | 500.25 | 1.74 | 2.31 | 0.81 |
| $c_p$ (7)* | -50% | 0.4950 | 0.3498 | 35.0 | 344.05 | 1.72 | -29.63 | 0.15 |
| | -25% | 0.4881 | 0.3448 | 34.5 | 416.51 | 1.72 | -14.81 | 0.07 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4752 | 0.3355 | 33.5 | 561.38 | 1.72 | 14.81 | -0.07 |
| | +50% | 0.4691 | 0.3311 | 33.1 | 633.80 | 1.72 | 29.62 | -0.14 |
| $c_i$ (10)* | -50% | 0.4399 | 0.3101 | 31.0 | 482.59 | 1.71 | -1.30 | -0.46 |
| | -25% | 0.4612 | 0.3254 | 32.5 | 485.84 | 1.72 | -0.63 | -0.22 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.5010 | 0.3542 | 35.4 | 491.93 | 1.73 | 0.61 | 0.21 |
| | +50% | 0.5197 | 0.3677 | 36.8 | 494.80 | 1.73 | 1.20 | 0.42 |
| $c_u$ (0.1)* | -50% | 0.4817 | 0.3402 | 34.0 | 486.88 | 1.72 | -0.42 | 0.002 |
| | -25% | 0.4816 | 0.3401 | 34.0 | 487.92 | 1.72 | -0.21 | 0.001 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4814 | 0.3400 | 34.0 | 489.99 | 1.72 | 0.21 | -0.001 |
| | +50% | 0.4813 | 0.3399 | 34.0 | 491.02 | 1.72 | 0.42 | -0.002 |
| $c_{h1}$ & $c_{h2}$ (2.5 & 0.5)* | -50% | 0.5904 | 0.4192 | 41.9 | 475.44 | 1.74 | -2.76 | 1.20 |
| | -25% | 0.5276 | 0.3735 | 37.3 | 482.54 | 1.73 | -1.31 | 0.51 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4458 | 0.3143 | 31.4 | 494.84 | 1.72 | 1.20 | -0.39 |
| | +50% | 0.4170 | 0.2936 | 29.4 | 500.31 | 1.71 | 2.32 | -0.71 |
| $c_d$ (2)* | -50% | 0.4852 | 0.3428 | 34.3 | 486.74 | 1.72 | -0.45 | 0.04 |
| | -25% | 0.4834 | 0.3414 | 34.1 | 487.85 | 1.72 | -0.23 | 0.02 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4797 | 0.3388 | 33.9 | 490.05 | 1.72 | 0.22 | -0.02 |
| | +50% | 0.4779 | 0.3375 | 33.7 | 491.16 | 1.72 | 0.45 | -0.04 |
| $c_w$ (0.5)* | -50% | 0.4815 | 0.3400 | 34.0 | 488.75 | 1.72 | -0.04 | 0.00 |
| | -25% | 0.4815 | 0.3400 | 34.0 | 488.85 | 1.72 | -0.02 | 0.00 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4815 | 0.3401 | 34.0 | 489.05 | 1.72 | 0.02 | 0.00 |
| | +50% | 0.4815 | 0.3401 | 34.0 | 489.16 | 1.72 | 0.04 | 0.00 |
| *a* (0.02)* | -50% | 0.4837 | 0.3417 | 34.2 | 483.30 | 1.72 | -1.15 | 0.02 |
| | -25% | 0.4826 | 0.3409 | 34.1 | 486.11 | 1.72 | -0.58 | 0.01 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4804 | 0.3393 | 33.9 | 491.82 | 1.72 | 0.59 | -0.01 |
| | +50% | 0.4792 | 0.3384 | 33.8 | 494.72 | 1.72 | 1.18 | -0.02 |
| *v* (1.7)* | -50% | 0.4990 | 0.3527 | 35.3 | 486.38 | 1.69 | -0.53 | -1.83 |
| | -25% | 0.4900 | 0.3462 | 34.6 | 487.68 | 1.71 | -0.26 | -0.90 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4734 | 0.3342 | 33.4 | 490.20 | 1.74 | 0.26 | 0.87 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | +50% | 0.4657 | 0.3287 | 32.9 | 491.44 | 1.75 | 0.51 | 1.72 |
| $\theta$ *(0.1)** | -50% | 0.5085 | 0.3552 | 35.5 | 485.35 | 1.71 | -0.74 | -0.44 |
| | -25% | 0.4944 | 0.3473 | 34.7 | 487.18 | 1.72 | -0.36 | -0.21 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4698 | 0.3335 | 33.3 | 490.66 | 1.73 | 0.35 | 0.21 |
| | +50% | 0.4589 | 0.3274 | 0.7864 | 492.33 | 1.73 | 0.69 | 0.40 |
| *E[u]* *(0.02)** | -50% | 0.4837 | 0.3359 | 33.6 | 483.30 | 1.71 | -1.15 | -0.96 |
| | -25% | 0.4826 | 0.3380 | 33.8 | 486.11 | 1.71 | -0.58 | -0.48 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4804 | 0.3422 | 34.2 | 491.82 | 1.73 | 0.59 | 0.49 |
| | +50% | 0.4792 | 0.3444 | 34.4 | 494.72 | 1.74 | 1.18 | 0.98 |
| $e_p$ *(80)** | -50% | 0.4871 | 0.3441 | 34.4 | 426.86 | 0.90 | -12.70 | -47.98 |
| | -25% | 0.4843 | 0.3421 | 34.2 | 457.91 | 1.32 | -6.35 | -23.99 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4788 | 0.3381 | 33.8 | 519.99 | 2.14 | 6.35 | 23.99 |
| | +50% | 0.4761 | 0.3361 | 33.6 | 551.04 | 2.55 | 12.70 | 47.98 |
| $e_w$ *(8)** | -50% | 0.4990 | 0.3527 | 35.3 | 486.38 | 1.69 | -0.53 | -1.83 |
| | -25% | 0.4900 | 0.3462 | 34.6 | 487.68 | 1.71 | -0.26 | -0.90 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4734 | 0.3342 | 33.4 | 490.20 | 1.74 | 0.26 | 0.87 |
| | +50% | 0.4658 | 0.3287 | 32.9 | 491.44 | 1.75 | 0.51 | 1.72 |
| $C_{TX}$ *(75)** | -50% | 0.5052 | 0.3573 | 35.7 | 424.25 | 1.73 | -13.23 | 0.26 |
| | -25% | 0.4930 | 0.3484 | 34.8 | 456.62 | 1.72 | -6.61 | 0.13 |
| | Base value | 0.4815 | 0.3401 | 34.0 | 488.95 | 1.72 | 0 | 0 |
| | +25% | 0.4708 | 0.3323 | 33.2 | 521.24 | 1.72 | 6.60 | -0.12 |
| | +50% | 0.4608 | 0.3251 | 32.5 | 553.49 | 1.72 | 13.20 | -0.23 |

## REFERENCES


Al-Salamah, M. (2016). Economic production quantity in batch manufacturing with imperfect quality, imperfect inspection, and destructive and non-destructive acceptance sampling in a two-tier market. *Computers & Industrial Engineering*, 93, 275-285.

Belvedere, V., & Grando, A. (2017). *Sustainable operations and supply chain management*. West Sussex: John Wiley & Sons Ltd.

Daryanto, Y., & Wee, H.M. (2018). Sustainable economic production quantity models: an approach toward a cleaner production. *Journal of Advanced Management Science*, 6(4), 206-212.

Datta, T.K. (2017). Effect of green technology investment on a production-inventory system with carbon tax. *Advances in Operations Research*, 2017, Article ID 4834839.

Fogarty, D.W., Blackstone Jr., J.H., & Hoffmann, T.R. (1991). *Production & Inventory Management*( 2nd ed.). Ohio, USA: South-Western Publishing, Co., p. 218.

Hariga, M., As'ad, R., & Shamayleh, A. (2017). Integrated economic and environmental models for a multi stage cold supply chain under carbon tax regulation. *Journal of Cleaner Production*, 166, 1357-1371.

Hayek, P.A., & Salameh, M.K. (2001). Production lot sizing with the reworking of imperfect quality items produced. *Production Planning & Control*, 12(6), 584-590.

Li, N., Chan, F.T.S., Chung, S.H., & Tai, A.H. (2015). An EPQ model for deteriorating production system and items with rework. *Mathematical Problems in Engineering*, 2015, Article ID 957970.

Marchi, B., Zanoni, S., Zavanella, L.E., & Jaber, M.Y. (2019). Supply chain models with greenhouse gases emissions, energy usage, imperfect process under different coordination decisions. *International Journal of Production Economics*, 211, 145-153.

Misra, R.B. (1975). Optimum production lot size model for a system with deteriorating inventory. *International Journal of Production Research*, 13(5), 495–505.

Monte, M.C., Fuente, E., Blanco, A., & Negro, C. (2009). Waste management from pulp and paper production in the European Union. *Waste Management*, 29(1), 293-308.

Mukhopadhyay, A., & Goswami, A. (2014). Economic production quantity models for imperfect items with pollution costs. *Systems Science & Control Engineering*, 2(1), 368-378.

Rosenblatt, M.J., & Lee, H.L. (1986). Economic production cycles with imperfect production processes. *IIE Transactions*, 18(1), 48-55.

Sinha, S., & Modak, N.M. (*in press*). An EPQ model in the perspective of carbon emission reduction. *International Journal of Mathematics in Operational Research*.

Soleymanfar, V.R., Taleizadeh, A.A., & Zia, N.P. (2015). A sustainable lot-sizing model with partial backordering. *International Journal of Advanced Operations Management*, 7(2), 157-172.

Taleizadeh, A.A., Soleymanfar, V.R., & Govindan, K. (2018). Sustainable economic production quantity models for inventory systems with shortage. *Journal of Cleaner Production*, 174, 1011-1020.

Taleizadeh, A.A., Wee, H.M., & Jalali-Naini, S.G. (2013). Economic production quantity model with repair failure and limited capacity. *Applied Mathematical Modelling*, 37(5), 2765-2774.

Walker, H., Seuring, S., Sarkis, J., & Klassen, R. (2014). Sustainable operations management: recent trends and future directions. *International Journal of Operations & Production Management*, 34(5).

Wangsa, I.D. (2017). Greenhouse gas penalty and incentive policies for a joint economic lot size model with industrial and transport emissions. *International Journal of Industrial Engineering Computations*, 8(4), 453-480.

Wee, H.M. (1993). Economic production lot size model for deteriorating items with partial back-ordering. *Computers & Industrial Engineering*, 24(3), 449-458.

Wee, H.M., & Law, S.T. (1999). Economic production lot size for deteriorating items taking account of the time-value of money. *Computer & Operations Research,* 26(6), 545-558.

Widyadana, G.A., & Wee, H.M. (2012). An economic production quantity model for deteriorating items with multiple production setups and rework. *International Journal of Production Economics*, 138(1), 62-67.

.