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RESEARCH ARTICLE

A vendor-constrained economic production quantity model integrating scrap recovery under sustainability

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Abstract

Growing environmental and financial challenges emphasize the importance of incorporating sustainability into production inventory systems, particularly in areas where waste generation and scrap removal highly contribute to ecological impact and operational expenses. This study proposes a sustainable Economic Production Quantity model by incorporating a dual mechanism of scrap recovery and vendor-side capacity limitations. The model is formulated under two scenarios: (i) an economic production quantity model with faulty items and fixed scrap disposal and (ii) a sustainable model incorporating Waste to Energy recovery, excessive fines, and managing system level expenses. An analytical cost formulation is developed and evaluated using closed form expressions. The results confirm that Model II is the best optimum method since the sustainable model reduces the overall annual cost from $71,702 to $71,566. This demonstrates that sustainability and financial efficiency can be simultaneously attained when operational constraints and recovery possibilities are systematically modelled.

Keywords: Economic Production Quantity Model, Defective Items, Rework, Shortage, Vendor Handling Cost, Scrap Recovery, Sustainability.
关键词： 经济生产数量模型、缺陷品、返工、短缺、供应商处理成本、废料回收、可持续性。

Introduction

In the contemporary business world, inventory management is vital for lowering operational expenditures and guaranteeing product accessibility. The economic production quantity (EPQ) model is often employed to estimate ideal production quantities while minimizing overall system costs. However, with the growing attention on sustainable practices and ecological consciousness, conventional models that neglect sustainability, like waste generation, inadequate scrap destruction, and insufficient recovery systems are becoming inappropriate for today's manufacturing industries. Incorporating sustainable ideas into EPQ models is crucial for firms seeking to balance financial performance with environmental responsibility.

Scrap production is a widespread issue in inventory models involving flawed processes, rework, and quality variability. Instead of investigating the possibility of recovery or reuse, traditional EPQ models usually consider scrap as an unrecoverable loss with fixed disposal costs. Furthermore, these models overlook the operational restrictions specifically the difficulties in vendor side cooperation required for handling high scrap volumes. As industries attempts to adopt more sustainable and cost-effective strategies, these restrictions highlight a significant gap in the existing literature on inventory models.

Recent research has attempted to integrate sustainability into production inventory systems through various mechanisms, including rework strategies, backordering policies, vendor coordination, and environmental cost internalization. Nobil et al. (2024) explored an EPQ model that incorporates strict inspection procedures, rework, and scrap disposal under quality control constraints. Mishra et al. (2021) introduced a sustainable production-inventory model with imperfect quality under preservation technology and quality improvement investment. Li et al. (2016) analyzed a stochastic production inventory model in a two-state production system with inventory deterioration, rework process, and backordering. Meijer et al. (2021) investigated inventory and capacity optimization in large scale systems

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using extreme value theory to analyze overload risk and capacity planning. Sepehri et al. (2023) devised a green inventory model that takes into account the existence of imperfect items as well as scrutiny and quality improvement tasks, to optimize both ecological and environmental outcomes under diverse scarcity scenarios. Gharaei et al (2020) created a bi-objective EPQ model for multi-product systems with limitations, including defective items. Fallahi et al. (2023) established a sustainable production model that incorporates numerous deliveries and preventive maintenance for imperfect items, emphasizing the importance of scrap disposal costs in the total cost framework. Despite the fact that a lot of researchers have examined the scrap cost in the context of production inefficiencies or quality deterioration, they rarely incorporate recovery strategies that mitigate disposal costs or compute system overload consequences from logistical constraints.

To the best of our knowledge, no previous EPQ model has structurally considered Waste to Energy (WTE) recovery, vendor imposed managing capacity charges, and actual system bin cost allocation into overall system cost. To tackle these obstacles, this study proposes a sustainable Economic Production Quantity model that integrates a dual mechanism: cost-offsetting via Waste to Energy recovery, and soft capacity penalties related to vendor-imposed scrap handling constraints. The model compares two production scenarios: (i) Economic production quantity model with faulty items and fixed scrap disposal and (ii) Sustainable economic production quantity model incorporating Waste to Energy recovery and vendor-side handling penalties. This method not only reconsiders cost behaviour in the context of imperfect manufacturing, but it also offers a framework that can be modified to accommodate real vendor situations and sustainable economic tactics. Numerical example is provided to show the effectiveness of the suggested model. According to the optimum results obtained, the sustainable model lowers total costs, proving that cost efficiency and environmental sustainability can go hand-in-hand.

Model Formulation

This study considers an industrial environment where quality control methods such as scrutiny and rework classification plays an important role in the production process. Every cycle starts with a thorough inspection procedure in which a certain percentage of faulty products are found and removed from the manufacturing batch. At the end of the scrutiny period, some of these faulty items are considered reworkable and processed, while the others are classified as scrap and kept for disposal or recovery. Throughout each cycle, perfect items are employed to satisfy demand while reworkable items are reconditioned and then returned to inventory. Additionally, the model permits shortages, thus temporary items unavailability is tolerated and completely backordered for fulfilment in subsequent cycles. The total cost consists of setup costs, production and rework costs, scrap cost, holding cost for perfect and reworkable items, and shortage cost. The model aims to formulate overall costs according to such system performance and access effectiveness under two distinct frameworks: one that incorporates sustainability aspects like scrap recovery, vendor fines, and system costs, and another which includes fixed disposal cost and standard costs like rework and shortages.

Notations

R : Rate of rework per unit of time.
M : Production rate per unit of time.
S : Rate of screening per unit of time.
D : Rate of demand per unit of time.
γ : Fraction of reworkable products.
δ : Fraction of scrapped products.
μ : Fraction of faulty products.
U : Cost of production setup.
V : Cost of rework setup.
W : Cost of production per product.
X : Rework expense per reworkable product.
Y : Cost of disposal for each scrapped product.
R_e : Recovery value of scrap per unit of time.
ω : Cost of penalty for each scrap unit that exceeds vendor's capacity.
S_c : Fixed annual system cost for scrap management.
H : Cost of holding each perfect item per unit of time.
Z : Cost of holding each reworkable item per unit of time.
F : Cost of shortage each item per unit of time.
T_0 : Cycle Duration.
C_m : Production time per cycle.
C_s : Screening time per cycle.
C_r : Rework time per cycle.
C_d : Consumption time per cycle.
A_m : Maximum available inventory during the production period.
A_r : Maximum available inventory during the rework period.
A_s : Maximum available inventory during the screening period.
Q_0 : Amount of production per cycle.
K_0 : Amount of shortage per cycle.

Assumptions

- A fixed proportion of faulty products is generated in every phase.
- A certain number of deficient items is reworkable and processed within the same manufacturing cycle.
- Items classified as scrap incurs disposal expenses and have a specific recovery value.
- Scrap that exceeds vendor capacity leads to penalty.
- A fixed annual service cost covers scrap management operations.
- Shortages are permitted and completely backordered.

Model I: Economic Production Quantity Model With Faulty Items And Fixed Scrap Disposal

The production, screening, and rework periods are

$$C_m = \frac{Q_0}{M}\ ;\ \ C_s = \frac{Q_0}{S}\ ;\ C_r = \frac{\gamma Q_0}{R}$$

The remaining time period are determined as

$$C_1 = \frac{K_0}{M-(\gamma+\delta)S-D} \tag{1}$$

$$C_2 = C_m - C_1 \tag{2}$$

$$C_3 = C_s - C_m \tag{3}$$

$$C_4 = \frac{K_0}{D} \tag{4}$$

$$C_d = \frac{A_r}{D} \tag{5}$$

Also, the maximum level of stocks in each period is

$$A_m = (M-(\gamma+\delta)S-D)\frac{Q_0}{M} - K_0 \tag{6}$$

$$A_r = A_s + (R-D)\frac{\gamma Q_0}{R} \tag{7}$$

$$A_s = A_m - ((\gamma+\delta)S-D)(C_3) = \frac{((1-\gamma-\delta)S-D)Q_0}{S} - K_0 \tag{8}$$

The cycle duration is defined as

$$T_0 = C_1 + C_2 + C_3 + C_4 + C_r + C_d = \frac{(1-\delta)Q_0}{D} \tag{9}$$

Setup cost for Production and Rework

Setup cost per time unit is caused by preparing the tools, supplies, and resources needed for the production and rework processes.

$$SC_{PR} = \frac{D(U+V)}{(1-\delta)Q_0} \tag{10}$$

Production and Rework cost

Cost of production and rework per time unit is related with production of standard items and a portion of defective items being reworkable.

$$PRC = \frac{D(W+X\gamma)}{(1-\delta)} \tag{11}$$

Scrap cost

Scrap cost per unit time is incurred by disposing faulty items which is not reworkable.

$$DC = \frac{DY\delta}{(1-\delta)} \tag{12}$$

Cost of holding perfect items

Holding cost per unit time for perfect items is

$$HC_p = \frac{H}{2T_0}\left[(A_m)C_2 + (A_m + A_s)C_3 + (A_s + A_r)C_r + (A_r)C_d\right]$$

$$HC_P = \begin{bmatrix} \dfrac{H(M-(\gamma+\delta)S-D)D}{2(1-\delta)MS} + \\ \dfrac{H((1-\gamma-\delta)S-D)((1+\gamma-\delta)M-D)}{2(1-\delta)MS} \\ + \dfrac{H\gamma^2(R-D)}{2(1-\delta)R} \end{bmatrix} Q_0 - HK_0 + \left(\frac{H(M-(\gamma+\delta)S)}{2(1-\delta)(M-(\gamma+\delta)S-D)}\right)\frac{K_0^2}{Q_0} \tag{13}$$

Cost of holding reworkable items

In order to keep such items in the warehouse, the system has to pay holding costs.

Holding cost per unit time is expressed as

$$HC_R = \frac{Z\gamma Q_0(C_s + C_r)}{2T_0} = \frac{Z\gamma D(R+\gamma S)Q_0}{2(1-\delta)SR} \tag{14}$$

Shortage cost

The economic consequences of not meeting consumer demand during shortage situations is determined as

$$BC = \frac{F}{2T_0}(K_0(C_1 + C_4))$$

$$BC = \frac{F(M-(\gamma+\delta)S)K_0^2}{2(1-\delta)(M-(\gamma+\delta)S-D)Q_0} \tag{15}$$

Therefore, the total cost is determined as follows

$$TC_1 = SC_{PR} + PRC + DC + HC_P + HC_R + BC$$

$$TC_1 = \frac{D(U+V)}{(1-\delta)Q_0} + \beta Q_0 - HK_0 + \alpha\left(\frac{K_0^2}{Q_0}\right) + \frac{D(W+X\gamma)}{(1-\delta)} + \frac{DY\delta}{(1-\delta)} \tag{16}$$

whereas,

$$\alpha = \frac{(F+H)(M-(\gamma+\delta)S)}{2(1-\delta)(M-(\gamma+\delta)S-D)} \tag{17}$$

$$\beta = \frac{H(M-(\gamma+\delta)S-D)D}{2(1-\delta)MS} + \frac{H((1-\gamma-\delta)S-D)((1+\gamma-\delta)M-D)}{2(1-\delta)MS} + \frac{H\gamma^2(R-D)}{2(1-\delta)R} + \frac{Z\gamma D(R+\gamma S)}{2(1-\delta)SR} \tag{18}$$

Model II: Sustainable Economic Production Quantity Model Incorporating Waste To Energy Recovery And Vendor-Side Handling Penalties

This model advances the classical approach by incorporating scrap rescue via Waste to Energy initiatives and vendor's penalty based on operational capacity. Moreover, a system cost is considered for vendor service contracts. This approach seeks to strive a balance between financial and ecological goals through an improved cost model. In contrast to the traditional model, which treats scrap as a loss, Model II redesigns scrap as a resource that may be partially recoverable, enabling enterprises to use monetised recovery in order to mitigate their environmental impact. By modelling real-world vendor cooperation constraints, the soft capacity penalty assures that excessive scrap generation is financially discouraged. The inventory model gains practical realism from the system cost, which considers actual needs like bulk pickup agreement, trash bin location, and vendor adherence. By implementing these characteristics into the deterministic EPQ framework, this model enhances the system's resilience and promotes circular manufacturing processes.

The scrap recovery cost is determined as

$$DC_V = \frac{D\delta(Y - R_e + \omega)}{(1-\delta)} + S_c \tag{19}$$

Except scrap cost, all other cost expressions remain the same as model I.

Therefore, the manufacturing firm's total cost for the sustainable EPQ model is defined as

$$TC_2 = SC_{PR} + PRC + DC_V + HC_P + HC_R + BC$$

$$TC_2 = \frac{D(U+V)}{(1-\delta)Q_0} + \beta Q_0 - HK_0 + \alpha\left(\frac{K_0^2}{Q_0}\right) + \frac{D(W+X\gamma)}{(1-\delta)} + \frac{D\delta(Y-R_e+\omega)}{(1-\delta)} + S_c \tag{20}$$

Solution Methodology

The first order partial derivative of Equation (16) with respect to K_0 is

$$K_0 = \frac{HQ_0}{2\alpha} \tag{21}$$

The second order partial derivative of Equation (16) with respect to Q_0 is

$$Q_0 = \sqrt{\frac{\frac{D(U+V)}{(1-\delta)} + \alpha K_0^2}{\beta}} \tag{22}$$

By substituting K_0 in Equation (20), we obtain

$$Q_0 = \sqrt{\frac{D(U+V)}{(1-\delta)(\beta - \frac{H^2}{4\alpha})}} \tag{23}$$

Result

To demonstrate the applicability of the suggested model in real world scenarios, a comparison study is performed using traditional and sustainable model. Secondary data from Nobil's (2024) research were taken. This study aims to minimize scrap cost by integrating waste to energy recovery and vendor constraint penalties.

$D = 1000\, items / year$;
$U = 800\$ / production\, cycle$;
$W = 50\$ / produced\, item$; $\delta = 0.15$;
$F = 20\$ / shortage / year$;
$V = 500\$ / rework\, cycle$;
$X = 30\$ / reworked\, item$; $\gamma = 0.2$;
$R = 3500\, items / year$; $S = 2800\, items / year$;
$M = 3000\, items / year$; $R_e = 1.36\$ / unit$;
$\omega = 0.034\$ / unit$; $S_c = 98\$ / unit$;
$H = 10\$ / perfect\, item / year$;
$Y = 15\$ / scrap\, item$;
$Z = 5\$ / reworked\, item / year$.

By using the traditional model, optimum production quantity, cycle length and the total cost adopting scrap disposal are determined as follows.

From equations (21), (23), (16), we obtain

$$K_0 = 137.9;\ Q_0 = 964.1;\ TC_1 = \$71,702.$$

By using the sustainable model, optimum production quantity, cycle length and the total cost adopting scrap recovery are determined as follows.

From equations (21), (23), (20), we obtain

$$K_0 = 137.9;\ Q_0 = 964.1;\ TC_2 = \$71,566.$$

The efficiency of the suggested model is shown in Table 1.

The comparative analysis between Model I and Model II reveals that the overall annual cost dropped from $71,702 to $71,566. This cost reduction indicates that incorporating scrap recovery and operational constraints can achieve quantifiable economic gains which promote sustainability.

Discussion

The existing research has extensively focused on EPQ model in diverse situations including imperfect items, rework, and partial backordering (AlArjani et al., 2021; Taleizadeh et al., 2018). However, the sustainable management of waste items, especially the incorporation of efficient recovery techniques and vendor-based limits, remains widely unexplored. Although some of the recent researchers have dealt with green inventory approaches, they frequently depend on carbon emissions or environmental penalties without analyzing how scrap recovery and operational restrictions impact total costs (Chen et al., 2019; Sepehri et al., 2023). In particular, no previous study has structurally incorporated an integrated system with scrap cost balancing via waste to energy recovery and handling cost for exceeding vendor limits in EPQ formulation. So, this study bridges this gap by integrating scrap recovery and vendor-imposed constraints

Table 1: Displays the efficiency of the suggested model

Total cost of the production process	Model I	Model II
	$71,702	$71,566

within the economic production quantity model to optimize the total cost of an organization while balancing both sustainability and practical reality.

Conclusion

Modern industrial sectors face intense pressure to minimize waste, improve resource allocation, and promote environmentally sustainable goals. One of the ongoing problems is how to handle production scrap, which is frequently thrown away at a cost that affects operating budgets and the environment. This study fills this gap by suggesting an enhanced economic production quantity model that not only handles faulty and reworkable products, but also reframes scrap as a possible recoverable benefit. By embedding an integrated system – balancing scrap recovery and vendor-side managing penalties, this model provides a practical, economical and sustainability aligned structure. Additionally, an annual system cost is incorporated to represent the financial investment required to handle these environmental initiatives. Numerical data proves that the sustainable approach reduces cost over the conventional paradigm, demonstrating its practical significance and economic appeal. The industrial organization that employs scrap recovery has an overall cost of $71,566, whereas the production firms that does not utilize scrap recovery has an overall cost of $71,702. This model supports the principles of circular economy by promoting a change in the way scrap is seen from a burden to a resource that can be recovered. Furthermore, it draws attention to soft limits in waste disposal that are often ignored by enterprises. This model offers a framework for decision making that helps firms and policymakers strike a balance between social responsibilities and financial targets. To further enhance this approach, future studies may delve into multi product or multi stage frameworks, dynamic vendor capability, or varying scrap recovery rates.

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