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Economic production quantity model involving repair, waste disposal, electricity tariff, and emissions tax

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ABSTRACT

This research aims to develop a new model for a comprehensive Economic Production Quantity (EPQ) by considering repair processes, waste disposal, electricity tariffs, and emission taxes to optimize inventory management decisions in two shops. The first shop is responsible for providing new manufacturing and remanufacturing products required by the second shop, which focuses on inventorying finished products to meet demand. The main objective of the proposed Model is to minimize total cost. The Model is formulated as Integer Non-Linear Programming (INLP) to represent the complexity of production and inventory decisions. This study applies a Genetic Algorithm (GA) approach run using Microsoft Excel software with the Solver feature To optimize the solution of the proposed Model. Sensitivity analysis shows that while increases in electricity tariffs and emissions taxes significantly increase the total costs incurred by firms, these factors do not directly reduce total energy consumption or carbon emissions. Instead, increased costs generally result in smaller optimal production batch sizes, which does not necessarily translate into reduced energy use, as operational energy requirements remain constant. Our findings emphasize the delicate balance between cost components and energy use, highlighting that increased electricity costs and emissions do not directly lead to overall cost savings or improved energy efficiency.

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1. INTRODUCTION

In the modern sustainable industrial era, sustainable manufacturing and production are organizations' main focus [1], [2], [3], [4]. Industries should adopt environmentally friendly practices and improve operational efficiencies to encourage sustainable manufacturing, minimize environmental impacts, and lower production costs [5], [6]. One of the key challenges in manufacturing is managing the production process by taking into account various factors, including repair processes [5], waste disposal management [7], electricity tariffs [7], and emission taxes [8], [9]. Repair processes, waste management, electricity tariffs, and emission taxes are essential aspects that must be considered in designing sustainable production and inventory strategies [10], [11]. In addition, the economic aspect is also a significant concern, which demands the right decisions in production and inventory so that production costs are minimized [4], [12], [13], [14]. Therefore, the EPQ model is one of the appropriate decision models for determining production and inventory quantities by considering factors such as repair processes, waste management, electricity rates, and emission taxes [15], [16], [17]. The EPQ model is proven to help organizations optimize their production and inventory processes economically and minimize environmental impacts [18], [19].

Along with the complexity and challenges faced by industries in optimizing production processes and reducing environmental impacts, production and inventory decisions need to consider two shops [20],

[21]. Most production and inventory models only consider one shop point, which only partially reflects the operational reality of modern enterprises [22], [23], [24]. In a model with two shops, we can explore more accurate dynamics of the production, collection, repair, and waste processes, enabling a more comprehensive analysis of production activities' economic and environmental aspects [25]. Through this approach, decision-makers can gain deeper insights into how production, repair processes, and waste disposal decisions can affect the company's overall operational efficiency and environmental sustainability [26], [27]. Therefore, in exploring models with two shops, decision-makers can develop more holistic strategies to improve production efficiency while minimizing negative environmental impacts [28], [29].

In production and inventory models, it is important to consider aspects such as repair, waste disposal, electricity rates, and emission taxes to achieve cost efficiency and sustainability. Repair allows companies to extend product life and reduce the need for new production, which keeps costs down and supports sustainability by reducing waste. Waste disposal should also be considered, as the production process often generates residual waste that must be appropriately managed not to increase costs and still meet environmental regulations [30]. On the other hand, electricity tariffs are a significant cost component and tend to fluctuate, affecting operational expenses. By optimizing electricity usage, companies can better control production costs. Finally, emission taxes on carbon emissions encourage companies to consider more environmentally friendly production practices. Companies can balance cost efficiency, regulatory compliance, and environmental responsibility by incorporating these factors in production and inventory planning.

Previous research on EPQ has been conducted with various considerations to reduce carbon emissions and manage carbon trading [31], [32]. These models usually include taxes on carbon emissions, penalty fees for exceeding emission limits, and revenue from carbon trading [33], [34]. Some studies have also developed fuzzy inventory models for sustainable goods, where demand is affected by time and inventory levels [4], [35], [36], [37]. These models consider carbon emissions and trade policies and show that new methods can increase profits for retailers [34], [35], [38]. In addition, considering environmental factors in EPQ models indicates a relevant direction for future research in sustainable production and inventory management [39], [40], [41]. Another study developed an EPQ model that considers aspects of scrap, rework, and multiple deliveries [42]. Another study developed an inventory model considering new products, repairs, and controllable emissions [43]. These studies show that models considering sustainability and actual operational conditions are increasingly crucial in managing inventory efficiently [9], [44], [45]. However, this study differentiates itself by integrating the impact of electricity tariffs and emission taxes into the EPQ model, a factor not addressed in the work of El Saadany and Jaber [46]. Based on these previous studies, developing an EPQ model involving repairs, waste disposal, electricity tariffs, and emission taxes is a relevant and significant step in production and inventory management [47].

This study's contribution goes beyond previous research by incorporating a comprehensive approach that includes electricity cost and emission tax components. This integration is significant as it directly affects production and inventory management decision-making, providing a more nuanced understanding of how these cost components impact overall production strategies. Additionally, our solution approach utilizes GA techniques, which offer several advantages over traditional heuristic methods. Unlike heuristic procedures, which may provide reasonable solutions but are often less precise, GA provides a more robust and optimal approach to solving INLP problems. GA's ability to explore a wider solution space and its inherent optimization capabilities make it a valuable tool for handling complex production and inventory management scenarios more effectively.

The main contributions of this research are described as follows:

1) This research develops an EPQ model that considers two-shop operations. The Model simultaneously includes aspects of repairs, waste disposal, electricity rates, and emission taxes.
2) Investigation of the interaction of variables such as repairs, waste disposal, electricity rates, and emission taxes interacting with each other and affecting the EPQ production strategy in the context of two-shop operations.
3) This paper provides insights on Sustainable Production Strategy Optimization. It will discuss optimizing a sustainable production strategy in a two-store environment by balancing operational efficiency and environmental sustainability.
4) Serves as a practical guide for managers and decision-makers in designing sustainable production strategies in two-store operations.

The structure of this paper is as follows: Section 2 reviews related works in sustainable production models. Section 3 discusses the proposed methodology, detailing the EPQ model and its components. Section 4 presents the results and insights, followed by a comprehensive discussion. Section 5 concludes the paper with critical findings and suggestions for future research.

2. RELATED WORK

The Economic Order Quantity (EOQ) Model was initially formulated by Harris in 1913. Subsequently, in 1918, Taft expanded and refined the Model, renaming

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Table 1. Literature review on EPQ

Author	Year	Method	Type	Production	Repair	Waste disposal	Electricity tariff	Emission tax
Liao [48]	2015	EPQ	One shop	✓	✓			
Yassine [15]	2020	EPQ	One Shop	✓				✓
Mohubedu [49]	2017	EPQ	One Shop	✓			✓	
Li, *et al*. [44]	2020	EPQ	One Shop	✓		✓		✓
Zhang and Liu [50]	2018	EPQ	One Shop	✓				✓
Karim and Nakade [18]	2022	EPQ	One Shop	✓	✓			✓
El Saadany and Jaber [46]	2008	EPQ	Two Shop	✓	✓	✓		
This research	2024	EPQ	Two Shop	✓	✓	✓	✓	✓

it the EPQ model [51]. The EPQ model seeks to minimize total production costs by optimizing inventory costs [52]. According to Ballou [53], the EPQ model relies on three basic parameters: demand, production setup cost, and storage cost per unit. However, Kostić [54] argues that these parameters are insufficient to address real-world challenges, as the traditional EPQ model does not consider realistic company conditions such as imperfect quality and defective goods, imperfect repair processes, and lost sales. Moreover, additional challenges, such as electricity tariffs for production waste disposal and emission taxes, should also be considered in a more comprehensive EPQ model.

According to the analysis given in Table 1 about previous research, the EPQ model has been widely used to overcome EPQ challenges. The earlier researchers mainly used EPQ models that considered important values such as production, repair, etc. In addition, some studies also included consideration for defective items that require rework. This research proposes an EPQ model that specifically adds determining variables to optimize total cost. Notably, the parameters used in this study are aligned with the study by El Saadany and Jaber [46], which mostly discusses EPQ influenced by production, repair, and waste disposal values. Therefore, our study aims to contribute to the literature by adding additional variables that may affect the EPQ value, such as the variables of Electricity Tariff and Emission Tax.

3. RESEARCH METHODS

3.1 System characteristics

In this proposed Model, this research considers a system in which two shops are involved in product production and usage cycle. The first shop is responsible for providing homogeneous products required by the second shop. The product demand from the second shop is assumed to remain constant at a rate per unit of time. The first shop has two main activities: producing new products and repairing products shipped back from the second shop. It is important to note that repaired products are equivalent to new products in this Model. Repaired products are returned to the second shop for reuse, while products that cannot be repaired are immediately disposed of as waste. This repair and waste disposal process occurs according to the set repair and waste disposal rates.

At the end of each time interval [0, T], the products collected in the second shop are returned to the first shop for temporary storage and repaired as needed. Suppose products have been restored and are ready for use. In that case, the production process fulfils the remaining demand during the following time interval. This Model assumes that all processes occur instantaneously, including manufacturing, repair, and product usage. Fig. 1 illustrates the inventory stock that appears in this system. The functions of Shop 1 and Shop 2 support each other in the production and product recovery cycle. Shop 1 is responsible for producing new products and repairing products returned from Shop 2, while Shop 2 plays a role in storing and fulfilling stable product demand. The assumption of infinite production and recovery capacity is used in this Model to simplify the analysis, allowing a focus on optimizing order quantities without considering the technical limitations of machines or the limited capacity of warehouses. This assumption is relevant in situations with high and stable demand, such as a company managing an inventory of repairable electronic products. As such, companies can focus on managing demand and recovery cycles effectively, minimizing model complexity arising from capacity limitations. The role of Shop 1 and Shop 2 becomes vital in maintaining product flow, where Shop 1 supports demand fulfilment through production and repair. At the same time, Shop 2 ensures the availability of stock that is ready for distribution.

In this Model, Shop 1 is responsible for producing new products and repairing products collected from Shop 2. During the first cycle, no products are repaired since no used products are available yet. However, in

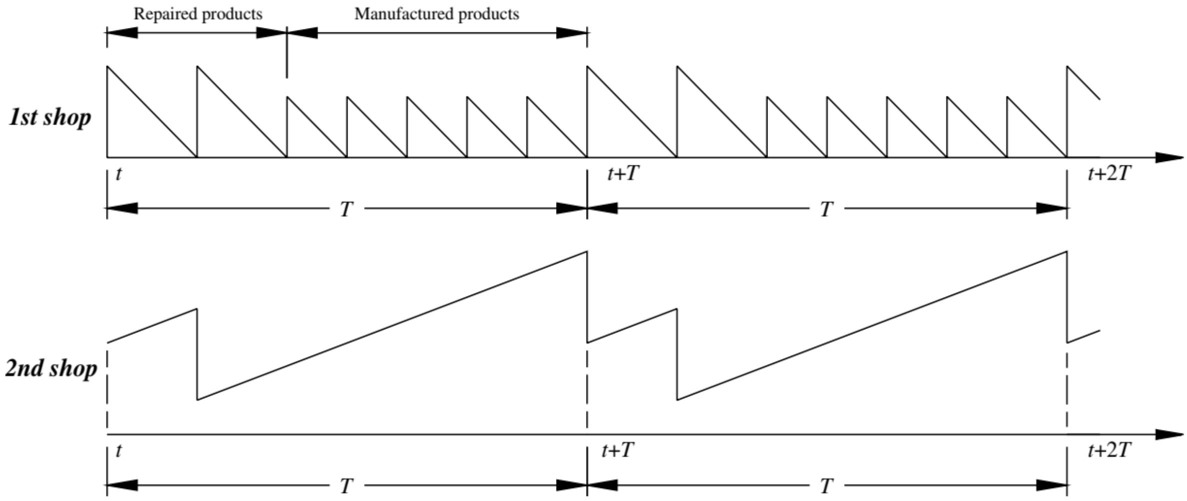

Fig. 1. Inventory system for two shops

the second cycle, used products accumulated during the production interval at Shop 2 are sent to Shop 1 for repair once the final production batch in Shop 1 is completed. Shop 1 focuses solely on production in the first cycle, as no used products are available for repair at the start. Starting from the second cycle, repair processes begin as Shop 1 receives used products collected during the first cycle. It is important to note that repaired products are not available at the start of any cycle. Instead, used products must be gathered in Shop 2 during production intervals before being sent for repair in Shop 1. Additionally, Fig. 1 illustrates the inventory system in Shop 2, which should be referenced to understand better the flow and timing of product repair and inventory management between the two shops.

3.2 Assumptions and notations

The assumptions of the proposed Model are described as follows:

1) Manufacturing and recovery rates are unlimited [46], which assumes that production and repair can be carried out indefinitely. It is similar to semi-conductor manufacturing, where highly automated processes enable continuous production and recovery without significant downtime, ensuring that demand can always be matched with product availability.
2) Repaired goods are as good as new [46], implying that the repair process's outcome is of equivalent quality to a new product. It enables the reuse of damaged goods.
3) Demand is known, constant, and independent, which implies that demand does not change over time and is not influenced by external factors [46].
4) Zero lead time means no delay between demand and product delivery, ensuring that products are available as soon as requested [46].
5) The single product case assumes that only one product type is produced and repaired, simplifying the analysis to focus on one product entity [46].
6) No shortages are allowed, which implies that any demand can be fully met without any shortages in product supply [46].
7) Unlimited storage capacity is available, which means the number of products that can be stored is limitless, allowing for sizable inventories [46].
8) Infinite planning horizon assumes that planning can be done for a very long period without any time constraints, allowing for long-term production strategies [46].

Meanwhile, the notations used are as follows:

T: Length of a manufacturing and repairing time interval (units of time), where $T > 0$

T_1: Length of the first manufacturing time interval (units of time),where $T_1 < T$ and $T_1 > 0$

x : batch size for interval T, which includes n newly manufactured and m repaired batches

d : Demand Rate (unit/month)

h: Storage cost per unit for shop 1 ($/month)

u : Storage cost per unit for shop 2 ($/month)

r : Repair cost per batch ($/month)

s : Production cost per batch ($/month)

α : Waste Disposal Rate $0<\alpha<1$

β : Scrap repair rate $0<\beta<1$

m: Number of repaired batches in an interval of length T

n : Number of newly manufactured batches in an interval of length T

θ : Emissions generated at production in Kg

λ : Electricity tariff ($/kWh)

μ : Emission Tax ($/Kg)

ω : Electricity use in production in kWh

ρ : Electricity use in shop 1 in kWh

ψ : Electricity usage in shop2 in kWh

Υ: Electricity usage in repair in kWh

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K : Emission Usage Repair in Kg
ζ : Emissions generated in shop 1 in Kg
ς : Emissions generated in shop 2 in Kg
TC : Total Cost ($)
SC : Total Setup Cost for shop1 and shop2
$S1$: Storage Cost for Shop 1 ($)
$S2$: Storage Cost for Shop 2 ($)

3.3 Proposed Model

Based on the assumptions and notations previously described, we developed a mathematical model based on the models proposed by Richter [20], Richter [22], and El Saadany and Jaber [46]. The proposed EPQ model considers two main cost components: setup and storage costs at the first and second shops. The setup cost includes the costs associated with production preparation and repair. In contrast, the storage cost consists of the costs arising from the storage of products during a specific time interval at shops 1 and 2.

In the setup cost (SC), this research develops a model by considering electricity tariffs and emission taxes. Several critical parameters are used in this setup cost, including the level of demand, production batches, electricity consumption, and emissions generated by each setup. The Model integrates these factors to provide a more accurate total setup cost. In Equation (1), the total SC for new production and repair is calculated by incorporating additional factors such as electricity usage and emissions generated in the repair and production processes. Thus, this Model considers traditional costs and emphasizes the importance of energy efficiency and emission reduction in production and repair processes.

$$SC = \frac{d}{x} \times \left(m \times \left(r + (\Upsilon \times \lambda) + (\kappa \times \mu)\right) + n \times \left(s + (\omega \times \lambda) + (\theta \times \mu)\right)\right) \quad (1)$$

Furthermore, this section elaborates on the holding cost of Shop 1 (S1). Essential parameters in calculating the holding cost include holding cost, production batch size, scrap disposal rate, and scrap repair rate. In addition, electricity tariffs and emission taxes are also incorporated into the Model to reflect operating costs more accurately and in line with actual environmental conditions. Combining these factors provides a comprehensive picture of the storage cost that Shop 1 has to bear during a specific period. The storage cost model for Shop 1 is formulated in detail in Equation (2), which will show how each parameter contributes to the total storage cost.

$$S1 = \frac{x}{2} \times \left((h + (\rho \times \lambda) + (\zeta \times \mu)) \times \left(\frac{\alpha^2}{n} + \frac{\beta^2}{m}\right)\right) \quad (2)$$

Meanwhile, as discussed earlier regarding the storage cost of the first shop, electricity tariffs and emission taxes are also significant components in the calculation of the storage cost of the second shop. The Model for Shop 2 (S2) saving cost is formulated in detail in Equation (3). This study emphasizes the importance of incorporating external factors such as electricity tariffs and emission taxes in the analysis of shelf cost, which is an integral part of optimizing inventory management strategies by considering comprehensive aspects of sustainability and operational efficiency.

$$S2 = \left(u + (\psi \times \lambda) + (\varsigma \times \mu)\right) \times \beta - \frac{u \times \beta^2 \times (m-1)}{m}) \quad (3)$$

From the previously described equations for SC, S1, and S2, it can be concluded that both setup cost and storage cost components in the first and second shops play an essential role in determining the overall Total Cost. This Total Cost can be described mathematically in Equation (4). This research emphasizes the integration of various cost aspects involved in the production, repair, and inventory management processes, as well as the importance of considering the interaction between setup cost and storage cost in both shops to achieve optimal efficiency in operational decision-making.

$$TC = \frac{d}{x} \times \left(m \times \left(r + (\Upsilon \times \lambda) + (\kappa \times \mu)\right) + n \times \left(s + (\omega \times \lambda) + (\theta \times \mu)\right)\right) + \frac{x}{2} \times \left(\left(h + (\rho \times \lambda) + (\zeta \times \mu)\right) \times \left(\frac{\alpha^2}{n} + \frac{\beta^2}{m}\right) + \left(u + (\psi \times \lambda) + (\varsigma \times \mu)\right) \times b - \frac{u \times b^2 \times (m-1)}{m}\right) \quad (4)$$

Therefore, based on Equation (4), a total cost optimization model was developed using an INLP approach. The objective function of the Model is described in Equation (5), which is designed to minimize the total cost, including setup costs, storage costs at S1 and S2, and factors such as electricity rates and emission taxes. In addition, relevant operational and environmental constraints are formulated in Equations (6)-(9).

Min $TC = SC + S1 + S2$ (5)
Constraints:
$0 \leq m \leq d$ (6)
$0 \leq n \leq d$ (7)
$0 \leq x \leq d$ (8)
m, n, x $integer$ (9)

Equation (5) shows the objective function of the total cost in the Model discussed in this study, which must be minimized. This optimization process must adhere to several constraints, each essential in determining the optimal solution. First, the number of batch cycles of repaired products (m) must be greater than 0 and must not exceed the demand level (d), as shown in Equation (6). Furthermore, the number of batch cycles for the new product produced (n) should also be greater than 0. It should not exceed the demand level (d), as described in Equation (7). In addition, the batch size (x) should be greater than 0 and should not exceed the level of demand (d), as stated in Equation

(8). The determination of these decision variables, namely the number of repaired batch cycles (m), the number of new product batch cycles produced (n), and the batch size (x), must be in the form of integers, as per the formulation in Equation (9). By optimizing these variables simultaneously, it is expected to achieve a significant reduction in total cost.

The proposed Model calculates the total cost of the production and repair system by considering factors such as repair costs, production, storage, electricity usage, and emissions. The SC formula (1) calculates the total cost for one period based on demand by separating the cost between the new batch produced and the repaired batch. This cost includes repairs, electricity usage during the repair process, emission taxes, and the cost of producing a new batch with similar factors.

Then, the storage cost formula (2) in Shop 1 takes into account the average storage cost by including the storage cost per unit, electricity usage, as well as the emission tax, where the influence of the production waste and scrap rate of the new batch and the repaired batch is also included to account for the impact of production quality. For (3), the storage cost formula in Shop 2 focuses on the repaired storage cost by considering the scrap rate, electricity usage, and emission tax. As the number of repaired batches increases, the cost decreases as more batches allow the spread of waste and scrap handling costs, reflecting the efficiency of scale in the repair process.

Overall, the Model considers sustainability aspects such as energy usage and emissions, in addition to traditional cost factors in the production and storage processes, which align with the objectives of a sustainable production strategy.

The parameters mentioned above are customized parameters based on the product. Parameter κ refers to the cost factor related to emissions on the setup cost. The parameter ζ indicates the emissions associated with the product in Shop 1, while ς represents the emissions occurring in Shop 2. ς represents the emissions that occur in Shop 2.

These problems are categorized as INLP, which are often difficult to solve heuristically because such methods can only sometimes find the optimal solution for the decision variables [55]. Therefore, this study proposes using a novel approach by applying a GA, which has never been investigated before in the context of an EPQ model involving repair processes, waste disposal, electricity tariffs, and emission taxes. This approach aims to efficiently optimize solutions and generate more informed decisions in managing production and inventory under complex and dynamic conditions.

3.4 Experimental data and procedures

This section will detail the data used in the experiments for the proposed EPQ model. The relevant numerical data for this study can be found in Table 2. The table includes critical parameters such as setup costs, storage costs, electricity tariffs, emission taxes, and demand levels for manufactured and repaired products.

The numerical values in this study were taken from El Saadany and Jaber [46], which provided the basis for the relevant parameters for modelling. The electricity and emission tariffs are based on the estimated tariff prevailing in the United States at the time of this study. For the time interval ***[0, T]***, t is an actual number where $\boldsymbol{T = 1}$, so the analysis is performed from $t = 0$ to $t = 1$, which covers one entire production cycle. This approach ensures the Model evaluates costs and emissions over the whole production cycle, not per batch or product.

Meanwhile, this study also involves sensitivity analysis of two key variables: electricity tariff and emission tax. The study considered five data variations for each variable to evaluate the impact of changes in electricity tariffs and emission taxes on total cost and decision variables such as batch size, number of production batch cycles, and number of repair batch cycles. The variation for electricity tariff ranges from \$0.044 per kWh to \$0.122 per kWh. In contrast, for emission tax, the variation ranges from \$0.012 per kg to \$0.115 per kg. Once the data values were determined, numerical experiments were conducted by integrating the data into the previously formulated mathematical Model. These experiments aim to observe how changes in the values of these critical variables can affect the total inventory cost generated by the Model and the selected decision variables. This sensitivity analysis will provide a deep insight into the effect of variability in electricity tariffs and emission taxes, which are crucial in making inventory decisions.

Table 2. The parameters and their encoding

Parameter	Unit	Value
d	unit/month	1000
h	\$/month	0.5
u	\$/month	0.8
r	\$/month	50
s	\$/month	40
λ	\$/kWh	0.1222
μ	\$/Kg	0.02
ω	kWh	0.54
ρ	kWh	0.31
ψ	kWh	0.31
Υ	kWh	0.43
κ	Kg	0.01
ζ	Kg	0.006
ς	Kg	0.006
θ	Kg	0.02
α	-	0.3
β	-	0.7

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The numerical experiment procedure was performed by optimizing the Model using a GA implemented with the help of Microsoft Excel through the Solver feature. The Solver settings involved several relevant GA parameters (Table 3). The genetic algorithm was used to find the optimal solution by minimizing the total cost value according to the predefined objective function. In addition, during the solution process, the estimated values of carbon emission and electrical energy consumption of all activities performed were also calculated to consider the sustainability aspect. The application of GA in this experiment was designed to achieve optimal values of decision variables, including the number of batch cycles repaired, the number of batch cycles of new products produced, and the batch size for production and repair. The use of GA in this study was chosen due to its ability to handle optimization problems with high complexity and many variables, such as in the EPQ model, which involves repairs, waste disposal, electricity rates, and emission taxes. Compared to analytical methods often stuck in local solutions, GA offers a more effective global search and can handle non-linear and discrete objective functions. In addition, GAs are easier to implement and can diversify solutions, making them a more robust option than other heuristic methods.

Table 3. Parameter genetic algorithm

Data	Value
Convergence	0.0001
Mutation Rate	0.075
Population Size	100

4. RESULTS AND DISCUSSION

4.1. Optimization results

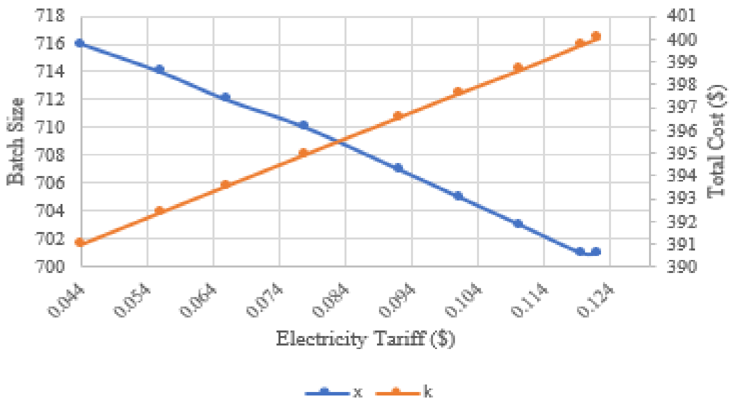
The optimization results using genetic algorithms reveal that the minimum total cost is $400,037, with emissions of 0.51223 kg and electricity usage of 38.1382 kWh. This optimal solution represents the best arrangement of decision variables as per the formulated Model. Specifically, the interval batch size (x) of 716 units produced in each production cycle indicates an efficient balance between production volume and operational costs. Producing in smaller or larger batch sizes could increase costs due to higher setup frequencies or increased holding costs. Furthermore, the optimal solution includes two new product batch cycles (m) and one repair product batch cycle (n). This configuration suggests that the company should prioritize new production while maintaining a repair cycle to efficiently manage returns or defective items.

The decision to produce two batches of new products and 1 batch of repaired products is likely a strategic approach to balance production flow with repair needs, minimizing disruptions while controlling costs. The estimated carbon emissions of 0.51223 kg and electricity usage of 38.1382 kWh provide crucial insights into the environmental impact of this operational strategy. These figures highlight the trade-off between economic and ecological objectives. The company optimizes its financial performance and aligns with sustainability goals by minimizing total costs while maintaining low emissions and energy consumption. The insights from this study underscore the importance of integrating environmental considerations into the company's decision-making process, particularly in the context of regulatory pressures and the growing emphasis on corporate social responsibility.

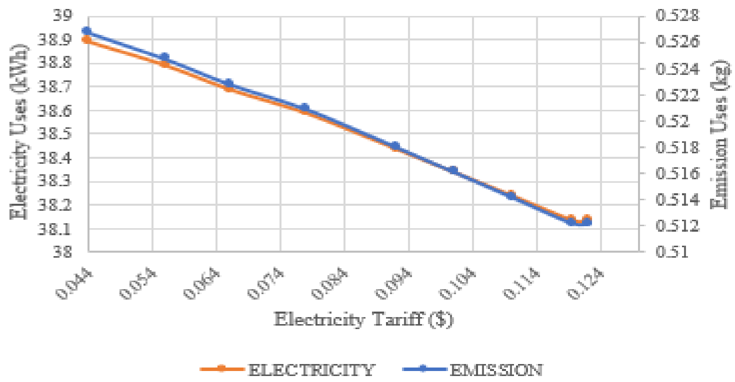
4.2. Sensitivity analysis

The sensitivity analysis of electricity tariff changes is presented in Fig 2. This figure illustrates the impact of electricity tariff variations on total cost, electrical energy consumption, emissions, and production batch size. The analysis shows that an increase in electricity tariff increases the total cost (TC) generated. Simultaneously, the production batch size (x) tends to decrease. This reduction in batch size directly responds to the increased cost per unit of electricity, which forces the system to minimize energy-intensive operations, thus reducing energy consumption and emissions. However, the assertion that the number of production cycles (m and n) remains unchanged under varying electricity tariffs reflects a vital characteristic of the production system under study. The Model assumes that the demand must be met without incurring shortages, so the reduction in batch size due to higher electricity tariffs does not increase the number of production cycles. It is because the production system optimizes batch sizes while ensuring the number of cycles remains stable to minimize disruptions and operational inefficiencies. Hence, while energy consumption and emissions decrease due to smaller batch sizes, the overall production structure (i.e., the number of production and repair cycles) remains stable. This finding underscores the importance of the production system's ability to absorb fluctuations in electricity costs without altering its production and repair schedules, thereby maintaining operational continuity while adjusting batch sizes to optimize costs. Therefore, the analysis suggests that the system is robust in maintaining a consistent production flow despite external cost pressures, with the trade-off being reduced energy usage and emissions through smaller batch sizes.

An increase in electricity tariffs often increases the TC generated in a company's operations because electricity tariffs are one of the significant operating cost components. When electricity tariffs rise, the cost of running production machinery and storage systems that use electricity also increases, resulting in higher setup and storage costs (especially energy). Therefore,



(a)



(b)

Fig. 2. Sensitivity analysis of electricity tariff changes to (a) batch size (x) and total cost (tc) and (b) emission and electricity

total costs increase due to the rise in overall operating costs. On the other hand, the production batch size (x) tends to decrease as the increase in electricity tariffs encourages the company to reduce the optimal production batch size. It can be explained by the company's attempt to avoid additional costs from more extensive production operations. By reducing the batch size, the company can reduce the frequency and volume of production that requires more electrical energy, thereby reducing the impact of the electricity tariff increase on operating costs. The rise in electricity tariffs significantly reduces energy consumption and emissions generated by operations. It can be seen as a positive effect of higher electricity tariffs, encouraging companies to use energy more efficiently [56], [57].

The sensitivity analysis of emission tax changes is presented in Fig 3. The figure illustrates the impact of emission tax variations on total cost, electrical energy consumption, total carbon emissions, and the optimal number of production batches. As in the sensitivity analysis of electricity tariffs, the results show that an increase in emission tax increases total cost. This occurs because the emission tax directly adds to the operational costs associated with the carbon footprint of the production process. As companies aim to minimize these additional costs, they reduce the production batch size (x) to lower their emissions, decreasing carbon taxes. Moreover, the decrease in production batch size (x) also reduces energy consumption, as smaller batches require less energy for production. This reduction in energy use naturally leads to lower carbon emissions, aligning to minimize the impact of the emission tax. An interesting observation is that changes in emission tax do not affect decision variables such as the number of new product batch cycles produced (m) and the number of repair batch cycles (n). These variables are more closely related to operational and market demands than the cost factors driven by emission tax. The emission tax primarily influences the cost structure associated with production and energy usage rather than the overall production strategy or cycle frequency. An increase in emission tax results in an increase in total costs, adding additional costs to operational activities that produce carbon emissions. The emissions tax directly increases production and repair costs, as the company has to pay more for each unit of emissions produced during the operational process. Thus, the total cost increases due to the additional burden of taxation on carbon emissions.

On the other hand, production batch size (x) tends to decrease when emission taxes increase. It happens

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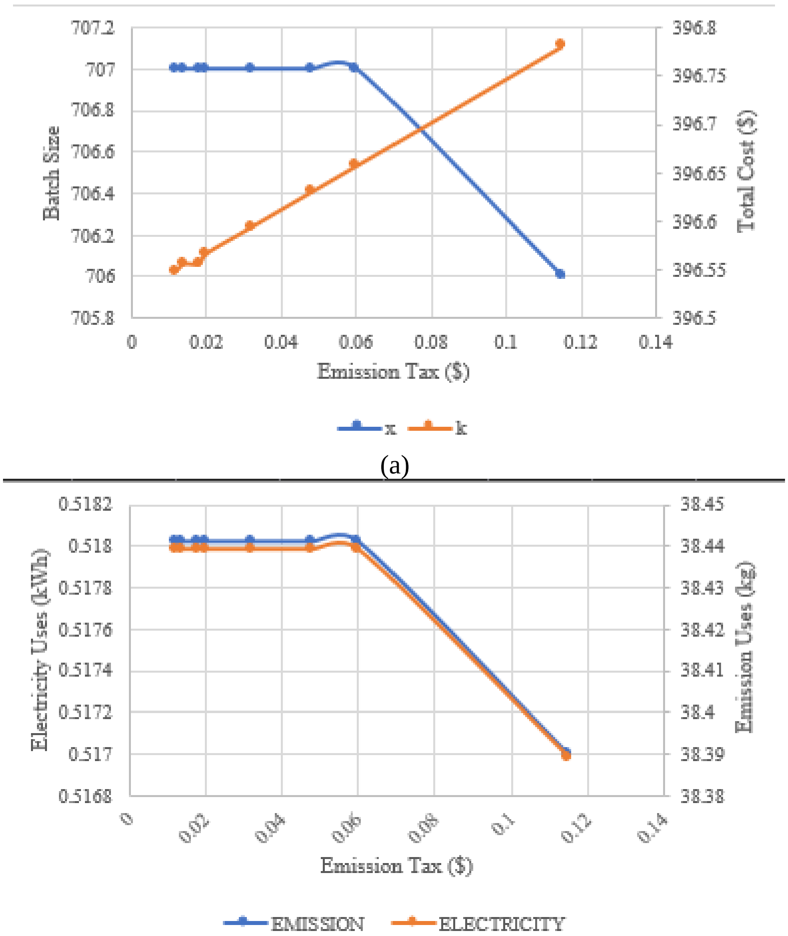

(a)

(b)

Fig. 3. Sensitivity analysis of emission tax changes to (a) tc and x; (b) emission and electricity

because companies try to reduce the amount of production that requires processes that produce high carbon emissions. By lowering the production batch size, the company can reduce carbon emissions generated and mitigate the impact of the emission tax increase on overall operating costs. In addition, an increase in emission tax also has a positive effect by reducing the use of electrical energy and carbon emissions generated from operational processes [57], [58].

When the emissions generated during the setup and inventory processes are low, the setup cost is higher than the inventory cost. It is because setup costs include the preparation and adjustment required for each batch of production, while inventory costs are related to the storage of products. In other words, if the emissions from the setup process and inventory are insignificant, the company will face higher setup costs.

If setup costs can be reduced, the production batch size (x) tends to shrink. Reduced setup costs reduce the burden of fixed costs that must be paid each time, making companies more likely to produce in smaller batches. It provides more flexibility in meeting demand while reducing total setup costs.

Reducing batch size in response to lower setup costs can affect total emissions and production costs. While smaller batch sizes may reduce emissions per batch, the total and overall costs will depend on the Model's interaction between setup and inventory costs.

While electricity does not directly generate carbon emissions during its use, the methods of electricity production can. Therefore, while higher electricity tariffs do not directly reduce carbon emissions from electricity use, they can influence energy production and consumption decisions. It may encourage companies to adopt more efficient technologies or switch to alternative energy sources, ultimately affecting the total carbon emissions associated with the production process. Not all countries experience emissions from electricity use, as some developed countries have switched to green energy for electricity production. However, some countries still produce emissions from their electricity production process. In addition, carbon emissions can also come from other activities that are not directly related to electricity consumption. Table 4 explains that two parameters observed, λ and μ, affect emissions, electricity use, and TC. Generally, the

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Table 4. Sensitivity analysis

Parameters	Change	Emission (Kg)	Electricity usage (kWh)	TC	x
λ	0.0440	0.526712	38.89141	390.993	716
	0.0560	0.524700	38.79093	392.394	714
	0.0660	0.522800	38.6904	393.557	712
	0.0780	0.520900	38.5901	394.949	710
	0.0920	0.518024	38.4393	396.567	707
	0.1012	0.516093	38.3389	397.627	705
	0.1104	0.514160	38.2386	398.644	703
	0.1196	0.512235	38.1382	399.739	701
	0.1222	0.512230	38.1382	400.037	701
μ	0.0120	0.518020	38.4393	396.549	707
	0.0140	0.518020	38.4393	396.556	707
	0.0180	0.518020	38.4393	396.556	707
	0.0200	0.518020	38.4393	396.567	707
	0.0320	0.518020	38.4393	396.594	707
	0.0480	0.518020	38.4393	396.630	707
	0.0600	0.518020	38.4393	396.657	707
	0.1150	0.517000	38.3891	396.781	706

higher the value of λ, the emission (Kg) decreases gradually, while the electricity usage (kWh) is relatively stable.

On the other hand, the TC value increases slightly as λ increases, although the change is not very significant. For the μ parameter, changes in the μ value did not show significant changes in emissions, electricity use, or total costs. The emissions and electricity use values remain constant, and TC increases slightly, but these fluctuations are smaller than the effect of parameter λ. It indicates that parameter λ has a more significant influence on the table's measured variables than μ.

Compared with Pervin *et al.* [59] and *Roy et a*l. [60], our research shows more comprehensive results in optimizing the EPQ model by considering operational costs, emissions, and electricity usage. Our numerical results, which utilized a genetic algorithm, resulted in a minimum cost of $400,037 with emissions of 0.51223 kg and electricity usage of 38.1382 kWh. This optimal production configuration includes 716 units per production cycle, which shows an efficient balance between production volume and operating costs. Compared to Pervin *et al.* [59], which focuses on reducing storage costs with a trade credit policy without considering environmental factors, our research integrates the impact of emissions and energy consumption, which makes it more relevant to current sustainability demands. While Roy *et al*. [60] focus on managing product damage with inspection policies, our Model offers a broader solution by optimizing costs and environmental impacts in one integrated system. Thus, our results are more efficient in managing costs and contribute to corporate sustainability goals, which are increasingly crucial amid increasingly stringent regulations on emissions and corporate social responsibility.

4.3. Research implication

This research provides several critical insights companies should consider when planning and managing their production and inventory processes.

1. Optimization Tool: The research introduces a valuable tool designed to help manufacturing companies optimize their production and inventory management by incorporating environmental factors. Companies can use the EPQ model developed in the study to plan their production schedules and manage their inventory in a way that not only meets operational needs but also considers environmental sustainability. This tool is handy for companies balancing efficiency with environmental responsibility.
2. Adaptation to Fluctuations: The EPQ model allows companies to dynamically adjust their operational strategies based on changes in vital external factors such as electricity rates, emission taxes, and waste management costs. For instance, if electricity prices rise, the Model can help companies recalibrate their production processes to minimize costs. Similarly, if new taxes on emissions are introduced, the Model can guide companies in adjusting their operations to maintain profitability while complying with the latest regulations. This adaptability leads to cost savings and promotes sustainable practices.
3. Regulatory Compliance: The Model aids companies in efficiently complying with environmental regulations by clearly quantifying how these regulations impact their financial performance. For example, if a company is subject to stringent emission regulations, the Model can quantify the financial penalties of non-compliance versus the costs of implementing greener technologies. It helps companies make informed decisions about aligning their operations with environmental laws, reducing

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the risk of legal penalties, and improving their environmental footprint.

4. Decision-Making Framework: The EPQ model offers a comprehensive framework for informed decision-making in complex, two-shop operations. It simultaneously accounts for factors like repairs and waste disposal.
5. Operational Efficiency: The Model improves efficiency by optimizing production schedules and resource allocation. For example, by considering real-time data on energy consumption and production rates, the Model can suggest the most efficient production schedule that minimizes waste and maximizes output. It reduces operational costs and enhances the company's overall productivity.
6. Environmental Footprint Reduction: The Model incorporates emission taxes and waste disposal into production planning, helping companies minimize their environmental impact while supporting corporate sustainability goals.
7. Reputation Enhancement: Effective environmental management through the Model enhances the company's reputation among stakeholders and customers.
8. Dynamic Adjustment Capability: The Model's ability to integrate real-time data on operational costs allows companies to dynamically adjust their production processes, resulting in more efficient resource use and reduced waste.

5. CONCLUSION

This research has successfully developed a comprehensive EPQ model for two shops while considering several essential operational management factors. The Model includes aspects of repairs, waste disposal, electricity rates, and emission taxes in optimizing inventory management decisions. The results of the sensitivity analysis show that an increase in electricity tariff and emission tax significantly increases the total cost to be borne by the company. It indicates that environmental policies such as electricity tariffs and emission taxes directly impact the company's operating costs. On the other hand, this study also reveals that firms tend to reduce production batch size (x) in response to these cost increases, suggesting adaptability in operational strategies to minimize the economic impact of environmental policies. In addition to the financial effects, the increase in electricity tariffs and emission taxes also yielded positive results by reducing electrical energy use and carbon emissions generated in the operational process. It suggests that effectively implemented environmental policies can drive companies towards more sustainable operational practices. Although this study successfully developed a comprehensive EPQ model for two shops by considering various important factors such as repairs, waste disposal, electricity tariffs, and emission taxes, some limitations must be acknowledged. Firstly, this Model may not have holistically covered all factors affecting inventory management decisions. For example, this Model has not fully considered external factors such as market fluctuations or changes in production technology.

For future research, it is strongly recommended that the scope of analysis be broadened to encompass a wider array of relevant environmental and economic considerations. It could include examining the impact of government subsidies or incentives for green technologies, such as renewable energy adoption, energy-efficient machinery, or carbon capture initiatives, which may significantly influence production and operational costs. Furthermore, the integration of renewable energy sources directly within the production process, such as solar or wind power, should be considered to understand potential cost savings and environmental benefits more holistically. Another promising avenue would be to test the Model's applicability across various industrial sectors, particularly those that operate under diverse environmental and regulatory frameworks. Studying sectors with stringent emissions controls and those with looser environmental standards would help reveal how regulatory variances affect inventory management strategies and overall cost structures. In addition, integrating stochastic components, such as fluctuations in market demand, volatility in raw material prices, or supply chain disruptions, could add to the Model's adaptability and resilience. Such stochastic modelling would allow the framework to simulate real-world uncertainties, providing firms with a more robust decision-making tool that accommodates market unpredictability and operational risks. Incorporating these elements would deepen the understanding of how firms can strategically optimize their production and inventory practices in complex, dynamic, and often unpredictable environments. This broader, more integrated approach would offer insights into cost minimization and sustainable and adaptive operational strategies for businesses facing evolving environmental and economic pressures.

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