Opsi p-ISSN 1693-2102
Vol. 18, No. 1, June 2025 e-ISSN 2686-2352

Optimizing multi-item EPQ under defect and rework: A case in the plastic molding industry

Laila Nafisah [1]*, Rika Apriyanti Magdalena Sinaga [2], Apriani Soepardi [1], Melati Salma [3], Irianto [4]
[1]Department of Industrial Engineering, Universitas Pembangunan Nasional Veteran Yogyakarta, Babarsari 2 Tambakbayan Yogyakarta, 55281, Indonesia
[2]PT Indo Tambangraya Megah Tbk. Pondok Indah Office Tower III, Jl.Sultan Iskandar Muda Kav.V-TA, P.O. Box 178 Bontang, Kalimantan Timur 75311, Indonesia
[3]Department of Industrial and Process Engineering, Kalimantan Institute of Technology, Jl. Soekarno Hatta No.KM 15, Karang Joang, Balikpapan, Kalimantan Timur 76127, Indonesia
[4]Department General Education, Faculty of Resilience, Rabdan Academy, Abu Dhabi, United Arab Emirates

*Corresponding Author: laila@upnyk.ac.id

Article history:
Received: 26 May 2025
Revised: 18 June 2025
Accepted: 30 June 2025
Published: 30 June 2025

Keywords:
EPQ model
Defective items
Multi-item inventory
Rework
Backorder

ABSTRACT
Product availability is a key indicator of service performance and is closely linked to production planning. Inaccurate decisions in lot sizing may lead to either overstock or stockout, resulting in substantial financial losses. Classical Economic Production Quantity (EPQ) models generally assume perfect quality and ignore real-world factor such as defects, rework, and backorders. This study proposes an extended EPQ model for multi-item production systems that integrates random defect rates, rework, and backordering within a single framework. Unlike previous studies that focus on single-item scenarios or deterministic defect rates, this model reflects a more realistic setting faced by companies by accounting for stochastic defects, the cost of crushing and rework, and customer backorder fulfillment. The model aims to determine the optimal lot size and production cycle that minimize the total inventory-related costs. The proposed model is validated using real case data from a plastic molding company. Results show that the model yields cost savings of 0.19% compared to the current company policy. Although modest, these savings are significant when scaled across production periods. More importantly, the model demonstrates strong adaptability to operational constraints and provides a practical decision-support tool for industries managing multiple products, quality variation, and uncertain demand.

DOI:
https://doi.org/10.31315/opsi.v18i1.14740

1. INTRODUCTION

In the era of globalization, business competition has intensified, compelling companies to adopt effective and dynamic strategies to survive and remain competitive in the market. A customer-oriented approach enables companies to thrive by responding more precisely to evolving consumer preferences [1]–[4]. Delivering customer satisfaction hinges on three critical aspects: competitive pricing, consistent product quality, and reliable service performance [5], [6].

Providing quality products at affordable prices alone does not guarantee customer satisfaction unless accompanied by dependable service, particularly in ensuring product availability [7]–[9]. Product availability is closely linked to the company's production planning and capacity. Inaccuracies in production decisions, especially in determining lot sizes, may lead to overstock or stockout situations [10]. Stockouts result in missed profit opportunities and potential loss of customer trust , while overstocks contribute to inefficiencies such as higher holding costs, product obsolescence, and material waste [10], [11].

In manufacturing settings, especially in the plastic molding industry, the problem is further complicated by the occurrence of defective products. Data from a molding company case study indicates that product shortages, averaging 23%, are largely attributed to defects generated during production. Common defects in injection molding include voids, surface blemishes, short shots, flashing, jetting, flow marks, weld lines, burning, and warpage [12]. These defects not only prevent customer demand from being fulfilled but also represent significant production losses [13]. To mitigate these issues, rework is often conducted. Rework is an integral part of quality control that enables defective items to be processed again into conforming products [14],[15]. However, rework incurs additional costs, such as crushing and reproduction costs [9], [16], [17]. Improper execution may also lead to traceability issues that compromise the quality management system [18].

The classic Economic Production Quantity (EPQ) model has served as a fundamental framework in inventory management, assuming perfect production and deterministic parameters [19]. This oversimplification renders the model less applicable in real industrial environments where imperfect production is unavoidable [20],[21]. Several researchers have extended the EPQ framework by incorporating defective products and rework. For instance, Hayek & Salameh [22] modeled defectives as random variables and proposed reworking them at a constant rate. Bayati et al. [23] categorized items into perfect, imperfect, reworkable, and non-reworkable classes, and optimized lot sizes while accounting for marketing and pricing decisions. Shah et al. [24] developed an EPQ model with time-dependent demand, reworkable defective items, and random preventive maintenance. Defective items are reworked after production, followed by maintenance. Shortages due to increasing demand are treated as lost sales.

Recent studies have further developed EPQ models by integrating additional complexities. Taleizadeh et al. [25] introduced an EPQ model that simultaneously optimizes pricing, lot size, and backorder levels while considering rework processes, demonstrating significant profit improvements. Sajjad et al. [26] expanded upon previous models by incorporating distributors into the supply chain, addressing defective products, backorders, and warranty policies. Eroğlu & Aydemir [27] proposed a novel EPQ model under grey uncertainty, accounting for imperfect production, screening, and rework with backorders, enhancing decision-making under uncertainty. Moreover, sustainability considerations have been integrated into EPQ models. Priyan et al. [28] developed a cleaner EPQ inventory model involving synchronous and asynchronous rework processes with green technology investments. Previous studies in multi-item inventory control have demonstrated the relevance of integrating complex real-world factors such as defective items, shortages, and fuzzy demand [29], [30]. In particular, the leather and dairy industries have shown that multi-objective and fuzzy-based approaches can enhance inventory decisions under uncertainty. Moreover, the issue of defective products in plastic molding—often simulated to evaluate variability in outcomes—has also been addressed using stochastic methods such as Monte Carlo simulation [31].

Although extensions of the EPQ model have gained increasing attention,, only limited studies consider a multi-item environment combined with random defect rates and explicit backordering policies. Most studies simplify the system by assuming single-product scenarios [20], [22], [24], ignoring the operational complexity present in real-world manufacturing. This research attempts to fill this gap by proposing an extended EPQ model for multi-item production that integrates random defective proportions, rework processes, and backorders into a unified decision-making framework.

Based on this background, the research problem can be formulated as follows: how can an extended EPQ model be developed for a multi-item production system that accounts for random defect rates, rework, and backorders, in order to determine the optimal production lot size and cycle time that minimize total inventory costs while satisfying customer demand?

The objective of the proposed model is to determine the optimal production lot size and cycle time that minimize total inventory-related costs, including setup, production, holding, shortage, disposal, and rework costs, while still meeting customer demand. To assess its practical applicability and cost-effectiveness, the model is validated through a case study conducted in a plastic molding company.

2. MODEL DEVELOPMENT

This section describes the problem definition, notations and assumptions, the mathematical model, and the proposed solution procedure.

2.1 Problem Definition

Manufacturing systems do not always produce products of perfect quality. The occurrence of defective items is often unavoidable and random in nature. These defective items not only cause production losses but also prevent production targets from being met and fail to fulfill customer demands. To minimize such losses, companies typically conduct rework activities. Rework incurs additional costs, including crushing and reproduction costs. Therefore, this study develops a multi-item production inventory model that considers defective products, rework processes, and shortages. The objective is to determine the optimal production lot size and cycle time to meet customer demand at a higher service level while minimizing the total cost of losses.

2.2 Notations and Assumptions

The following are the notations used in this model
Decision variables
T^* : production cycle time, period
Q_i^* : optimal production lot size of item i, unit

Parameters
P_i : production rate of item i, unit/period
D_i : demand rate of item i, unit/period
d_i : defective rate from regular production of item i ($d = Px$)
$t_{1(i)}$: production time of Q_1 item i, period
$t_{2(i)}$: rework time of item i, period
$t_{3(i)}$: production time of Q_2 item i, period
$t_{4(i)}$: shortage time of item i, period
$t_{5(i)}$: backorder time of item i, period
S_i : set-up time of item i
B_i : number of backordered items of product i, unit
$E(x_i)$: expectation proportion of defect item i
x_i : proportion of defect item i
$C_{o(i)}$: set-up cost item i, IDR
$C_{p(i)}$: production cost item i, IDR/unit
$C_{h(i)}$: holding cost item i, IDR/unit/period
$C_{s(i)}$: backorder cost item i, IDR/unit/period
$C_{r(i)}$: rework cost item i, IDR /unit
$C_{cr(i)}$: crushing cost item i, IDR /unit
PC : production cost per period
OC : set-up cost per period
HC : holding cost per period
SC : backorder cost per period
RC : rework cost per period
LC : crushing cost per period
Q_1 : on hand inventory level at time (0, t_1)
Q_2 : on hand inventory level at time (t_1, t_2)
$\bar{I}$: average on hand inventory level at time (0, t_5), unit
The assumptions used in this model:

1. A single-stage production system is used to manufacture multiple types of products.
2. The production rate is constant and greater than the demand rate.
3. The proportion of defective items follows a known probability distribution.
4. All defective items are reworkable, and reworked items meet quality standards.
5. All demands must be satisfied.
6. Backorders are permitted.
7. Inspection cost is negligible.

2.3 Mathematical Model

This study proposes an extended Economic Production Quantity (EPQ) model that incorporates multiple items, random defective rates, rework processes, and backorders. The model is developed based on a real case study conducted in a plastic molding company located in Yogyakarta, Indonesia. Its formulation is adapted and extended from the foundational models proposed by [20] and [25].

The decision variables of this model are the optimal production lot size and cycle time. The objective function is to minimize the total inventory cost per period. To determine the optimal values of the decision variables, a standard analytical optimization method is applied, by taking the first derivative of the total inventory cost function with respect to the decision variables.

The total inventory cost consists of the setup costs, production costs, holding costs, backorder costs, crushing costs, and rework costs:

1. Set-up Cost per period (OC)

The set-up cost per period for n-item is given by:

$$OC = \sum_{i=1}^{n} \frac{C_{o(i)}}{T} \tag{1}$$

2. Production Cost per period (PC)

The production cost per period for n-item is

$$PC = \sum_{i=1}^{n} C_{p(i)}.D_i \tag{2}$$

3. Holding Cost per period (HC)

The holding cost per period depends on the unit holding cost per period and the average on hand inventory level at $0 \le t \le t_3$. The average level of inventory on hand for each item i $(\bar{I})$ at $0 \le t \le t_3$ is

$$\bar{I} = \frac{1}{T}\left[\frac{1}{2}Q_1 t_1 + Q_1 t_2 + \frac{1}{2}(Q_2 - Q_1)t_2 + \frac{1}{2}Q_2 t_3\right] \tag{3}$$

where,

$$T = t_1 + t_2 + t_3 + t_4 + t_5 \tag{4}$$

$$Q_1 = (P - D - d)\frac{Q}{P} - B \tag{5}$$

$$t_2 = \frac{E(x)Q}{P} \tag{6}$$

$$Q_2 = Q_1 + (P - D)t_2$$

$$Q_2 = (P - D)\frac{Q}{P} - Qx - B + (P - D)\frac{xQ}{P} \tag{7}$$

$$t_3 = \frac{Q_2}{D}$$

$$t_3 = \frac{1}{D}\left[(P - D)\frac{Q}{P} - Qx - B + (P - D)\frac{xQ}{P}\right] \tag{8}$$

By substituting equations (4) to (8) and let $T = Q/D$, the average on-hand inventory level for item i $(\bar{I})$ at $0 \le t \le t_3$ is

$$\bar{I} = \frac{Q}{2P}[P - D(1 + x + x^2)] - \frac{DB}{2P}(1 + 2x) \tag{9}$$

The holding cost of n-item during period t is

$$HC = \sum_{i=1}^{n} \frac{C_{h(i)}Q_i}{2P_i}[P_i - D_i(1 + E(x_i) + E(x_i)^2)] - \frac{C_{h(i)}D_iB_i}{2P_i}[1 + 2E(x_i)] \tag{10}$$

4. Shortage cost per period (SC)

The shortage cost depends on the unit backorder cost per period and the average backorder at $t_4 \le t \le t_5$. The average backorder item i ($\bar{I}_s$), at $t_4 \le t \le t_5$ is

$$\bar{I}_s = \frac{1}{T}\left[\frac{1}{2}Bt_4 + \frac{1}{2}Bt_5\right] \tag{11}$$

where,

$$t_4 = \frac{B}{D} \tag{12}$$

$$t_5 = \frac{B}{P - D - d} \tag{13}$$

By substituting equations (12) and (13) to equation (11), and $T = \frac{Q}{D'}$ so that the average number of backorder item i at $t_4 \le t \le t_5$ is

$$\bar{I}_s = \frac{B^2P(1 - x)}{2Q(P - D - d)} \tag{14}$$

The shortage cost of n-item during period t is

$$SC = \sum_{i=1}^{n} \frac{C_{s(i)}P_iB_i^{\,2}(1 - E(x_i))}{2Q_i(P_i - D_i - d_i)} \tag{15}$$

where,

$$E(x_i) = \sum_{j=1}^{m} x_{ij}f(x_{ij}) \tag{16}$$

5. Crushing cost per period (LC)

This cost exists because of the presence of defective products that need to go through a crushing process first and become raw materials ready to be processed into new products (rework). The crushing cost per period depends on the unit crushing cost and the expected number of defective products. The set-up cost before rework of n-item during period t is

$$LC = \sum_{i=1}^{n} C_{cr(i)}.D_i.E(x_i) \tag{17}$$

6. Rework cost per period (RC)

The rework cost is the cost of re-producing defective products, which depends on the unit production cost and the expected number of defective products. The rework cost of n item during period t is

$$RC = \sum_{i=1}^{n} C_{r(i)}.D_i.E(x_i) \tag{18}$$

The total inventory cost per period t is

$$\begin{aligned} TC = \sum_{i=1}^{n} C_{p(i)}D_i + \frac{\sum_{i=1}^{n} C_{o(i)}}{T} + \sum_{i=1}^{n} \frac{C_{h(i)}D_iT}{2P_i}[P_i - D_i(1 + E(x_i) + E(x_i)^2)] \\ - \sum_{i=1}^{n} \frac{C_{h(i)}D_iB_i}{2P_i}[1 + 2E(x_i)] + \sum_{i=1}^{n} \frac{C_{s(i)}P_iB_i^{\,2}(1 - E(x_i))}{2D_iT(P_i - D_i - d_i)} + \sum_{i=1}^{n} C_{r(i)}D_iE(x_i) \\ + \sum_{i=1}^{n} C_{cr(i)}D_iE(x_i) \end{aligned} \tag{19}$$

To find the optimal cycle time T^*, the total cost function is differentiated with respect to T and set to zero:

$$\frac{\partial(TC)}{\partial T} = 0, \qquad \frac{\partial^2 TC}{\partial T^2} > 0 \tag{20}$$

An optimal solution T^* exists if the second derivative is positive, indicating a minimum. Based on equations (20) the following is obtained:

$$T^* = \sqrt{\frac{\sum_{i=1}^{n} \frac{P_i {B_i}^2 C_{s(i)}(1 - E(x_i))}{D_i(P_i - D_i - d_i)} + \sum_{i=1}^{n} C_o}{\sum_{i=1}^{n} \frac{C_{h(i)} D_i}{2P_i}\left[P_i - D_i(1 + E(x_i) + E(x_i)^2)\right]}} \tag{21}$$

$$B_i = \frac{D_i C_{h(i)}}{2P_i}\left[1 + 2E(x_i)\right].\frac{Q_i(P_i - D_i - d_i)}{C_{s(i)} P_i (1 - E(x_i))} \tag{22}$$

If $Q = T^* \cdot D$, then equation (22) becomes:

$$B_i = \frac{D_i C_{h(i)}}{2P_i}\left[1 + 2E(x_i)\right].\frac{D_i T(P_i - D_i - d_i)}{C_{s(i)} P_i (1 - E(x_i))} \tag{23}$$

Substitute equation (23) into equation (21), and the result is

$$T^* = \sqrt{\frac{\sum_{i=1}^{n} C_o}{\left[\sum_{i=1}^{n} \frac{C_{h(i)} D_i}{2P_i}\left[P_i - D_i(1 + E(x_i) + E(x_i)^2)\right] - \sum_{i=1}^{n} \frac{\left(\frac{D_i C_{h(i)}}{2P_i}\left[1 + 2E(x_i)\right]\right)^2 D_i(P_i - D_i - d_i)}{2C_{s(i)} P_i(1 - E(x_i))}\right]}} \tag{24}$$

The total time used for production and rework for all products must not exceed the cycle time T^*. Thus, the constraint is:

$$\sum_{i=1}^{n}\left(t_{1(i)} + t_{2(i)} + t_{5(i)}\right) + \sum_{i=1}^{n} S_i \le T^* \tag{25}$$

$$\sum_{i=1}^{n}\left(1 + E(x_i)\right)\frac{D_i}{P_i} T + \sum_{i=1}^{n} S_i \le T^* \tag{26}$$

Therefore,

$$T^* \ge \frac{\sum_{i=1}^{n} S_i}{\left[1 - \sum_{i=1}^{n}(1 + E(x_i))\frac{D_i}{P_i}\right]}$$

$$T_{min} = \frac{\sum_{i=1}^{n} S_i}{\left[1 - \sum_{i=1}^{n}(1 + E(x_i))\frac{D_i}{P_i}\right]} \tag{27}$$

2.4. Model solution

The solution procedure used in solving the developed model is as follows:

1. Calculate the total time required for the production of all products during the planning period, and check that the number of operating days is greater than or equal to the total time required for production during that period. This is expressed as:

$$N \ge \sum_{i=1}^{n} \frac{D_i}{P_i} \tag{28}$$

2. Determine the length of the production cycle, T^* using equation (24).

3. Calculate T_{min} from equation (27) and check whether the machine capacity is sufficient to fulfill customer demand, the condition being that the total production time is less than the cycle time, i.e., $T_{min} \leq T^*$. Calculate the optimal production quantity for each product i using the equation $Q_i{}^* = T^*.D_i$
4. Calculate the number of backordered products for each product i, B_i, using equation (23).
5. Calculate the length of the production process, consisting of regular production time ($t_{(i)1}$), rework time ($t_{(i)2}$), production stoppage time ($t_{(i)3}$), shortage time ($t_{(i)4}$), and backorder time ($t_{(i)5}$) for each product i, respectively, using equations (4), (6), (8), (12), and (13), to ensure whether the total process time per product is equal to T^*.
6. Calculate the total inventory cost using equation (19).

3. RESULT

To validate the proposed model, a case study was conducted in a plastic molding industry involving three types of products. The parameter data used in the model are presented in Table 1.

Table 1 The required parameter data

Parameter	Product		
	Product-1	Product -2	Product -3
D_i	2,162,000	628,000	285,000
P_i	5,868,000	5,868,000	5,868,000
$C_{o(i)}$	55,925	55,925	55,925
$C_{p(i)}$	526.81	523.76	531.45
$C_{h(i)}$	52.52	52.52	52.52
$C_{s(i)}$	16.60	16.60	16.60
$C_{cr(i)}$	2.04	2.04	2.04
$C_{r(i)}$	111.77	111.77	111.77
$E(x_i)$	6.52	6.19	5.21
S_i	64.80	64.80	64.80

Based on the solution steps of the proposed model, the available production time for all products is 178 days, while the total required production time is calculated as $\sum_{i=1}^{n} \frac{D_i}{P_i} = 157$ days, with an additional rework and setup time amounting to a total of 17 days per product with $T_{min} = 7$ hours, thus fulfilling the constraint $T_{min} \leq T^*$. The optimal production cycle length or production interval, T^* is determined to be 17 days. The optimal production lot sizes obtained for the three products are product-1: 110,874 units, product-2: 32,218 units, and product-3: 14,637 units. While the corresponding optimal number of backordered units is product-1: 4,235 units, product-2: 157 units, and product-3: 64 units.

The breakdown of the total time allocated to each production process component per product is shown in Table 2. Each product completes its entire production-rework cycle in exactly 17 days, which matches the optimal cycle time derived from the model. The total inventory cost incurred using the proposed model is IDR 1,647,363,602, which is lower than the cost incurred under the company's existing policy. This results in a cost savings of 0.19%, confirming that the model is effective and capable of optimizing the company's inventory strategy.

Table 2 Length of production process time for each product

Product	t_1 (days)	t_2 (days)	t_3 (days)	t_4 (days)	t_5 (days)	T^* (days)
Product-1	1,87	0,41	3,58	6,86	4,46	17
Product-2	1,46	0,11	12,33	2,89	0,37	17
Product-3	0,76	0,04	14,91	1,38	0,07	17

To evaluate the sensitivity of the model, a parameter variation test was conducted on the expected proportion of defective products by applying variations of -10%, -5%, +5%, and +10%. The results are summarized in Table 3 and Figure 1.

Table 3 Summary of sensitivity analysis

Product	Δx %	$E(x_i)$ %	T^* (days)	Q (units)	TC IDR
Product-1	-10	0,0586	17,68	110.800	1.430.988.200
	-5	0,0620	17,70	110.911	1.431.945.750
	+5	0,0685	17,73	111.137	1.433.860.700
	+10	0,0717	17,75	111.251	1.434.818.100
Product-2	-10	0,0557	17,68	32.184	1.430.988.200
	-5	0,0588	17,70	32.216	1.431.945.750
	+5	0,0650	17,73	32.282	1.433.860.700
	+10	0,0681	17,75	32.315	1.434.818.100
Product-3	-10	0,0469	17,68	14.606	1.430.988.200
	-5	0,0495	17,70	14.621	1.431.945.750
	+5	0,0547	17,73	14.650	1.433.860.700
	+10	0,0573	17,75	14.665	1.434.818.100

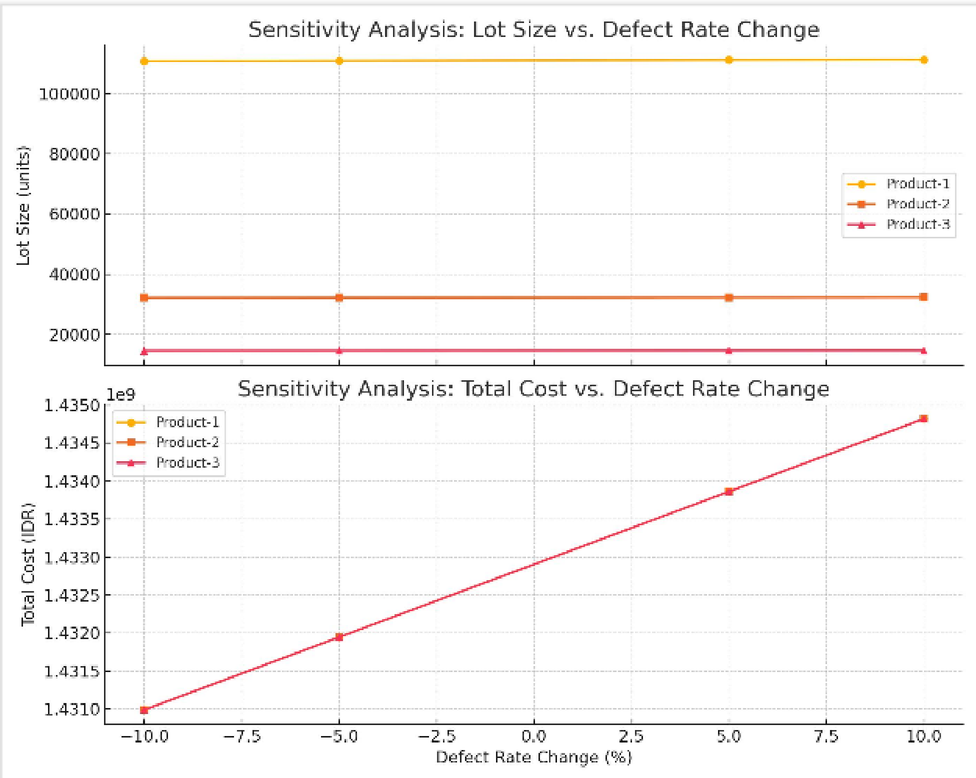

Figure 1 Sensitivity analysis graph

The analysis shows that changes in the expected defect proportion have little impact on the production cycle time T^*, but significantly influence the production lot size Q and the total inventory cost TC. Specifically, higher defect rates increase both Q and TC, which is logical since more units must be produced to compensate for defects, and this in turn increases associated costs such as production, rework, and holding. This confirms that the model is sensitive to changes in defect rate, highlighting the importance of quality control and defect prevention in production planning.

4. DISCUSSION

The results of the model application to the case study of a molding company indicate that the proposed multi-product EPQ model effectively addresses production planning under uncertainty related to defective products and backorders. Based on the calculation results, the total available operating time for producing all items is 178 days, while the total required production time amounts to 157 days. This indicates that the existing production capacity is sufficient to fulfill the entire customer demand without the need for additional machine capacity, subcontracting, or overtime. In this model, production is carried out sequentially for each item; however, the sequence or prioritization of items is not considered in the analysis. The model yields an optimal production cycle length of 17 days, implying that the cumulative demand for all products is to be fulfilled by initiating production at fixed 17-day intervals throughout the 178-day planning horizon.

The model determined the following optimal production lot sizes: 110,874 units for product-1, 32,218 units for product-2, and 14,637 units for product-3. These lot sizes are significantly influenced by each product's demand rate and defective rate, confirming the model's responsiveness to operational inputs. Additionally, the corresponding optimal backorder quantities—4,235 for product-1, 157 for product-2, and 64 for product-3—demonstrate the model's ability to manage shortages dynamically without resorting to rigid zero-shortage assumptions, which are often unrealistic in modern production environments. The total cost incurred using this optimal policy is IDR 1,647,363,602, which is slightly lower than the cost under the company's current strategy, resulting in a cost saving of 0.19%. While the percentage reduction may appear modest, in real manufacturing operations, even small improvements can translate to substantial savings when accumulated over time or scaled across product lines. More importantly, this cost reduction is achieved while maintaining service levels and accommodating the rework process—an aspect often neglected in classical EPQ models.

In comparison to existing models in the literature—such as those proposed by Hayek and Salameh [19], and Taleizadeh et al. [22]—this model adds value by integrating three critical dimensions simultaneously: multi-item planning, random defective rates, and backorder allowance. Most prior models either treat single-item systems or assume fixed defect rates, which limits their practical applicability. By relaxing those assumptions, the proposed model aligns more closely with the complex realities faced by industries like plastic injection molding, where product variation and quality issues are inherently stochastic.

An additional strength of the model lies in its ability to manage the rework process explicitly. Defective items are not discarded but reprocessed, incurring both crushing and rework costs. Including these two cost components allows for a more accurate and comprehensive cost estimation. As shown in Table 2, each product's total time allocation includes crushing and rework periods, all of which fall within the 17-day cycle. This result validates the model's internal consistency and its adaptability to shop floor constraints. From a managerial standpoint, this model offers a decision support tool that enables production planners to make informed decisions regarding lot sizing and production scheduling, taking into account the inevitable presence of defects and the strategic use of backorders. It also underscores the importance of quality control, as the sensitivity analysis revealed that increases in the defect rate directly inflate production cost and required production quantity.

The sensitivity analysis in this study focuses on variations of –10%, –5%, +5%, and +10% in the expected defect rate. These specific ranges were selected for two primary reasons. First, they reflect realistic fluctuations in defect rates observed in actual production settings, where minor deviations in process control, material quality, or operator performance can cause measurable changes in output quality within this margin. Second, these percentage changes are sufficient to illustrate the model's responsiveness without introducing extreme or implausible conditions that may not occur under normal operations. By analyzing both small and moderate deviations, the study can effectively evaluate how sensitive the model's performance—particularly lot size, cycle time, and total cost—is to variations in product quality, thereby providing insights into the robustness of the proposed solution.

In the sensitivity analysis Table 3, variations in the expected proportion of defects by ±10% show that the cycle time T^* remains relatively stable, varying only between 17.68 and 17.75 days. However, both production quantity and total cost are significantly affected. For example, product-1's lot size increases from 110,800 units to 111,251 units increases by 10%, while the total inventory cost for product-1 alone increases from IDR 1,430,988,200 to IDR 1,434,818,100. This finding supports the argument that while time scheduling may be robust, cost and capacity planning are sensitive to product quality variability—an insight with direct implications for resource allocation, supplier control, and quality assurance.

In summary, the model is not only mathematically sound but also operationally relevant. It integrates key operational parameters and real-world constraints, offering both analytical rigor and practical utility. These results highlight the model's potential to be adapted and applied to other manufacturing contexts beyond plastic molding, particularly in environments with multiple products, variable defect rates, and constrained resources.

5. CONCLUSION

In reality, defective products produced during production activities cannot always be avoided. The presence of defective products not only results in losses but also prevents production targets from being achieved and meeting the minimum quantity of product delivery to customers. To address these losses, companies often perform rework. Rework activities are part of quality control in production that incur costs. In this paper, a multi-item EPQ model has been developed, taking into account random defect proportions, rework, and backorders. With this proposed model, companies can determine the optimal production lot size and when production should be carried out to meet customer demand while minimizing total loss costs. Model validation has been performed based on actual data and has been shown to provide a production cost savings of 0.19%.

This model is a simplified representation of the real system and relies on several assumptions. Therefore, it has its limitations. For further research, several aspects could be considered for development, including considering varying setup times, the order in which items need to be produced, and the cost of late order penalties. The model would become more dynamic when considering multi-stage cases and machine reliability at each stage.

REFERENCES

[1] N. Rane, A. Achari, and S. P. Choudhary, "Enhancing customer loyalty through quality of service: effective strategies to improve customer satisfaction, experience, relationship, and engagement," *Int. Res. J. Mod. Eng. Technol. Sci.*, no. May, 2023, doi: 10.56726/irjmets38104.

[2] E. Dasipah, "Strategi bisnis yang berorientasi konsumen," *Paspalum J. Ilm. Pertan.*, vol. 4, no. 1, p. 49, 2017, doi: 10.35138/paspalum.v4i1.23.

[3] F. Graciela, T. S. Dewayana, and A. N. Habyba, "Enhancing customer satisfaction towards the service quality of Soekarno-Hatta International Airport using servqual and binary logistic regression," vol. 17, no. 2, 2024.

[4] M. Djunaidi and R. D. Gunari, "Analysis of factors affecting consumer satisfaction using SEM (Structural Equation Modeling) method," *Opsi*, vol. 15, no. 1, p. 85, 2022, doi: 10.31315/opsi.v15i1.6808.

[5] A. Thoumrungroje and O. C. Racela, "Innovation and performance implications of customer-orientation across different business strategy types," *J. Open Innov. Technol. Mark. Complex.*, vol. 8, no. 4, p. 178, 2022, doi: 10.3390/joitmc8040178.

[6] M. Konečnik Ruzzier, M. Ruzzier, and R. D. Hisrich, "Value, satisfaction and customer loyalty," *Mark. Entrep. SMEs*, no. November, 2014, doi: 10.4337/9781781955970.00008.

[7] P. Rita, T. Oliveira, and A. Farisa, "The impact of e-service quality and customer satisfaction on customer behavior in online shopping," *Heliyon*, vol. 5, no. 10, p. e02690, 2019, doi: 10.1016/j.heliyon.2019.e02690.

[8] D. C. Hutagaol and R. Erdiansyah, "The effect of service quality, price, customer satisfaction on customer loyalty of Airasia customers," vol. 439, no. Ticash 2019, pp. 356–363, 2020, doi: 10.2991/assehr.k.200515.063.

[9] R. S. Hutapea, S. N. Dewi, and C. M. Lasambouw, "Quality costs in improving the efficiency production costs," *Proc. Int. Conf. Appl. Sci. Technol. Soc. Sci. (ICAST-SS 2020)*, vol. 544, pp. 535–540, 2021, doi: 10.2991/assehr.k.210424.105.

[10] L. Nafisah, W. Sally, and P. Puryani, "Model persediaan pada produk yang mendekati masa kadaluwarsa: mempertimbangkan diskon penjualan dan retur," *J. Tek. Ind.*, vol. 18, no. 1, 2016, doi: 10.9744/jti.18.1.63-72.

[11] D. Idayani and S. Subchan, "Optimal control of multi-supplier inventory management with lead time," *Int. J. Comput. Sci. Appl. Math.*, vol. 6, no. 1, p. 23, 2020, doi: 10.12962/j24775401.v6i1.5040.

[12] S. M. Mohamed Yusoff, J. Mohd. Rohani, W. H. W. Hamid, and E. Ramly, "A plastic injection molding process characterization using experimental design technique: A case study," *J. Teknol.*, no. December 2004, 2012, doi: 10.11113/jt.v41.686.

[13] X. Lin, B. Chen, and H. Xie, "Study on principle of product defect identification," *Procedia Eng.*, vol. 43, pp. 393–398, 2012, doi: 10.1016/j.proeng.2012.08.068.

[14] European Comission, "Guidance on Waste Definitions," no. September, pp. 2–42, 2021.

[15] R. A. Bennett, "Recycled Plastics," pp. 26–38, 1992, doi: 10.1021/bk-1992-0513.ch003.

[16] E. C. Okechukwu, O. O. Uchendu, O. C. Ndubuisi, and O. C. Charles, "An evaluation of actual costs of rework and scrap in manufacturing industry," *J. Multidiscip. Eng. Sci. Technol.*, vol. 2, no. 4, pp. 3159–40, 2015, [Online]. Available: www.jmest.org

[17] K. Winarso and M. Jufriyanto, "Rework reduction and quality cost analysis of furniture production processes using the House of Risk (HOR)," *J. Phys. Conf. Ser.*, vol. 1569, no. 3, 2020, doi: 10.1088/1742-6596/1569/3/032022.

[18] J. Andersson and M. Holmström, "Rework of defect products with maintained traceability," p. 89, 2015.

[19] S. W. Chiu, C. T. Tseng, M. F. Wu, and P. C. Sung, "Multi-item EPQ model with scrap, rework and multi-delivery using common cycle policy," *J. Appl. Res. Technol.*, vol. 12, no. 3, pp. 615–622, 2014, doi: 10.1016/S1665-6423(14)71641-4.

[20] M. Sanjai and S. Periyasamy, "An inventory model for imperfect production system with rework and shortages," *Int. J. Oper. Res.*, vol. 34, no. 1, pp. 66–84, 2019, doi: 10.1504/IJOR.2019.096939.

[21] L. Nafisah, N. C. D. Maharani, Y. D. Astanti, and M. S. A. Khannan, "Multi-item inventory policy with time-dependent pricing and rework cost," *Int. J. Ind. Optim.*, vol. 2, no. 2, p. 99, 2021, doi: 10.12928/ijio.v2i2.4370.

[22] P. A. Hayek and M. K. Salameh, "Production lot sizing with the reworking of imperfect quality items produced," *Prod. Plan. Control*, vol. 12, no. 6, pp. 584–590, 2001, doi: 10.1080/095372801750397707.

[23] M. F. Bayati, M. R. Barzoki, and S. R. Hejazi, "A joint lot-sizing and marketing model with reworks, scraps and imperfect products," *Int. J. Ind. Eng. Comput.*, vol. 2, no. 2, pp. 395–408, 2011, doi: 10.5267/j.ijiec.2010.07.005.

[24] N. H. Shah, D. G. Patel, and D. B. Shah, "EPQ Model for trended demand with rework and random preventive machine time," *ISRN Oper. Res.*, vol. 2013, pp. 1–8, 2013, doi: 10.1155/2013/485172.

[25] A. A. Taleizadeh, L. E. Cárdenas-Barrón, J. Biabani, and R. Nikousokhan, "Multi products single machine EPQ model with immediate rework process," *Int. J. Ind. Eng. Comput.*, vol. 3, no. 2, pp. 93–102, 2012, doi: 10.5267/j.ijiec.2011.09.001.

[26] W. Sajjad, M. Ullah, R. Khan, and M. Hayat, "Developing a comprehensive shipment policy through modified epq model considering process imperfections, transportation cost, and backorders," *Logistics*, vol. 6, no. 3, 2022, doi: 10.3390/logistics6030041.

[27] E. Aydemir, F. Bedir, G. Ozdemir, and A. Eroglu, "An EPQ model with imperfect items using interval grey numbers," *An Int. J. Optim. Control Theor. Appl.*, vol. 5, no. 1, pp. 21–32, 2014, doi: 10.11121/ijocta.01.2015.00204.

[28] S. Priyan, P. Mala, and M. Palanivel, "A cleaner EPQ inventory model involving synchronous and asynchronous rework process with green technology investment," *Clean. Logist. Supply Chain*, vol. 4, no. May, p. 100056, 2022, doi: 10.1016/j.clscn.2022.100056.

[29] L. Nafisah, N. I. Pramasthi, A. Soepardi, and M. Chaeron, "Fuzzy EPQ model considering demand uncertainty , imperfect quality , and backorder : A case study in a Goat Milk SMEs Model EPQ Fuzzy yang mempertimbangkan ketidakpastian permintaan , kualitas produk , dan backorder pada UMKM,"*Opsi*,vol. 15, no. 2, pp. 323–332, 2022, doi.: 10.31315/opsi.v15i2.7574.

[30] L. Nafisah, G. J. Prasetyo, E. Nursubiyantoro, M. Chaeron, A. Soepardi, and S. Suharsih, "Multi objective optimization approach for multi-item inventory control: A case study in leather industry," *Opsi*, vol. 17, no. 1, p. 164, 2024, doi: 10.31315/opsi.v17i1.11106.

[31] L. M. Cahya Wulandari and L. D. Indrianto Putri, "Inventory control analysis of plastic raw materials using Monte Carlo simulation approach," *Opsi*, vol. 14, no. 1, p. 104, 2021, doi: 10.31315/opsi.v14i1.4744.