11th International Conference on Industrial and Systems Engineering
ICISE 2025
24 & 25 Sep. 2025 ■ ۲ و ۳ مهر ۱۴۰۴
Ferdowsi University of Mashhad ■ دانشگاه فردوسی مشهد
یازدهمین کنفرانس بین‌المللی مهندسی صنایع و سیستم‌ها

Multi Period Closed-Loop Supply Chain Modeling for Plastic Box Production with the Objective of Cost Minimization

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***Abstract*— In this study, a multi-period Mixed Integer Linear Programming is developed to optimize a closed-loop supply chain in the plastic box manufacturing industry. The supply chain includes multiple product types, a production center, several Distribution centers (DCs), and Original Equipment Manufacturers (OEMs) as the final consumers. The distribution centers handle the management of new products, returned products in good condition, and products requiring refurbishment. The model assumes predetermined locations for production and distribution centers and focuses on optimizing resource allocation and material flow over several consecutive time periods. The primary objective is to minimize the total costs related to production, refurbishment, inventory holding, transportation, raw material procurement, and electricity consumption. The model incorporates periodic constraints on electricity quotas and stepwise discounts on raw material purchases. Additionally, penalty costs associated with product shortages and environmental costs arising from production and refurbishment processes are considered. The results demonstrate that the proposed multi-period approach effectively ensures optimal resource allocation in each period and significantly reduces the total costs of the closed-loop supply chain. Specifically, when a similar model is implemented without accounting for the return of healthy and refurbished products, costs increase substantially. Moreover, the model facilitates improved product lifecycle management and reduces environmental impacts through effective management of the returned product flows.**

Keywords— Multi-Period Optimization, Closed-Loop Supply Chain, Stepwise Purchase Discounts

I. Introduction

With the rapid advancement of technology and globalization, manufacturing and industrial firms—including those in the plastic packaging sector—are increasingly conducting production, refurbishment, packaging, and distribution processes across multiple, often geographically dispersed locations within integrated closed-loop supply chains[1] This structural change in supply chains has significantly increased the demand for various types of packaging materials, which play a vital role in the effective collection, storage, handling, and transportation of raw materials, components, semi-finished, and finished products.

Packaging materials are broadly classified into single-use and reusable categories. Reusable packaging—such as pallets, trays, plastic boxes, and racks—has gained prominence in modern supply chains due to its strength, durability, recyclability, and waste reduction benefits [2–4]. These reusable systems not only enhance product safety during transport and storage but also improve operational efficiency, optimize space utilization, reduce packaging costs, and importantly, decrease greenhouse gas emissions and environmental impacts [5]. Among reusable packaging, plastic boxes are extensively used in diverse industries (e.g., automotive parts, food, and pharmaceuticals), where concerns about environmental sustainability and the drawbacks of the traditional linear "extract-produce-consume-dispose" model have drawn considerable attention. Consequently, designing and implementing Closed-Loop Supply Chains (CLSCs) that manage new product inflows alongside collection, inspection, refurbishment, recycling, and redistribution of returned products have become strategic necessities to achieve sustainability goals and operational cost reductions [6].

While existing studies on reusable packaging mainly focus on inventory management, return forecasting, and recovery methods [7-8], there remains a need for a comprehensive multi-period approach that integrates CLSC network design across production, distribution, and recovery stages for various products.

In this context, the present research develops a multi-period linear programming model for the design and optimization of a closed-loop supply chain for plastic boxes. The model simultaneously considers new products, returned reusable products (usable without repair), and defective products requiring refurbishment over multiple consecutive periods. Predefined locations for production and distribution centers are assumed, with the main focus on optimizing resource allocation and material flows over the planning horizon. The objective function minimizes total costs related to production, refurbishment, storage, transportation, raw material procurement, and energy consumption. Additionally, constraints such as electricity quotas in different periods, tiered discounts on raw material purchases, and environmental pollution costs are included to reflect more realistic decision-making conditions.

II. Literature Review

Reusable products, due to their durability and recyclability, are suitable alternatives to single-use packaging. However, their effective utilization requires optimal design of supply chain flows. Numerous studies have shown that optimal use of these products demands special attention to issues such as return rate forecasting, usage cycle time, quality of returned packages, and determining the need for purchasing new products [9-10] .Particularly when product flows are designed as closed-loop systems, accurate modeling of return processes, distinguishing reusable products from those needing refurbishment, and scheduling transportation and storage become even more critical. With the development of technologies like RFID and IoT, product tracking and management in supply chains have become smarter [11], yet many organizations still face challenges such as return forecasting, rental or purchase decisions, inventory constraints, and balancing costs with service levels.

Most existing research separately addresses inventory policies, comparisons between recycled and traditional systems, or life cycle analysis [12]. However, less attention has been given to developing a comprehensive multi-period model for designing and optimizing closed-loop supply chains of these products across multiple product types. Such a model should simultaneously optimize decisions related to production, distribution, return, refurbishment, storage, and raw material procurement under real-world uncertainties and constraints (e.g., electricity quotas or tiered purchasing discounts).

Some studies explicitly state that the existing literature has yet to provide a complete solution to this issue and emphasize the need for developing systemic, multilayered models for reusable packaging .Further research also shows that even in industries with extensive use of reusable packaging, like automotive, supply chain network design considering up-to-date environmental and cost policies is not fully developed [13 ,14]. Therefore, developing an integrated model for designing a closed-loop supply chain network for plastic boxes, which covers strategic and operational decisions over multiple periods and considers costs, flows, capacities, and real constraints, is an inevitable necessity on the path toward sustainable production and higher logistical efficiency.

III. Problem Definition

This study addresses a multi-period operational design of a closed-loop supply chain for reusable plastic boxes. The supply chain consists of one manufacturing plant and multiple predefined distribution centers that fulfill customer demands over several consecutive periods. Figure 1 illustrates this model. At the beginning of the first period, electricity and raw materials must be procured under quota restrictions and quantity discount policies, followed by production and shipment of products to distribution centers.

From the second period onward, used boxes return to the supply chain in three categories: reusable (undamaged), defective (requiring refurbishment), and non-recoverable (to be replaced). Distribution centers manage the inventory of reusable and refurbished boxes to meet future demands.

The developed model optimizes material flow, resource procurement, utilization of returned items, and capacity management while considering costs related to production, refurbishment, storage, shortage penalties, transportation, electricity and raw material purchasing, and environmental impacts. The objective is to minimize the total supply chain cost while enhancing environmental sustainability.

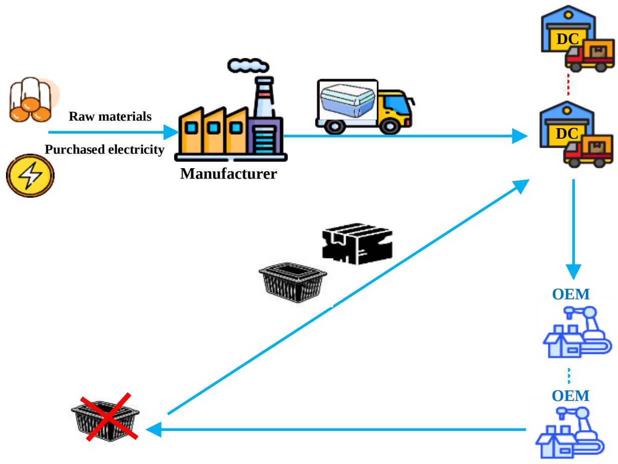

Fig. 1. Closed-loop supply chain for reusable plastic boxes

A. *Tiered Discount in Procurement*

In many industries, sellers use discount policies to encourage customers to purchase in larger quantities. One of the most common policies is the tiered discount, where the unit price decreases as the purchase quantity increases. In this study, such a structure is considered for both raw material procurement and electricity supply. Figure 2 illustrates this tiered discount method. In this framework, when the purchase amount passes certain thresholds, discounts are applied stepwise, leading to a reduction in total costs. Decision-making must be planned to optimally leverage these discounts to minimize overall procurement costs while efficiently allocating resources. This type of procurement policy can play a significant role in the economic efficiency and financial sustainability of supply networks. The figure below shows how the unit price decreases with increasing purchase volumes after passing specific thresholds.

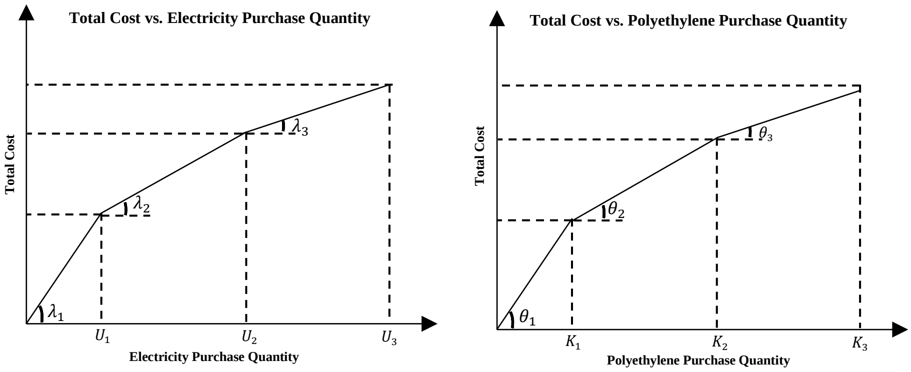

Fig. 2. Tiered discount structure for purchasing electricity and raw materials at the beginning of the period.

IV. Mathematical Model

This section presents a multi-period mathematical model for the closed-loop supply chain of reusable plastic boxes. It optimizes raw material flow, production, distribution, recovery, and refurbishment while considering capacity, costs, tiered discounts, and environmental constraints. The goal is to minimize total system cost over the planning horizon and satisfy demand with minimal shortages. Sets, parameters, variables, and equations are detailed below.

TABLE I. Parameters, Indices, and Decision Variables

Sets	
i	Electricity purchase discount tiers
j	Polyethylene purchase discount tiers
o	Set of OEM's indexed by o
p	Set of type of Product indexed by p
t	Time periods

Parameters	
c_p	Production cost of new product p at the factory
$\bar{c}_p$	Refurbishment cost of product p at DC
h_{opdF}	Shipping cost of product p from DC d to OEM o
h_{pdR}	Shipping cost of product p from factory to DC d
h_{opdR}	Functional product shipping cost (OEM to DC)
$\bar{h}_{opdR}$	Refurbishable product shipping cost (OEM to DC)
a_p	Handling cost of product p in DC
b_p	Purchase cost of usable product p from OEM
$\bar{b}_p$	Purchase cost of refurbishable product p from OEM
ρ_p	Penalty cost for unmet demand of product p by OEM
z_p	Environmental cost for producing product p
$\bar{z}_p$	Environmental cost for refurbishing product p
m_p	Polyethylene consumption per unit of product p
U_i	Maximum electricity purchase allowed for tier i
K_j	Maximum polyethylene purchase allowed for tier j
e	Electricity consumption for producing new products
$\bar{e}$	Electricity consumption for refurbishing products
D_{pot}	Demand of product p for OEM o in period t
$\bar{x}_{Et}$	Electricity quota in period t
w_h	Factory warehouse capacity for finished products
w_p	Factory polyethylene storage capacity
α	Ratio of unusable products
β	Ratio of refurbishable products
l_p	Storage cost for product p
λ_1	Electricity purchase price in tier 1
λ_2	Electricity purchase price in tier 2
λ_3	Electricity purchase price in tier 3
θ_1	Polyethylene purchase price in tier 1
θ_2	Polyethylene purchase price in tier 2
θ_3	Polyethylene purchase price in tier 3

Variables	
k_1	Polyethylene purchase quantity at tier1
k_2	Polyethylene purchase quantity at tier2
k_3	Polyethylene purchase quantity at tier3
u_1	Electricity purchase quantity at tier 1
u_2	Electricity purchase quantity at tier 2
u_3	Electricity purchase quantity at tier 3
q_{optdF}	Product p sent from DC d to OEM o at period t
q_{optR}	Return of usable product p (OEM to DC) at t
$\bar{q}_{optR}$	Return of refurbishable product p (OEM to DC) at t
q_{ptR}	Product p sent from factory to DC d at period t
q_{ptd}	Total product p processed at DC d in period t
ω_{opt}	Unmet demand of product p for OEM o at period t
x_{Et}	Total electricity available at period t
I_{ptd}	Inventory of product p at DC d in period t
ξ_t	Electricity consumed in period t
y_i	Binary variable for electricity purchase tier i
g_j	Binary variable for polyethylene purchase tier j

A. *Objective Function*

The objective function is formulated to minimize the total cost associated with the supply chain. This includes the costs of production, refurbishment, transportation, raw material procurement, energy consumption, inventory holding, and penalties for unmet demand.

Min Z:

$$(\lambda_1 u_1 + \lambda_2 u_2 + \lambda_2 u_2) + (\theta_1 k_1 + \theta_2 k_2 + \theta_3 k_3)$$
$$+ \sum_p \sum_t \sum_d (c_P \; q_{ptdR}) + \sum_p \sum_o \sum_t \sum_d (\bar{c}_p \; \bar{q}_{optdR})$$
$$+ \sum_p \sum_o \sum_t \sum_d \big(\bar{h}_{opdR} \; \bar{q}_{optdR} + h_{opdR} \; q_{optdR} + h_{opdF} \; q_{optdF} \big) + \sum_p \sum_t \sum_d \big(h_{pdR} \; q_{ptdR} \big)$$
$$+ \sum_p \sum_t \sum_d (a_P \; q_{Ptd})$$
$$+ \sum_p \sum_o \sum_t \sum_d (b_p \; q_{optdR} + \bar{b}_p \; \bar{q}_{optdR})$$
$$+ \sum_p \sum_o \sum_t (\rho_p \omega_{opt})$$
$$+ \sum_p \sum_t \sum_d (z_P \; q_{ptdR}) + \sum_p \sum_o \sum_t \sum_d (\bar{z}_p \; \bar{q}_{optdR})$$
$$+ \sum_p \sum_t \sum_d (I_{ptd} \; l_P)$$

- The model minimizes the total cost of the reverse supply chain, comprising:
- Procurement costs for electricity and polyethylene, with tiered volume discounts
- Production and refurbishment costs at the plant and DCs
- Transportation costs for both forward and reverse logistics
- Processing costs at DCs for reuse or refurbishment
- Procurement from OEMs of returned functional and refurbishable items
- Shortage penalties for unmet OEM demand
- Environmental costs from production and refurbishment
- Inventory holding costs for raw materials and finished goods at all locations

B. *Model Constraints*

This model incorporates a set of operational constraints to ensure that all decision variables remain within the feasible and realistic boundaries defined by resource availability, demand fulfillment, environmental considerations, and logistical capacities. These constraints guarantee that the flow of materials and products within the reverse supply chain is optimally and practically aligned with organizational goals and sustainability policies

$$(k_1 + k_2 + k_3) \le W_{PE} \quad (1)$$

$$\sum_p q_{ptdR} + \sum_p \sum_o (q_{optdR} + \bar{q}_{optdR}) + \sum_p I_{p(t-1)d} \le W_h \quad \forall d, t > 1 \quad (2)$$

$$\sum_p q_{ptdR} + \sum_p \sum_o (q_{optdR} + \bar{q}_{optdR}) \le W_h \quad \forall d, t = 1 \quad (3)$$

$$\xi_t + \bar{X}_{Et} = X_{Et} \quad \forall t \quad (4)$$

$$\sum_t \xi_t \le (u_1 + u_2 + u_3) \quad (5)$$

$$\sum_p \sum_d (q_{ptdR} \, E) + \sum_p \sum_o \sum_d (\bar{q}_{optdR} \, \bar{E}) \le X_{ET} \quad \forall t \quad (6)$$

$$\sum_p \sum_t \sum_d (M_P \; q_{ptdR}) \le (k_1 + k_2 + k_3) \quad (7)$$

$$\sum_o q_{optdF} \le q_{ptdR} + \sum_o (q_{optdR} + \bar{q}_{optdR}) + I_{p(t-1)d} \quad \forall p, t, d \quad (8)$$

$$\sum_d q_{optdF} + \omega_{pot} = D_{pot} \quad \forall p, t, o \quad (9)$$

$$q_{optdR} \le (1 - \alpha - \beta) \, q_{optdF} \quad \forall t, p, o, d \quad (10)$$

$$\bar{q}optdR \le (\beta) \, q_{optdF} \quad \forall t, p, o, d \quad (11)$$

$$I_{ptd} = I_{p(t-1)d} + q_{ptdR} + \sum_o (q_{optdR} + \bar{q}_{optdR} - q_{optdF}) \quad \forall p, d, t > 1 \quad (12)$$

$$I_{ptd} = 0 \quad \forall t = 0 \quad (13)$$

$$q_{optdR} = 0 \quad \forall t = 1 \quad (14)$$

$$\bar{q}_{optdR} = 0 \quad \forall t = 1 \quad (15)$$

$$U_1 y_1 \le u_1 \le U_1 \quad (16a)$$

$$U_2 \, y_2 \le u_2 \le U_2 \, y_1 \quad (16b)$$

$$0 \le u_3 \le U_3 \, y_2 \quad (16c)$$

$$K_1 \, g_1 \le k_1 \le K_1 \quad (17a)$$

$$K_2 g_2 \le k_2 \le K_2 g_1 \quad (17b)$$

$$0 \le k_3 \le K_3 g_2 \quad (17c)$$

Constraints 1, 2, and 3 define the storage capacity limits for raw materials and finished products at both production and distribution centers, ensuring inventory levels do not exceed facility capabilities.

Constraints 4, 5, and 6 regulate electricity balance and consumption by accounting for allocated quotas and purchased amounts within each planning period, preventing overuse.

Constraint 7 restricts the total consumption of polyethylene used in manufacturing to the purchased quantity, ensuring material availability aligns with production needs.

Constraints 8 ,9, 10, and 11 manage product logistics, including transportation, shipment quantities, and returns, to maintain accurate flow control at distribution centers.

Constraints 12 through 15 govern inventory management by tracking initial inventories, incoming shipments, and outgoing deliveries, ensuring accurate stock levels across planning periods.

Constraints 16 and 17 model stepwise discount policies applied to electricity and raw material purchases, reflecting volume-based pricing incentives effective at the beginning of the planning horizon.

V. Numerical Example

To better understand the presented mathematical model, a simple numerical example with a small but illustrative structure is considered. In this example, the model is examined over a two-period horizon involving two product types that must be managed across two distribution centers and three consumer units (OEMs). The overall structure of the model for this example is illustrated below. Table 2 presents the parameters used in the model, while Table 3 provides a guide to the flow representation.

TABLE II. Flow Representation Guide

Variables	Description
q_{ptdR}	←
$\bar{q}_{optdR}$	←
q_{optdR}	←
q_{optdF}	t2 ← t1 ←

TABLE III. Parameters Used in the Model

Parameters	Number (p_1, p_2)	Parameters	Number(p_1, p_2)
c_P	(3.374, 8.746)	l_P	(3.636, 2.095)
$\bar{c}_p$	(5.302, 3.807)	α	0.5
a_P	(15.078, 12.731)	β	0.3
b_P	(14.686, 13.411)	λ_1	10
$\bar{b}_p$	(12.700, 7.978)	λ_2	8
ρ_P	(549.166, 563.373)	λ_3	7
z_P	(1.346, 1.410)	θ_1	10
$\bar{z}_p$	(3.374, 8.746)	θ_2	6
m_P	(3.374, 1.218)	θ_3	5
e	3.283	U_1	500000
$\bar{e}$	1.126	U_2	600000
$\bar{x}_{Et}$	(986.690, 875.988)	U_3	500000
w_h	3000000	K_1	450000
w_P	3000000	K_2	500000
		K_3	300000

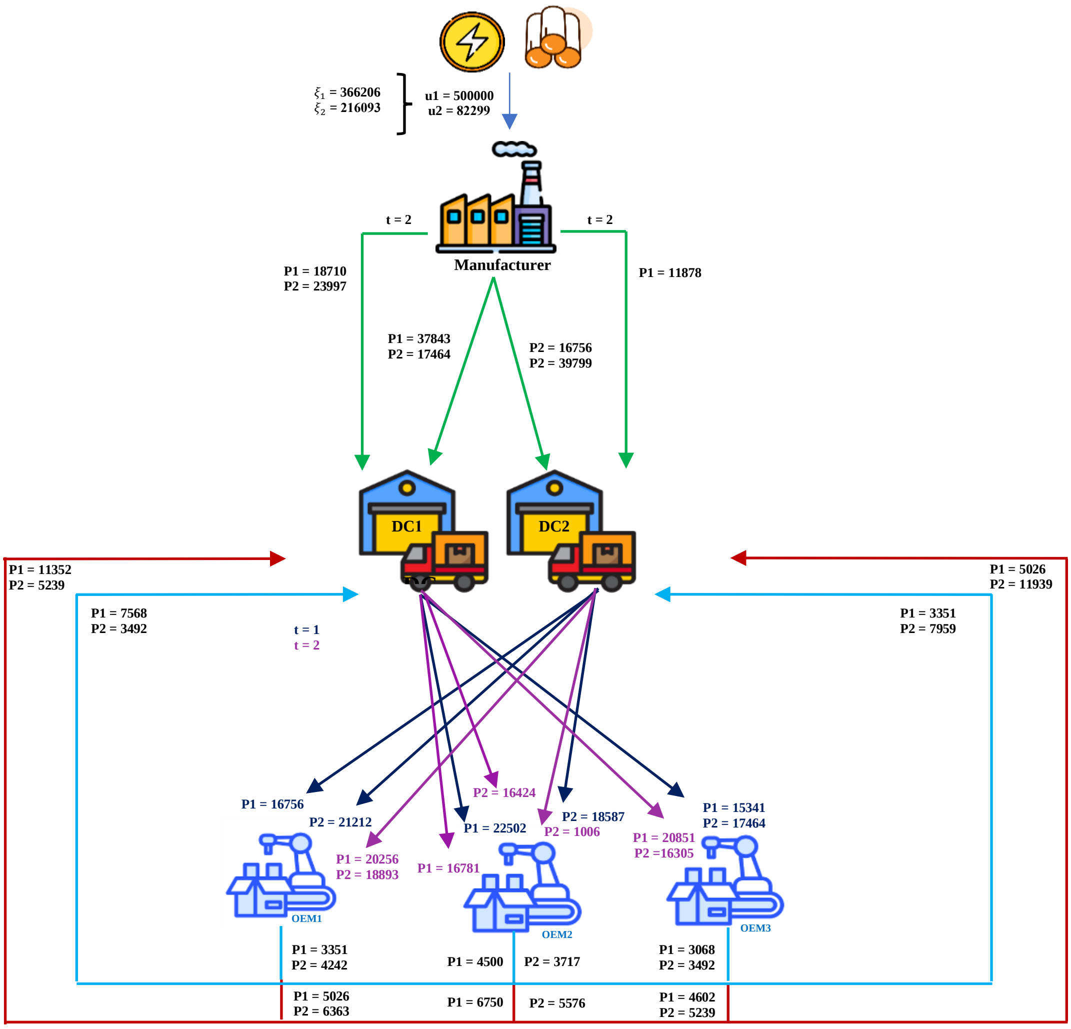

Fig. 3. Model Behavior in the Designed Scenario

TABLE IV. Transportation Costs and Demand Data

h_{opdF}			h_{opdR}		
(DC, OEM)	p_1	p_2	**(DC, OEM)**	p_2	p_2
1.1	4.338	3.792	1.1	3.276	4.001
1.2	4.799	8.850	1.2	7.351	5.483
1.3	2.537	6.002	1.3	4.878	4.812
2.1	9.985	6.630	2.1	3.052	3.201
2.2	9.929	8.098	2.2	6.713	8.647
2.3	3.046	7.118	2.3	3.847	7.326
$\bar{h}_{opdR}$			D_{pot}		
(DC, OEM)	p_1	p_2	**(DC, OEM)**	p_1	p_2
1.1	3.281	8.980	1.1	20256	22250
1.2	4.121	4.287	1.2	16781	15341
1.3	6.752	7.782	1.3	20851	21212
2.1	7.026	5.710	2.1	18893	18587
2.2	5.306	2.942	2.2	17430	17464
2.3	4.514	2.372	2.3	16305	24334

h_{pdR}		
DC	p_1	p_2
1	6.431	3.126
2	1.773	4.517

To compare the remanufacturing and non-remanufacturing models, a 10-period scenario was analyzed. The blue line shows the non-remanufacturing (open-loop) model, and the orange line shows the remanufacturing (closed-loop) model. Results indicate that remanufacturing significantly reduces total costs over time, demonstrating its superior long-term efficiency.

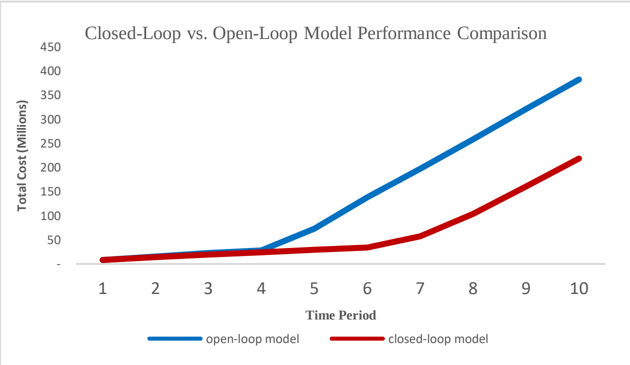

Fig. 4. Total Cost Trends Over 10 Periods: Open vs. Closed Loop

VI. Conclusion

The integration of remanufactured products and resource reutilization significantly reduces operational costs and provides notable economic and environmental benefits. The proposed model shows that incorporating reverse flows and remanufacturing lowers total supply chain costs by reducing raw material and energy usage, thus minimizing emissions and waste. A comparison between scenarios with and without remanufacturing reveals that excluding remanufacturing leads to higher costs and reduced system efficiency.

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