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Optimization Of a Sustainable Closed Loop Supply Chain Network (SCLSCN): A Modified NSGA-III Method

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ABSTRACT

For a generic closed-loop supply chain network (CLSCN), a mixed-integer Linear programing (MILP) Model was developed that simultaneously optimizes three of the fundamental elements of sustainability: cost, social impact, and environmental effect. Many real-world features of SC operations, which includes multiple products types, multiple echelons, multiple production technologies, and multiple modes of transportation, were all incorporated into the model during its development. As a result of the complexity of the model and need to provide Pareto front for decision maker, a novel hybrid NSGA III (HNSGA-III) was developed to solve the model. The Relative Gap was used result of the model was validated using the ε-constraint method. the algorithm parameters were tuned using Taguchi design then the performance of HNSGA III as compared to NSGA III, HypE and MOEA/D was assessed using RNS, SNS, IGD, CPU times and HC index. The result clearly shows the HNSGA III outperforms the other meta-heuristic algorithms.

Keywords: Closed loop supply chain network, Sustainability, CO2 Emission, Multi-objective model, HNSGA III, NSGA III, MOEA/D, HypE

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1. INTRODUCTION

"Supply chain Management (SCM)" According to Cardenas-Barron and Sana (2014), is defined as "the effective planning, execution, and control of all operations that involves the collective effort of the manufacturers, customers, warehouses, retailers, and suppliers". A supply chain, in its most basic level, is a collection of activities that work together to fulfill a customer request (Soleimani, Seyyed-Esfahani and Shirazi, 2018). It includes not only manufacturers and suppliers, but also transporters, warehouses, retailers, and customers. To update this definition, we must consider environmental impacts as well as social responsibilities, which leads us to consider "Reverse Logistics" of "end of life (EOL)" products (called return products). In order to ensure the sustainability of distribution chains, it is necessary to make decisions on operations meeting existing needs while ensuring that products will continue to be useful in the future. The concept of sustainability takes into account the impacts on society and the environment in addition to economic ones when making a decision.

The basis of our existence on Earth is provided by natural resources, including fertile land, water, energy, and materials. However, the quick consumption of these resources by humanity is seriously harming the ecosystem, leading to alterations in land use, the creation of toxic waste, and increased emissions into the air and water. Our lives will need to change to be more sustainable if we want to survive on this planet and safeguard its vulnerable eco-systems and supply of natural resources. Nowadays, it is acknowledged that economic growth and development have a detrimental impact on ecosystems. The swift depletion of non-biodegradable and toxic wastes, along with minerals and natural assets, has forced governments worldwide to respond. Globally, there is a growing shift or migration toward sustainable supply chain management. (Jinn et al., 2023).

The automotive sector is one of those that is now most ecologically conscious. The automotive sectors are switching from conventional *supply chains* to *CLSC* as a result of government-imposed strict environmental restrictions, such as sustainability, the obligation of producers in End-of-Life Vehicle (ELV) recovery, and emission laws of Gas (GHG). The *CLSC* management, which takes into account both social and environmental aspects, has grown enormously important for the automotive sector (Jinn, Nwosu and Shadrach, 2023). This research is aimed at optimizing a sustainable closed loop supply chain network using a modified metaheuristic approach (HNSGA III).

2. LITERATURE REVIEW

Fahimnia et al. (2013) developed an all-encompassing *MILP* model for a *CLSC* with which the amount of carbon emitted was evaluated in light of the impact of both the traditional chain and reverse *supply chain* and the resulting carbon dioxide emitted were expressed in terms of dollar carbon cost. For the purpose of *supply chain* evaluation and decision-making, including lot allocation and EOQ, under various carbon regulatory frameworks, Benjaafar, Li, and Daskin (2013) introduced new optimization frameworks almost simultaneously. You et al. (2012) utilized the "ε-constraint" technique to optimize the *supply chains* for sustainable cellulosic biofuels as an example of how to apply the method to *supply chain* optimization problems. Liu and Papageorgiou (2013) employed the ε-constraint method to effectively plan theproduction, distribution, and resource management of *supply chains* around the world. Under mixed uncertainty, Zhalechian, Tavokkoli-Moghaddam, Zahiri and Mohammadi (2016) created a *CLSC* with a location allocation, vehicle routing and inventory control.

A CLSC development issue was raised by Soleimani et al. (2017), involving different levels of facilities, such as, manufacturing facilities, warehouse centers, customer's zones, collection centers and return points. The model specifically reinforced three different alternatives for returns: the repatriation of raw materials, EOL product and recycled products.

Shi, Zhang and Sha (2017) created a MIP model with multiple objectives for the *CLSC* design. Cost and attentiveness of the network are both taken into account concurrently. Dehghan, Nikabadi, Amiri and Jabbarzadeh (2018) presented a systematic MIP model of a *CLSC* network problem for edible oil production. In this regard, blended uncertainties were taken into account. A multi-stage MIP model was developed by Baptista et al. (2019) for the design of a multi-period multi-product *CLSC* network. Model solving took into account risk management at various time periods. Zeballos, Mendez and Barbosa-Povoa (2018) utilizing Stackelberg game concept and a dual channel *CLSC* system, researchers looked into how advertising efficiency affected *supply chain* members' ability to make the best choices and reap the most financial rewards. Taleizadeh et al. (2018) employed a multiple phased MIP framework that blended with the concept of "Conditional Value at Risk (CVaR)" to address the problems of product andCLSC network design with multiple product.

Pourjavad and Mayorga (2018) presented a fuzzy model based on multiple objective "*mixed integer linear programming* (*MILP*)" for multiple periods and a multiple echelon "*CLSC* network" that concurrently optimizes the environmental effects, the cost of transportation and establishing facilities while increasing social impacts of the SC on the society. Zhen et al. (2019) described an integrated viewpoint for establishing a green and sustainable CLSC network. A model of bi-objective optimization was postulated. Atabaki et al. (2019) created a multi-stage closed-loop supply network that includes both dedicated and hybrid facilities and as a result, a MILP model was proposed to make location, allocation and pricing decisions. Dai and Lei (2019) proposed an improved decomposition-based multi-objective evolutionary algorithm with adaptive weight adjustment to solve the problem of a CLSC. Baptista et al. (2019) formulated a multiple stage MIP model for the design of a multi-period multiproduct CLSC network. Model solving took into account risk management at various time periods. Hasanov et al. (2019) created a four-tiered closed-loop supply chain (CLSC) with multiple customers, tier-one suppliers, tier two suppliers and a manufacturer. Leng et al. (2020) provided an overall structure for optimizing CLSC that addresses the encompassing lowered emission caps and location routing problem (LRP) using a cold chain as a case study. Goli et al. (2020) developed a multi-period, multi-product, and multi-level *CLSC* system that is sustainable. A new *MILP* framework for a green vehicle routing problem using temporary in-between depots that takes into account urban energy usage, roadway circumstances, uncertainty in demand and time frame for service delivery for goods that are perishable was presented by Tirkolaee et al. (2020).

A carbon market-based integrated LRIP model was proposed by Li et al. (2022). Katsoras and Georgiadis (2022) presented a System Dynamics (SD) based analysis for natural disasters on the operational efficiency of *CLSC*s. The dynamics at the level of the producer, components manufacturer, collection facility, and disassembly center are studied by means of this response, which is done by offering mechanisms for control for resolute *CLSC*s under an emergency impact. Because fish is so valuable in a household's food basket, it is perishable and recycling waste products is crucial, Fasihi et al. (2023) looked into a sustainable *CLSC* of fish products.

A decomposition-based algorithm using weight vectors during the evolution process was put forth by Junqueira et al. in 2022. The algorithm is referred to as *"Multi-Objective Evolutionary Algorithm based on Decomposition with Local-Neighborhood Adaptation (MOEA/D-LNA)"*. Through the *Generalized Position-Distance (GPD)* benchmark generator, sets of standard functions having inconsistent qualities is put forward in order to more accurately assess the adaptability of weight vectors. The suggested method is then contrasted with alternative approaches in the literature using three more sets of standard functions and a pair of distinct techniques for initializing weight vectors. Results from studies conducted on irregular Pareto fronts have been encouraging, particularly for pareto fronts that are inverted and have discontinuity.

A unified evolutionary optimization approach, called "U-NSGA-III", is suggested by Seada and Deb (2014) to solve all three of the aforementioned problem types (single objective, bi-objective and many objective). It is centered on the NSGA-III methodology that has been established for many objective situations. To better distribute costs across various demand consumer markets, social concerns, and unfavorable environmental effects (such as carbon dioxide emissions and discarded products), the epsilon constraint method was employed by Fasihi et al. (2023) to solve the multi-objective sustainable supply chain model.

Methodology

Problem Description

This research shall be carried out using the Closed loop SC designed and modelled by Jinn et. al. (2023 A system of closed loop supply chains (CLSCs) that is being studied is shown in Figure 1. Within the delivery chain (traditional chain), there are a number of suppliers ($s \in S$), distinct product/goods ($l \in L$), a number of of plants ($p \in P$), a set of markets or customer zone ($c \in C$), multiple DC's ($q \in Q$), three modes of transportation ($m \in M$), a set of collection facility ($k \in K$), some recycling plants for reprocessing returned items ($r \in R$), and disposal facilities ($w \in W$) for disposal. In Figure 1, the SC network is illustrated. More detail on model assumption, notation and formulation are presented in the Appendix.

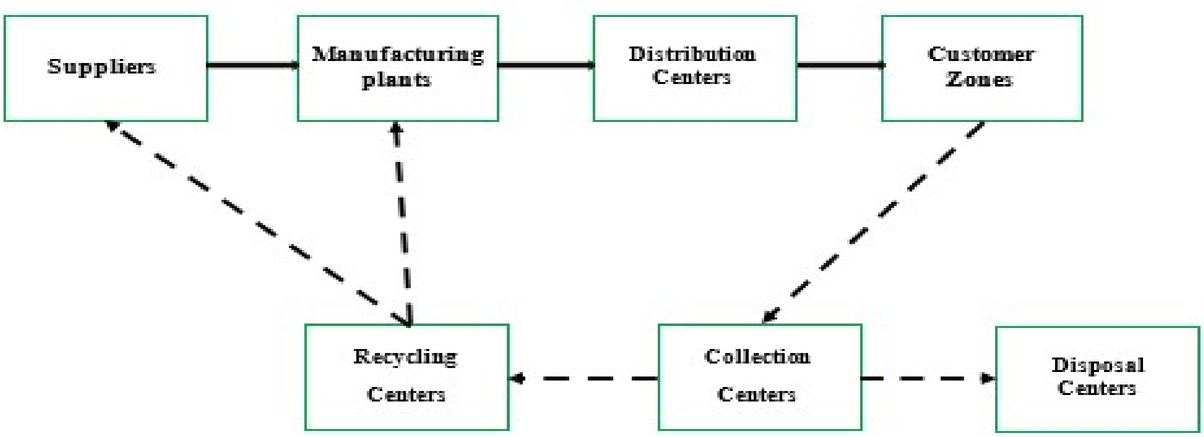

Figure 1: The Sustainable Closed Loop Supply Chain Network (SCLSCN)

The MILP Model for the CLSC

Equations (18) to (37) provide the model of the integrated closed loop supply chain network.

Minimize: $Z_1 = Z_{11} + Z_{12} + Z_{13} + Z_{14} + Z_{15}$ (1)

Minimize: $Z_2 = \rho^- e^- - \rho^+ e^+$ (2)

Maximize: $Z_3 = Z_{31} + Z_{32} + Z_{33} + Z_{34} + Z_{35} + Z_{36}$ (3)

Subjected to:

$$\sum_t QM_{plt} \leq \sum_{qm} QMD_{pqlm} \qquad \forall\, pl \tag{4}$$

$$\sum_{p,m} QMD_{pqlm} \leq \sum_{c,m} QDA_{qclm} \qquad \forall\, ql \tag{5}$$

$$\sum_{q,m} QDA_{qclm} \leq D_{cl} \qquad \forall\, cl \tag{6}$$

$$\sum_{k,m} QAC_{cklm} \leq D_{cl}\alpha_l \qquad \forall\, cl \tag{7}$$

$$\sum_{w,m} QCY_{kwlm} \leq \sum_{c,m} \gamma_l QAC_{cklm} \qquad \forall kl \tag{8}$$

$$\sum_{s,m} QSM_{splm} \leq \sum_{s,m} QRS_{rslm} + \sum_{s} QBY_{s,l} \qquad \forall\, p\ l\ r \tag{1}$$

$$\sum_{c.m} QAC_{c,klm} \leq \sum_{wm} QCY_{kwlm} + \sum_{rm} QCR_{krlm} \qquad \forall kl \tag{10}$$

$$\sum_{pm} QRM_{rplm} \leq \sum_{km} QCR_{krlm} \qquad \forall rl \tag{11}$$

$$\sum_{rm} QRM_{rplm} \leq \sum_{t} QM_{plt} \qquad \forall\, pl \tag{12}$$

$$\sum_{sm} QSM_{splm} \leq \sum_{t} QM_{plt} \qquad \forall\, pl \tag{13}$$

$$\sum_{l} S_l QM_{plt} \leq SM_{pt\,l} ZM_{pt} \qquad \forall\, pt \tag{2}$$

$$\sum_{plm} S_l QMD_{pqlm} \leq SD_{ql} ZD_q \qquad \forall\, q \tag{15}$$

$$\sum_{slm} SS_l QSM_{\mathrm{splm}} \leq \mathrm{SM}_{ptl} \mathrm{ZM}_{\mathrm{pt}} \qquad \forall\, k\ p \tag{16}$$

$$\sum_{klm} S_l QCR_{krlm} \leq SR_r ZR_r \qquad \forall\, r \tag{3}$$

$$\sum_{klm} S_l QCY_{kwlm} \leq SY_w ZY_w \qquad \forall\, w \tag{4}$$

$$\sum_{t} ZD_{pt} \leq 1 \qquad \forall\, p \tag{5}$$

$$\sum_{plt} EM_{plt}ZM_{pt} + \sum_{ql} ED_{ql}ZD_q + \sum_{kl} EC_{kl}ZC_k + \sum_{rl} ER_{rl}ZR_r + \sum_{pqlm} EMD_{pqlm}QMD_{pqlm} + \sum_{qclm} EDA_{qclm}QDA_{qclm} + \sum_{cklm} EAC_{cklm}QAC_{cklm} + \sum_{krlm} ECR_{krlm}QCR_{krlm} + \sum_{rplm} ERD_{rplm}QRD_{rplm} + \sum_{kwlm} ECY_{kwlm}QCY_{kwlm} + e^- \leq C^{cap} + e^+ \tag{20}$$

$$e^+, e^-, QMD_{pqlm}, QDA_{qclm}, QAC_{c.k.l.m}, QCR_{krlm}\ , QCY_{kwlm}, QRM_{rplm} \geq 0 \tag{21}$$

$$ZD_{pt}\ , ZC_k\ , ZR_r\ , ZY_w\ \in \{0,1\} \tag{22}$$

The model's constraints are expressed as equations (4) to (22). The constraint (4) guarantees the fact that the total quantity of product exiting every manufacturing facility does not exceed its capacity for production. Equation (5) ensures that the total the quantity of product exiting each distribution warehouse does not exceed the incoming flow of item at every single distribution warehouse. Equation (6) ensures that the total the quantity of goods leaving the DC warehouse must satisfy the demand of the consumer. Equation (7) represents a connection between demand from the market and goods rate of product return at the collection facility. Equation (8) describes the interactions between discarded quantity of goods and products that are returned to the collection facility. The flow of materials from suppliers to production facilities is balanced by equation (9). Equation (10) regulates the flow of product into and out of the collecting location. Equation (11) represents the balance equation for goods entering and leaving the recycling facility.

Equation (12) states that the flow out of each recycling facility cannot be more than the plant's capacity for output. Equation (13), which represents the flow balance equation from the suppliers to the production plants, is provided. Equation (14) suggests that each manufacturing plant's production capacity is not exceeded by the number of items produced during each planning period. Equation (15) ensures that the distribution center's total incoming flow is not greater than its capacity for holding the product type. Equation (16) represents a capacity limitation that guarantees that the supplier does not exceed the production plant's raw material requirements. Equation (17) assures that the total amount of used product returned to the collection center does not exceed the capacity of the collection center. Equation (18) assures that the total quantity of EOL product departing each collecting center to disposal centers does not exceed the capacity of the disposal center. Equation (19) assures that each possible plant site can only support one technology type. Carbon balance, Equation (20), The non-negativity restriction is expressed in Equation (21). Equation (22) limits the binary variables to either 0 or 1.

Solution Method

In multi-objective optimization, the solution should be spread across the pareto front. For a multi-objective problem, it might be challenging to quantify the distance between nondominated solutions hence, MOEA is proposed. The NSGA-III with slight modification shall be used. The performance of HNSGA-III shall be compared to that of NSGA-III, MOEA/D and HypE.

HNSGA-III

A consistent distribution of reference points is required for good solutions. The key difference between the NSGA III and HNSGA III is the reference points determination process. As previously stated, the reference point is a specific location in the goal space that, if selected appropriately, may serve as a suitable guide for the algorithm. The goal of this novel HNSGA III is to produce these points using an evolutionary bee algorithm. Equations (23) and (24) are used to generate dispersed reference points for solution *i* with respect to objective function *j*.

$$R_i^j = f_i^j(x) - \omega^j \qquad \forall\, j \in M \tag{23}$$

$$\omega^j = \vartheta(f_{max}^j - f_{min}^j) \tag{6}$$

where $0 < \vartheta < 1$ is a parameter, f_i^j is the value of objective function *j* in solution *i* and f_{min}^j and f_{max}^j and are the minimum and maximum values of the objective function j in set Q_t, respectively. $Ri = (R_i^1, R_i^2, \ldots, R_i^m)$ is the array of reference points for solution *i*. Considering the formed set of reference points to be Z^p. The crowding distance for reference point set R_p corresponding to solution member i is determined using Equation (25).

$$d_i = \sum_{j=1}^{m} d_i^{\mathrm{j}}, \qquad d_i^{\mathrm{j}} = \frac{|R_{k+1}^j - R_{k-1}^j|}{R_{\max}^j - R_{\min}^j} \tag{25}$$

If somehow, the number of enlisted bees per each site equals the parameter n_b in relation to crowding distance, it is possible to accept or reject this solution for future searches. Let $\pi(i)$ represent the chance of abandonment of member i and is presented in Equation (26).

$$\pi(i) = \begin{cases} 0.6 & d_i < 0.9 \\ 0.2 & 0.9 \le d_i \le 0.95 \\ 0.05 & 0.95 \le d_i \le 1.15 \\ 0 & d_i \ge 1.15 \end{cases} \tag{26}$$

The flow chart of the modified HNSGA-III is presented in Figure 1. In executing the flowchart, four algorithms are executed and they are described in Figures 2-6.

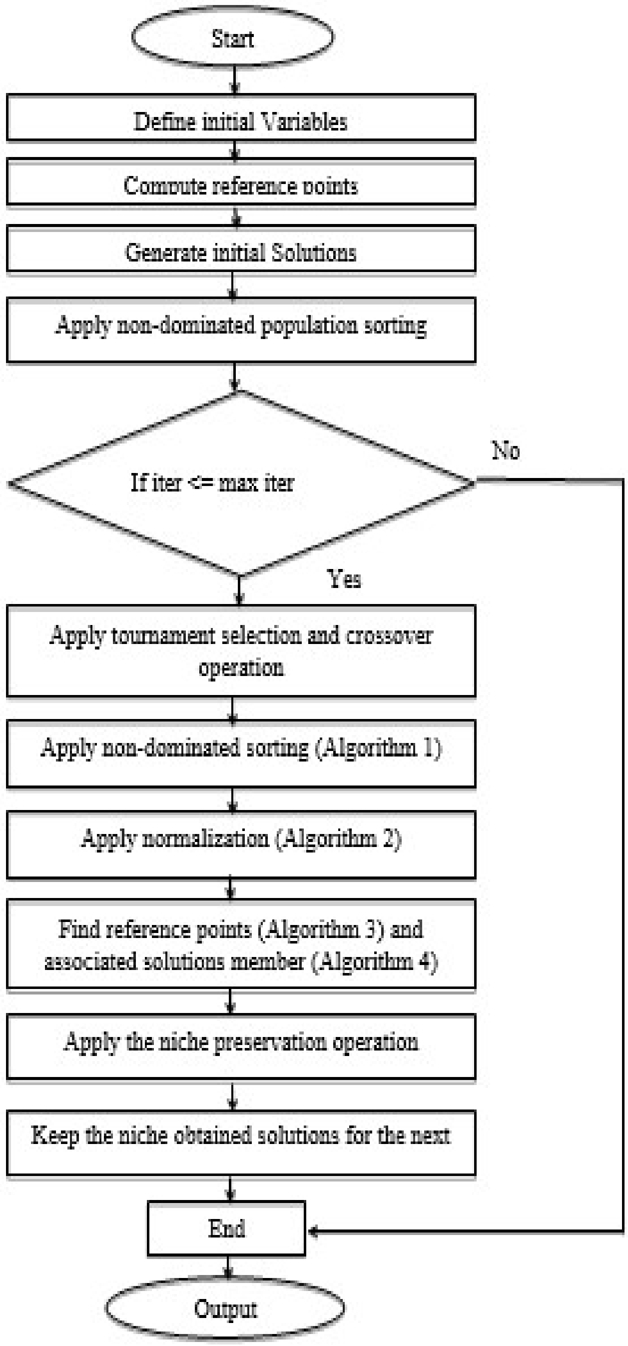

Figure1: Flow diagram of HNSHA-III procedure

Algorithm 1: Generation of t of NSGA-III Procedure

Input: H structured reference points Z^s or supplied aspiration points Z^a, parent population P_t

Output: P_{t+1}

1. Initialize: $S_t = \emptyset, i = 1$
2. Produce offspring population: Q_t =Reconbination+Mutation(P_t)
3. Combine Parent and Offspring population: $R_t = P_t \cup Q_t$
4. Sort the combined Population into non-dominated levels: $(F_1, F_2, \cdots) =$ non-dominated-sort (R_t)
5. **for** $i \leq N$
6. $S_t = S_t \cup F_i \,;\, i = i + 1$
7. **end for**
8. include last front: $F_l = F_i$
9. **if** $|S_t| = N$ **then**
10. $\boldsymbol{P_{t+1} = S_t}$
11. **else**
12. $P_{t+1} = \cup_{j=1}^{l-1} F_j$
13. Update points to include in the last front, F_l: $K = N - |P_{t+1}|$
14. Create Z^r by applying the normalize operator: Normalize $(f^n, S_t, Z^r, Z^s, Z^a)$
15. Apply the association operator: $[\pi(s), d(s) =$ associate (S_t, Z^r). π(s): closest reference point, d: distance between s and π(s)
16. Calculate the reference point niche count: $j \in Z^r : p_j = \sum_{s \in S_t/F_l}\big((\pi(s) = j)?\, 1{:}\,0\big)$
17. Apply the niche operator: Niching $(K, \rho_j, \pi, d, Z^r F_l, P_{t+1})$
18. **end if**

Figure 2: Algorithm I

Algorithm 2: Normalization Procedure of NSGA-III

Input: S_t, Z^s (structured points) or Z^a (supplied points)

Output: f^n, Z^r (reference points on normalized hyper-plane)

1. for $j = 1$ to M

2. compute ideal solution: $z_j^{min} = min_{s \in S_t} f_j(s)$

3. Translate the objectives: $f_j'(s) = f_j(s) - z_j^{min} \ \ \forall s \in S_t$

4. compute values of extreme point: $(z_j^{max}, j = 1,2,\cdots,M)$ of S_t

5. end for

6. Compute intercepts a_j for, $j = 1,2,\cdots,M$

7. Apply Equation (3.40) for normalizing objectives (f^n)

8. **if** Z^a is given **then**

9. Using Equation (3.40), map each supplied point on the normalized hyperplane and update the points inside the set Z^r

10: **else**

11: $Z^r = Z^s$

12: **end if**

Figure 3: Algorithm 2

Algorithm 3: CBA Procedure for reference point determination

Input Q_t, n_b

Output Z^r

1 Initialize Z^r using Equation (3.42)
2 Compute d_l using Equation (3.44)
3 Set $j = 1$
4 **while** $j \leq SC$ **do**
5   **for** $i \leq Q_t$ **do**
6   Compute crowding distance for each reference point
7   **if** $Rand(0,1) \leq \pi(i)$ **then**
8   this site should be accepted for further search
9             $\vartheta = 0.8 * \vartheta$
10   Improve this site (3.42)
11   Update Z^r
12   **else**
13   Reject solution site and move to 7
14   **end if**
15   **end for**
16 **end while**

Figure 4: Algorithm 3

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Results and Discussion

The numerical parameters data are utilized in the computation of the model are drawn from a uniform distribution considering their lowest and maximum values, as shown in Table 1. For the transfer and flow of goods within the SC network, three different types of shipment M=3). It's well knowledge that various means of transportation produce dramatically varied quantities of CO2 per ton mile. This is seen in Table 2.

Table 1. Selected Parameter Values for the SCLSCND.

Param	Values	Unit	Param	Values	Unit
$D_{c,l}$	Uniform (1500,5000)	Units	$SC_{k,l}$	Uniform (1500,4000)	Unit
$FM_{p,r1}$	Uniform (1500000,2000000)	Naira	$SR_{r,l}$	Uniform (1300,3500)	Unit
$FM_{p,r2}$	Uniform (2000000,3000000)	Naira	$SY_{w,l}$	Uniform (3000,6000)	Unit
FD_q	uniform (400000,600000)	Naira	$vo_{p,r}$	Uniform (50,70)	Unit
FC_k	uniform (140000,200000)	Naira	vo_v	Uniform (15,25)	Unit
FR_r	Uniform (500000,900000)	Naira	α_l	Uniform (0.3,0.5)	-
FY_w	Uniform (350000,500000)	Naira	γ_l	Uniform (0.10,0.15)	-
$fj_{p,r}$	Uniform (150,300)	Naira	p^-	100	N/kg
fj_v	Uniform (20,40)	Naira	p^+	200	N/kg
$SM_{p,l,r}$	Uniform (3000,6000)	Unit	C^{cap}	10000	kg
$SD_{q,l}$	Uniform (2000,3000)	Unit			

Table 2. The Cost and Emission of Different Transportation Modes.

Mode	Cost (N / ton-mile)	Emission factor (kg/ton-mile)
Road	.120	0.256
Rail	980	0.0342
water	900	0.0510

When the accuracy of the algorithms is confirmed, the results are reliable. The Epsilon-constraint (ε-constraint) method is used to validate the algorithm in this study. In this research, twenty target problem instances were used to access and compare the proposed algorithms performance. Table 3 shows the different dimension of instance used in this research. The set parameters and their levels of the proposed HNSGA III, NSGA III, HypE and MOEA/D algorithm are shown in Table.4.

Table 3. Different Model Configuration/Instances for Testing Meta-Heuristic Algorithms Performance.

Indices /Instances	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
S	1	1	1	2	2	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4
P	1	2	2	2	2	3	3	3	3	3	5	5	5	6	6	7	7	8	9	10
L	3	3	3	4	4	4	5	5	6	6	6	7	7	7	7	8	8	8	9	10
C	3	5	5	7	7	7	8	8	9	9	10	14	16	17	18	18	19	19	20	30
R	2	2	2	3	3	3	4	5	6	6	12	7	7	7	8	8	8	9	10	10
K	3	4	4	5	5	6	6	7	7	7	12	12	14	14	15	17	17	19	19	20
Q	3	3	3	4	5	5	6	6	6	6	18	22	25	27	28	31	32	31	32	33
W	1	2	2	2	2	3	3	3	3	3	10	10	12	12	12	13	13	14	14	15

Table 4. Algorithms Parameters and their Levels for Design of Experiment.

Algorithm	Parameters	Levels		
		1	2	3
HNSGA III	Population size, N_{pop}	20	30	50
	Rate of cross over, p_c	0.70	0.80	0.90
	Rate of mutation, p_m	0.20	0.25	0.30
	MaxGeneration, $maxGen$	200	300	500
NSGA III	Population size, N_{pop}	20	30	50
	Rate of cross over, p_c	0.70	0.80	0.90
	Rate of mutation, p_m	0.20	0.25	0.30
	Number of Generation,	200	300	500
HypE	Population size, N_{pop}	30	50	75
	Fitness parameter, k	0.1	0.2	0.3
	No. of sampling points, M	3500	5000	7000
	No. of offspring, N	30	40	50
MOEA/D	Population size, N_{pop}	30	50	75
	$N_{Subproblems}$	5	10	20
	Rate of cross over, p_c	0.70	0.80	0.90
	No. of neighbors, T	20	30	50

Validation of the HNSGA-III method

Table 5 presents the difference in values obtained from the NSGAIII and ε-constraint algorithms. The relative gap is presented computed using Equation (27). The average value of each of the objectives 1.18%, 1.02%, and 0.3% corresponding to objective functions one, two and three respectively, which are practically acceptable values demonstrate the efficiency of the HNSGA-III in solving the MILP.

$$Relative\ GAP = \frac{|Z_{NSGAIII} - Z_{exact}|}{Z_{ezact}} \tag{27}$$

Table 5. Validation of the HNSGA-III Algorithm with the Exact ε-constraint Method.

Problem number	HNSGA III			ε-constraint			Relative GAP		
	F1 (x10^6)	F2 (x10^6)	F3	F1 (x10^6)	F2 (x10^6)	F3	F1	F2	F3
1	153.32	38.93	4344	153.32	38.93	4343	0.0000	0.0000	0.0002
2	162.94	43.93	5230	164.73	44.43	5243	0.0110	0.0115	0.0026
3	174.02	47.93	5458	175.23	48.48	5488	0.0070	0.0115	0.0050
4	183.54	53.93	6013	183.58	54.38	6085	0.0002	0.0083	0.0114
5	194.12	57.93	6343	196.62	59.06	6366	0.0129	0.0196	0.0024
6	202.56	85.56	7234	209.47	86.49	7257	0.0341	0.0109	0.0023
7	212.74	87.56	7964	212.88	87.60	7974	0.0007	0.0005	0.0008
8	219.18	91.56	8343	219.68	93.57	8372	0.0023	0.0220	0.0036
9	226.34	95.56	9342	230.49	95.80	9361	0.0184	0.0026	0.0020
10	237.09	100.56	10971	-	-	-	-	-	-
Average	-	-	-	-	-	-	0.0118	0.0102	0.0030

Analysis of Taguchi design

Each meta-heuristic algorithm has some parameters on which its performance is highly dependent on. The algorithm's performance will improve if these parameters are correctly set. First, an analysis of variance which is a standard approach was used, followed by using the signal to noise (S/N) ratio for the same stages of the analysis. A Taguchi L9 design was recommended for all algorithms.

To interpret the results of the experiments, two criteria were defined: mean of means and signal to noise ratio (S/N). The main effect plot of the mean of means and the signal-to-noise ratios are presented in Figures 7-8 for the proposed HNSGA III algorithm. Following the completion of the Taguchi experiments for other algorithms, the selected values for the parameters of those algorithms are also shown in Table 6.

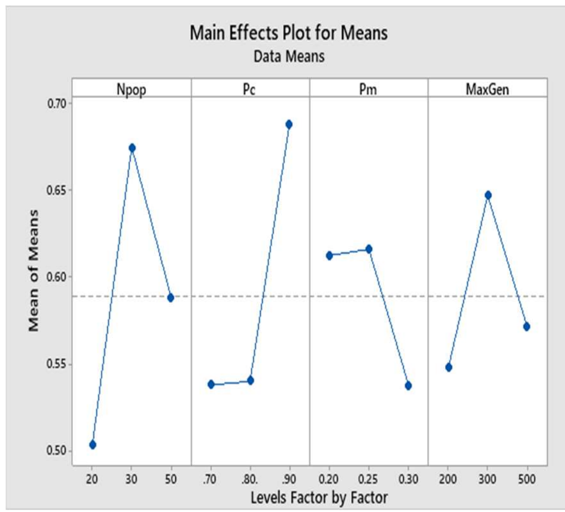

Figure 7: Plot of The Mean of Means.

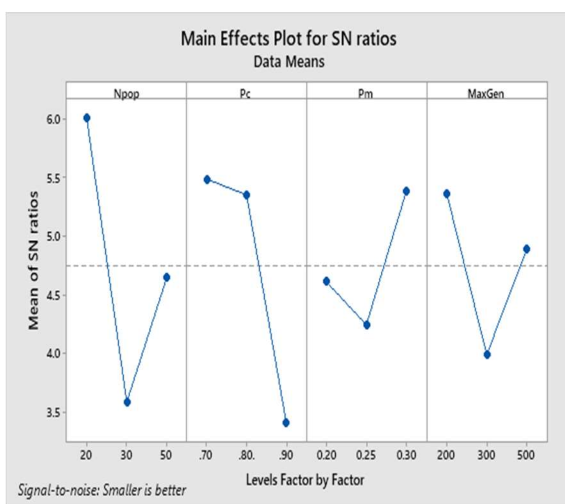

Figure 8: Plot of the Signal to Noise Ratio.

Table 6. Selected Parameters for the Algorithms after Taguchi Analysis.

HNSGA III	NSGA III	HypE	MOEA/D
$N_{pop} = 30$	$N_{pop} = 20$	$N_{pop} = 75$	$N_{pop} = 75$
$p_c = 0.9$	$p_c = 0.9$	$k = 0.2$	$N_{Subproblems} = 20$
$p_m = 0.3$	$p_m = 0.25$	$M = 5000$	$p_c = 0.8$
$MaxGen = 300$	$MaxGen = 500$	$N = 50$	$T = 30$

Using the tuned parameter of all algorithm presented in this research, the Pareto solution for problem instance five (5) is shown in Figure 9. Figure 9 shows proper diversity of solution for all algorithms under consideration.

Performance Assessment

The ratio of non-dominated solutions (RNS), inverted generational distance (IGD), spread of non-dominated solution (SNS)and CPU times (T_{CPU}) are used to access the performance of the Algorithms. The RNS, SNS, IGD are evaluated using Equation (28), (29) and (30) respectively.

$$RNS = \frac{|Q|}{N_{pop}} \tag{7}$$

where $|Q|$ is the size of the non-dominated solution set obtained from the population and N_{pop} is the size of algorithm population. It is very obvious that larger values of RNS (it values are ranged between 0 and 1 i.e., $RNS \in [0, 1]$) is desirable.

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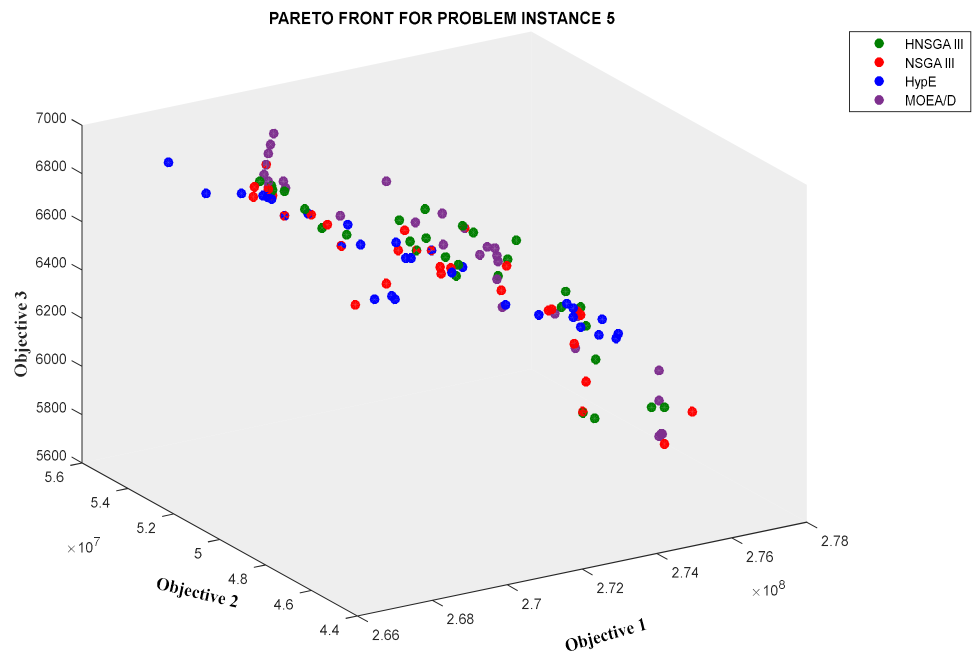

Figure 9: Pareto Front for Problem Instance 5.

$$SNS = \frac{\sum_{m=1}^{3} d_m^e + \sum_{i=1}^{|Q|}(d_i - \bar{d})}{\sum_{m=1}^{3} d_m^e + |Q|.\bar{d}} \tag{29}$$

With d_i being the Euclidean distances between neighboring solutions given the average value $\bar{d}$. The variable d_m^e is the length between the m^{th} objective function's extreme solutions of F^* and Q.

$$IGD(F^*, F) = \frac{\sum_{v \in F^*} d(v, F)}{|F^*|} \tag{30}$$

Where, $d(v, F)$ denotes the shortest Euclidean distance between v and F. The performance metrics for the HNSGA-III, NSGA-III, MOEA/D and HypE are presented in Table 7. For the HNSGA-III, NSGAIII, HypE, and MOEA/D algorithms, the average RNS index values are 0.64, 0.56, 0.49, and 0.52; for the SNS, the average values for this metrics are 0.63, 0.73, 0.75, and 0.86; for the metric IGD, the average values for this metric are 0.0072, 0.00866, 0.00937, and 0.00784; the Average CPU Time T_{CPU} are 530s, 494s, 963s and 850s respectively. To compare the algorithm based on all criteria discussed, the hybrid metric based on weighting criterion is employed using Equation (31).

$$HC = \frac{\sum_{i=1}^{k} C_i w_i}{\sum_{i=1}^{k} w_i} \tag{31}$$

The number of criteria is presented with k, C_i is the obtained criterion's value, and w_i is the criterion's weight as ascertained by the user.

The weights are: $w_{RNS} = 10,\ w_{IG} = 20, w_{SNS} = 10,\ w_{T_{CPU}} = 1$.

Because higher RNS index values are more favorable and lower values are recommended in this hybrid criterion, the value of RNS index must be reversed to establish the hybrid metric's consistency. Figure 4.8 shows the Hybrid criteria index for all four algorithms. As depicted in Figure 4.8, in small-sized problems, NSGA III algorithm performance is as good as that of the proposed algorithm. As the size of the integrated closed loop supply chain increases as described by the problem instances, better performance of HNSGA III becomes apparent. The proposed HNSGA-III clearly outperforms other three algorithms.

Table 7. Performance Assessment of Algorithms

problems	HNSGA III				NSGA III				HYPe				MOEA/D			
	RNI	*SNDS*	IGD	T	RNI	*SNDS*	IGD	T	RNI	*SNDS*	IGD	T	RNI	*SNDS*	IGD	T
1	0.62	0.60	4.97E-03	168	0.53	0.64	4.56E-03	180	0.51	0.68	4.76E-03	342	0.57	0.72	4.12E-03	328
2	0.66	0.71	5.15E-03	195	0.53	0.70	4.34E-03	201	0.37	0.72	5.27E-03	419	0.48	0.82	4.07E-03	393
3	0.53	0.61	4.33E-03	222	0.48	0.65	4.63E-03	231	0.43	0.63	5.66E-03	497	0.41	0.67	4.64E-03	438
4	0.53	0.66	5.98E-03	267	0.42	0.67	5.72E-03	272	0.50	0.68	6.41E-03	572	0.49	0.99	8.02E-03	490
5	0.56	0.62	6.36E-03	315	0.48	0.68	6.21E-03	317	0.35	0.63	8.35E-03	638	0.55	0.89	6.68E-03	555
6	0.79	0.73	7.09E-03	340	0.66	0.79	9.16E-03	357	0.60	0.83	9.83E-03	684	0.50	0.83	7.56E-03	593
7	0.56	0.72	7.30E-03	371	0.51	0.83	9.21E-03	390	0.45	0.85	8.28E-03	734	0.55	0.97	7.74E-03	668
8	0.69	0.61	7.62E-03	405	0.51	0.71	8.90E-03	434	0.60	0.78	1.02E-02	776	0.46	0.85	8.61E-03	735
9	0.79	0.65	7.93E-03	449	0.73	0.77	8.75E-03	465	0.46	0.77	1.11E-02	852	0.66	0.91	9.94E-03	780
10	0.75	0.64	6.64E-03	480	0.68	0.73	1.14E-02	498	0.65	0.76	8.92E-03	912	0.59	0.93	7.89E-03	854
11	0.80	0.71	6.76E-03	537	0.72	0.80	8.65E-03	519	0.49	0.78	8.90E-03	955	0.66	0.90	7.27E-03	895
12	0.66	0.70	7.22E-03	568	0.63	0.79	7.48E-03	542	0.54	0.86	9.32E-03	1035	0.48	0.82	6.63E-03	934
13	0.63	0.70	5.71E-03	624	0.62	0.83	7.78E-03	581	0.57	0.82	9.34E-03	1089	0.41	0.91	9.11E-03	977
14	0.54	0.61	9.51E-03	680	0.46	0.73	7.95E-03	604	0.43	0.84	1.01E-02	1176	0.41	0.88	7.30E-03	1038
15	0.55	0.51	6.23E-03	722	0.36	0.64	8.07E-03	644	0.49	0.64	9.22E-03	1257	0.42	0.73	7.56E-03	1080
16	0.51	0.56	8.45E-03	760	0.49	0.65	1.14E-02	666	0.45	0.69	1.09E-02	1346	0.49	0.94	8.93E-03	1124
17	0.67	0.52	8.47E-03	811	0.58	0.70	1.17E-02	688	0.58	0.68	1.21E-02	1389	0.67	0.89	9.50E-03	1184
18	0.74	0.51	9.50E-03	857	0.62	0.72	9.88E-03	726	0.60	0.75	1.34E-02	1456	0.58	0.77	9.86E-03	1256
19	0.59	0.59	8.57E-03	892	0.56	0.80	1.29E-02	766	0.41	0.84	1.22E-02	1539	0.56	0.82	1.06E-02	1318
20	0.71	0.56	9.56E-03	934	0.66	0.78	1.45E-02	799	0.37	0.76	1.32E-02	1599	0.49	0.93	1.07E-02	1365
Average	**0.64**	**0.63**	**7.17E-03**	**530**	**0.56**	**0.73**	**8.66E-03**	**494**	**0.49**	**0.75**	**9.37E-03**	**963**	**0.52**	**0.86**	**7.84E-03**	**850**

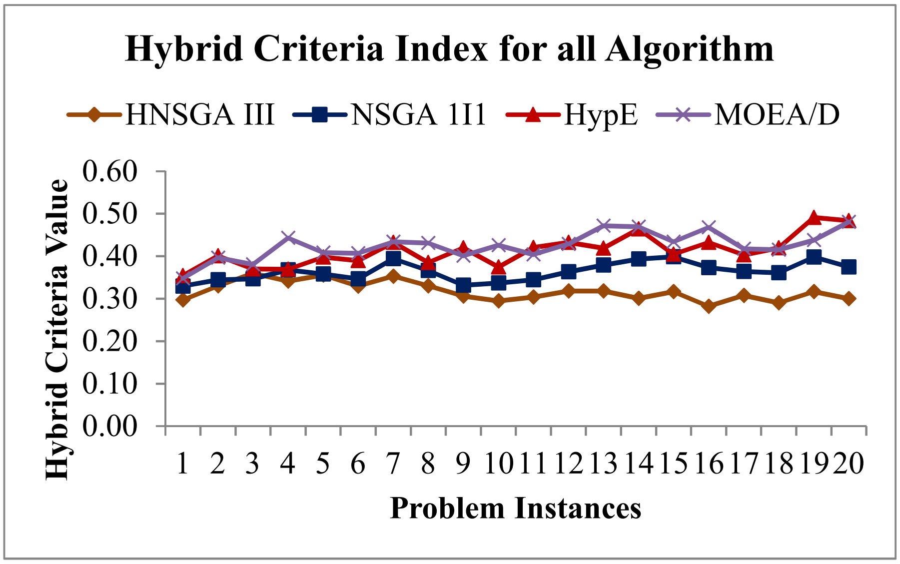

Figure 10: Hybrid Criteria Performance Index

4. CONCLUSION

The following conclusions can be drawn from this study:

i. The developed MILP model is capable of solving the Problem of the closed loop supply chain. The HNSGA III Algorithm was capable of solving and optimizing MILP model of the network design.
ii. Parameters of meta-heuristic algorithms for solving CLSC network designs should be tuned for better performance.
iii. The HNSGA III out performed other meta heuristic algorithm and should be considered first when assessing the performance of other meta heuristic algorithms.

Future research of the study should include the comparison of other Meta-Heuristic algorithms performance to the proposed HNSGA-III method.

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APPENDIX

Model Assumptions

In the network configuration, the following assumptions will be made:

i. All facilities in the chain are known in relation to the number, capacity and potential location.
ii. The rate of return of used products/goods for each customer zone and the mean disposal rate are predetermined.
iii. Flows between two successive stages are authorized. There are also no concurrent flows among facilities.

Model Notations

The following notations are used in formulating the Mixed Integer Linear Programming (MILP) models to describe the above-mentioned SCLSC network:

Sets/indices:

s	Index of supplier, $s \in S$.
p	Index of prospective sites for production plant, $p \in P$.
q	Index of prospective sites for distribution center, $q \in Q$.
c	Index of customer zones, $c \in C$.
k	Index of collection facilities, $k \in K$.
r	Index of recycling facilities, $r \in R$.
v	Index of facilities $v \in \{q, k, r, w\}$.
w	Index of disposal facilities, $w \in W$.
l	Index of products $l \in L$.
m	Index of modes of transportation, $m \in M$.
t	Index of production technologies, $t \in T$.

Parameters:

D_{cl}	Customer demand at customer zone c of product l.
R_{cl}	Rate of Return of used product l from customer zone c.
FS_s	Fixed cost of maintaining supplier contracts for s.
FM_{pt}	Fixed cost of establishing a plant at site p with technology t.
FD_q	Fixed cost of establishing site q.
FC_k	Fixed cost of establishing site k.
FR_{rt}	Fixed cost of establishing site r with technology t.
FY_w	Fixed cost of establishing and running the disposal center at location w.

Capability of facilities:

S_l	Capacity of supplier s for supplying raw material for product l.
SS_l	Capacity of p for manufacturing product l with technology t.
SS_{sl}	Capacity of q for holding product l.
SD_{ql}	Capacity of k for collecting returned product l.
SR_{rl}	Capacity of r for recycling product l.
SM_{plt}	Capacity of w for disposing scrapped product l.
SC_{kl}	Unit volume of product l.
SY_{wl}	Unit volume of raw material for product l.

Unit cost:

CS_{spl}	Unit supply cost of raw material for product l from supplier s to manufacturing plant p.
CM_{plt}	Unit manufacturing cost of product l at p with Technology t.
CC_{kl}	Unit collection and inspection cost of returned product l at k.
CR_{rl}	Unit recycling cost of product *l* at *r.*
CY_{wl}	Unit disposal cost of scrapped product *l* at *w*.
CSM_{splm}	Unit transportation cost of raw material for product l shipped from *s* to *p* using mode m.
CMD_{pqlm}	Unit transportation cost for product *l* shipped from *p* to *q* using mode *m.*
CDA_{qclm}	Unit transportation cost for product *l* shipped from *q* to c using mode m.
CAC_{cklm}	Unit transportation cost for retuned product *l* shipped from *c* to *k* using mode m.
CCR_{krlm}	Unit transportation cost for recyclable product *l* shipped from *k* to *r* using mode m.
CRM_{rplm}	Unit transportation cost for recycled product *l* shipped from *r* to *p* using mode m.
CCY_{rwlm}	Unit transportation cost for recycled product *l* shipped from *r* to *w* using mode m.
CRS_{rslm}	Unit transportation cost of recycled product *i* shipped from *r* to *s* using mode m.
α_l	Return ratio for used product *l*
γ_l	Disposal ratio for used product *l*

Parameters related to job creation:

fj_{pt}	Fixed job opportunities created by establishing plant center p with technology t.
fj_v	Fixed job opportunities created by establishing facility *v*, $v \in \{q, k, r, w\}$.
vo_{pt}	Variable job opportunities created at manufacturing at center p with technology t.
vo_v	Variable job opportunities created through working of facility *v*, $v \in \{q, k, r, w\}$.

Parameters related to CO_2 emission:

EM_{lpt}	Carbon emission (kg/unit) for manufacturing product l at p with technology t.
ED_{ql}	Carbon emission (kg/unit) of handling a unit of product l at distribution facility q.
ER_{rlt}	Carbon emission (kg/unit) of recycling a unit of product l at recycling facility r.
EC_{kl}	Carbon emission (kg/unit) in handling a unit of returned product l at collection facility k.
EMD_{pqlm}	Carbon emission (kg/unit) of moving product l from p to q using m
EDA_{qclm}	Carbon emission (kg/unit) of moving product l from q to c using m.
EAC_{cklm}	Carbon emission (kg/unit) of moving returned product l from c to k using m.
ECR_{krlm}	Carbon emission (kg/unit) for moving recyclable product l from k to r using m.
ECY_{kwlm}	Carbon emission for moving scrapped component of product l from k to w using m.
ERM_{rplm}	Carbon emission (kg/unit) for moving recycled components of product l from r to p using m.
ERS_{rslm}	Carbon emission measured in (kg/unit) of moving recycled components of product l from r to s using m.
C^{cap}	Fixed carbon emission cap in kg over the entire planning period.
ρ^+	The price of selling carbon per unit (kg) in the carbon trade.
ρ^-	The price of buying carbon per unit (kg) in the carbon trade.

Decision Variables

Binary variables:

ZS_s	1 if Supplier s is selected, otherwise, 0
ZM_{pt}	1 if manufacturing plant, p is open with Technology, t otherwise, 0.
ZD_q	1 if distribution facility, q is open, otherwise, 0.
ZC_k	1 if collection facility, k is open, otherwise, 0.
ZR_r	1 if recycling facility, r is open, otherwise, 0.
ZY_w	1 if disposal site, w is open otherwise, 0.
ZA_{qc}	1 if customer zone c is open to distribution center q, otherwise, 0.
ZA_{kc}	1 if collection center is open to customer zone c, otherwise, 0.

Continuous variables:

QBY_{sl}	Quantity of raw material out sourced by s for product l.
QSM_{splm}	Quantity of raw material for product l shipped from s to p using mode m.
QM_{plt}	Quantity of product l manufactured in production plant p using technology t.
QMD_{pqlm}	Quantity of product l shipped from p to q using mode m.
QDA_{qclm}	Quantity of product l shipped from q to c using mode m.
QAC_{cklm}	Quantity of returned product l shipped from c to k using mode m.
QCR_{krlm}	Quantity of recycled product l shipped from k to r using mode m.
QRM_{rqlm}	Quantity of recycled product l shipped from r to q using mode m.
QRS_{rslm}	Quantity of recycled product l shipped from r to s using mode m.
QCY_{kwlm}	Quantity of scrapped product l shipped from k to w using mode, m.
e^+	Amount of Carbon purchased.
e^-	Amount of carbon sold.

Cost Objective

The economic objective is expressed in terms of operational cost of the integrated *"supply chain network"*. The total cost is expected to be the sum of all costs incurred in the *supply chain* over the planning horizon. They are fixed cost of running and establishing facilities, cost of producing products, cost associated in collection and inspection of returned products, cost of recycling retuned product, cost of transporting manufactured goods and returned product throughout the network and cost of disposal. The fixed cost is the sum of fixed cost of maintaining supplier's contracts, opening the manufacturing facilities, distribution warehouses, inspection/collection facilities, recycling plant, disposal sites and supplier. It is given by Equation (1).

The fixed cost of establishing facilities is given by Equation (1).

$$Z_{11} = \sum_{s} FS_s ZS_s + \sum_{p,t} FM_{p,t} ZM_{p,t} + \sum_{q} FD_q ZD_q + \sum_{k} FC_k ZC_k + \sum_{r} FR_{r,t} ZR_r + \sum_{w} FY_w ZY_w + \sum_{s} FS_s ZS_s \quad (8)$$

The production cost is presented in Equation (2).

$$Z_{12} = \sum_{plt} CD_{plt} QM_{plt} \quad (9)$$

The collection and inspection cost of end-of-life product *l* is given by Equation (3).

$$Z_{13} = \sum_{cklm} CC_{kl} QAC_{cklm} \tag{10}$$

The cost of recycling the end-of-life product *l* is given by Equation (4).

$$Z_{14} = \sum_{rplm} CR_{rl} QRM_{rplm} \tag{11}$$

The cost of disposal of end-of-life product *l* is given by Equation (5).

$$Z_{15} = \sum_{kwlm} CY_{wl}\, QCY_{kwlm} \tag{12}$$

The transportation cost of the entire loop is given by Equation (6).

$$\begin{aligned} Z_{16} = \sum_{splm} CSM_{splm} QSM_{splm} + \sum_{pqlm} CMD_{pqlm} QMD_{pqlm} + \sum_{qclm} CDA_{qclm} QDA_{qclm} \\ + \sum_{cklm} CAC_{cklm} QAC_{cklm} + \sum_{krlm} CCR_{krlm} QCR_{krlm} \\ + \sum_{rplm} CRM_{rplm} QRM_{rplm} \\ + \sum_{kwlm} CCY_{kwlm} QCY_{kwlm} + \sum_{rslm} CRS_{rslm} QRS_{splm} \end{aligned} \tag{13}$$

The cost of supply of raw material is given by Equation (7).

$$Z_{17} = \sum_{splm} CS_{spl} QSM_{splm} \tag{14}$$

The cost objective which is expected to minimize the operational cost of the supply chain is given by Equation (8).

$$Z_1 = Z_{11} + Z_{12} + Z_{13} + Z_{14} + Z_{15} + Z_{16} + Z_{17} \tag{15}$$

Carbon Objective

The carbon emission objective provided by Equation (9) aims to optimise the total carbon dioxide emissions of the integrated closed loop supply chain.

$$Z_2 = \rho^- e^- - \rho^+ e^+ \tag{16}$$

Social Objective

Equation (10) demonstrates the social aspects of employment options that should be optimized.

$$Z_3 = Z_{31} + Z_{32} + Z_{33} + Z_{34} + Z_{35} + Z_{36} + Z_{37} \tag{17}$$

Equation (11) gives the fixed employment opportunities for the production plant.

$$Z_{31} = \sum_{pt} fj_{pt}\, ZM_{pt} \tag{18}$$

Equation (12) presents the fixed job opening for establishing other facilities in the supply chain network.

$$Z_{32} = \sum_{q} fjD_q ZD_q + \sum_{k} fjC_k ZC_k + \sum_{r} fjR_r\, ZR_r + \sum_{w} fjY_w ZY_w + \sum_{s} fjS_s ZS_s \tag{19}$$

Equation (13) represents the variable employment opportunity pertaining to the quantity of good manufactured.

$$Z_{33} = \sum_{p,t,l} vo_{p,t} QM_{p,l,t} / SM_{p,l,t} + \sum_{p,t,r,q,l,m} vo_{p,t} QRM_{r,q,l,m} / SM_{p,l,t} \tag{20}$$

The variable employment opportunity created as a result of Quantity of raw material supplied is presented in Equation (14).

$$Z_{34} = \sum_{s} vo_s QBY_{sl} / SS_{sl} + \sum_{rslm} vo_s QRS_{rslm} / SS_{sl} \tag{21}$$

The variable job created in regards of distribution and goods sold are presented in Equations (15) and (16) respectively.

$$Z_{35} = \sum_{qclm} vo_q QMD_{pqlm} ZA_{qc} / SD_{ql} \tag{22}$$

$$Z_{36} = \sum_{kcl} vo_k ZA_{kc} \alpha_l D_{cl} \tag{23}$$

Other variable jobs created as a result of flow of material is given by Equation (17).

$$Z_{37} = \sum_{cklm} vo_k QAC_{cklm} / SC_{kl} + \sum_{krlm} vo_r QCR_{krlm} / SR_{rl} + \sum_{kwlm} vo_w QCY_{kwl,m} / SY_{wl} \tag{24}$$