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A Meta-Heuristic Approach to Design an Agricultural Closed-Loop Supply Chain Network

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Abstract

This paper introduces a streamlined sugarcane supply chain network (SSCN) aimed at efficiently managing the substantial by-products of the sugar industry, with the primary objective of seamlessly reintegrating them into the supply chain with minimal alterations. The effective management of these by-products is crucial for minimizing overall operational costs. To tackle the inherent complexity of supply chain challenges, commonly utilized meta-heuristic techniques such as Genetic Algorithm (GA) and Particle Swarm Algorithm (PSO). Validation of the proposed approach is carried out through a real-world case study, while hypothetical test scenarios are utilized to further underscore its reliability. The results highlight a promising balance between solution effectiveness and computational efficiency, underscoring the viability of the approach.

Keywords
Optimization, Closed loop supply chain, Sugarcane supply chain.

1. Introduction

Supply chain is the effective management of goods from producers to the consumers. Managing the effective flow of these goods constitutes the supply chain management that helps in making money and the acceptance of the product by the consumers measures the success rate. The major capital of any firm is invested on the supply chain so the original equipment manufacturer (OEM) designs their supply chain in such a manner that it can compete effectively in the market with the other competitors see (Hajiaghaei-Keshteli, Mostafa, and Amir Mohammad, 2018). The supply chain is nothing but the effective management of goods from source to destination without compromising the need of the consumers. In contrary to this, the Reverse Logistic (RL) helps in collecting those parts or products and bringing back to the initial chain after its use. Recovering this reclaimable parts help in cut down the total production cost to some extent. Jayaraman *et al.* (1999) focused on collecting the cores for reverse logistics considering the case of demand uncertainty. Brito and Dekker *et al.* (2004) presented a study on the reverse logistics stating that what type of products are flowing back and how they can be recovered and who is executing and managing the various operations. Many government legislations are actively focusing on varies countries where during the design of a product itself manufacturers are responsible for the disposal of product after use Soo *et al. (2018*) and Cremiato *et al. (2018)*

Close Loop Supply Chain (CLSC) is the linkage between the forward logistics (FL) and reverse logistics (RL). It also helps in managing the waste throughout the value chain. From the last two decades various studies reported highlights the need of the closed loop. Kannan et al. (2010) presented a model for lithium-ion battery recovery. Das and Nayak (2017) presented a model for the rice supply chain and considered uncertainty in distribution. Santosh et al. (2017) presented a multi-echelon model for the Cartridge supply chain. Cheraghalipour et al. (2018) proposed a citrus CLSC for the waste fruits from each echelon and vermicomposting of the spoiled fruits to produce manure.

Sugarcane is a tropical perennial grass and important food crop worldwide. It majorly grows in tropical and subtropical regions. Stems turn into cane once it become mature. Cane being a fibrous material can become a raw material for some other industries such as power and paper industry Cordeiro *et al. (2009*). Sugar industry utilizes sugarcane as raw material which is processed and turned into the white sugar crystals. Sugarcane industry produces three by-products press-mud, bagasse and molasses, all of three wastes have some usefulness and can be utilized further Paturau and J. Maurice (1989).

Any Closed Loop Supply chain network is based on the type of product that is returned. To reuse the collected product reuse options can be Recovery, Repair, Refurbish, Remanufacturing, and recycling. The concept of sustainability and green supply chain has forced companies to recover values from the used products. The industries in the developed countries strongly believe that these recovery options are good strategies to improve their business as they could profit from them. The extensive by product of any agricultural waste is a concern to the environment and considered a loss if not made profitable by value extraction from the by-products (Heshmati and Almas, 2016).

In a nutshell, this paper deals with design of a new and efficient supply chain model that will consider the waste coming out from the factory and how that waste can be utilized by bring back it into the initial value chain. Considering this, for the very first sugarcane supply chain (SSC) model has been proposed.

The rest of the paper is organized as follows. In section 2, the intended literature review is presented. Section 3 explains the problem definition and section 4 shows the model formulation. Section 5 conclude the effectiveness of the designed supply chain network.

2. Literature Review

Many literatures have been reported that considers the cost minimization of a closed loop supply chain. It may or may not highlights the economical, socials and environmental issues. This proposed work is novel and reported for the very first time in agriculture supply chain. SSC Model is very efficient and includes the recycling of the waste by-product from the sugarcane industry, so that the literature review presented here also contain the survey of agriculture supply chain.

2.1 Agriculture Supply Chain

Agriculture is the primary source of the livelihood of any country. The large amount of the population depends on it [6]. The agricultural goods can be of perishable and non-perishable type. Goods which can spoil within short period of time comes under perishable goods such as seafoods, eggs, meat and poultry etc. while those can last for a long period are non-perishable such as pulses, rice, canned goods.

This work includes a sugarcane supply chain model so that literature survey focusing the agricultural supply chain is presented. Romero (2000) proposed a Risk minimization model for handling the decisions in agricultural problems. Timely harvesting model for orange is presented by Caixeta (2006) helps in achieving the good quality fruits. Agri food production and distribution model presented by Ahumada and Villalobos (2009) is the early study of the last two decades. Fuzzy goal programming approach for rice supply chain model is presented by Dinesh et al. (2009), to maximize the rice yield a proper combination of fertilizer is needed set as fuzzy goal and genetic algorithm is used to solve the problem.

2.2 Closed Loop Supply Chain

Constant consumption of the goods and coming out waste has now become a serious issue for the people and for the society. It is required to recycle the end of use (EoU) and end of life (EoL) waste so that pilling of such waste and the pollution can be controlled. Guide et al. (2003) highlighted the challenges of closed loop shown how a waste product can be useful for value chain. A closed loop model addressing the case of battery case study proposed by Kannan et al. (2010) model had a lack of dataset Subramanian et al. (2010) presented another work by modifying the dataset.

Closed loop model is widely accepted model for design of any supply chain since it helps in minimizing the total cost of chain in addition to this also reduces the environment pollution. Santosh and Shahul (2016) presented a study on environment conscious CLSC for product recovery developed model also included vehicle routing option to minimize cost as well as emission. CLSC problems are complex problems the general solver cannot.

solve the large size problem so to overcome with this problem Various meta-heuristic techniques are also used to solve these types of the problem. The solution obtained with this type of approach usually gives near optimal solution it never promises a best solution Chouhan *et al. (2017*). Sahebjamnia et al. (2018) proposed a sustainable tire CLSC model for scrap tires used four new hybrid metaheuristics algorithms. Hajiaghaei-Keshteli and Fathollahi-Fard (2018) designed sustainable CLSC network for discount supposition on transportation cost where, solution methodology includes hybrid metaheuristics to evaluate the better performance.

3. Problem Definition

This work is a novel work in the field of agriculture supply chain. The model is an efficient closed loop for a sugarcane industry which is an effort to reduce the waste in the factory simultaneously will also help in reducing the overall supply chain. The model is comprising of both FL and RL where FL consists of producer, storage units, sugar refineries, distribution units and other industries while the RL includes the fertilizer units, fertilizer markets.

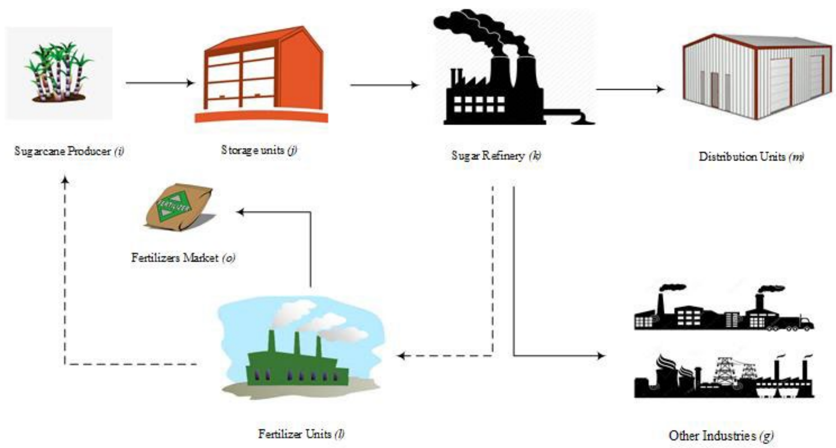

Figure 1. Sugarcane Supply Chain (SSC)

As shown in the Figure 1, In forward logistics the grown sugarcane after getting mature harvested in huge capacity and transported to the storage units. The stored canes sent to the sugar refinery where juice is extracted, and the left-out cane part know as bagasse is sent the other unit which is fibrous materials used by the power and paper-pulp industry. Industrial process of converting sugarcane juice to sugar is a typical process and utilizes several stages to come up with fine sugar crystal. Initially the extracted juice is heated and filtered the first by-product comes is filter mud or press mud then the remaining thin is moved sent to the three stages of centrifugation and boiling where the finally we get sugar as well as another by-product molasses.

4. Model Formulation

i	Index of production locations, $I \in \{1,2\ldots\ldots I\}$
j	Index of storage locations, $j \in \{1,2\ldots\ldots J\}$
k	Index of processing unit locations, $k \in \{1,2\ldots\ldots K\}$
m	Index of distribution unit locations, $m \in \{1,2\ldots\ldots M\}$
l	Index of fertilizer unit locations, $l \in \{1,2\ldots\ldots L\}$
o_1	Index of fertilizer markets, $o_1 \in \{1,2\ldots\ldots O\_1\}$
o_2	Index for some of producers and gardeners as fertilizers customers, $o_2 \in \{1,2\ldots\ldots O\_2\}$
O	Index of fertilizers customers locations, $O \in \{ o_1 + o_2 \}$

g other industry location

4.1 Parameters

f_j Fixed cost of opening storage units
f_k Fixed cost of opening sugar refinery units
f_m Fixed cost of opening distribution units
f_l Fixed cost of opening fertilizer units
Cx_{ij} Shipping cost per unit of products from producer i to storage unit j
Cu_{jk} Shipping cost per unit of products from storage unit j to sugar refinery unit k
Cp_{km} Shipping cost per unit of products from sugar refinery unit k to distribution unit m
Cv_{kg} Shipping cost per unit of products from sugar refinery unit k to other industry g
Ce_{kl} Shipping cost per unit of products from sugar refinery unit k to fertilizer units l
Cf_{lo} Shipping cost per unit of products from fertilizer units l to fertilizer market o
Ch_t Holding cost per unit of inventory (Sugarcane) from storage units j at time t
Cb_t Holding cost per unit of inventory (white sugar) from distribution units m at time t
Cp'_t Production cost per unit of product (sugarcane) from producers i
Ck'_t Processing and packaging cost per unit of products (white sugar) from sugar refinery unit k at time t
Cl'_t Fertilizer manufacturing cost per unit of product from fertilizer units l at time t
d_{mt} Demand of processed product (sugar) by distribution unit m at time t
d_{ot} Demand of reprocessed product (fertilizers) by fertilizer markets o at time t
μc_{it} Maximum production capacity of producer i at time t
μh_{jt} Holding capacity of storage units j at time t
μb_{mt} Holding capacity of distribution units m at time t
μr_{lt} fertilizer manufacturing capacity of fertilizer units l at time t
β_t Percentage waste bagasse from the sugar refinery unit k at time t
θ_t Percentage waste Press-mud and molasses from the processing unit k at time t
$\emptyset$ Conversion rate of the waste product to the reprocessed product
M A Big Positive number

4.2 Decision Variables

X_{ijt} Quantity of product shipped from producer i to storage unit j at time t
U_{jkt} Quantity of product shipped from storage unit j to processing unit k at time t
P_{kmt} Quantity of product shipped from sugar refinery unit k to distribution unit m at time t
E_{klt} Quantity of product shipped sugar refinery unit k to fertilizer units l at time t
V_{kgt} Quantity of product shipped from sugar refinery unit k to other industry g at time t
F_{lot} Quantity of product shipped fertilizer units l to fertilizer market o at time t
q_{it} Quantity of production by producer i at time t
Ih_{jt} Quantity of stored raw sugarcane by storage unit j at time t
Ib_{mt} Quantity of stored processed sugar by distribution unit m at time t
V_j Equal to 1 if storage unit j is opened at location, 0 otherwise.
W_k Equal to 1 if sugar refinery unit k is opened at location, 0 otherwise.
Y_m Equal to 1 if distribution unit m is opened at location, 0 otherwise.
Z_l Equal to 1 if fertilizer unit l is opened at location, 0 otherwise.

Minimize total SSC Cost (Z) = Fixed opening costs (Z_1) + Transportation Costs (Z_2) + Holding cost (Z_3) + Production and Processing and packaging and reprocessing cost (Z_4)

$$\text{Min } Z = Z1 + Z2 + Z3 + Z4 \tag{1}$$

$$Z1 = \sum_{j=1}^{J} f_j * V_j + \sum_{k=1}^{K} f_k * W_k + \sum_{m=1}^{M} f_m * Y_m + \sum_{l=1}^{L} f_l * Z_l \tag{2}$$

$$Z2 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Cx_{ij} \times X_{ijt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Cu_{jk} \times U_{jkt} + \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{t=1}^{T} Cp_{km} \times P_{kmt} + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T} Ce_{kl} \times E_{klt} + \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{t=1}^{T} Cv_{kg} \times V_{kgt} + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} Cf_{lo} \times F_{lot} \tag{3}$$

$$Z3 = \sum_{j=1}^{J}\sum_{t=1}^{T} Ch_t \times Ih_{jt} + \sum_{m=1}^{M}\sum_{t=1}^{T} Cb_t \times Ib_{mt} \tag{4}$$

$$Z4 = \sum_{i=1}^{I}\sum_{t=1}^{T} Cp' \times q_{it} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} Ck'_t \times U_{jkt} + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} Cl'_t \times F_{lot} \tag{5}$$

4.3 Constraints

$$q_{it} \le \mu c_{it} \quad \forall i \in I, \forall t \in T \tag{6}$$

$$Ih_{jt} \le \mu h_{jt} \quad \forall j \in J, \forall t \in T \tag{7}$$

$$Ib_{mt} \le \mu b_{mt} \quad \forall m \in M, \forall t \in T \tag{8}$$

$$\sum_{o=1}^{O} F_{lot} \le \mu r_{lt} \ \forall l \in L, \forall t \in T \tag{9}$$

$$\sum_{k=1}^{K} V_{kgt} \le \beta_t \times \sum_{j=1}^{J} U_{jkt} \quad \forall k \in K, \forall t \in T \tag{10}$$

$$\sum_{l=1}^{L} E_{klt} \le \theta_t \times \sum_{j=1}^{J} U_{jkt} \quad \forall l \in L, \forall t \in T \tag{11}$$

$$\sum_{m=1}^{M} P_{kmt} \le (1 - \{\beta_t + \theta_t\}) \times \sum_{j=1}^{J} U_{jkt} \ \forall l \in L, \forall t \in T \tag{12}$$

$$\emptyset \times \sum_{k=1}^{K} E_{klt} = \sum_{o=1}^{O} F_{lot} \quad \forall l \in L, \forall t \in T \tag{13}$$

$$Ih_{j(t-1)} + \sum_{i=1}^{I} X_{ijt} = Ih_t + \sum_{k=1}^{K} U_{jkt} \ \forall j \in J, \forall t \in T \tag{14}$$

$$\sum_{m=1}^{M} P_{kmt} \le d_{mt} \ \forall m \in M, \forall t \in T \tag{15}$$

$$\sum_{l=1}^{L} F_{lot} \le d_{ot} \ \forall o \in O, \forall t \in T \tag{16}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} X_{ijt} \le M \times V_j \ \forall j \in J, \forall t \in T \tag{17}$$

$$\sum_{j=1}^{J}\sum_{t=1}^{T} U_{jkt} \le M \times W_k \ \forall k \in K, \forall t \in T \tag{18}$$

$$\sum_{k=1}^{K}\sum_{t=1}^{T} P_{kmt} \le M \times Y_m \ \forall m \in M, \forall t \in T \tag{19}$$

$$\sum_{k=1}^{K}\sum_{t=1}^{T} E_{klt} \le M \times Z_l \ \forall l \in L, \forall t \in T \tag{20}$$

$$V_j, W_k, Y_m, Z_l \in \{0,1\} \tag{21}$$

$$X_{ijt}, U_{jkt}, P_{kmt}, E_{klt}, V_{kgt}, F_{lot} \ge 0 \tag{22}$$

$$Ih_{jt} \ge 0, Ib_{mt} \ge 0, q_{it} \ge 0 \tag{23}$$

Constraint (6) ensures that the product from producer is less or equal to the maximum production rate. Constraint (7) ensures that inventory at storage unit in each period is less than or equal to maximum holding capacity of the storage unit. Constraint (8) ensures that inventory at distribution unit in each period is less than or equal to maximum holding capacity of the distribution unit. Constraint (9) and (16) finalize that, the quantity of the fertilizer shipped to the fertilizer markets in each period is less or equal to manufacturing capacity and demand of each fertilizer market. Constraint (10) ensures that the quantity of waste bagasse coming out of sugar refinery unit is less or equal to the beta times of the quantity of sugarcane U_{jkt} received by the sugar refinery unit. Constraint (11) ensures that the quantity of the press-mud E_{klt} coming out of sugar refinery unit is less or equal to the theta times of the quantity of sugarcane U_{jkt} received by the sugar refinery unit. Constraint (12) ensures that the quantity of the sugar produced by the sugar refinery unit is less or equal to (1 -{βt+θ_t}) times of the quantity of sugarcane U_{jkt} received by the sugar refinery unit. Constraint (13) shows that the amount of the press-mud received by the fertilizer unit multiplied by the conversion rate is equal to the total reprocessed product (fertilizer) sent to the fertilizer market. Constraint (14) ensures that each storage unit inventory level in each period is equal to previous period inventory plus the quantity of products received from producer minus the quantity of the product shipped to the sugar refinery unit.

Constraint (15) ensures that quantity of sugar received by distribution unit is less or equal to the demand at distributor side. Constraints (17) shows that the products are shipped to potential location only if a storage unit is opened in that location. Constraints (18) shows that the products are shipped to potential location only if a sugar refinery unit is opened in that location. Constraints (19) shows that the products are shipped to potential location only if a distribution unit is opened in that location. Constraints (17) shows that the products are shipped to potential location only if a fertilizer unit is opened in that location. Constraints (21) represents the binary variables. Constraints (22) and (23) enforces the positivity of the decision variables.

5. Solution Approach

In this study, a MILP problem is introduced, focusing on a location-allocation model. Traditionally, such problems in supply chain management are classified as NP-hard, necessitating the use of advanced search techniques like meta-heuristics to achieve optimal solutions efficiently. The forthcoming subsection elaborates on the solution strategies employed, comprising (1) an encoding and decoding procedure, and (2) the application of meta-heuristics (Table 1).

Table 1. Problem Size

Test Problem		i	j	k	n	l	o_1	o_2	O
Small Size	1	2	3	4	5	2	2	1	2
	2	3	4	7	10	4	3	5	6
	3	6	7	10	15	8	6	8	10
	4	8	9	12	29	10	9	10	14
	5	9	11	13	23	12	11	12	18
Medium Size	6	16	20	18	22	16	15	15	26
	7	20	24	26	22	18	18	18	30
	8	24	28	30	28	24	20	20	36
	9	28	32	34	30	26	23	22	38
	10	32	38	39	36	28	27	25	42
Large Size	11	44	48	46	42	34	29	26	48
	12	54	58	49	56	38	34	29	54
	13	68	66	52	64	42	36	31	66
	14	72	74	68	88	54	39	32	72
	15	86	88	84	98	62	42	35	76

To gauge the effectiveness of the solution approach, three metrics are introduced: hitting time, RPD, and computational time. Hitting time signifies the point when the algorithm first reaches the best solution, serving as a measure of its speed. RPD, on the other hand, indicates the deviation of the obtained solution from the best one, thereby aiding in predicting solution quality. Computational time represents the total duration required by the algorithm to produce a solution (Table 2).

RPD=relative deviation among trial $\left(\frac{\mathrm{Cost_{algo}} - \mathrm{Cost_{best}}}{\mathrm{Cost_{best}}}\right)$

Table 2. Final Results

Problems	Algorithm	Cost	Hitting time	Computational time	RPD
1	GA	285968.4	6.08	74.56	0.0754
	PSO	286054.6	4.1	62.08	0.1235
2	GA	522656.8	11.52	91.82	0.2564
	PSO	521758.2	15.63	96.54	0.1234
3	GA	848647.4	21.58	120.62	0.4342
	PSO	837489.6	27.86	126.21	0.3530
4	GA	1152802.10	39.99	149.23	0.4749
	PSO	1150420.56	41.29	162.21	0.3008
5	GA	1446820.98	52.92	178.01	0.3222
	PSO	1447230.38	56.65	196.12	0.3210
6	GA	2295010.58	92.81	260.61	0.6626
	PSO	2294506.16	99.82	278.80	0.3724
7	GA	2708516.02	128.56	299.10	0.6023
	PSO	2705124.85	147.23	335.35	0.4228
8	GA	3405483.17	168.18	346.87	0.4560
	PSO	3399982.24	189.30	402.28	0.3998
9	GA	3567572.02	209.36	388.42	0.6028
	PSO	3757412.62	226.96	468.48	0.4230
10	GA	4222299.03	258.82	431.08	0.3988
	PSO	4243821.10	284.91	508.89	0.2940
11	GA	5632182.53	360.18	569.10	0.4471
	PSO	5629122.68	404.08	688.43	0.3634
12	GA	6702844.28	463.84	666.86	0.4916
	PSO	6701840.18	588.24	810.86	0.3984
13	GA	7779110.12	576.78	778.12	0.5387
	PSO	7784248.87	706.89	948.33	0.5930
14	GA	8766084.24	693.16	888.29	0.3685
	PSO	8786128.88	898.52	1056.36	0.5965
15	GA	9803998.72	802.20	998.78	0.4880
	PSO	9812432.28	1120.83	1220.67	0.5328

6. Conclusion

In this paper, a novel closed-loop supply chain problem for sugarcane is modeled. The objective is to minimize the total network costs. We considered all main specifications of sugarcane those influence in designing its supply chain both in forward and backwards phase along with its cost. The proposed model can be solved by using heuristics and meta-heuristics with different approaches for real word scale. The supply chain model can also be designed to have multiple fuzzy-objective and other techniques can be developed to solve the proposed model. Proposed model in similar fields of fresh fruits and food can be utilized for the future studies.

The issue of significant by-products generated by sugarcane refineries presents an intriguing challenge. This study has raised numerous questions that warrant further investigation, offering potential avenues for future research. There are several opportunities for future work, such as enhancing and redesigning the model to accommodate assumptions and constraints from other countries. Additionally, the current model could be expanded to address multiple objectives, incorporating sustainability considerations. Implementing combined or hybrid techniques could lead to more accurate optimal solutions within shorter computational timeframes. Moreover, future research could explore the development of supply chain networks for other food or agricultural-based products, which have yet to be studied comprehensively.

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Biography

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