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Synopsis Of

Design and Optimization of Product Reuse Economics in Multi-Echelon Closed-Loop Supply Chain

A Thesis

To be submitted by

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For the award of the degree

Of

DOCTOR OF PHILOSOPHY

1 Abstract

The presented study mainly focuses on the integrated network, often called the Closed-Loop Supply Chain (CLSC). The manufactured product moves from the manufacturer to the consumer in the forward flow of the supply chain. In contrast, important decisions or actions are to be taken regarding the reuse of discarded products by the consumer in the reverse flow. When the system is integrated, the designed network entirely depends on the return from the end-users, and therefore, profit largely depends on the amount of return. In addition to this, the appropriate number of facilities are required to manage this bulk return. A wrong decision may significantly increase the overall cost of the supply chain . Hence, the presented work utilizes the facility location-allocation approach to deal with these issues. This approach is efficient because it uses the lowest fixed cost while locating the optimal number of facilities and allocating optimal quantities among these facilities.

This thesis is presented with three studies that are focused on the aim of a circular economy of zero waste generation. Initially, a recovery model is proposed for end-of-use or end-of-life returns. These returns are inspected and dismantled into disposable, reusable and reprocessable parts. Finally, these segregated parts are sent for reuse in the next period. In the second work, a sustainable network is designed based on the concept of zero waste for the reuse of by-products generated in the sugarcane mills. This objective is then further extended in the third work to analyze the environmental impact associated with the model. For this purpose, the model considers carbon taxes for emissions that come out during the production and transportation of the goods. Considering all these aspects, this thesis presents multi-echelon, multi-period closed-loop supply chain models. To bring closer to real-world experiences, the developed optimization framework is mixed-integer linear programming models. The generated instances are inherent with the increasing complexity, making the problem NP-hard (Sahebjamnia *et al.* (2018); Alkahtani *et al.* (2021)). Therefore, exact solvers are not promising methods to deal with these increasing complexities in a reasonable time.

Higher-order search techniques such as metaheuristic algorithms are efficient in dealing with these problems in a reasonable time. The local and global searches are done by the exploitation and exploration phases, respectively, ensuring the optimal solution. But, due to the stochastic nature of metaheuristics algorithms, they fail to perform well for each and every optimization problem, i.e., the No Free Lunch Theorem. This inspired us to improve the algorithm phases by replacing them with the strong phases of the other algorithm. This strategy balances the exploitation and exploration ability of the algorithm to reach the optimal allocation quickly and efficiently. This work uses Genetic Algorithm (GA), Keshtel Algorithm (KA), Red-Deer Algorithm (RDA), Simulated Annealing (SA), Social Engineering Optimizer (SEO) and hybrid based on these algorithms namely, Genetic-Simulated Annealing (GASA), Genetic-Social Engineering Optimizer (GASEO), Keshtel-Simulated Annealing (KASA), and Red Deer- Simulated Annealing (RDASA). Metaheuristic algorithms are problem independent and usually have the control parameters that need to be tuned for fair results. The perfectly tuned algorithms are applied to the generated small, medium, and large instances. The obtained results are then compared with calculated Relative Percentage Deviation (RPD) values. In order to validate the statistical validity of the obtained results, a one-way

ANOVA test is performed. Results confirm that the proposed hybrid optimization algorithms perform significantly better than the original in different test problems.

2 Motivation

Products are usually thrown away after use, making their reuse impossible. These products discarded by end-users eventually become a matter of concern to both the environment and society. Therefore, the theme of this research points to serious and imminent side effects whose prevention is imperative. Society is still ignorant of the efforts of the circular economy. The purpose of this research is to remove the lack of information among consumers as well as make them aware of the goals related to their reuse. This is possible only when the consumer himself considers this as his responsibility and returns the products after use. The remaining values of these returned products can be derived from them by putting them back into the initial chain. In addition, systematic management of the by-products of the sugarcane industry (i.e., bagasse, filter mud, and molasses) is also included in this research to better pinpoint the issues. These by-products are dumped so wastage of landfills and resources, which pollutes the air as well as groundwater. Therefore, their proper management or treatment is an urgent issue. Filter mud is a nutrient-rich substance that can be used as a soil amendment. But most often, the filter mud is burnt in the kiln resulting in the loss of millions of tons of nutrients. These by-products can be sold to a variety of small-scale industries such as power, paper-pulp, animal feed, etc. The suggested proposal will help the industry to operate optimally and try to reduce the overall cost of the supply chain.

3 Objectives

This research aims to develop a sustainable model to collect and reuse the products after their useful life. The existing literature reveals that by adopting reverse logistics into the value chain; an organization can reduce the overall working cost of the supply chain(Jayaraman *et al.* (1999); Kannan *et al.* (2010); Devika *et al.* (2014)). In addition to this, designing a CLSC model involves various decision-making processes such as locating facilities and allocating goods, inventory optimizations, routing decisions are the most challenging tasks. This research develops a mixed-integer linear programming (MILP) optimization framework to deal with the proposed problems. The designed facility location and allocation model uses all the real-world constraints to seem like a real situation. The research objectives for this study are outlined as follows:

- This work proposes a multi-echelon CLSC network for End-of-Use (EoU) or End-of-Life (EoL) product returns. The objective is to minimize the total cost of a supply chain where a product upon use is recovered from end-users and circled back to the initial chain. The proposed MILP formulation uses the lowest fixed cost for locating a facility and related routing decisions to efficiently handle the demand that arises from the market during a specific period and ensures the minimum overall supply chain cost.

- A novel sugarcane supply chain network is proposed to deal with the huge amount of by-products coming out of the sugarcane industry. These by-products can become alternate raw materials for a variety of industries such as fertilizers, power, etc. This study offers a MILP model for the proposed multi-echelon network that uses the minimum opening cost to locate the facilities and related decisions to minimize the total cost of the supply chain. Besides, this study also provides economical means to recycle the waste from the industries in an environment-friendly manner.

- This study is the extension of previous work that discusses the design of a sustainable sugarcane supply chain network that considers the waste/by-product of the sugarcane industry and their reuse strategy. To consider the environmental impact, the model also considers carbon taxes on emission that comes out during the production and the transportation of goods. This study offers a MILP model that uses the minimum opening cost to locate the facilities and related decisions to minimize the total cost of the value chain.

4 Existing Gaps Which Were Bridged

Based on the studied literature, it has been observed that the sustainability issue is not much raised for utilization of discarded products or by-products. These products are frequently dumped into the landfills resulting in the wastage of millions of tons of resources (Catalá *et al.* (2016); Banasik *et al.* (2017); Cheraghalipour *et al.* (2018)). As most research suggests, integrating economic, environmental issues, and social impact for a multi-period is becoming critical. Therefore, decision-making is required while integrating the logistics networks. Ultimately, it leads to the sustainable manufacturing which is less in the literature. In addition to this, only a handful of work reported to date on designing an optimization frameworks where the actual design has been considered. These areas need to be explored more to deal with the real-world instances.

The cost is an important criterion during the supply chain planning phase; if the focus is more on one area of supply chain, it often leads to higher costs in another area (Ghaderi *et al.* (2016)). There is thus a strong need to integrate decision-making in closed-loop supply chain problems. Apart from this, another issue is the inherent complexity of the optimization model. This complexity gives rise to large mathematical formulations; as a result, exact solvers fail to solve the real-sized instances in a reasonable amount of time (Govindan *et al.* (2019); Diabat and Jebali (2021)). Developing new solution methodologies which would be capable of achieving better results in a reasonable time is required. Hence, higher-order search techniques such as metaheuristics are used to deal with the aforementioned issues.

5 Most Important Contributions

The first stage in developing any solution technique needs a convenient solution representation scheme to solve an optimal solution quickly.This study adopts a famous encoding scheme known as Priority-Based Encoding proposed by Gen *et al.* (2006) which is shown in Figure 1. This scheme generates a chromosome design for allocating goods between the facilities. The chromosome design is achieved by generating a random number in the interval of (0, 1). These random numbers are known as random keys.

Later, these random keys are assigned with priorities known as a priority order. Once the priorities are assigned to the chromosome design matrix, it is called the priority-based matrix. The decoding scheme is designed and proposed to satisfy the presented encoding plan can be seen in Algorithm 1. This decoding scheme also satisfies all the related constraints of the proposed model. In addition, the binary variables used ensure the existence of the facilities.

Random keys	0.23	0.15	0.86	0.49	0.61
Priority Orders	2	1	5	3	4

Figure 1: Solution representation scheme.

Algorithm 1 The proposed decoding scheme for goods allocation

Input: I Set of sources
J Set of destination
Ca_i Capacity of source i
D_j Demand of the destination j
$S(I+J)$ Encode solution for period t
Output: $Aloc_{ij}$ Amount of shipment between nodes.
Y_j Binary variables showing the opened destinations
$Aloc_{ij} = 0$
for t = 1 to T **do**
    while $\sum_i Ca_i \geq 0$ **do**
        Select values of the first column of sub-segment I for i index
        Select value of the first column of sub-segment J for j index
        $Aloc_{ij} = min(Ca_i, D_j)$
        Update demand and capacities
        $Ca_i = Ca_i - Aloc_{ij}$
        $D_j = D_j - Aloc_{ij}$
        if $Ca_i = 0$ **then**
            $S(I+J) = 0$
        end if
        if $D_j = 0$ **then**
            $S(I+J) = 0$
        end if
    end while
    for i = 1 to J **do**
        if $\sum_j Aloj_{ij} \geq 0$ **then**
            $Y_j = 1$
        end if
    end for
end for

5.1 Product acquisition model

The primary contributions of this chapter are as follows:

- A multi-echelon, multi-period closed-loop supply chain network is proposed to recover and reuse the EoU or EoL return products. The proposed model can be seen in Figure 2.
- This work offers a mixed-integer linear programming optimization framework to consider all the real-world constraints, costs, and other related model parameters.
- This work utilizes the priority-based encoding method to generate the chromosome design and to allocate goods and locate facilities; a decoding algorithm is developed.
- Considering the complexity of the developed model, three well-known metaheuristics, Genetic Algorithm (GA), Simulated Annealing (SA), Keshtel Algorithm (KA), and two hybrids based on these metaheuristics, Genetic-Simulated Annealing (GASA) and Keshtel-Simulated Annealing (KASA), are proposed to solve the model.
- To validate the effectiveness of the solution methodology, one-way ANOVA has been performed. The test confirms the statistical validities of obtained results. The performance of GASA is found superior to all other algorithm.
- In addition to this, sensitivity analysis is performed to check the behavior of the model under varying parameters.

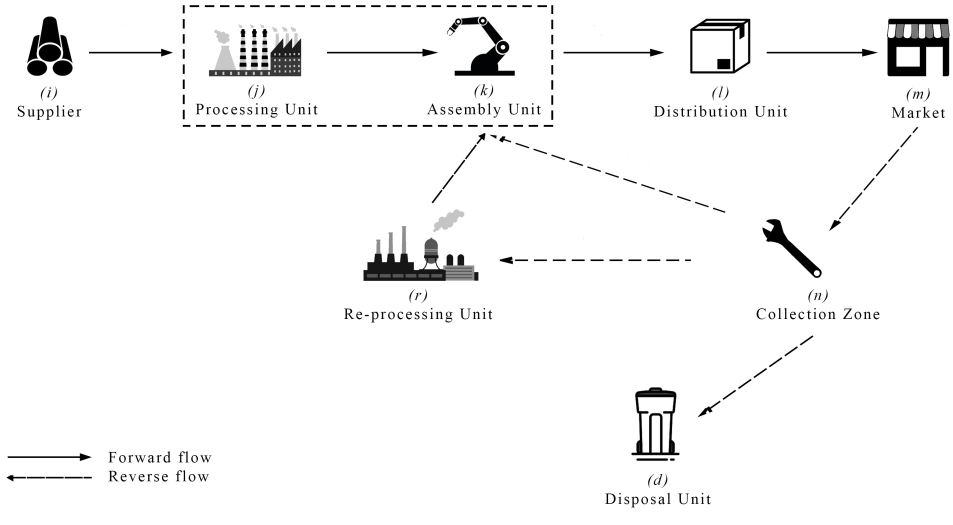

Figure 2: Proposed recoverable supply chain network.

5.2 A novel sugarcane supply chain design

The primary contributions of this chapter are as follows:

- A multi-echelon, multi-period sugarcane closed-loop supply chain network is proposed to effectively utilize the amount of by-products emanating from the sugarcane industries. The proposed model can be seen in Figure 3.
- This study emphasizes the reuse of the by-products, which are simply dumped or burnt into the kiln, while the reuse is possible.
- This work offers a mixed-integer linear programming optimization framework to consider all the real-world constraints, costs, and other related model parameters.
- This work utilizes the priority-based encoding method to generate the chromosome design and to allocate goods and locate facilities; a decoding algorithm is developed.
- Considering the complexity of the developed model, four well-known metaheuristics, Genetic Algorithm (GA), Simulated Annealing (SA), Red-Deer Algorithm (RDA), Keshtel Algorithm (KA), and three hybrids based on these metaheuristics Genetic-Simulated Annealing (GASA), Keshtel-Simulated Annealing (KASA), and Red-Deer - Simulated Annealing (RDASA) are proposed to solve the model.
- To validate the effectiveness of the solution methodology, one-way ANOVA has been performed. The test confirms the statistical validities of obtained results. The performance of RDASA is found superior to all other algorithms.
- In addition to this, sensitivity analysis is performed to check the behavior of the model under varying parameters.

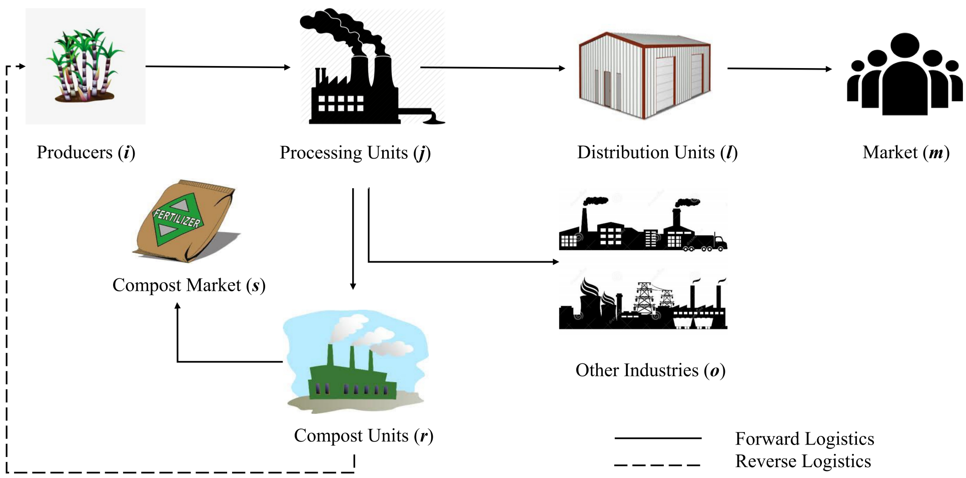

Figure 3: Proposed sugarcane supply chain network.

5.3 Sugarcane supply chain design considering environmental impacts

The primary contributions of this chapter are as follows:

- A multi-echelon, multi-period sugarcane closed-loop supply chain network is proposed to model the carbon footprint for the emissions caused by the factory producing the goods and transporting them to various facilities. The proposed model can be seen in Figure 4.
- This study introduces carbon taxes to control/reduce the environmental's carbon footprint impact.
- This work offers a mixed-integer linear programming optimization framework to consider all the real-world constraints, costs, and other related model parameters.
- This work utilizes the priority-based encoding method to generate the chromosome design and to allocate goods and locate facilities; a decoding algorithm is developed.
- Considering the complexity of the developed model, three well-known metaheuristics, Genetic Algorithm (GA), Simulated Annealing (SA), Social Engineering Optimizer (SEO), and two hybrids based on these metaheuristics Genetic-Simulated Annealing (GASA), Genetic-Social Engineering Optimizer (GASEO) are proposed to solve the model.
- To validate the effectiveness of the solution methodology, one-way ANOVA has been performed. The test confirms the statistical validities of obtained results. The performance of GASEO is found superior to all other algorithms.
- In addition to this, sensitivity analysis is performed to check the behavior of the model under varying parameters.

6 Conclusions

The studies presented in this thesis are focused on the aim of a circular economy of zero waste generation. Considering the problem statement, mathematical models are formulated, which are multi-echelon, multi-period closed-loop supply chain models. The important highlights are:

- The encoding procedure is used for decision-making during the selection of the facilities to ensure the lowest cost. A solution algorithm is developed to locate an adequate number of facilities and allocate goods to them.
- To deal with the complexity of the optimization model metaheuristic algorithms such as GA, SA, KA, SEO, RDA and their hybrids such as GASA, KASA, RDASA, and GASEO are employed.
- The responses from these algorithms are normalized and compared over generated problem instances, and to statistically validate these obtained results one-way ANOVA test is performed.

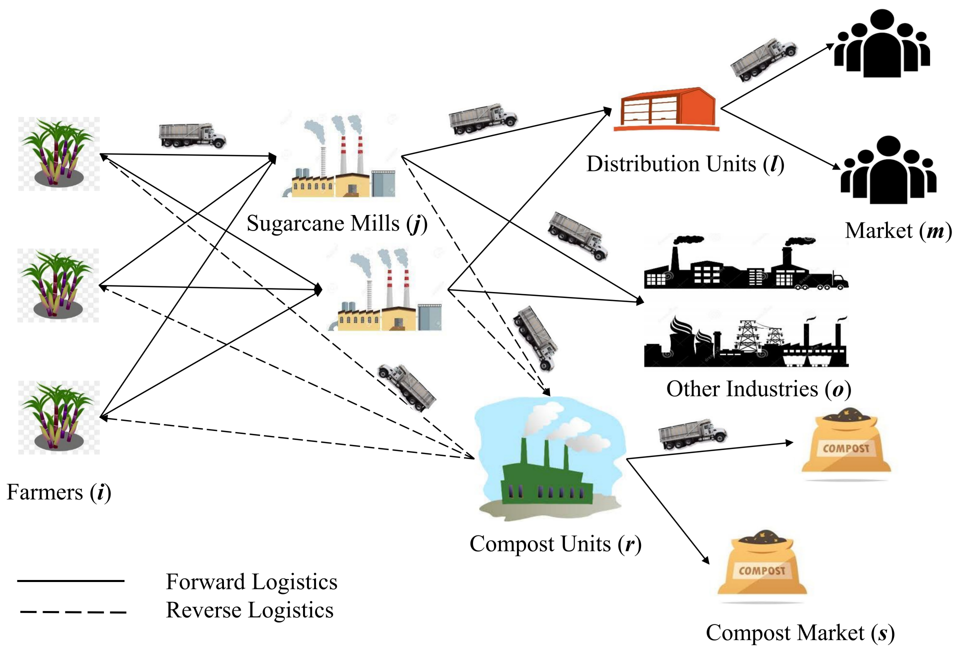

Figure 4: The proposed sustainable sugarcane supply chain network.

- The ANOVA results confirm that the proposed optimization algorithms perform significantly different in all three problems sizes.
- Sensitivity analysis are conducted under varying critical parameters to justify the applicability of the proposed model, which helps the decision makers to analyse the risk or profit associated with the model.
- Several opportunities can be identified for future work; for example, the model can be redesigned and improved by other countries' assumptions and constraints; other food or agricultural-based product supply chain networks can be developed whose study is not done; the existing model can be reconsidered for multiple objectives by including sustainability aspects, and combined or hybrid techniques may be implemented to achieve optimal solutions more accurately with less computational time.

7 Organization of the Thesis

The proposed outline of the thesis is as follows:

- Chapter 1: Introduction
- Chapter 2: Literature Review
- Chapter 3: Solution Methodology
- Chapter 4: Product Acquisition Model
- Chapter 5: A Novel Sugarcane Supply Chain design

- Chapter 6: Sugarcane Supply Chain Design Considering Environmental Impacts
- Chapter 7: Conclusions and Future Scope

8 List of Publications

I. REFEREED JOURNALS BASED ON THE THESIS

1. **Vivek Kumar Chouhan**, Shahul Hamid Khan, Mostafa Hajiaghaei-Khehteli, Saminathan Subramanian, Multi-facility based improved closed-loop supply chain network for handling uncertain demands, *Soft Computing*, Volume 24, Issue 10, 7125-7147, (2020). doi: 10.1007/s00500-020-04868-x
2. **Vivek Kumar Chouhan**, Shahul Hamid Khan, Mostafa Hajiaghaei-Khehteli, Metaheuristic approaches to design and address multi-echelon sugarcane closed-loop supply chain network, *Soft Computing*, Volume 25, Issue 16, 11377-11404, (2021). doi: 10.1007/s00500-021-05943-7
3. **Vivek Kumar Chouhan**, Shahul Hamid Khan, Mostafa Hajiaghaei-Khehteli, Sustainable planning and decision-making model for sugarcane mills considering environmental issues, *Journal of Environmental Management*, Volume 303, 114252, (2022). doi: 10.1016/j.jenvman.2021.114252

II. PRESENTATIONS/PUBLICATIONS IN CONFERENCES

1. **Vivek Kumar Chouhan**, Shahul Hamid Khan, Implementation of water cycle algorithm for modelling and optimization of supply chain network, *Fifth International Conference on Business Analytics and Intelligence (ICBAI) held at IIM Bangalore*, 1-13 December (2017).
2. **Vivek Kumar Chouhan**, Shahul Hamid Khan, Select the best supply chain by risk analysis, *International Conference on Mathematical Computer Engineering (ICMCE- 2017) held at VIT Chennai*, 3-4 November (2017).

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6. **Diabat, A.** and **A. Jebali** (2021). Multi-product and multi-period closed loop supply chain network design under take-back legislation. *International Journal of Production Economics*, **231**, 107879, doi:10.1016/j.ijpe.2020.107879.

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