OPTIMAL DESIGN OF SUPPLY CHAIN FOR PLASTIC UPCYCLING CONSIDERAING ECONOMIC AND ENVIRONMENTAL INDICATORS

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Abstract

The rapid increase in the production of plastics products has overwhelmed the world's ability to deal with them, resulting in one of the most pressing environmental issues. In this study, we consider a multi-period, multi-echelon supply chain design network for plastic wastes transformation. The goal for the supply chain problem addressed here is, given the collections sites, to design a network that transforms plastic waste into value-added products and optimally distributes these products to refineries for further processing, cities, and plastic end-users. The network choice is selected to achieve a tradeoff between economic feasibility and environmental impact. The case study selected covered the areas of Delaware, New Jersey, New York, Philadelphia, and Maryland. The results obtained achieves optimal plastic upcycling by selection of technology and spatial distribution of technologies that are profitable and environmentally friendly. This work contributes to improving the long-term environmental and economic viability of plastic management.

Keywords

Supply Chain Management, Multi-Objective, Upcycling.

Introduction

During the past few decades, rapid technological development and economic growth have improved people's living standards, but with significant strain on the world's natural systems and tremendous environmental consequences including pollution from plastic wastes. Plastic waste is ubiquitous and has been identified as a significant component of marine debris because of its prevalence in the waste streams and longevity (Koelmans et al., 2014; Pham et al., 2014). Studies have linked plastics to causing diseases in marine lives (Rochman et al., 2013). New technologies are emerging to upcycle – transform into forms of higher value – plastic wastes into value-added products; these products (majorly olefins, paraffin, and hydrogen) are used as starting material in refineries.

Without a doubt, eliminating plastic is practically impossible; the ideal approach is to regulate and manage the plastics produced so that the process is profitable, environmentally friendly, and socially acceptable (Mohammadi et al., 2019). To achieve an economically effective and environmentally friendly waste management system, the location of plastic waste collections through transportation and transformation means to the final end-use must be integrated (Cooper et al., 1997; Zhao and Huang, 2019). There is an extensive literature developed on effectively managing waste through the integrated supply chain (Allman et al., 2021; Brandão et al., 2021; Rathore et al., 2022; Saif et al., 2022). These studies have collectively provided essential insights into the critical role of an integrated supply chain approach to the performance of a waste management system.

The objective of the supply chain design is to achieve a balance between responsiveness - meeting customer needs in an environmentally friendly manner - and being economically profitable. An integrated approach has proved to improve supply chain performance effectively as it considers how the logistical and cross-functional drivers interact (Badejo and Ierapetritou, 2022; Dias and Ierapetritou, 2017). These drivers include the facilities, inventory, transportation, and sourcing (Chopra, 2019). Facilities decisions includes the location, role, and facility capacity. Increasing the number of facilities increases investment and inventory costs but decreases transportation

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costs and reduces response time. Similarly, increasing the flexibility or capacity of a facility increases the facility costs but decreases inventory costs and response time (Bhosekar and Ierapetritou, 2020; Golpîra, 2020). Transportation modes offer a tradeoff between cost, delivery time, and environmental impact. A fast transportation mode raises the overall cost and reduces the inventory holding costs (Elbert et al., 2020). Thus, each supply chain must find the appropriate tradeoff when designing the facilities' network. In this article, we address the problem of optimal supply chain design for plastic upcycling. This is done by simultaneously maximizing profit and reducing the environmental impact of the entire supply chain. The formulation integrates facility location, production, logistics, and inventory minimization to ensure optimal waste plastics flow. Three alternative routes are considered here: upcycling, recycling, and incineration. By leveraging the available collection centers within the specified region, and the previous study on the plastic upcycling technologies (Garcia and Robertson, 2017; Volk et al., 2021), the objective is to design the optimal supply chain by connecting the plastic collection sites to the transformation facilities, and to the end-users. The customer location (refineries) and collection sites are fixed for this problem. In what follows, the problem statement is described, followed by the model development and solution approach, and then the results and conclusions.

Problem Statement

The problem is to design a supply chain network that moves waste plastics from collection sites through transformation processes (incineration, recycling, gasification, and pyrolysis) to distribution centers and then to the final users (refineries and cities). Plastic waste in the collection sites is transferred to a pre-treatment or incineration unit. In the incineration unit, the plastics are combusted for energy generation, while pre-treated plastics are either transferred to recycling units where they are mechanically transformed for reuse or to transformation sites for upcycling into chemicals used as raw material in the petroleum refineries. As shown in Figure 1, the location of the collection sites considered are in New Jersey, Philadelphia, Washington DC, New York, Delaware, and Maryland. There are 130 collection sites and 11 refineries considered in this region.

The supply chain problem considered is described by a multi-period, multi-echelon network design problem where decisions are made concerning the nodes to open, their capacity, and the transportation links connecting the nodes. Adopting a graph structure notation, we aim to design a directed and connected network $G(n, e)$ with a set of n nodes and arcs $e(n, n')$ connecting nodes n and n'. Figure 2 shows a schematic of network where the supply nodes (collection sites) and demand nodes (refineries and cities) are fixed. Between the supply nodes and the demand nodes are transshipment nodes that carryout the transformation of materials to value-added products at a cost $\mathscr{p}(n)$, store some of the products at a cost $\mathscr{h}(n)$, and transport some through arcs. Flow through an arc is allowed only in the direction indicated by the arrowhead, each arc is multimodal with $\mathscr{m}$ modes. The capacity of the arcs provides an upper bound on maximum transportation through this arc.

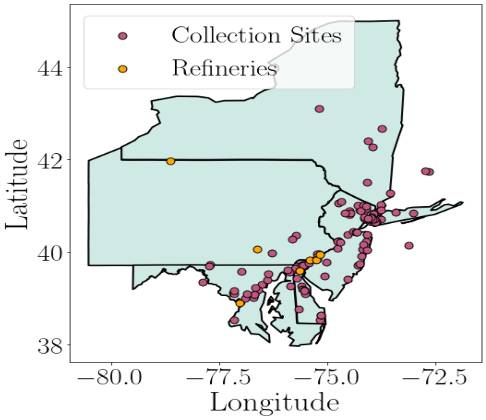

Figure 1: Collection Sites and Refineries

The cost of flow through each arc mode, $\mathscr{t}(m)$, is proportional to the amount of that flow and the distance $\delta(n, n')$ between nodes. The cost of operating nodes is also proportional to the amount of materials transformed and stored at the nodes. It should be noted that the nodes are multidimensional, and the arcs are also multi-modal.

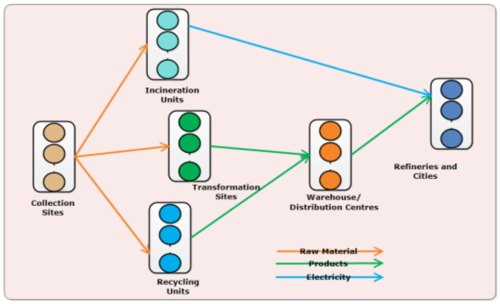

Figure 2: Supply Chain Topology

The objective is to maximize the total profit of sending the available supply through the network to satisfy the demand with minimal environmental impact. The problem is solved for a time period of 12 months, and the decisions are to determine the transshipment nodes and establish connecting links (arcs) for optimal flow between supply and demand nodes.

Model Development

The supply chain problem is modeled as a multi-objective optimization that simultaneously optimizes economic and environmental objectives. In this section, first, we discuss the constraints, followed by the objectives and solution procedure.

Following a network structure, Equation (1) ensures that the arcs between nodes only exist if the nodes are present.

$$x(n, n') \leq y(n)\,; x(n, n', t) \leq y(n') \quad \forall\, n, n', t \tag{1}$$

Equations $(2a)$ ensure that if a facility is opened only one capacity k can be selected, once the capacity is selected from the candidate capacity set $c(n,k)$, the capacity is computed by equation $(2b)$ while the investment cost for this capacity is calculated using equation $(2c)$.

$$\sum_{k} y(n,k) \leq y(n) \qquad (2a)$$

$$cap(n) = \sum_{k} y(n,k) \times c(n,k) \qquad (2b)$$

$$Icost(n) = \sum_{k} y(k,n) \times \mathscr{n}cost(n,k) \qquad (2c)$$

At facility nodes, only one technology can be selected, and each technology has a pretreatment unit. According to equation $(3a)$, we select a single technology and equation $(3b)$ ensures that a specific capacity is selected for the facility nodes that are open. Finally, the cost is calculated using equation $(3c)$.

$$\sum_{k,tech} yt(n,k,tech) \leq y(n) \quad \forall n \in F \qquad (3a)$$

$$cap(n) = \sum_{k,tech} yt(n,k,tech) \times c(n,k) \qquad (3b)$$

$$Icost(n) = \sum_{k,tech} yt(n,k,tech) \times fcost(n,k,tech) \quad (3c)$$

The transshipment nodes n receive materials, transform them, keep some as inventory and transfer others to the successor nodes n'. Equations $(4a)$ and $(4b)$ show the transformation and inventory balance for nodes other than the warehouse nodes.

$$Q^{tr}(n',t) = \sum_{n,m} \alpha(n) \times Q^{\mathscr{f}}(n,n'm,t) \qquad (4a)$$

$$Q^{tr}(n',t) \leq cap(n) \qquad (4b)$$

The inventory balances for all materials leaving a given node are shown in equations $(4c) - (4e)$.

$$I(n,t) = I(n,t-1) + Q^{tr}(n,t) - \sum_{n',m} Q^{\mathscr{f}}_{n,n'm,t} \qquad (4c)$$

$$Imin(n) \leq I(n,t) \leq Imax(n) \qquad (4d)$$

$$Q^{\mathscr{f}}_{n,n'm,t} \leq x(n,n') \times trCap(m) \qquad (4e)$$

In order to avoid out-of-stock situation, inventory which is equal to or greater than the safety stock is stored in each facility. The safety stock, $Imin$, is assumed to be proportional to the throughput, the constant of proportionality, $\beta(n)$, is the risk of out-of-stock situation (Brunaud et al., 2019) as given by equation (*4f*).

$$Imin(n) = \frac{\beta(n)}{|T|} \sum_{n',m,t} Q^{\mathscr{f}}(n,n',m,t) \qquad (4f)$$

Product demands $d(n,t)$ are generated from the demand node n (refineries and cities), the unsatisfied demands $\mathscr{b}^{+}(n,t)$ are penalized, and $\mathscr{b}^{-}(n',t)$ ensures that facilities can supply beyond demand requirements. Equation $(4g)$ shows the balance between the demands and what is supplied.

$$d(n',t) - \textstyle\sum_{n,m} Q^{\mathscr{f}}(n,n',m,t) = \mathscr{b}^{+}(n',t) \; - \; \mathscr{b}^{-}(n',t) \qquad (4g)$$

There are two objectives considered, the economic and the environmental objective. The economic objective is shown in Equation (5), consisting of two components, capital cost given by Equation $(5a)$, and the operating cost given by Equation $(5b)$. The revenue is calculated in Equation $(5c)$ and the final profit in Equation $(5d)$.

$$capCost = \sum_{n} Icost(n) \qquad (5a)$$

$$\begin{aligned} OptCost = {} & \sum_{n,t} \big(\mathscr{p}(n) \times Q^{tr}(n,t)\big) + \big(\mathscr{h}(n) \times I(n,t)\big) \\ & + \sum_{n,n',m,t} \mathscr{t}(m) \times \delta(n,n') \\ & \quad \times Q^{\mathscr{f}}\;(n,n',m,t) \\ & \quad + \sum_{n,t} \mathscr{p}en \times \mathscr{b}(n,t) \end{aligned} \qquad (5b)$$

$$revCost = \sum_{n,n',m,t} \mathscr{p}r \times Q^{\mathscr{f}}(n,n',m,t) \qquad (5c)$$

The economic objective is given in Equation $(5d)$

$$EcoObj = revCost - (capCost + OptCost) \qquad (5d)$$

The environmental objective is calculated as the CO$_2$ equivalent for generation at each node and arc as shown in Equation $(5e)$ using the weighted average for each node $eImp(n)$, and transportation modes at the arc $eImp(m)$.

$$EnvObj = \sum_{n,t} eImp(n) \times Q^{tr}(n,t) \;\; + \sum_{n,n',m,t} eImp(m) \times \delta(n,n') \times Q^{\mathscr{f}}(n,n',m,t) \qquad (5e)$$

Solution Approach

Due to the large number of collection sites involved, Kmeans algorithm is used to cluster the collection sites and their capacity aggregated. The algorithm chooses a number of centroid that minimizes the within-cluster-sum-of-squares (WCSS) (Pedregosa et al., 2011). The Elbow method is used to select the optimal number of clusters. In this method, the number of clusters are varied and WCSS is calculated for each variation and a plot showing the WCSS for each variation is used to select the optimal number of clusters.

To make decisions x subject to equations (1) – (4), which forms the feasible space $\mathfrak{F}$ of the problem, we follow a goal programming approach, where we determine the desired level, $\{EcoObj^*, EnvObj^*\}$, for each objective called the utopia points, and the goal is to find the solution closest to each objective function's desired level (Ransikarbum and Mason, 2016). Equation (6) shows the reformulation of the problem.

$$Min\ Z = \sum_{i \in \{1,2\}} w_i \times (d_i^+ + d_i^-) \qquad (6a)$$

$$st \;\; EcoObj - d_1^+ + d_1^- = EcoObj^* \qquad (6b)$$

$$EnvObj - d_2^+ + d_2^- = EnvObj^* \qquad (6c)$$

$$\sum_{i} w_i = 1 \qquad (6d)$$

$$x \in \mathfrak{F} \qquad (6e)$$

$$d_i^+, d_i^- \in \mathbb{R}_+ \;\forall\; i \in \{1,2\} \qquad (6f)$$

The utopia point is calculated using equation (7).

$$EcoObj^* = \max\{EcoObj \mid x \in \mathfrak{F}\} \qquad (7a)$$

$$EnvObj^* = \min\{EnvObj \mid x \in \mathfrak{F}\} \qquad (7b)$$

In order to get the pareto set of solutions, the weights w_i for objective in equation (6) are parameterized and solved for each w_i combination.

Results and Discussion

The clustering results is shown in Figure 3 from which it can be observed that the WCSS monotonically decreases and as the WCSS decreases the curve becomes asymptotic to the x-axis. For this problem, 6 clusters were selected the centroid of each cluster is referred to as secondary collection centers. With the aggregation of the collection centers, the supply chain problem is formulated and solved using GAMS/CPLEX (v 38.2.1) on a PC with intel® core™ i7-10510U /2.30 GHz and 16GB of RAM. Following the approach described in the solution methodology, each objective was first optimized individually to obtain the utopia point. Each objective was normalized to reduce numerical errors.

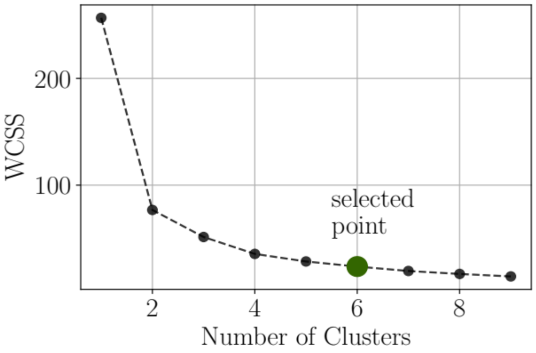

Figure 3: Elbow method for clustering

Table *1* shows the maximum values that can be achieved for each of the objective whereas Figure 4 shows the selections made when optimizing each objective separately. It should be noted that the selected solutions aim to satisfy the demands of all products first before selecting technologies according to the objectives. In the case of profit maximization, shown in Figure 4a the selection is such that the maximum profit is \$154M weekly, however this comes at an increased GWP corresponding to 420 tons of CO_2 equivalent weekly, and Figure 4b shows that when the environmental impact minimized, the global warming potential (GWP) is reduced by approximately 765 tons of CO_2 weekly while keeping profit to \$1.3M. In terms of selected technologies, pyrolysis 2 is more profitable and for environmentally friendly technologies, pyrolysis 1 and recycling are the preferred candidates.

Table 1: Payoff Matrix for Objectives

Objective	Profit	Env. Impact
Max {Profit}	153.602	417.295
Min {Env Impact}	1.548	-764.282

The Pareto front for the solutions is shown in Figure 5 as it clearly observed that the profit increases linearly with environmental impact. A solution which reduces the GWP by 177 tons of CO_2 equivalent weekly is selected with profit at \$82M. The selection choices for this point are shown in figure 6. Relative to the more profitable selection, the selected solution reduces the number of pyrolysis 2, increased pyrolysis 1, increased recycling technology, and increased capacity for the warehouses.

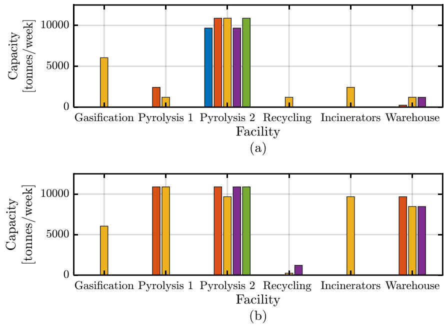

Figure 4: Facility selections: (a) Maximum Profit; (b)Minimum Environmental Impact

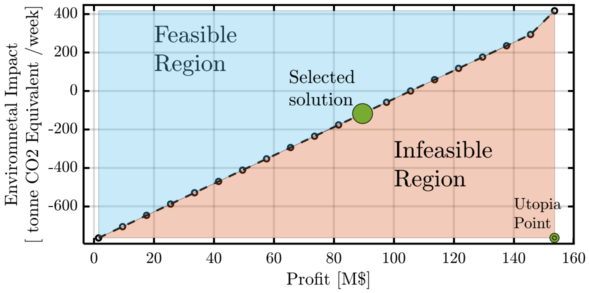

Figure 5: Trade-off among objective functions for Environmental Impact and Profit

The recommended spatial arrangement for the solution is shown in Figure 7. It should be noted that choice of location balances the distribution and inventory of materials to satisfy the objectives The technology arrangement shows a good spatial distribution across the geographic area of consideration. Furthermore, technologies such as Gasification and Incinerators are centrally located.

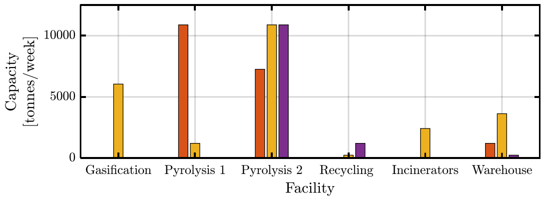

Figure 6: Technology arrangement for selected solution

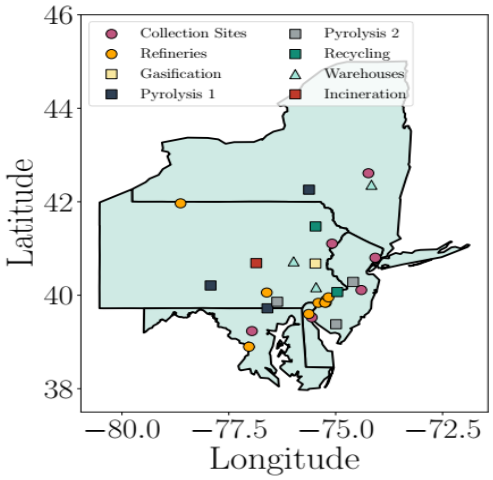

Figure 7: Spatial arrangement for selected solutions

Conclusions

This article discusses the optimal supply chain design for plastic upcycling technology for a given products' demands and collection sites. Goal programming was used to design a supply chain network by considering the tradeoff between economic and environmental objectives. The results achieve technology selection and spatial distributions that achieves a tradeoff between the profit and environmental impact.

In the future development, additional technologies can be considered, and decomposition approaches proposed to solve larger problems can be adapted.

Acknowledgements:

The authors acknowledge the financial support of National Science Foundation's Grant No. OIA – 2119754.

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