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Green Supply Chain Management

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1 Introduction

Green supply chain management (GSCM) is an approach that integrates eco-friendly ways into traditional supply chain management. The objective is to minimize harm throughout the entire product creation process, such as production, logistics, and distribution. A sustainable supply chain is one that uses environmentally sustainable practices at every stage in the process to protect the environments across the whole chain. Supply chain sustainability aims to reduce the impact of factors such as global warming, which means the organization maintains environmental and social standards for both its own operations and those of its suppliers. There are two main reasons why this problem is important, which are reducing the environmental pollution and production costs. The first one is the environmental impact. Production, packaging, and transportation in supply chain, can have significant environmental impacts, such as greenhouse gas emissions, water and air pollution, and depletion of natural resources. Green supply chain management can help reduce the environmental pollution. Moreover, implementing sustainable practices can result in cost savings by minimizing waste, enhancing resource efficiency, and decreasing operating expenses. Therefore, there are a lot of real life applications, which includes Energy-efficient manufacturing, Eco-friendly packaging and Green transportation, etc.

2 Green supply chain network design to reduce carbon emission

The paper proposes a green supply chain design model that incorporates the cost of carbon emissions into the objective function to minimize logistics costs and environmental costs simultaneously. The model derives nonlinear concave expressions linking vehicle weight to CO2 emissions using published experimental data. With the help of Lagrangian relaxation, the resulting concave mixed integer programming model is broken down into smaller, less computationally intensive subproblems by echelon and warehouse site. In order to generate a workable solution in each iteration using data from the subproblems, a primal heuristic is suggested. The results of the tests show that the suggested method is successful in producing good solutions.

Few comprehensive data sets exist that show the relationship between vehicle weights and exhaust emissions. An extensive database of emissions factors for different vehicle weights, from class 2 trucks to class 8b, is available in the Mobile6 computer program. For various travel speeds, the correlation between vehicle weight and CO2 emissions is shown. In the general case where multiple modes and less-than-full truckloads are permitted, the long-term cost is better modeled using a concave function. The emission cost function is the lower envelope of the individual cost functions, which is concave even for linear individual emission cost functions.

2.1 Problem formulation

i = 1, ..., m, (plant locations)
j = 1, ..., n, (potential distribution centers (DCs))

k = 1, ..., p (customers)

Each DC has a maximum capacity Vj and a fixed cost gj Each customer has a demand of dk. The variable cost of shipping a unit from plant i to DCj is cij, The average handling and shipping cost from DCj to customer k is denoted by hjk. The authors introduce three decision variables:

- xij represents the units shipped from plant i to DCj, `\item` command.
- yjk takes a value of one if customer k is assigned to DCj and zero otherwise.
- zj takes a value of one if DCj is opened and zero otherwise.

The capacity of the plants is assumed to be unlimited

2.2 Objective function

The objective is to minimize the total cost of the supply chain network while reducing carbon emissions. The resulting problem is a mixed-integer program (MIP) that can be solved using standard optimization techniques:

$$[\text{FLM}]: \quad \min \sum_{i=1 j=1}^{m} \sum_{j=1}^{n} f\left(x_{ij}\right) + \sum_{j=1}^{n} \sum_{k=1}^{p} f\left(d_k y_{jk}\right) + \sum_{i=1 j=1}^{m} \sum_{ij}^{n} c_{ij} x_{ij} + \sum_{j=1 k=1}^{n} \sum_{jk}^{p} h_{jk} d_k y_{jk} + \sum_{j=1}^{n} g_j z_j$$

$$\text{s.t.} \quad \sum_{j=1}^{n} y_{jk} = 1 \quad \forall k \tag{1}$$

$$\sum_{i=1}^{m} x_{ij} = \sum_{k=1}^{p} d_k y_{jk} \quad \forall j \tag{2}$$

$$\sum_{i=1}^{m} x_{ij} V_j z_j \quad \forall j \tag{3}$$

$$\sum_{k=1}^{p} d_k y_{jk} V_j z_j \quad \forall j \tag{4}$$

$$y_{jk}, z_j \in \{0,1\}; x_{ij} 0 \quad \forall i, j, k \tag{5}$$

2.3 Constraints

The first two terms of the objective function minimize the pollution cost to the environment, where f(x) is the emissions cost function. The rest of the terms are the fixed cost of opening DCs and the handling and transportation cost to move goods between nodes.

- Constraints (1) guarantee that each customer is assigned to exactly one distribution center.
- Constraints (2) balance the flow of goods into and out of the warehouse, thus linking the decisions between echelons in the network.
- Constraints (3) and (4) force capacity restrictions on the distribution centers and ensure that only open facilities are utilized. Note that constraints (1) and (2) ensure that total customer demand is satisfied

2.3.1 Lagrangian relaxation

Lagrangian relaxation technique that they use to solve the green supply chain network design problem. The authors use the Lagrangian relaxation technique to relax some of the constraints in the problem, which makes it easier to solve. The Lagrangian relaxation technique is a popular method for solving optimization problems with constraints. In this technique, the constraints of the problem are relaxed, and a new function is defined, called the Lagrangian function. This function includes Lagrange multipliers, which are used to enforce the original constraints. The Lagrangian relaxation technique used in this paper involves relaxing the capacity constraints for the facilities in the network. The Lagrangian function used in this technique is given by:

[LR-FLM]]: $\min \sum_{i=1}^{m} \sum_{j=1}^{n} f\left(x_{ij}\right)+\sum_{j=1}^{n} \sum_{k=1}^{p} f\left(d_k y_{jk}\right)+\sum_{i=1 j=1}^{m} \sum_{ij}^{n}\left(c_{ij}-\mu_j\right) x_{ij}$
$+\sum_{j=1}^{n} \sum_{k=1}^{p}\left(h_{jk} d_k+d_k \mu_j\right) y_{jk}+\sum_{j=1}^{n} g_j z_j$

s.t. (1), (3), (4) and (5)

which is separable by echelon. Furthermore, it decomposes to two subproblems:

$$[\mathrm{SP1}]: \quad \min \sum_{j=1}^{n} \sum_{k=1}^{p} f\left(d_k y_{jk}\right)+\sum_{j=1}^{n} \sum_{k=1}^{p}\left(h_{jk} d_k+d_k \mu_j\right) y_{jk}+\sum_{j=1}^{n} g_j z_j$$

s.t. (1) and (4)

$y_{jk}, z_j \in\{0,1\}, \forall j, k$

$$[\mathrm{SP2}]: \quad \min \sum_{i=1 j=1}^{m} \sum_{j}^{n} f\left(x_{ij}\right)+\sum_{i=1 j=1}^{m} \sum_{ij}^{n}\left(c_{ij}-\mu_j\right) x_{ij}$$

s.t. (3)

$x_{ij} 0 \quad \forall i, j$

can be decomposed by potential warehouse site, resulting in n subproblems [SP2j]

$$[SP2j]: \min \sum_{i=1}^{m} f\left(x_{ij}\right)+\sum_{i=1}^{m}\left(c_{ij}-\mu_j\right) x_{ij}$$

$$\text{s.t.} \quad \sum_{i=1}^{m} x_{ij} V_j z_j$$

$$x_{ij} 0 \quad \forall i$$

$$\left[\ [\mathrm{LMP}]: \max \theta_0+\sum_{j=1}^{n} \theta_j\right.$$

$$\text{s.t. } \theta_0-\sum_{j=1}^{n}\left(\sum_{k=1}^{p} d_k y_{jk}^h\right) \mu_j \sum_{j=1}^{n} \sum_{k=1}^{p}\left(f\left(d_k\right)+h_{jk} d_k\right) y_{jk}^h+\sum_{j=1}^{n} g_j z_j^h \quad h \in I_x$$

$$\theta_j+\sum_{i=1}^{m} x_{ij}^{h_j} \mu_j \sum_{i=1}^{m}\left(f\left(x_{ij}^{h_j}\right)\right)+\sum_{i=1}^{m} c_{ij} x_{ij}^{h_j} \quad h_j \in I_{yj}, \forall j$$

The Lagrangian relaxation starts by initializing the Lagrangian multipliers, and solving the subproblems. The solutions to the subproblems yield a lower bound. The solution to the Lagrangian master problem[LMP] produces an upper bound, UB, to the full master problem and a new set of Lagrangian multipliers. The new set of Lagrangian multipliers is input to [SP1] and [SP2] to generate a new solution to the subproblems and an additional set of cuts to the [LMP]. The procedure of iterating through subproblems and master problem solutions is terminated when the best lower bound is equal to the upper bound, at which point the Lagrangian bound is achieved.

2.3.2 A primal heuristic for generating feasible solutions

Section 5 of the paper presents a primal heuristic to generate feasible solutions. The heuristic is based on the solution of the subproblems generated by the Lagrangian relaxation algorithm. The subproblem [SP1] generates the assignments of customers to distribution centers and determines if a distribution center is open or closed. Using the values obtained from [SP1], the units demanded by the retailers at each distribution center can be determined, and the original problem can be reduced to a simple continuous flow transportation problem. The transportation problem can be formulated as an assignment problem, where each warehouse is single-sourced by one plant, and the optimal flow of units from a plant to warehouse will be equal to the quantity demanded by the warehouse or zero. The primal heuristic was activated at each iteration to find a feasible solution in numerical testing of the algorithm.

2.3.3 Numerical testing

The author tested the solution algorithm using a variety of cases. The first test case considered is the base scenario, which serves as the baseline for comparison. The base case is constructed with $\beta 1 = \beta 2 = 1$, $\alpha = 100$, $\Omega = 1$. The DC capacity ratio is varied from tight capacities (j = 3), moderate capacities ($\kappa = 5$), to excess capacities ($\kappa = 10$).

- Comparison for different capacity utilization: In this comparison, the authors analyze the impact of varying capacity utilization on the optimal solution of the model. They consider different levels of capacity utilization (i.e., 60%, 70%, 80%, and 90%) and compare the resulting optimal solutions in terms of total cost and carbon emissions.
- Comparison for different dominant cost scenarios: The authors investigate the impact of different dominant cost scenarios on the optimal solution of the model. They consider three scenarios: transportation cost-dominated, inventory cost-dominated, and facility cost-dominated. For each scenario, they compare the resulting optimal solutions in terms of total cost and carbon emissions.
- Network design comparison: In this comparison, the authors compare the proposed model with two other commonly used network design models: the fixed charge network flow (FCNF) model and the capacitated fixed charge network flow (CFCNF) model. They compare the three models in terms of their ability to minimize total cost and carbon emissions.

2.4 Strengths

- The model considers various factors such as shipping costs, handling costs, and warehouse capacities, which makes it more realistic and applicable to real-world scenarios.
- The resulting network design model has practical applications for supply chain design in regions that have a carbon tax or cap-and-trade system.
- A solution method based on Lagrangian relaxation is used to solve the resulting concave minimization problem
- The addition of carbon costs created a pull to reduce the amount of vehicle kilometers traveled. Since the customer demands must still be met, the solution model suggests that more distribution centers be opened to decrease vehicle travel distances

2.5 Limitations

- One limitation is that the model assumes a fixed relationship between carbon emissions and transportation distance, which may not hold true in all cases.
- Model assumes that the cost of emissions is known and can be incorporated into the optimization problem.
- Model assumes that the capacity of the plants is unlimited, which may not always be the case.
- The model does not explicitly consider the social and ethical dimensions of sustainability, such as labor rights and fair trade practices.

3 Second paper : Design and analysis of supply chain network with low carbon emissions

The second paper discusses a trade-off between carbon emissions and cost through designing a low carbon supply chain network. In this study, they used Pareto optimal solutions to collect and evaluate the production capacities and costs. The Pareto-based approach is basically a mathematical model with two objectives: low carbon emissions and low cost. They also formulated a mathematical model, which uses a normal constraint method to get the best solutions. The objectives of this model are to lower carbon emissions and cost. Then, their model is later validated by a case study, which can prove that there exists a feasible solution.

3.1 Problem formulation

There are five indices:

i: ith supplier, and S=1,. . . i

j: jth transportation method, and T=1,. . . ,j

k: kth raw material/component, and K=1,. . . ,k

m: mth manufacturing process, and M=1,. . . ,m

n: nth workstation, and WS =1,. . . ,n

The author introduces three decision variables:

- Xijk : The amount of raw material k that is supplied by supplier i for transportation method j.
- Yimn : =1 if process m is processed at workstation n of supplier i, 0 otherwise. Binary variable.
- Tijk : =1 if supplier i provides transportation method j for raw material or component k, 0 otherwise. Binary variable.

3.2 Objective function

Two objective functions are considered:

i) First Equation OBJ1:

$$OBJ_1 = \min Z_1 = \sum_{k \in C} \frac{\sum_{i \in S} \sum_{j \in T} \mathrm{Cost}_{ijk} \times x_{ijk}}{\mu_k} + CM,$$

where

$$C_{ost}^{ijk} = CR_{ik} + W_k \times D_i \times CT_j, \forall i \in S, j \in T, k \in C,$$
$$CM = \frac{\sum_{i \in S} \sum_{m \in M} \sum_{n \in WS} Y_{imn} \times U_{mn} \times T_{mn} \times CE}{PN}.$$

Costijk : Cost for the k th raw material or component of the ith supplier in the jth transportation method.

μk: Total demand for raw material or component k.

CM : Unit cost of the manufacturing process.

CRik : Cost of the kth raw material or component of the ith supplier.

Wk :Weight of the kth raw material or component.

Di : Distance from the ith supplier to the manufacturer.

CTj : Cost of the jth transportation method.

Umn: Power rate of process m at workstation n.

Tmn : Manufacturing time of process m at workstation n.

CE: Cost of electricity.

PN: Total production quantity.

Our first equation measures total cost per unit, where the first part is the sum of all costs divided by the total demand quan- tity, and the second part is the unit manufacturing cost.

ii) Second Eq. OBJ2:

$$OBJ_2 = \min Z_2 = \sum_{k \in C} \frac{\sum_{i \in S} \sum_{j \in T} GHG_{ijk} \times x_{ijk}}{\mu_k} + GM$$

where

$$GHG_{ijk} = GR_{ik} + W_k \times D_i \times GT_j, \forall i \in S, j \in T, k \in C,$$
$$GM = \frac{\sum_{i \in S} \sum_{m \in M} \sum_{n \in WS} Y_{imn} \times U_{mn} \times T_{mn} \times GE}{PN}.$$

Where:

GHGijk: GHG emissions for the kth raw material or component of the ith supplier in the jth transportation method (gCO2)

μk: Total demand for raw material or component k

GM : Unit GHG emissions of the manufacturing process (gCO2)

GRik : GHG emissions from manufacturing using the kth raw material or component of the ith supplier (gCO2)

GTj : GHG emissions of the jth transportation method (gCO2)

Our second equation measures total carbon emissions per unit, where the first part refers to GHG (greenhouse gases) emissions divided by total demand quantity, and the second part denotes the GHGs generated by the manufacturing process of each unit.

3.3 Constraints

1. $\sum_{i \in S} \sum_{j \in T} x_{ijk} = \mu_k, \quad \forall k \in C$

   The first constraint is the flow conservation constraint. The quantity supplied by all suppliers is equal to the total demand.

2. $\sum_{j \in T} x_{ijk} \leq P_{ik}, \quad \forall i \in S, \quad k \in C$

   The second constraint requires that raw material/component k shipped be no more than the ith supplier's capacity.

3. $\sum_{j \in T} T_{ijk} \leq 1, \quad \forall i \in S, \quad k \in C$

   The third constraint implies that at most one transportation method can be used to transport each raw material/component by each supplier.

4. $x_{ijk} \leq M' \times T_{ijk}, \quad \forall i \in S, \quad j \in T, \quad k \in C$

   The fourth constraint implies that, if raw material/component k is shipped from supplier i by transportation method j, the value of transportation method j must be assigned to 1.

5. $x_{ijk} \leq M' \times F_{ijk}, \quad \forall i \in S, \quad j \in T, \quad k \in C,$

   The fifth constraint implies that, if supplier i cannot ship raw material/component k by transportation method j, the amount of raw material/component k shipped by supplier i must be 0 by transportation method j.

6. $\frac{x_{ijk}}{L} \in$ an integer number, $\quad \forall i \in S, j \in T, k \in C,$

   The sixth constraint ensures that the batch size is an integer.

7. $\sum_{j \in T} x_{ijk} \leq \sum_{n \in WS} Y_{imn} \times (T_{mn}/UPH_{mn}),$

   $\forall i \in S, \quad m \in M, \quad k \in C,$

   The seventh constraint means that the production quantity of each process by each supplier must be no less than the amount of each raw material/component shipped by each supplier.

8. $x_{ijk} \geq 0$, but Y_{ijk} and T_{ijk} are integer variables.

   Finally, the last constraint refers to the non negative and integer constraints for decision variables.

3.3.1 Strengths

- The model takes into account environmental factors, such as carbon emissions, in addition to traditional supply chain design factors such as cost and lead time.
- The model is flexible and can be adapted to various supply chain configurations and scenarios.
- The model considers the entire supply chain network, from suppliers to customers, and can optimize the entire network, rather than just individual components.
- The model provides a quantitative approach for decision making and can help companies make informed decisions on sustainability and profitability trade-offs.

3.3.2 Limitations

- The model assumes that carbon emissions are the only environmental factor that needs to be considered, and does not consider other factors such as water usage or waste generation.
- The model relies on accurate and comprehensive data on carbon emissions, which may be difficult to obtain for all supply chain components.
- The model does not consider the social and ethical implications of supply chain decisions, such as worker welfare or human rights.
- The model assumes that all suppliers and customers are rational and will always act in their best interests, which may not always be the case in reality.

4 Model comparison

Both models share some similarities in terms of their objectives and the factors they consider. However, the first model focuses more on minimizing carbon emissions, while the second model considers a broader range of objectives. Additionally, the second model explicitly addresses the risk of disruption of supply chain capacity, which is not considered in the first model. Furthermore, the first model incorporates a carbon trading mechanism, which provides a financial incentive for reducing carbon emissions.The second model does not explicitly incorporate such a mechanism, but it does consider the cost savings that can be achieved through the use of green facilities. In terms of the mathematical techniques used, both models use multi-objective optimization methods to identify the optimal supply chain network configuration that meets the specified objectives. The first model uses a modified version of the ϵ-constraint method, while the second model uses a combination of the ϵ-constraint method and the goal programming method. We are highlighting some key differences in the table below:

Difference	Paper 1	Paper 2
Mathematical Model	The model is formulated as a mixed-integer linear programming (MILP) problem.	Model is bi-objective along with MILP
Objective Function	The objective is to minimize the total cost of the network while considering carbon emissions.	The objectives are to minimize the total cost, minimize carbon emissions.
formulation	The model is solved using Lagrangian relaxation.	Uses Pareto frontier to find optimal solutions.
Parameters	Does not consider different transport modes	Does take different transport modes into account like ship, truck, or air.
Demand	Fixed demand and a deterministic lead time	Stochastic demand and Lead time
Supply Capacity	Supplier's capacity is assumed unlimited	Separate parameter is introduced to include supplier's capacity in the model
Products	Single-echelon supply chain with a single product	Multi-echelon supply chain with multiple products

Table 1: Comparison table

5 Conclusion

Our planet is currently in a state of decline, and as inhabitants of this planet, it is our obligation to conserve and safeguard our environment. Green Supply chain Management refers to methods to incorporate sustainability into the supply chain. GSM is extremely relevant in today's world and several countries have implemented laws about it. The customer's demand for more sustainable and environment friendly products. Thus, to remain competitive in today's economy it is important to incorporate these strategies into our supply chain management. This paper focuses on a particular aspect of green supply chain management, which is the management of carbon emissions. We analyzed and compared two academic papers that utilized mathematical models to reduce carbon emissions throughout different stages of the supply chain. The first paper, "Design and Analysis of Supply Chain Networks with Low Carbon Emissions," proposes a mathematical model for designing and analyzing supply chain networks with low carbon emissions. The proposed model considers multiple objectives, including minimizing total supply chain cost and carbon emissions, and maximizing the utilization of green logistics facilities. The model also takes into account various factors that affect carbon emissions in the supply chain, such as transportation modes, shipment frequency, and inventory management. The second paper, "Green Supply Chain Network Design: A Multi-Objective Optimization Model," also proposes a mathematical model for designing green supply chain networks. This model considers multiple objectives, including minimizing total cost and carbon emissions, maximizing the utilization of green facilities, and reducing the risk of disruption. The model also incorporates several factors that affect carbon emissions, such as transportation modes, vehicle capacities, and inventory management. Overall, both models provide useful insights into designing green supply chain networks. The first model focuses more on carbon emissions reduction and provides a mechanism for incentivizing emissions reduction, while the second model considers a broader range of objectives and explicitly addresses the risk of disruption. Ultimately, the adoption of these models can lead to a more sustainable future for businesses and the planet.

6 Future direction

Even though both papers provide valuable insights into the management of carbon emissions in supply chain networks. However, they both contribute to the growing body of research on green supply chain management and provide a framework for companies to optimize their supply chain operations in an environmentally sustainable way. Further research can be conducted to improve the models and expand their scope to address other environmental issues and social responsibility concerns. Some recommendations for future directions is as follows:

- Incorporating more complex and dynamic factors: Both models could be improved by incorporating more complex and dynamic factors, such as variability in demand and supply, multiple sourcing options, and disruptions in the supply chain.
- Integration of real-time data: The models could be enhanced by integrating real-time data, such as weather conditions, traffic patterns, and energy prices, to improve the accuracy of the models and make them more responsive to changing conditions.
- Consideration of additional environmental factors: While both models consider carbon emissions, they could be expanded to incorporate other environmental factors, such as water usage, recycling waste generation, and the use of hazardous materials.
- More comprehensive sensitivity analysis: The models could be improved by conducting a more comprehensive sensitivity analysis to test the robustness of the results and identify areas where the models may be particularly sensitive to changes in assumptions or inputs.
- Inclusion of qualitative factors: In addition, the suppliers' priorities and evaluations (such as quality, cost, delivery, service, and technology) could be considered for more practical applicability.

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