Sustainable Supply Chain Optimisation

Autumn 2022

IIT Indore

REPORT

Index

OVERVIEW

To maintain a profitable and ethical business, sustainability is essential. Environmental and social implications must also be considered when assessing sustainability, in addition to economic ones. We provide a multi-objective optimisation framework to enhance a sustainable supply chain. **The cost overall, GHG emissions and lead time** are the three sustainability metrics that have been taken into account.

For a firm to be sustainable, its operations must consider its actions' economic, environmental, and social implications. Historically, it has been the duty of each organizational unit within a firm to ensure sustainability. Adopting a more comprehensive strategy by optimizing the supply chain is a significant opportunity and problem.

Initiatives like the Carbon Disclosure Project and the Global Reporting Initiative clearly state that potential impacts need to be examined broadly. There may be significant opportunities to boost performance if we have a better understanding of how the structure and operation of the supply chain can affect emissions.

Along with customer service criteria like responsiveness and robustness, sustainability necessitates considering additional factors like greenhouse gas emissions and other potential environmental effects. The complexity of the issue is further increased when additional metrics are used, and this necessitates the gathering of data that are frequently not readily available. A multidimensional analysis, however, can highlight trade-offs between several goals and raise the probability that a particular solution will have more far-reaching and long-lasting advantages.

A generic optimisation framework combining numerous aspects and capable of resolving issues on an industrial scale is necessary for a comprehensive approach to supply chain management. In this study, we provide a methodology that supports choices about supply chain planning, growth, and design issues and quantifies the trade-offs between economic, environmental, and responsiveness performance.

PROBLEM STATEMENT

We take into account a supply chain network composed of producers, consumers, and raw material suppliers.

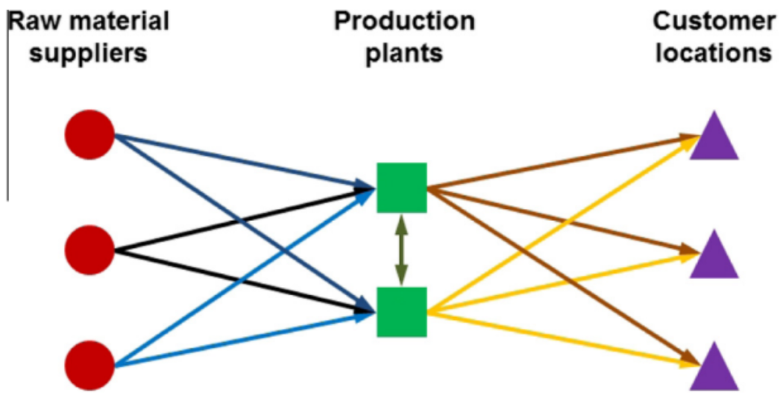
Each production facility receives a set of raw materials that are then transferred there and converted into finished goods. Distributing finished goods to customers satisfies specific wants. (for a more optimal solution, intermediate products can be delivered to other plants.)

Each plant's production procedure is considered a batch procedure and may include several steps, such as sequential reactions in different reactors. Simultaneously operating several units, such as blenders and reactors, is possible in each stage.

Locations of the raw material suppliers, the plants, and the customers are also provided, as well as potential transportation routes, customer demands, production and transportation capacities, processing times, transportation distances and times, fixed and variable costs, and environmental impact factors related to all proper supply chain operations.

The objective is to satisfy all customer demands while optimizing the tactical planning of such a supply chain for a single period, typically one year. The amounts of raw materials to be bought from each raw material supplier, the distribution of goods among plants and units, the quantities of goods to be produced in each unit, and the material flows from suppliers to plants, between plants, and from plants to customers are the decision variables in this case.

The overarching goal may be to find a balanced solution that considers two or all of these three objectives. It may be to minimize total cost, minimize total environmental impact, or maximize responsiveness.



DATASET

Obtaining a dataset was the biggest challenge. We tried to create a dummy dataset for the problem, but its creation was a significant problem because we had to set each data point manually. Since a vast number of variables were involved, we decided to use a small dummy dataset to illustrate the problem and get the desired results.

APPROACH

We employ the constraint method to solve the multi-objective optimization problem in this work. After providing a formal definition of Pareto optimality, we then go on to describe the constraint algorithm that we are employing.

Another solution that further reduces one objective function without increasing other objective functions cannot be found compared to a Pareto optimal solution. The trade-offs between various objectives are thus represented by Pareto optimal solutions. A clear front, also known as the Pareto optimal front or just the Pareto front, is typically obtained when all Pareto solutions are plotted on an objective plane. A bi-objective optimization produces a Pareto front. Every point below the Pareto curve is impractical, and every answer found above it is not optimal.

NOTE: For the quantification of GHG emissions, an entire case study needs to be done of the supply chain, including the emissions from suppliers of resources, from the production, from the electricity consumed in production, from the treatment of waste produced by the plant, and lastly the overheads in consumption of the product. All of the above might not be equivalent and in different forms, so are needed to be converted into the consumption of CO_2.

MATHEMATICAL FORMULATION

A MILP problem containing continuous and binary variables can be used to model the optimisation problem mentioned in the preceding section. Remembering that this model's continuous variables must have a non-negative value.

To simplify the problem, the following should be considered:

1. The network consists of
    a. Procurement from the raw materials/chemicals supplier.
    b. Production of chemicals from the raw materials (including waste generation)
    c. Distribution of chemical products to customers.

    Therefore, the existing network also provides the distances

    a. From suppliers to production plants
    b. From one production plant to another
    c. From production plants to customers

$$SUP_{i,m,p} + \sum_{q \in P_m} \overline{PRO}_{i,m,q,p} + PTP^{in}_{i,m,p} = \sum_{k \in K_{m,p}} FED_{i,m,p,k} \quad \forall m, p \in P_m,\ i \in I^{FED}_{m,p} \tag{1a}$$

$$FED_{i,m,p,k} = \sum_{j \in I^{PRO}_{m,p}} CF_{i,j,m,p,k} PRO_{j,m,p,k} \quad \forall m,\ p \in P_m,\ k \in K_{m,p},\ i \in I^{FED}_{m,p} \tag{1b}$$

$$\sum_{k \in K_{m,p}} PRO_{i,m,p,k} = \sum_{q \in P_m} \overline{PRO}_{i,m,p,q} + PTP^{out}_{i,m,p} + SAL_{i,m,p} \quad \forall m,\ p \in P_m,\ i \in I^{PRO}_{m,p} \tag{1c}$$

i mass balances are conducted at every step p of every plant m for every chemical. How this is done is demonstrated in the schematic. The quantity of chemical i FED into unit k of stage p at plant m is called $FED_{i,m,p,k}$, and it is made up of flows from the stage before it, suppliers, and other production facilities. With the appropriate conversion factors, $CF_{i,i,j,m,p,k}$, and $FED_{i,m,p,k}$ are translated in unit k into the products $PRO_{j,m,p,k.}$ The next step is to distribute the output from each stage to clients and other plants. As stated by the first equation, their mass balances.

The mass balance equations for supplies, plant flows, and the sold goods that are delivered to clients are given in equations (2), (3), and (4).

2. Equality constraints are given by mass balances and include the following:
    a. At each stage, all the chemicals purchased, flowed from the previous stage and transported from other plants should equal the amount of chemicals fed into that stage.
    b. All the chemicals fed into a stage should equal the amount produced times the conversion factor.
    c. All the chemicals produced should equal the amount transported to other plants, produced for the next stage or sold to the customers.
    d. All the chemicals supplied by the raw material supplier should equal the chemicals purchased.
    e. The chemicals which are not required should not be purchased to minimize costs.
    f. All the chemicals transported from production plants should equal the amount brought and fed from other plants.
    g. The chemicals not fed should not be transported out from other plants.
    h. All the chemicals produced should be sold to the customers.
    i. The chemicals which are not sold should not be produced.
    j. All the chemicals sold should be equal to the customer's demands.

$$\sum_{s} \overline{SUP}_{i,s,m} = \sum_{p \in P_m} SUP_{i,m,p} \qquad \forall m, i \tag{2a}$$

$$\overline{SUP}_{i,s,m} = 0 \qquad \forall s, m, i \notin I^{SUP}_{s,m} \tag{2b}$$

$$\sum_{n} \overline{PTP}_{i,n,m} = \sum_{p \in P_m} PTP^{in}_{i,m,p} \qquad \forall m, i \tag{3a}$$

$$\overline{PTP}_{i,m,n} = 0 \qquad \forall m, n, i \notin I^{PTP}_{m,n} \tag{3b}$$

$$\sum_{p \in P_m} PTP^{out}_{i,m,p} = \sum_{n} \overline{PTP}_{i,m,n} \qquad \forall m, i \tag{3c}$$

$$\sum_{p \in P_m} SAL_{i,m,p} = \sum_{c} \overline{SAL}_{i,m,c} \qquad \forall m, i \tag{4a}$$

$$\overline{SAL}_{i,m,c} = 0 \qquad \forall m, c, i \notin I^{SAL}_{m,c} \tag{4b}$$

$$\sum_{m} \overline{SAL}_{i,m,c} = D_{i,c} \qquad \forall i, c \tag{4c}$$

3. The inequality or capacity constraints include the following:
    a. The produced chemicals in each stage should be greater than the minimum amount and less than the maximum capacity.
    b. The amount of chemicals produced should be at most the plant production capacity.
    c. The processing time of chemicals should be at most the plant processing time capacity.
    d. The amount of chemicals purchased, transported among the plants and distributed to the customers should not exceed the maximum amount that can be transported.

$$CLO_{i,m,p,k} Y_{i,m,p,k} \leqslant PRO_{i,m,p,k} \leqslant CUP_{i,m,p,k} Y_{i,m,p,k} \quad \forall m, p \in P_m, k \in K_{m,p}, i \in I^{PRO}_{m,p} \tag{5a}$$

$$\sum_{p \in P_m} \sum_{k \in K_{m,p}} \sum_{i \in I^{PRO}_{m,p}} PRO_{i,m,p,k} \leqslant \overline{CUP}_m \qquad \forall m \tag{5b}$$

$$\sum_{i \in I^{PRO}_{m,p}} \frac{PRO_{i,m,p,k}}{R_{i,m,p,k}} \leqslant CUP^{T}_{m,p,k} \qquad \forall m, p \in P_m, k \in K_{m,p} \tag{5c}$$

Along with the three objective functions, various equality and inequality constraints are equally important to formulate the problem and get desired results.

Finally, the objective functions take into account the whole life cycle of the production process, and the three parameters, i.e. **total cost, GHG emissions** and **lead time,** are formulated as follows:

4. The total cost of production includes the two types of costs, i.e. fixed costs and variable costs.

   The unit costs include the following:

   a. Production of chemicals
   b. Transportation costs
   c. Cost of raw materials
   d. Treatment of generated waste

   The fixed costs include the following:

   a. Production of chemicals
   b. The setting of production of chemicals
   c. Waste Treatment

$$
\begin{aligned}
TCO = & \sum_{s}\sum_{m}\sum_{i \in I^{SUP}_{s,m}} UCO^{SUP}_{i,s}\, \overline{SUP}_{i,s,m} \\
& + \sum_{m}\sum_{p \in P_m}\sum_{k \in K_{m,p}}\sum_{i \in I^{PRO}_{m,p}} \Bigg(FCO^{PRO}_{i,m,p,k}\, Y_{i,m,p,k} + UCO^{PRO}_{i,m,p,k}\, PRO_{i,m,p,k} \\
& + FCO^{WT}_{i,m,p,k}\, Y_{i,m,p,k} + UCO^{WT}_{i,m,p,k}\, PRO_{i,m,p,k} \Bigg) \\
& + \sum_{m}\sum_{p \in P_m}\sum_{k \in K_{m,p}}\sum_{i \in I^{SU}_{m,p,k}} FCO^{SU}_{i,m,p,k}\, Y_{i,m,p,k} \\
& + \sum_{s}\sum_{m}\sum_{i \in I^{SUP}_{s,m}} UCO^{TRSUP}_{i,s,m}\, \overline{SUP}_{i,s,m} \\
& + \sum_{m}\sum_{n}\sum_{i \in I^{PTP}_{m,n}} UCO^{TRPTP}_{i,m,n}\, \overline{PTP}_{i,m,n} \\
& + \sum_{m}\sum_{c}\sum_{i \in I^{SAL}_{m,c}} UCO^{TRSAL}_{i,m,c}\, \overline{SAL}_{i,m,c} \qquad (7)
\end{aligned}
$$

5. To find the total GHG emissions, we consider the emissions from the production plants and the whole supply chain, i.e. the emissions from the waste and the supplier. Overall, GHG emissions include the following:
    a. Energy consumption by production plants
    b. Treatment of generated waste
    c. Transportation of chemicals
    d. Production of chemicals
        i. By supplier in the production of raw materials
        ii. By plants in the production of chemicals

$$
\begin{aligned}
TGHG = & \sum_{s}\sum_{m}\sum_{i \in I_{s,m}^{SUP}} EF_{i,s}^{SUP}\,\overline{SUP}_{i,s,m} + \sum_{m}\sum_{p \in P_m}\sum_{k \in K_{m,p}}\sum_{i \in I_{m,p}^{PRO}} \Big(EF_{i,m,p,k}^{PRO} \\
& + EF_{i,m,p,k}^{WT} + EF_{m}^{EC}\,UEC_{i,m,p,k}\Big)\,PRO_{i,m,p,k} \\
& + \sum_{s}\sum_{m} DIS_{s,m}^{SUP} \sum_{i \in I_{s,m}^{SUP}} EF_{i,s,m}^{TRSUP}\,\overline{SUP}_{i,s,m} \\
& + \sum_{m}\sum_{n} DIS_{m,n}^{PTP} \sum_{i \in I_{m,n}^{PTP}} EF_{i,m,n}^{TRPTP}\,\overline{PTP}_{i,m,n} \\
& + \sum_{m}\sum_{c} DIS_{m,c}^{SAL} \sum_{i \in I_{m,c}^{SAL}} EF_{i,m,c}^{TRSAL}\,\overline{SAL}_{i,m,c} \qquad (8)
\end{aligned}
$$

6. The total lead time considers the following:
    a. Rate of production of chemicals
    b. Transportation of chemicals

$$
\begin{aligned}
TLT = & \sum_{m}\sum_{p \in P_m}\sum_{k \in K_{m,p}}\sum_{i \in I_{m,p}^{PRO}} \frac{PRO_{i,m,p,k}}{R_{i,m,p,k}} + \sum_{s}\sum_{m}\sum_{i \in I_{s,m}^{SUP}} TT_{i,s,m}^{SUP}\,Y_{i,s,m}^{SUP} \\
& + \sum_{m}\sum_{n}\sum_{i \in I_{m,n}^{PTP}} TT_{i,m,n}^{PTP}\,Y_{i,m,n}^{PTP} + \sum_{m}\sum_{c}\sum_{i \in I_{m,c}^{SAL}} TT_{i,m,c}^{SAL}\,Y_{i,m,c}^{SAL} \qquad (9)
\end{aligned}
$$

ALGORITHM: ε - CONSTRAINT

ε - Constraint Algorithm $(f_i(x), \varepsilon_i, h(x), g(x), x, \varepsilon_i)$

begin process

$\varepsilon_2^1, \varepsilon_2^2, \varepsilon_2^3 \leftarrow solve(f_i(x), f_2(x), h(x), g(x), x, \varepsilon_2)$

$\varepsilon_2^U \leftarrow max(\varepsilon_2^1, \varepsilon_2^3)$

$\varepsilon_2^L \leftarrow \varepsilon_2^2$

$N \leftarrow rand\_int()$

$\varepsilon_2 \leftarrow \varepsilon_2^L + n\dfrac{(\varepsilon_2^U - \varepsilon_2^L)}{N} \quad : \quad n \in 1 — N$

for n in range 1 to N

$\varepsilon_2 \leftarrow \varepsilon_{2,n}$

$\varepsilon_2^1, \varepsilon_2^3 \leftarrow solve(f_i(x), f_2(x), f_3(x), h(x), g(x), x, \varepsilon_3)$

$\varepsilon_3^U \leftarrow \varepsilon_3^3$

$M \leftarrow rand\_int()$

$\varepsilon_3 \leftarrow \varepsilon_3^L + m\dfrac{(\varepsilon_3^U - \varepsilon_3^L)}{M} \quad : \quad m \in 1 — M$

for m in range 1 to M

$\varepsilon_3 \leftarrow \varepsilon_{3,m}$

sol^n apped $\leftarrow solve(f_1(x), f_2(x), f_3(x), h(x), g(x), x, \varepsilon)$

end for

end for

end process

$$\text{solve}\,(f_i(x), f_2(x), h(x), g(x), x, \varepsilon_2)$$
$$\min \; f_i(x)$$
$$\text{s.t.} \quad \varepsilon_2 = f_2(x)$$
$$h(x) = 0, \; g(x) \leq 0, \; x \in X, \; \varepsilon_2 \in \mathbb{R}$$

$$\text{solve}\,(f_i(x), f_2(x), f_3(x), h(x), g(x), x, \varepsilon_3)$$
$$\min \; f_i(x)$$
$$\text{s.t.} \quad f_2(x) \leq \varepsilon_2, \; \varepsilon_3 = f_3(x)$$
$$h(x) = 0, \; g(x) \leq 0, \; x \in X, \; \varepsilon_3 \in \mathbb{R}$$

$$\text{solve}\,(f_i(x), f_2(x), f_3(x), h(x), g(x), x, \varepsilon_i)$$
$$\min \; f_i(x)$$
$$\text{s.t.} \quad f_2(x) \leq \varepsilon_2, \; f_3(x) \leq \varepsilon_3$$
$$h(x) = 0, \; g(x) \leq 0 \quad x \in X$$

- In this algorithm we apply Simplex on GHG emission function repetitively to get points for our Pareto Optimal Front by varying the constants in constraints as they are the result of steps sizes encountered by applying Simplex on either Cost function first and then lead-time function or vice versa.
- The algorithm is initialized by the constraints given and then applying simplex on one of the functions such as cost or lead-time.
- The resultants are set as upper bound and lower bound for the steps for the subsequent iterations over the other function which wasn’t chosen in the previous step.
- Again, Simplex is applied with previous equality constraints changed to equality constraints and new equality constraints introduced as the previous function would be equal to the step variable

- Lastly, the results from this step are used to change the equality constraints to inequality constraints in the following the last step in which simplex is applied to get points for the Pareto optimal front.

MODIFIED ε - CONSTRAINT

This method can be modified for different problems by taking steps ε_i as n, n+1, n+2, . . . , N-1, N and m, m+1, m+2, . . . , M-1, M instead of $\varepsilon^L + n\,(\varepsilon^U - \varepsilon^L)\,/\,N$ and $\varepsilon^L + m\,(\varepsilon^U - \varepsilon^L)\,/\,M$ respectively. This can result in more equidistant solutions but can also reduce granularity in the required range.

To solve this problem instead of taking a fixed number of steps, a search-like algorithm can be deployed where it iterates between two points until the value reaches a specified provided range.

MODEL EXPANSION

The problem can be extended to solve the expansion of supply chain networks, i.e. either by setting up additional production plants or increasing the capacity of existing plants.

To increase the capacities of existing production plants, we will have to change the constraints by the following constraints and consider the additional costs for the same.

$$CLO_{i,m,p,k}\,Y_{i,m,p,k} \leqslant PRO_{i,m,p,k} \leqslant CUP_{i,m,p,k}\,Y_{i,m,p,k} + CI_{i,m,p,k} \quad \forall m, p \in P_m, k \in K_{m,p}, i \in I^{PRO}_{m,p} \tag{16a}$$

$$\sum_{p \in P_m} \sum_{k \in K_{m,p}} \sum_{i \in I^{PRO}_{m,p}} PRO_{i,m,p,k} \leqslant \overline{CUP}_m + \overline{CI}_m \quad \forall m \tag{16b}$$

$$\sum_{i \in I^{PRO}_{m,p}} \frac{PRO_{i,m,p,k}}{R_{i,m,p,k}} \leqslant CUP^T_{m,p,k} + CI^T_{m,p,k} \quad \forall m, p \in P_m, k \in K_{m,p} \tag{16c}$$

$$CI_{i,m,p,k} \leqslant CIUP_{i,m,p,k}\,Y^{CI}_{i,m,p,k} \quad \forall m, p \in P_m, k \in K_{m,p}, i \in I^{PRO}_{m,p} \tag{16d}$$

$$\overline{CI}_m \leqslant \overline{CIUP}_m\,\overline{Y}^{CI}_m \quad \forall m \tag{16e}$$

$$CI^T_{m,p,k} \leqslant CIUP^T_{m,p,k}\,Y^{CIT}_{m,p,k} \quad \forall m, p \in P_m, k \in K_{m,p} \tag{16f}$$

$$\begin{aligned}&\sum_m \sum_{p \in P_m} \sum_{k \in K_{m,p}} \sum_{i \in I^{PRO}_{m,p}} \left(FCO^{CI}_{i,m,p,k}\,Y^{CI}_{i,m,p,k} + UCO^{CI}_{i,m,p,k}\,CI_{i,m,p,k}\right)\\ &+ \sum_m \left(\overline{FCO}^{CI}_m\,\overline{Y}^{CI}_m + \overline{UCO}^{CI}_m\,\overline{CI}_m\right)\\ &+ \sum_m \sum_{p \in P_m} \sum_{k \in K_{m,p}} \left(FCO^{CIT}_{m,p,k}\,Y^{CIT}_{m,mp,k} + UCO^{CIT}_{m,p,k}\,CI^T_{m,p,k}\right)\end{aligned} \tag{17}$$

Otherwise, to add a production plant, we will have to incorporate its costs and GHG emissions into account and introduce a binary variable Y_m in the set of plants. Y_m is 1 if the plant is built and 0 otherwise.

$$Y_{i,m,p,k} \leqslant \overline{Y}_m \quad \forall m \in M^{new}, p \in P_m, k \in K_{m,p}, i \in I^{PRO}_{m,p} \tag{18}$$

$$\sum_{m \in M^{new}} FCO_m^{INV} \overline{Y}_m \quad (19)$$

$$\sum_{m \in M^{new}} GHG_m^{CON} \overline{Y}_m \quad (20)$$

This paper employs the ε-constraints method to solve the multi-objective optimization problem. Other multi-objective optimization techniques, such as Multi-Objective Simplex or Weighted Sum, can be used to compare and achieve a better solution.

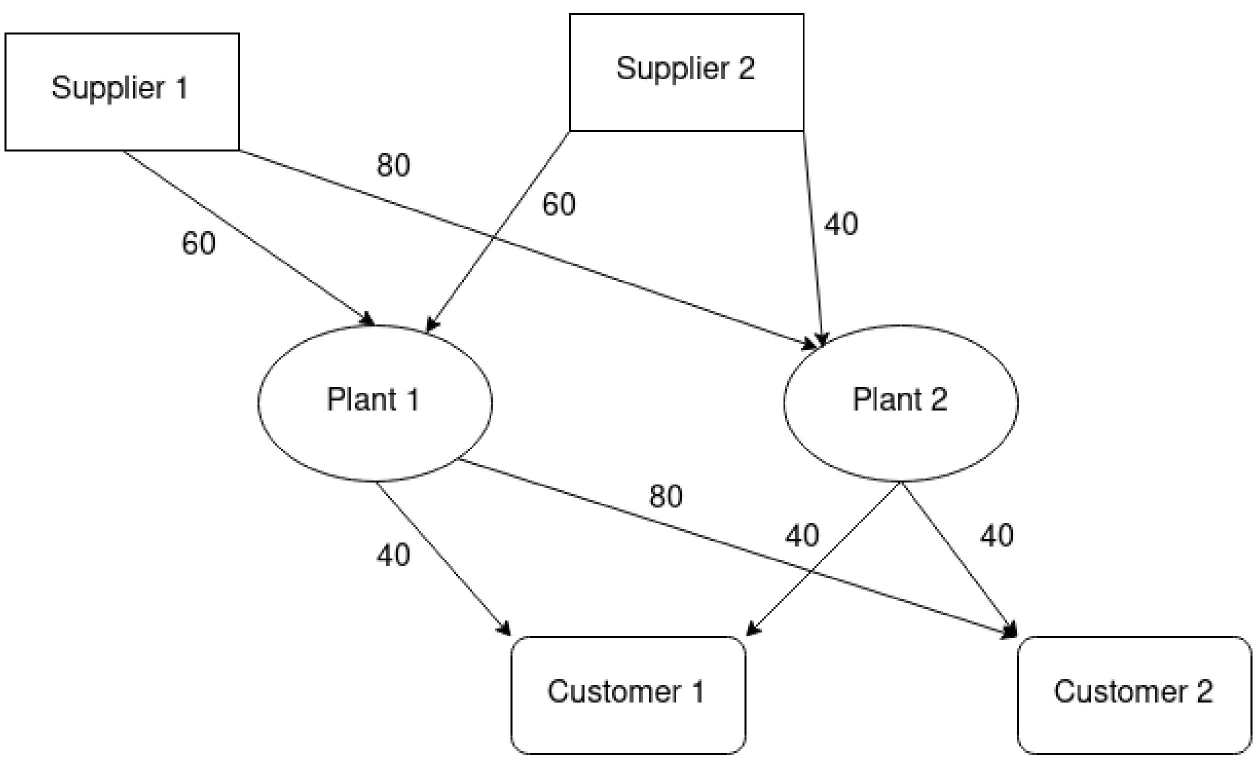
ILLUSTRATION

As a minimal multi-objective problem, we define the following supply chain problem.

Let us assume that there is just chemical reaction happening in the production plants i.e.

X -> Y.

There are two suppliers, two consumers and two production plants, with the following network.



Supplier 1 sends X1 amount of X to Plant 1, X2 amount of X to Plant 2 and Supplier 2 sends X3 amount of X to Plant 1 and X4 amount of X from Plant 2. The maximum capacities of the plants are 100 tons and 120 tons respectively.

Customer 1 receives Y1 amount of Y to Plant 1, Y2 amount of Y to Plant 2 and Customer 2 receives Y3 amount of Y to Plant 1 and Y4 amount of Y from Plant 2. Customer 1 requires 80 tons and Customer 2 requires 60 tons respectively.

The fixed cost of using Plant 1 is \$600 and using Plant 2 is \$900. The variable cost includes only transportation costs which are proportional to the distances with a factor of 1/20.

Therefore, the total cost of production is: $1500 + 3X1 + 4X2 + 3X3 + 2X4 + 2Y1 + 4Y2 + 2Y3 + 2Y4$

The GHG emissions factor from Supplier 1 is six times the amount of chemicals supplied whereas the GHG emissions factor from Supplier 2 is 12 times the amount of chemicals supplied. The GHG emissions from transportation are proportional to the distances with a factor of 1/20. The production plants emit 3 times and 9 times the amount of chemicals produced.

Therefore, the total GHG emissions are: $12X1 + 19X2 + 18X3 + 23X4 + 4Y1 + 2Y2 + 2Y3 + 2Y4$.

The total lead times include only transportation costs. Assuming the roads from plant 1 to customer 1 and from plant 2 to both the customers are worse, it takes four times the amount of chemical transported. Whereas since the road from plant 1 to customer 2 is very smooth, the multiplication factor is just 1. For rest, the multiplication factor is 2

Therefore, the total lead time is: $2X1 + 2X2 + 2X3 + 2X4 + 4Y1 + Y2 + 4Y3 + 4Y4$

The equality constraints include:

$X1 + X3 = Y1 + Y2$

$X2 + X4 = Y3 + Y4$

$Y1 + Y3 = 80$

$Y2 + Y4 = 60$

The inequality constraints include:

All the variables are non-negative.

X1 + X3 = Y1 + Y2 <= 100

X2 + X4 = Y3 + Y4 <= 120

We solved the above problem by programming the solution using the following software:

1. Python 3.10.6
2. Matplotlib Pyplot 3.5.3
3. Pyomo 6.4.3 (An open source optimisation package)
4. GLPK (GNU Linear Programming Kit)

Upon minimizing each optimisation function independently, we received the following results:

Minimizing Cost

X1 = 0.0 X2 = 0.0 X3 = 20.0 X4 = 120.0

Y1 = 20.0 Y2 = 0.0 Y3 = 60.0 Y4 = 60.0

Cost = 2080.0

GHG Emissions = 3440.0

Total Lead Time = 840.0

Minimizing GHG Emissions

X1 = 100.0 X2 = 40.0 X3 = 0.0 X4 = 0.0

Y1 = 40.0 Y2 = 60.0 Y3 = 40.0 Y4 = 0.0

Cost = 2360.0

GHG Emissions = 2320.0

Total Lead Time = 660.0

Minimizing Total Lead Time:

X1 = 0.0   X2 = 0.0   X3 = 60.0   X4 = 80.0

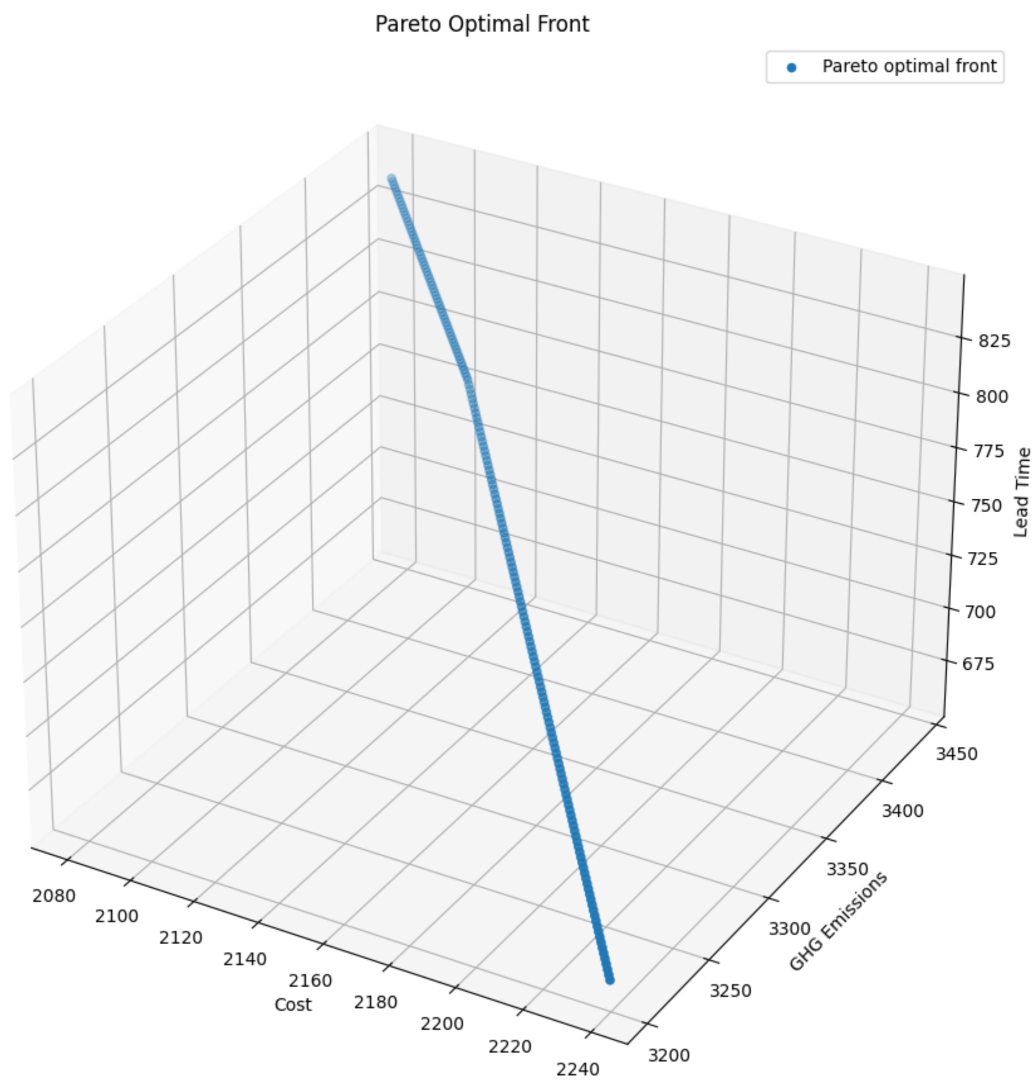
Y1 = 0.0   Y2 = 60.0   Y3 = 80.0   Y4 = 0.0

Cost = 2240.0

GHG Emissions = 3200.0

Total Lead Time = 660.0

By using the ε**-constraint** method, we received the following **Pareto Optimal Front.**



OBSERVATIONS

As clearly seen by the above illustrations and as expected, when GHG emissions are minimized, Cost and Total Lead Time increases compared to the values obtained by minimizing primarily minimizing cost or total lead time.

We can also see that total lead time in case to minimizing either GHG emissions or total lead time is the same, this implies that 660 units is the minimum possible lead time and at less than at 660 lead time units the GHG emissions and cost will be dependent on each other and independent of the lead time.

This leads to the Pareto Optimal Front as observed in the 3-D graph. From the graph we can infer that the firm can now decide to choose a point on the curve to operate on either prioritizing minimization as per the goals set by the firm of GHG emissions or cost of production.

When projected on a 2-D plane including Cost vs GHG emissions or Lead time vs GHG emissions or Cost vs Lead time, the Front will be distinguishably visible where the excluded factor was primarily optimized.

It will be in the form of a bent line because of the simpler size of data used in the generation of the graph. When the size and complexity of the dataset is increased there will be more and more points between the currently obtained points which would lie slightly offset from the line in the outward direction such that the obtained curve is convex hence forming a popularly recognizable pattern of a Front.

SUMMARY & CONCLUSIONS

Considering three essential performance characteristics, including total cost, total GHG emission, and total lead time, the best design and planning for sustainable industrial supply chains. These sustainability indicators are included in a multi-objective optimisation framework created and tested on an industrial test case. The findings demonstrate distinct trade-offs between the three goals. As a result, it is possible to determine the effect an inevitable cost increase might have on the supply chain's performance. Remarkably, the forms of the Pareto curves show that a modest increase in cost might already result in a significant reduction in GHG emissions or lead time. The usefulness of the suggested method for issues with network growth and plant development is further demonstrated. Large-scale supply chain problems can be resolved using the suggested optimisation framework. This work focuses on how the suggested methodology might be applied to a sizable industrial case study that uses actual data. With the necessary information, the suggested framework may be used to analyze a variety of supply chains in the chemical and process industries. The model can also serve as a foundation for other expansions, such as multi period supply chain optimization that considers inventory restrictions and time-dependent demand.

REFERENCES

1. Supply chain management. (2022, October 28). In *Wikipedia*. https://en.wikipedia.org/wiki/Supply_chain_management
2. Zhang, Q., Shah, N., Wassick, J., Helling, R., & van Egerschot, P. (2014). Sustainable supply chain optimisation: An industrial case study. *Computers & Industrial Engineering*, *74*, 68-83. https://doi.org/10.1016/j.cie.2014.05.002
3. Multi-objective optimization. (2022, November 25). In *Wikipedia*. https://en.wikipedia.org/wiki/Multi-objective_optimization

ACKNOWLEDGEMENT

We thank Prof. Kapil Ahuja for helping us understand the fundamental optimisation concepts. We also thank him for his guidance which helped fuel enthusiasm in working with the problem.

Team Members

1. Mukul Jain (200001050)
2. Nilay Ganvit (200001053)

Under the guidance of Dr. Kapil Ahuja, Professor, Computer Science and Engineering, IIT Indore.