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Distribution of Products from Factories to Warehouses

Semester – III – SYBBA - I

Submitted To: **Tejaswini Angre**

Subject: Operation Research

Name	Roll no.	Sap ID
Aarush Acharaya	I003	74142500077
Jaiv Trehan	I020	74142501801
Pushkar Patil	I044	74142500223
Rayhanali Dossa	I047	74142500778
Satyam Sharma	I052	74142500074

NMIMS

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1. Introduction

Transportation is a central component of supply-chain operations because products must be moved from production facilities to locations where they are required. When an organization has several factories and several destinations, management must decide how much product should be shipped along each possible route. If this decision is made without a systematic method, the firm may use an unnecessarily expensive allocation even when lower-cost alternatives exist.

Operations Research addresses this type of problem by representing the distribution network as a mathematical optimization model. In a transportation model, each source has an available supply, each destination has a required demand, and every possible source-destination combination has an associated unit transportation cost. The objective is normally to determine the shipment quantities that satisfy all requirements at minimum total cost.

It also requires an analytical treatment of the real-life context, problem formulation, objective function, constraints, assumptions, solution methodology, results, and critical analysis. The present report adopts the quantitative option and therefore concentrates on one research paper and a complete numerical application rather than a multi-paper literature review.

The selected application uses Amul/GCMMF as the real-world organizational context. Amul's published distribution material shows an extensive national network, including the study's chosen destinations such as Mumbai, Pune, Ahmedabad, Surat, Indore, Jaipur, Nashik and Nagpur. The source locations selected for the model are also consistent with Amul's published dairy-plant information.

Research Question

How can a quantitative transportation optimization model be used to determine the cost-minimizing allocation of Amul products from multiple dairy plants to multiple regional warehouse and market destinations while satisfying supply and demand requirements, and what cost improvement can be achieved by moving from an initial feasible distribution plan to the MODI-based optimal plan?



Quantitative Research Paper Foundation

The quantitative research paper selected as the methodological foundation is:

> **Arman, K., Organ, A., Yenilmezel, S., & Akay, M. (2021). Planning the Distribution Network of the Electronics Firm with the Transportation Model. Yeni Fikir International Journal of Academic Research and Ideas, 13(27), 13–22. [1]**

The article is a research study of an electronics firm operating in Istanbul. It considers product distribution from three factories to customers in nine different cities. The researchers use the Vogel Approximation Method to generate an initial feasible solution, the MODI method to obtain the optimal transportation cost, and then solve the same linear programming model in GAMS to compare the results.

The article is particularly appropriate for this project because its quantitative structure closely matches the selected problem. It demonstrates that a transportation model can be used when several origins, several destinations, known supply quantities, known demand quantities and route-specific unit transportation costs exist. The article also emphasizes that transportation algorithms can provide efficient solutions, while software can be useful when the number of variables and constraints becomes large.

Research-paper element	Description
Real-life setting	Electronics firm operating in Istanbul
Network structure	3 factories → 9 customer cities
Primary OR technique	Transportation model / Linear Programming
Initial solution	Vogel's Approximation Method (VAM)
Optimization method	Modified Distribution Method (MODI)
Verification	GAMS linear programming model
Outcome	Optimized distribution plan with lower transportation cost

2. Understanding the Real-Life Context

Distribution of Products from Factories to Warehouses — Amul / GCMMF

The Real-Life Problem

Amul, marketed by the Gujarat Cooperative Milk Marketing Federation (GCMMF),

produces its products at dairy plants located mainly in Gujarat, while its customers are spread across India. GCMMF reported a turnover of ₹65,911 crore in FY 2024-25, an increase of 11% over the previous year [2]. It handles about 300 lakh litres of milk per day, sourced from around 36 lakh farmers through 18 district unions and approximately 18,600 village cooperative societies [1][3]. Amul's own published material describes a marketing network of 76 sales offices, about 10,000 dealers and about 10 lakh retailers

This scale creates a recurring logistics decision. Each plant has a limited quantity of product available for dispatch in a planning period; each market (Mumbai, Pune, Indore, Nagpur, Jaipur and others) requires a specific quantity; and every plant-to-market route carries a different freight cost, driven mainly by distance. If routes are chosen one at a time — for example, "serve each city from its nearest plant" — the resulting plan can appear sensible locally yet be more expensive overall, because the nearest plant may exhaust its supply and force costly long-haul shipments elsewhere. Since dairy products are perishable, largely move under refrigeration, and are sold at low margins, freight is a significant and repeating cost; even a small percentage saving accumulates substantially over time. The problem studied in this report is therefore: how should cartons be shipped from four plants (Anand, Mehsana, Surat and Gandhinagar) to nine



destination hubs so that every hub's demand is met, no plant ships more than it has available, and total transportation cost is minimised?

Industry and Domain

Aspect Describe

Industry Dairy and food processing, part of India's FMCG sector, operated as a farmer-owned cooperative. Domain Supply chain management — specifically outbound distribution logistics (plants to warehouses / markets).

Special features Perishable, temperature-sensitive products requiring cold-chain handling; high volumes; geographically dispersed demand.

Why OR Techniques Were Suitable

• The problem already has the structure of a transportation model. It has clearly defined sources (plants) with known supply, destinations (hubs) with known demand, and a unit cost on each route — exactly the structure for which the classical transportation problem was designed.

There are too many interdependent combinations to judge by intuition. Four plants and nine hubs give 36 possible routes, and the choices affect one another: using more of one plant's capacity changes what every other plant should do. An optimisation model evaluates the entire network simultaneously.

• Costs are linear and the data are measurable. Freight cost per carton is

approximately distance × rate, so total cost rises in proportion to the quantity

shipped. This fits linear programming, and VAM followed by MODI yields a provably

optimal plan.

• The method is transparent and repeatable. MODI provides an explicit optimality

test, so managers can see why a route is or is not used, and the same model can be

re-run each planning period as demand changes.

• It supports "what-if" planning. Sensitivity analysis shows how cost and allocation

respond when freight rates rise, demand grows, or capacity shifts between plants

(see Section 12 of the report).

• Savings are meaningful at Amul's scale. The model in this report reduces cost by

1.61% relative to the VAM starting plan; applied across a network moving hundreds

of lakh litres per day, a gain of this size becomes significant.

Note: The organisational facts above are drawn from Amul/GCMMF publications and news

reports. The supply, demand and freight figures used in the model remain academic

assumptions, as stated elsewhere in the report.



3. Modelling and Problem Formulation

Problem Statement

Amul, operated by the Gujarat Cooperative Milk Marketing Federation (GCMMF), has an extensive distribution network through which dairy products are supplied to markets across India. Efficiently allocating products from manufacturing facilities to regional distribution destinations is important for minimising transportation expenditure while ensuring that market demand is fulfilled.

The present study examines a quantitative transportation problem involving four selected source locations—Anand, Mehsana, Surat and Gandhinagar—and nine destination markets—Mumbai, Ahmedabad, Pune, Surat, Indore, Vadodara, Nashik, Nagpur and Jaipur. Each source location has a specified supply capacity, while each destination has a predetermined demand for products. Transportation costs vary across routes according to the distances between the selected locations and the assumed freight rate.

The main problem is to determine the optimal quantity of products that should be transported from each source location to each destination so that the total transportation cost is minimised without exceeding the available supply or failing to satisfy the required demand. The study formulates this distribution problem as a balanced transportation model and applies Vogel's Approximation Method (VAM) to obtain an initial basic feasible solution, followed by the Modified Distribution Method (MODI) to test optimality and identify the minimum-cost allocation.

Why Operations Research Techniques Are Suitable

Operations Research techniques are suitable because the distribution decision involves several sources, several destinations, known supply and demand quantities, and different transportation costs for possible routes. Choosing routes independently may not minimize total cost because the allocation on one route affects quantities available for other destinations. A transportation model evaluates the network as a whole and provides a systematic, quantitative and auditable allocation.

Vogel’s Approximation Method (VAM) obtains an initial basic feasible solution. The Modified Distribution Method (MODI) then tests optimality and improves the allocation whenever a negative opportunity cost is found. These methods suit this structured transportation-cost minimization problem.

Objective Function

The objective is to minimize total transportation cost when shipping 1,600 cartons from the four selected sources to the nine destinations while meeting all supply and demand requirements.

Minimize Z = sum of c(i,j) × x(i,j) over all sources i and destinations j

Here, x(i,j) is the number of cartons shipped from source i to destination j, and c(i,j) is the transportation cost per carton on that route. The project calculates route cost using an illustrative freight rate of 0.80 per carton-kilometre multiplied by indicative distance. These figures are academic modelling assumptions, not official Amul operating data.

Constraints Used

Supply constraints: Total cartons shipped from each source must equal that source’s available supply.



Source	Constraint	Supply
Anand	Sum of shipments from Anand = 500	500 cartons
Mehsana	Sum of shipments from Mehsana = 400	400 cartons
Surat	Sum of shipments from Surat = 300	300 cartons
Gandhinagar	Sum of shipments from Gandhinagar = 400	400 cartons

Demand constraints: Total cartons received by each destination must equal its required demand.

Destination	Constraint	Demand
Mumbai	x11 + x21 + x31 + x41 = 250	250 cartons
Ahmedabad	x12 + x22 + x32 + x42 = 150	150 cartons
Pune	x13 + x23 + x33 + x43 = 200	200 cartons
Surat	x14 + x24 + x34 + x44 = 200	200 cartons
Indore	x15 + x25 + x35 + x45 = 200	200 cartons
Vadodara	x16 + x26 + x36 + x46 = 150	150 cartons
Nashik	x17 + x27 + x37 + x47 = 150	150 cartons
Nagpur	x18 + x28 + x38 + x48 = 150	150 cartons
Jaipur	x19 + x29 + x39 + x49 = 150	150 cartons

Balance check: Total supply = 1,600 cartons and total demand = 1,600 cartons. Therefore, the problem is balanced and no dummy source or destination is required.

Type of Problem

This is a balanced transportation problem, a special form of linear programming minimization. It has four sources, nine destinations and 4 × 9 = 36 possible shipment decision variables. Supply and demand totals are equal, and all shipment quantities must be non-negative.

Mathematical Model

Decision variable: x(i,j) = number of cartons shipped from source i to destination j, where i = 1, 2, 3, 4 and j = 1, 2, …, 9.

Parameters: c(i,j) = cost per carton on route i to j; S(i) = supply at source i; D(j) = demand at destination j.

Objective: Minimize Z = sum over i = 1 to 4 and j = 1 to 9 of c(i,j) × x(i,j).

Supply constraints: For each source i, sum over all destinations j of x(i,j) = S(i).

Demand constraints: For each destination j, sum over all sources i of x(i,j) = D(j). Non-negativity: x(i,j) ≥ 0 for every source-destination route.

The objective function adds the cost of every shipment. The constraints ensure that source supply is fully allocated and each destination receives exactly its required quantity.



Model Data Summary

Item	Value
Number of sources	4
Number of destinations	9
Possible routes / decision variables	36
Total supply and demand	1,600 cartons each
Cost basis	Indicative distance × ■0.80 per carton-kilometre
Initial solution method	Vogel's Approximation Method (VAM)
Optimization method	Modified Distribution Method (MODI)

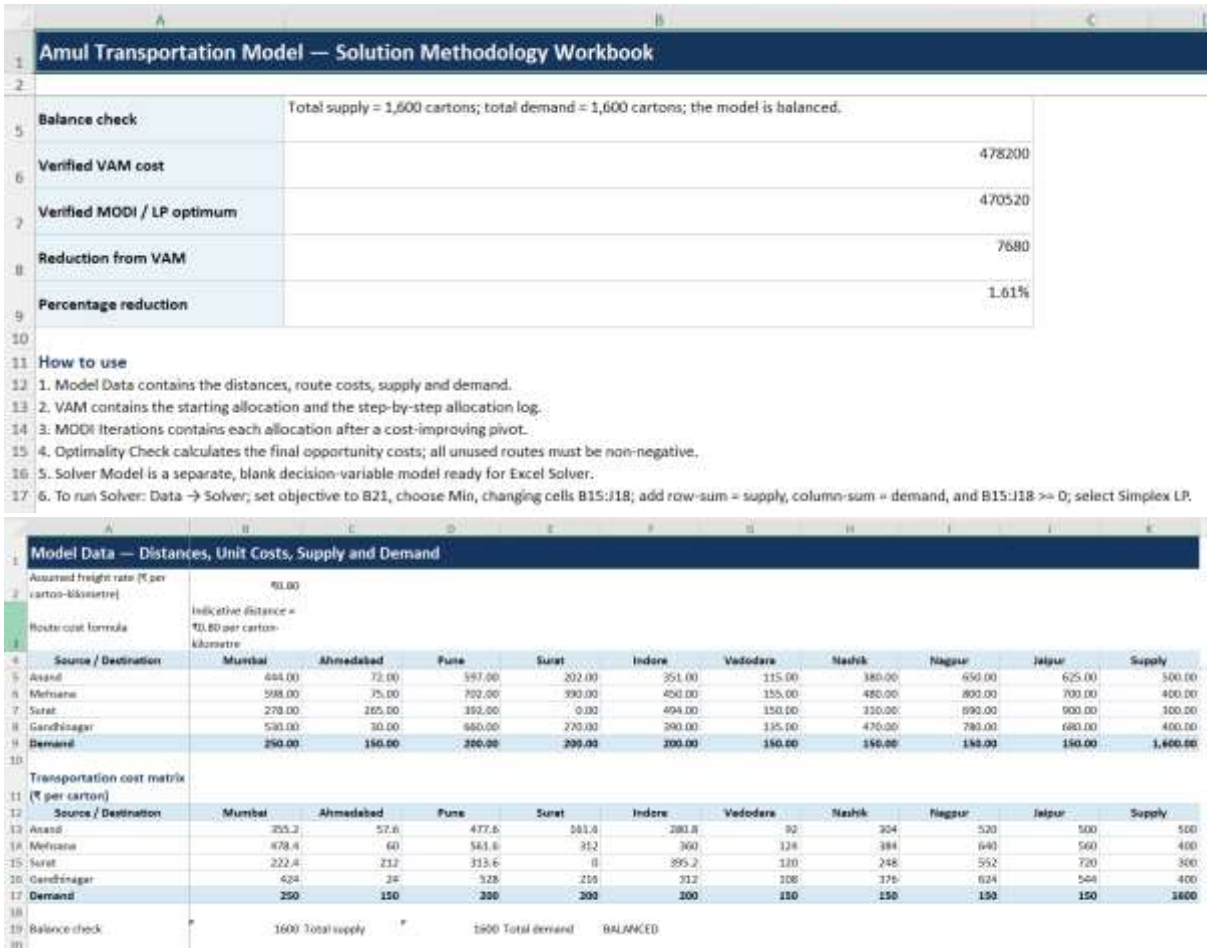
4. Solution Methodology

Solution Techniques Used

The transportation problem is formulated as a linear programming minimisation model. The objective is to minimise total transportation cost while satisfying the supply available at each source and the demand required at each destination.

Vogel's Approximation Method (VAM) is used to obtain an initial basic feasible solution. The method calculates penalties for the active rows and columns by finding the difference between their two lowest available transportation costs. The row or column with the highest penalty is selected, and the maximum possible quantity is allocated to its lowest-cost route. This process continues until all supply and demand requirements are satisfied.

Modified Distribution Method (MODI) is then applied to test and improve the initial solution. Row and column potentials are calculated for the occupied cells, and opportunity costs are determined for unoccupied routes. A negative opportunity cost indicates that the total cost can be reduced. A closed loop is formed around the entering route, and the allocation is adjusted until no negative opportunity costs remain.



Amul Transportation Model — Solution Methodology Workbook

Balance check	Total supply = 1,600 cartons; total demand = 1,600 cartons; the model is balanced.
Verified VAM cost	478200
Verified MODI / LP optimum	470520
Reduction from VAM	7680
Percentage reduction	1.61%

How to use

1. Model Data contains the distances, route costs, supply and demand.
2. VAM contains the starting allocation and the step-by-step allocation log.
3. MODI Iterations contains each allocation after a cost-improving pivot.
4. Optimality Check calculates the final opportunity costs; all unused routes must be non-negative.
5. Solver Model is a separate, blank decision-variable model ready for Excel Solver.
6. To run Solver: Data → Solver; set objective to B21, choose Min, changing cells B15:J18; add row-sum = supply, column-sum = demand, and B15:J18 >= 0; select Simplex LP.

Model Data — Distances, Unit Costs, Supply and Demand

Assumed freight rate (₹ per carton-kilometre) ₹0.80

Route cost formula: Indicative distance × ₹0.80 per carton-kilometre

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	444.00	72.00	597.00	202.00	351.00	115.00	380.00	650.00	625.00	500.00
Mehsana	598.00	75.00	702.00	390.00	450.00	155.00	480.00	800.00	700.00	400.00
Surat	278.00	265.00	391.00	0.00	494.00	150.00	310.00	690.00	900.00	300.00
Gandhinagar	530.00	30.00	660.00	270.00	390.00	135.00	470.00	780.00	680.00	400.00
Demand	**250.00**	**150.00**	**200.00**	**200.00**	**200.00**	**150.00**	**150.00**	**150.00**	**150.00**	**1,600.00**

Transportation cost matrix (₹ per carton)

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	355.2	57.6	477.6	161.6	280.8	92	304	520	500	500
Mehsana	478.4	60	561.6	312	360	124	384	640	560	400
Surat	222.4	212	313.6	0	395.2	120	248	552	720	300
Gandhinagar	424	24	528	216	312	108	376	624	544	400
Demand	**250**	**150**	**200**	**200**	**200**	**150**	**150**	**150**	**150**	**1600**

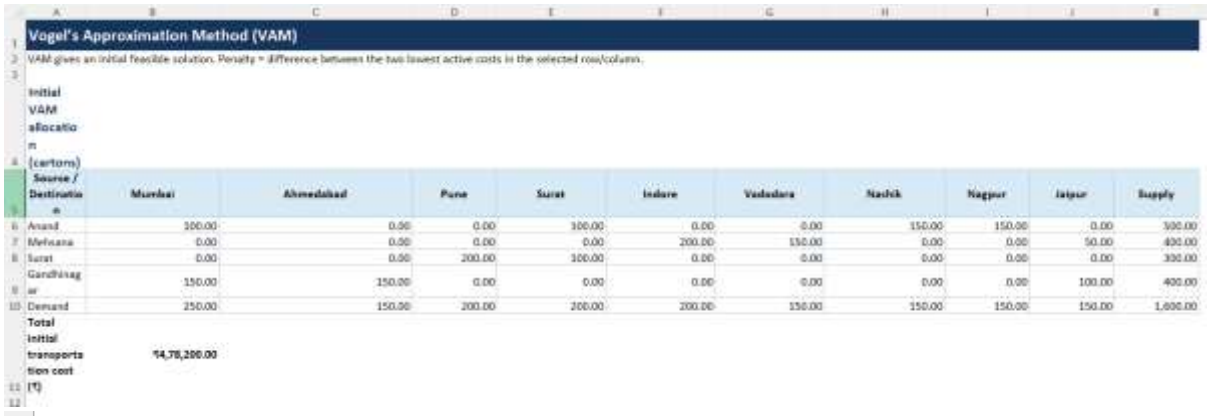
Balance check: 1600 Total supply — 1600 Total demand — BALANCED

Application of VAM and MODI

VAM produced an initial feasible allocation with a total transportation cost of ₹478,200. The allocation satisfied the supply of 1,600 cartons and the demand of 1,600 cartons.

The initial solution was subsequently improved through three MODI iterations. The first iteration reduced the cost to ₹475,000, the second reduced it to ₹471,320, and the third produced a final cost of ₹470,520. At the final stage, all unoccupied routes had non-negative opportunity costs, confirming optimality.

The total reduction from the initial VAM solution was ₹7,680, equivalent to approximately 1.61%. This saving represents an improvement over the initial mathematical allocation, not a verified saving against Amul's actual distribution expenditure.



Vogel's Approximation Method (VAM)

VAM gives an initial feasible solution. Penalty = difference between the two lowest active costs in the selected row/column.

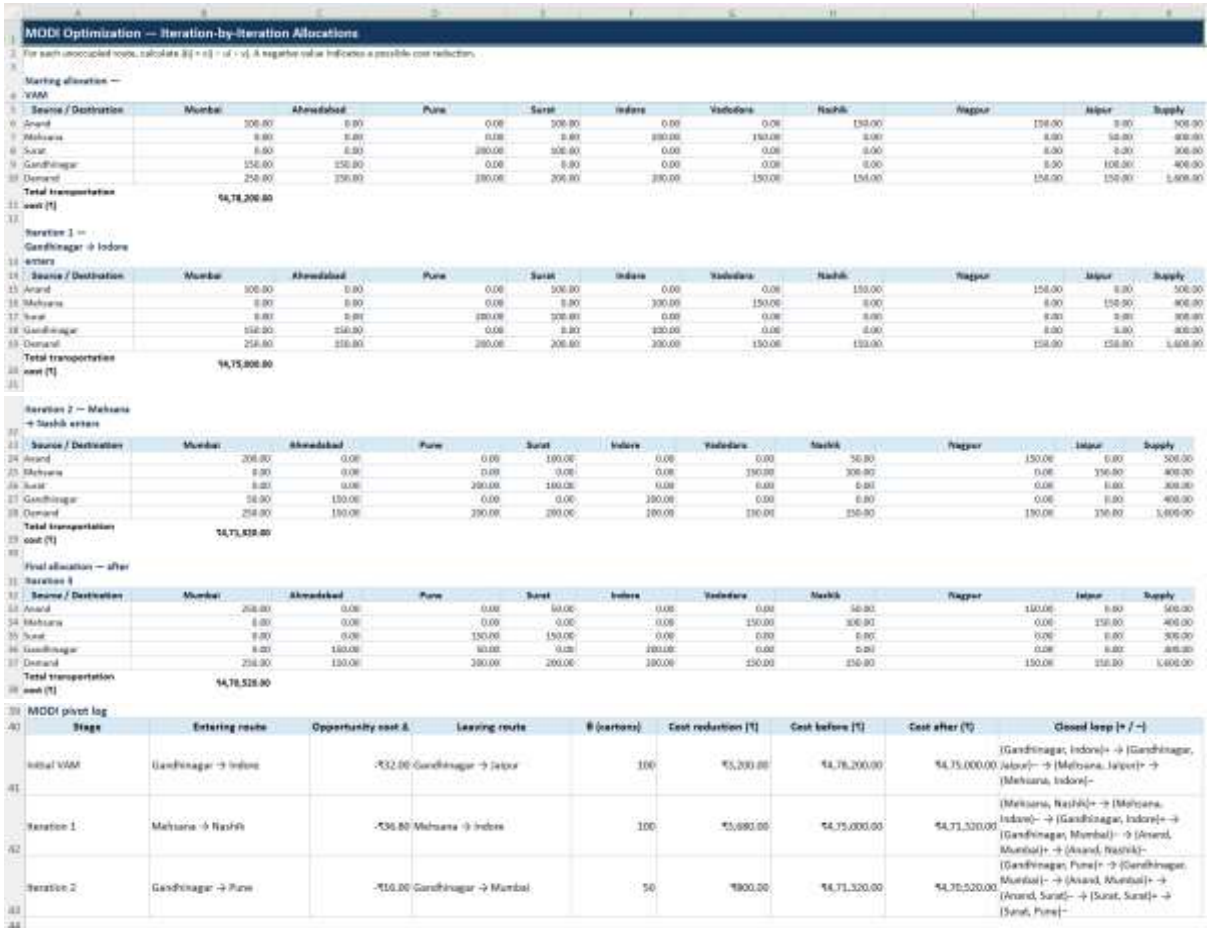
Initial VAM allocation (cartons)

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	100.00	0.00	0.00	300.00	0.00	0.00	150.00	150.00	0.00	500.00
Mehsana	0.00	0.00	0.00	0.00	200.00	150.00	0.00	0.00	50.00	400.00
Surat	0.00	0.00	200.00	100.00	0.00	0.00	0.00	0.00	0.00	300.00
Gandhinagar	150.00	150.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	400.00
Demand	250.00	150.00	200.00	200.00	200.00	150.00	150.00	150.00	150.00	1,600.00

Total initial transportation cost (₹): ₹4,78,200.00

Allocation sequence

Step	Selected row/column	Allocated route	Penalty	Cartons allocated	Cost/carton (₹)	Cost added (₹)	Running cost (₹)
1	Column: Pune	Surat → Pune	164.0	200	₹313.60	₹62,720.00	₹62,720.00
2	Column: Surat	Surat → Surat	161.6	100	₹0.00	₹0.00	₹62,720.00
3	Column: Nagpur	Anand → Nagpur	104.0	150	₹520.00	₹78,000.00	₹1,40,720.00
4	Row: Gandhinagar	Gandhinagar → Ahmedabad	84.0	150	₹24.00	₹3,600.00	₹1,44,320.00
5	Row: Mehsana	Mehsana → Vadodara	188.0	150	₹124.00	₹18,600.00	₹1,62,920.00
6	Row: Anand	Anand → Surat	119.2	100	₹161.60	₹16,160.00	₹1,79,080.00
7	Column: Nashik	Anand → Nashik	72.0	150	₹304.00	₹45,600.00	₹2,24,680.00
8	Row: Mehsana	Mehsana → Indore	118.4	200	₹360.00	₹72,000.00	₹2,96,680.00
9	Row: Anand	Anand → Mumbai	144.8	100	₹355.20	₹35,520.00	₹3,32,200.00
10	Row: Gandhinagar	Gandhinagar → Mumbai	120.0	150	₹424.00	₹63,600.00	₹3,95,800.00
11	Row: Mehsana	Mehsana → Jaipur	560.0	50	₹560.00	₹28,000.00	₹4,23,800.00
12	Row: Gandhinagar	Gandhinagar → Jaipur	544.0	100	₹544.00	₹54,400.00	₹4,78,200.00



MODI Optimization — Iteration-by-Iteration Allocations

For each unoccupied route, calculate δ(i,j) = c(i,j) − (uᵢ + vⱼ). A negative value indicates a possible cost reduction.

Starting allocation — VAM

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	100.00	0.00	0.00	300.00	0.00	0.00	150.00	150.00	0.00	500.00
Mehsana	0.00	0.00	0.00	0.00	200.00	150.00	0.00	0.00	50.00	400.00
Surat	0.00	0.00	200.00	100.00	0.00	0.00	0.00	0.00	0.00	300.00
Gandhinagar	150.00	150.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	400.00
Demand	250.00	150.00	200.00	200.00	200.00	150.00	150.00	150.00	150.00	1,600.00

Total transportation cost (₹): ₹4,78,200.00

Iteration 1 — Gandhinagar → Indore enters

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	100.00	0.00	0.00	300.00	0.00	0.00	150.00	150.00	0.00	500.00
Mehsana	0.00	0.00	0.00	0.00	200.00	150.00	0.00	0.00	50.00	400.00
Surat	0.00	0.00	200.00	100.00	0.00	0.00	0.00	0.00	0.00	300.00
Gandhinagar	150.00	150.00	0.00	0.00	100.00	0.00	0.00	0.00	100.00	400.00
Demand	250.00	150.00	200.00	200.00	200.00	150.00	150.00	150.00	150.00	1,600.00

Total transportation cost (₹): ₹4,75,800.00

Iteration 2 — Mehsana → Nashik enters

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	200.00	0.00	0.00	100.00	0.00	0.00	50.00	150.00	0.00	500.00
Mehsana	0.00	0.00	0.00	0.00	0.00	150.00	300.00	0.00	150.00	400.00
Surat	0.00	0.00	200.00	100.00	0.00	0.00	0.00	0.00	0.00	300.00
Gandhinagar	50.00	150.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	400.00
Demand	250.00	150.00	200.00	200.00	200.00	150.00	150.00	150.00	150.00	1,600.00

Total transportation cost (₹): ₹4,71,520.00

Final allocation — after Iteration 3

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	250.00	0.00	0.00	50.00	0.00	0.00	50.00	150.00	0.00	500.00
Mehsana	0.00	0.00	0.00	0.00	0.00	150.00	300.00	0.00	150.00	400.00
Surat	0.00	0.00	150.00	150.00	0.00	0.00	0.00	0.00	0.00	300.00
Gandhinagar	0.00	150.00	50.00	0.00	200.00	0.00	0.00	0.00	0.00	400.00
Demand	250.00	150.00	200.00	200.00	200.00	150.00	150.00	150.00	150.00	1,600.00

Total transportation cost (₹): ₹4,70,520.00

MODI pivot log

Stage	Entering route	Opportunity cost δ	Leaving route	θ (cartons)	Cost reduction (₹)	Cost before (₹)	Cost after (₹)	Closed loop (+ / −)
Initial VAM	Gandhinagar → Indore	-₹32.00	Gandhinagar → Jaipur	100	₹3,200.00	₹4,78,200.00	₹4,75,000.00	(Gandhinagar, Indore)+ → (Gandhinagar, Jaipur)− → (Mehsana, Jaipur)+ → (Mehsana, Indore)−
Iteration 1	Mehsana → Nashik	-₹36.80	Mehsana → Indore	100	₹3,680.00	₹4,75,000.00	₹4,71,320.00	(Mehsana, Nashik)+ → (Mehsana, Indore)− → (Gandhinagar, Indore)+ → (Gandhinagar, Mumbai)− → (Anand, Mumbai)+ → (Anand, Nashik)−
Iteration 2	Gandhinagar → Pune	-₹16.00	Gandhinagar → Mumbai	50	₹800.00	₹4,71,320.00	₹4,70,520.00	(Gandhinagar, Pune)+ → (Gandhinagar, Mumbai)− → (Anand, Mumbai)+ → (Anand, Surat)− → (Surat, Surat)+ → (Surat, Pune)−

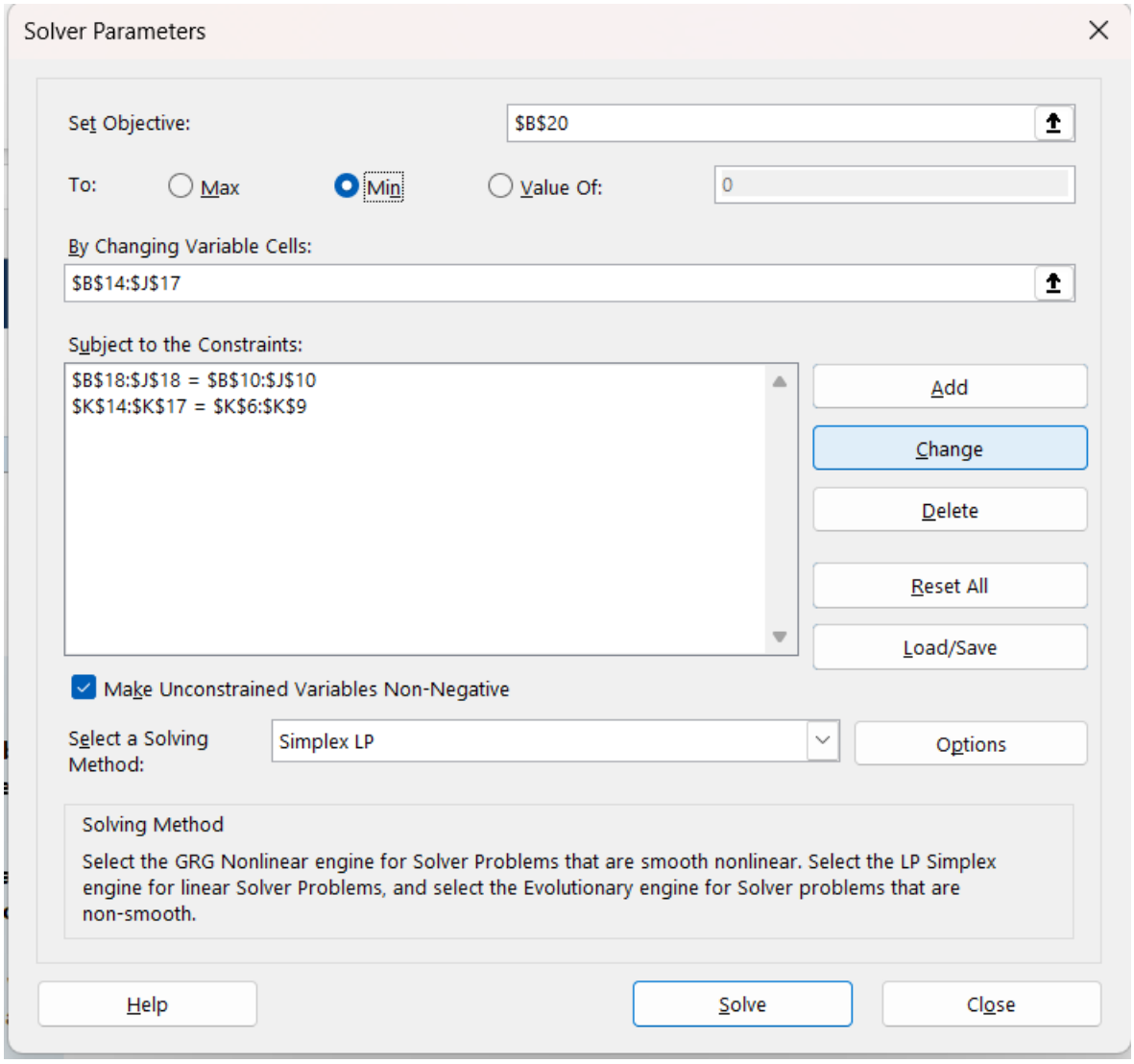


Software and Tools Used

Microsoft Excel is used to organise the transportation cost matrix, source supplies, destination demands and shipment decision variables. The SUMPRODUCT function calculates total transportation cost by multiplying each route's unit cost by its allocated quantity and adding the results.

Excel Solver is used to verify the optimal solution. The total transportation cost cell is selected as the objective to minimise, while the 36 shipment quantities are selected as the changing variable cells. Constraints ensure that each source's total dispatch equals its available supply, each destination receives its required demand, and all shipment quantities are non-negative. The Simplex LP solving method is appropriate because the objective function and constraints are linear.

The selected research paper by Arman et al. (2021) applies VAM and MODI and verifies its transportation model using GAMS. In the present project, VAM and MODI are applied to the illustrative Amul/GCMMF distribution model, while Microsoft Excel and Excel Solver are used for spreadsheet-based calculation and independent verification.



Methodological Outcome

The final model recommends an allocation that satisfies all supply and demand constraints at a minimum calculated transportation cost of ₹470,520. The agreement between the MODI optimality test and the independently calculated linear programming solution supports the correctness of the result. The numerical findings remain dependent on the illustrative supply, demand and freight-cost assumptions used in the project.



Excel Solver Model — Minimize Total Transportation Cost

This is the Solver-ready model. Shipment decision cells are initialised to zero; run Solver to find a feasible optimal allocation.

Route costs (₹ per carton)

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	355.2	57.6	477.6	161.6	280.8	92	304	520	500	500
Mehsana	478.4	60	561.6	332	360	124	384	640	560	400
Surat	222.4	212	313.6	0	895.2	120	248	552	720	300
Gandhinagar	424	24	528	216	332	108	376	624	544	400
Demand	**250**	**150**	**200**	**200**	**200**	**150**	**150**	**150**	**150**	**1600**

Decision variables: cartons shipped

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	250.00	0.00	0.00	50.00	0.00	0.00	50.00	150.00	0.00	500
Mehsana	0.00	0.00	0.00	0.00	0.00	150.00	100.00	0.00	150.00	400
Surat	0.00	0.00	150.00	150.00	0.00	0.00	0.00	0.00	0.00	300
Gandhinagar	0.00	150.00	50.00	0.00	200.00	0.00	0.00	0.00	0.00	400
Demand met	**250**	**150**	**200**	**200**	**200**	**150**	**150**	**150**	**150**	**1600**
Total transportation cost (₹)	**₹4,70,520.00**									

Solver configuration

Set Objective	$B$20; choose Min.
By Changing Variable Cells	$B$14:$J$17.
Supply constraints	$K$14:$K$17 = $K$6:$K$9.
Demand constraints	$B$18:$J$18 = $B$10:$J$10.
Non-negativity	Tick Make Unconstrained Variables Non-Negative).
Solving method	Simplex LP.
Expected verified optimum	₹470,520; compare your Solver result

Excel Formula Added Note:

1. **All of the Demand Row cells in cartons shipped table were set as =SUM to all cities from their respective column**
2. **All of the Supply Column cells in cartons shipped table were set as =SUM to all cities from their respective row**
3. **The 'Total transportation cost (₹)' amount formula was set as =SUMPRODUCT() array from Routes cost table and Cartons shipped table**

MODI Final Optimality Check

At the final basis, all unused-route opportunity costs must be non-negative. Occupied routes have Δ = 0 by construction.

Final allocation (cartons)

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur	Supply
Anand	250.00	0.00	0.00	50.00	0.00	0.00	50.00	150.00	0.00	500.00
Mehsana	0.00	0.00	0.00	0.00	0.00	150.00	100.00	0.00	150.00	400.00
Surat	0.00	0.00	150.00	150.00	0.00	0.00	0.00	0.00	0.00	300.00
Gandhinagar	0.00	150.00	50.00	0.00	200.00	0.00	0.00	0.00	0.00	400.00
Demand	250.00	150.00	200.00	200.00	200.00	150.00	150.00	150.00	150.00	1,600.00

Final MODI potentials

Source	u_i
Anand	0.0
Mehsana	80.0
Surat	-161.6
Gandhinagar	52.8

Destination	v_j
Mumbai	355.2
Ahmedabad	-26.6
Pune	475.2
Surat	161.6
Indore	259.2
Vadodara	44.0
Nashik	304.0
Nagpur	520.0
Jaipur	480.0

Opportunity costs $\Delta_{ij} = u_i + v_j - c_{ij}$

Source / Destination	Mumbai	Ahmedabad	Pune	Surat	Indore	Vadodara	Nashik	Nagpur	Jaipur
Anand	0.0	86.4	2.4	0.0	21.6	48.0	0.0	0.0	20.0
Mehsana	43.2	8.8	6.4	70.4	20.8	0.0	0.0	40.0	0.0
Surat	28.8	402.4	0.0	0.0	297.6	237.6	105.6	193.6	401.6
Gandhinagar	16.0	0.0	0.0	1.6	0.0	11.2	19.2	51.2	11.2

Minimum opportunity cost among unused routes (₹/carton)	1.6
Optimality conclusion	OPTIMAL: all unused routes have non-negative opportunity cost
Verified objective value (₹)	₹4,70,520.00

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Amul_Transportation_Solution_Methodolo



5. Critical Analysis and Summary

Summary and Key Findings

Research paper. Krishnan and Masrom (2022) apply linear programming to the polymer exports of MITCO Labuan Company Limited from four Petronas plants to four destinations. Capacity (405,000 tons) exceeds demand (375,000 tons), so a zero-cost dummy destination absorbs the 30,000-ton surplus. A North West Corner start (RM120,000 million) was cheaper than a VAM start (RM122,500 million) and was confirmed optimal at RM120,000 million; sensitivity analysis showed Plants 1–3 fully used and Plant 4 holding the slack. The paper reports no comparison with MLCL's actual pre-optimisation cost, so it demonstrates the method rather than a saving over existing practice.

Amul/GCMMF project. The project models four sources (Anand, Mehsana, Surat, Gandhinagar) and nine destinations, with 1,600 cartons of supply and demand and 36 possible routes. Route cost is indicative distance multiplied by an assumed ₹0.80 per carton-kilometre. VAM produced a feasible plan costing ₹478,200, and three MODI iterations (₹475,000, ₹471,320, ₹470,520) reached the optimum of ₹470,520, at which every unoccupied route has a non-negative opportunity cost. The saving is ₹7,680 (1.61%). It is modest because VAM already gave a strong start, and it is measured against VAM, not against Amul's actual practice.

The scenarios add insight. A 10% freight increase lifts cost to ₹517,572 with the allocation unchanged, since uniform scaling preserves route ranking. Adding 50 cartons of Mumbai demand raises cost by ₹17,760, exactly 50 × the Anand→Mumbai rate of ₹355.20, so the extra demand was absorbed without disturbing the network. Shifting 50 cartons of supply from Anand to Gandhinagar raises cost by ₹2,640, showing that where capacity sits matters even when total supply is fixed.

Connecting the two studies. Both use a heuristic start followed by an optimality test. In the paper the start was already optimal; in the project it was 1.61% above the optimum. The test is therefore valuable either way: it improves a weak start and certifies a good one. The figures come from different data and are not comparable.

Impact and Implications of the Solution

The model treats distribution as a network-wide decision, not a route-by-route choice, and the project's plan shows why. Surat's 300 cartons are exhausted by Pune (150) and local Surat demand (150, at zero cost), so Gandhinagar supplies 50 cartons to Pune at ₹528 per carton instead of the ₹313.60 Surat rate. That route is dearer in isolation but cheapest for the system. Allocating by nearest source would miss this.

Several opportunity costs are small (+₹1.6 for Gandhinagar→Surat, +₹2.4 for Anand→Pune), so near-optimal alternatives exist. A planner could therefore choose among them on non-cost grounds such as reliability or delivery time at little added cost. This is an inferred benefit, not a demonstrated one.

With real data, such a model could give Amul/GCMMF a repeatable, auditable basis for dispatch and for what-if planning on freight rates, demand growth and plant capacity, as Scenarios A–C illustrate. Because the inputs are academic assumptions, these remain potential benefits; no actual saving for Amul has been shown. For supply chain management, the broader lesson is that gains depend on the cost structure, and a 1.61% improvement is a realistic expectation, not a guaranteed large one.

Strengths of the Model

- Complete formulation. Explicit decision variables, one objective, supply and demand constraints and non-negativity capture all 36 routes at once, which manual reasoning could not reliably do.
- Proof of optimality. MODI certifies the plan with $\Delta_{ij} \geq 0$ for every unoccupied cell, rather than offering a merely plausible plan.
- Auditability. Each cost reduction (₹3,200, ₹3,680, ₹800) follows directly from the entering opportunity cost and the loop quantity, so every step can be checked.
- Managerial insight. Scenario results show how cost responds to rates, demand and capacity, beyond a single cost figure.



Limitations

- No real baseline. The saving is relative to VAM, so the project cannot claim an improvement over Amul's current practice. The paper has the same gap.
- Excluded operational factors. Vehicle capacity, fixed dispatch charges, tolls, loading costs, delivery-time limits and cold-chain requirements are not modelled. For a perishable dairy product, a cost-optimal route may be operationally unsuitable.
- Deterministic treatment of uncertainty. Demand, supply and fuel-driven freight rates are handled only through what-if scenarios, so the plan is not robust to fluctuation.
- Zero-cost local route. Surat→Surat costs ₹0.00 because its distance is zero. This favours local supply and overstates its attractiveness, since local delivery is never free.
- Illustrative data. Results demonstrate the method and cannot be read as Amul operating figures.

Assumptions

- One planning period and one homogeneous product measured in cartons.
- Supply, demand, distances and the ₹0.80 per carton-kilometre rate are known, fixed academic inputs.
- Cost is strictly proportional to distance and quantity.
- All 36 routes are available.
- All supply is dispatched and all demand is met exactly (a balanced problem, so no dummy is needed).

These simplifications make the problem solvable by a transportation algorithm, but real distribution involves step-wise truck costs, variable demand and route restrictions that the assumptions remove.

Possibilities for Extension or Improvement

None of the following is in the current model.

- Vehicle capacities and fixed dispatch costs (mixed-integer formulation), so plans reflect whole truckloads and non-linear costs.
- Delivery-time and cold-chain constraints with multiple products, to exclude routes that cannot preserve freshness.
- Multiple planning periods with storage costs, to support replenishment and seasonal planning.
- Historical demand data with stochastic or robust optimisation, for plans that survive fluctuation.
- Actual freight tariffs and fuel-cost updates with sensitivity ranges and shadow prices, to show which costs and capacities most affect the solution.