IS6055: Prescriptive Analytics

Sustainable Supply Chain Optimization for GreenGlow Cosmetics

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1. Executive Summary

GreenGlow Cosmetics, a rapidly growing sustainable skincare brand, aims to expand its global presence while maintaining its commitment to ethical sourcing, carbon-conscious production, and agile supply chain delivery *(Quantzig, 2023)*. As the company scales, it faces a classic dilemma: how to balance cost efficiency, environmental responsibility, and service-level targets across diverse global regions.

This project leverages prescriptive analytics, specifically, a mixed-integer linear programming (MILP) model, to optimize GreenGlow's supply chain network *(IBM, 2022)*. The model integrates supplier decisions, production capacity allocation, intercontinental transportation, and regional demand fulfillment. Crucially, the model balances three competing objectives: total operational cost, carbon emissions from production, and penalties for unmet demand.

Our analysis began with a base model that represents GreenGlow's current operational constraints and demand forecasts. We then developed and evaluated six future-oriented scenarios designed to test the model's responsiveness under stress and uncertainty:

1. Supplier Cost Surge: Simulating raw material price hikes to test sourcing flexibility
2. Demand Spike in Asia-Pacific: Stress-testing the system under regional growth
3. Transport Cost Increase: Evaluating logistics sensitivity to fuel or carrier disruptions
4. Expansion Disabled: Restricting plant growth to measure base network feasibility
5. Supplier Removal (MineralGlow): Removing a key supplier to examine network resilience
6. Sustainability Constraint (Emissions Cap): Capping CO_2 output to align with ESG goals*(Silva and Figueiredo, 2014)*.

Each scenario was solved using the MILP model, generating optimal production, transport, and unmet demand plans. Results were evaluated using a weighted objective value combining costs, emissions, and penalties. Scenario-specific insights were drawn from visualizations, shipping patterns, unmet demand heatmaps, and cost-emission trade-offs.

The analysis revealed critical insights: for instance, expansion may not always be cost-justified unless emissions or unmet demand costs increase. The removal of a key supplier introduced unmet demand in previously stable regions, highlighting the importance of supplier diversification. Implementing an emissions cap successfully reduced carbon impact with modest financial trade-offs, demonstrating the model's value for sustainability planning.

Overall, this study demonstrates how prescriptive analytics can guide strategic supply chain decisions under real-world constraints. The model provides GreenGlow with a robust decision support tool to inform long-term planning while aligning with the brand's ethical and environmental commitments.

2. Introduction & Problem Statement

2.1 GreenGlow Cosmetics: Purpose-Driven Growth in a Global Market

GreenGlow Cosmetics is a fast-growing sustainable skincare brand known for its commitment to natural ingredients, ethical sourcing, and environmentally conscious manufacturing. Headquartered in Europe, the company has experienced significant market growth across North America, AsiaPacific, the Middle East, and emerging markets in Africa and South America. This growth, while promising, introduces complexity in managing a globally dispersed supply chain that must balance cost-efficiency with social and environmental responsibility.

The company currently sources raw materials from four suppliers, manufactures in four regional plants, and distributes to six demand regions worldwide. With mounting demand pressure, fluctuating input costs, volatile transport logistics, and increasing ESG scrutiny, GreenGlow's leadership is seeking a data-driven, future-proof approach to supply chain planning.

2.2 The Strategic Challenge

GreenGlow faces multiple interconnected challenges:

- Cost Optimization vs. Sustainability: How can the company meet growing global demand while keeping costs under control and meeting its internal carbon emissions goals?
- Supplier Risk: What happens if a key supplier becomes unavailable due to geopolitical instability or environmental constraints?
- Demand Volatility: How resilient is the current network when regional demand unexpectedly spikes?
- Expansion Justification: Should the company expand capacity in one or more regions, and if so, where and when?

These are not simple questions. They involve trade-offs across finance, operations, and sustainability, which traditional forecasting and descriptive analytics cannot fully resolve.

GreenGlow needs a tool to simulate, optimize, and prescribe the best decisions under uncertainty.

2.3 The Role of Prescriptive Analytics

To address these challenges, we apply prescriptive analytics using a Mixed Integer Linear Programming (MILP) model *(IBM, 2022; Gurobi Optimization, 2022).* This mathematical model enables us to make optimal decisions given multiple constraints (supply, demand, emissions, transport limits) and objectives (minimizing cost, minimizing emissions, minimizing penalties for unmet demand).

Unlike predictive models that estimate what might happen, prescriptive models recommend what to do. In GreenGlow's case, the MILP model answers:

- How much raw material should be sourced from each supplier?
- How should production be allocated across manufacturing plants?
- What is the optimal shipping flow to meet regional demand?
- Where does unmet demand occur, and at what penalty cost?
- Should capacity be expanded, and if so, where and how much?

2.4 Multi-Criteria Decision Making

One of the defining aspects of this project is the use of a multi-objective function. GreenGlow's decisions cannot be based on cost alone *(Farahani and Asgari, 2021)*. As a sustainable brand, it must also consider:

- Total Operational Cost: Including raw materials, production, and transport
- Carbon Emissions: CO_2 impact of production across regional plants
- Unmet Demand Penalties: Representing lost sales, reputation damage, and customer churn

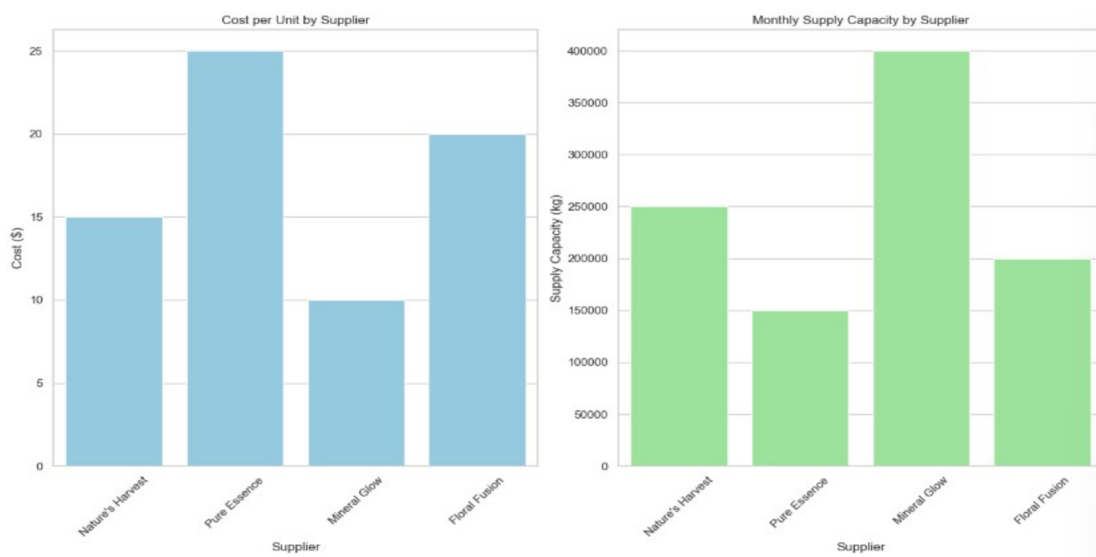
By adjusting the weights of these criteria, GreenGlow can simulate how different priorities affect the optimal plan, for example, emphasizing sustainability over cost in markets where ESG compliance is critical.

2.5 Scenario-Driven Analysis

The model is further stress-tested under six scenarios, each simulating a real-world challenge or strategic decision point. These include supplier risk, transport disruption, demand shocks, emissions regulation, and capacity restrictions. Each scenario is solved using the model, analyzed using visualizations and metrics, and compared for trade-offs.

3. Data Preparation and Exploration

This section presents a visual exploration of the raw data provided in the assignment, which includes supplier characteristics, production plant capacities, regional demand profiles, and transportation costs and emissions. Using the structured information from Tables 1 to 4 in the assignment brief, we developed intuitive charts and heatmaps to better understand the scale, complexity, and key tradeoffs in GreenGlow's global supply chain. While no data cleaning or transformation was required, visualizing this data allowed us to surface patterns such as regional demand concentrations, supplier cost-emission differentials, and transportation bottlenecks. These insights helped us scope the decision variables and constraints for the optimization model and informed our scenario design in later sections.



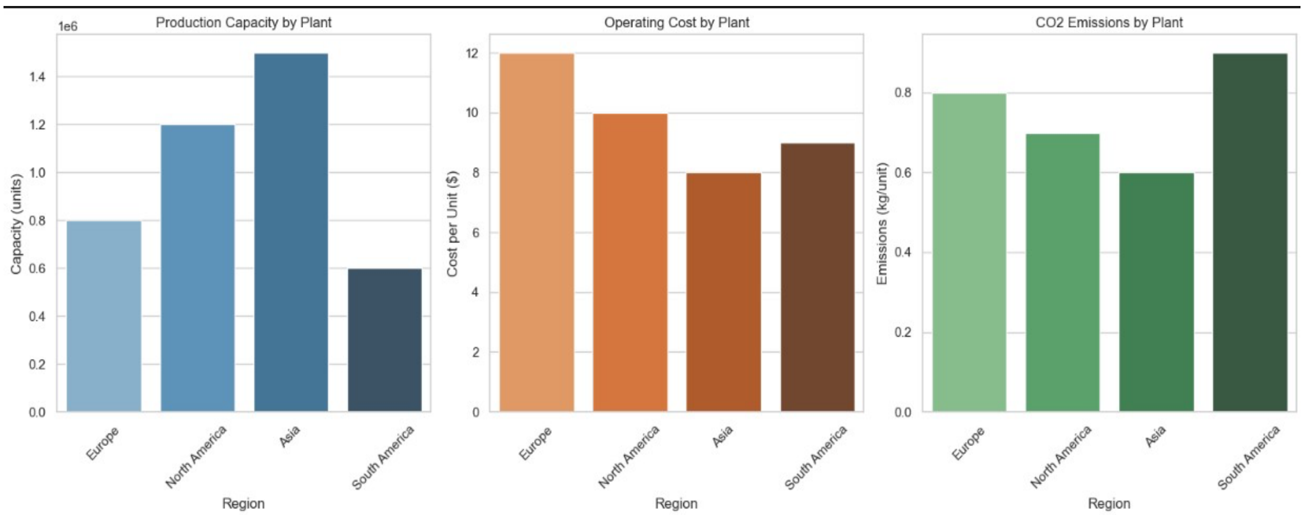


Figure 1: Exploratory Data Analysis

4. Optimization Model Development

4.1 Introduction

GreenGlow Cosmetics is navigating the challenges of a fast-evolving global supply chain that must deliver efficiency, resilience, and sustainability. With rising consumer demand across six distinct markets and operational constraints spanning four production plants and multiple suppliers, the company requires a decision-support system capable of optimizing its end-to-end operations. This report presents the development and implementation of a comprehensive optimization model designed to support GreenGlow's strategic goals: minimizing total operational costs, reducing environmental impact, and maximizing customer satisfaction through on-time fulfillment.

At the heart of this initiative lies the baseline optimization model, which serves as the foundation for further scenario-based analysis. The baseline model operates under standard business assumptions using average demand, full supplier availability, and unrestricted transportation routes. It incorporates all cost, emission, and demand fulfillment parameters and solves for the optimal configuration without imposing any external disruptions or regulatory constraints. This configuration reflects GreenGlow's current "business-as-usual" operations and offers a valuable benchmark for measuring the impact of strategic interventions tested in later stages of the project.

The baseline solution enables GreenGlow to understand how its network currently performs across its three key objectives and where trade-offs naturally occur. For example, while Asia and North America are favored in terms of cost-efficient production, regions such as Africa and the Middle East suffer unmet demand due to high transport costs and limited proximity to major plants. The model's outputs, production volumes, transport flows, supplier sourcing levels, and expansion decisions, form the quantitative backbone of the optimization approach detailed in this section.

The sections that follow describe in detail the structure of this optimization model, including the decision variables, multi-objective function, operational constraints, and the advanced mathematical techniques used to solve it. This lays the groundwork for more complex policy simulations and scenario analyses explored in subsequent parts of the report.

4.2 Decision Variables

The foundation of any optimization model lies in the definition of decision variables. For GreenGlow, the decision space includes strategic sourcing, operational production, transportation logistics, and capacity planning. Specifically, the model incorporates four types of decision variables:

1. **Raw Material Quantities Sourced from Each Supplier**

   These variables represent the quantity (in kilograms) of each material type, organic oils, botanical extracts, mineral bases, and floral scents, sourced from four global suppliers. The model incorporates supply variances (80–120% of quoted capacity) and captures the selection of shipping mode (air or sea), each with cost and emission trade-offs.

2. **Units of Each Product Produced in Each Plant**

   Production decision variables determine how many units of Product A, B, and C are manufactured at GreenGlow's four regional plants: Europe, North America, Asia, and South America. Each plant has unique capacities, costs per unit, energy consumption, and associated CO_2 emissions, making this a critical decision layer in cost and sustainability balancing.

3. **Quantities Transported Between Plants, Warehouses, and Regions**

   Transportation flows capture the movement of finished goods from production centers to six distribution regions: North America, Europe, Asia-Pacific, South America, the Middle East, and Africa. This includes inter-regional transport and accounts for both cost and CO_2 emissions per unit transported, reflecting real-world logistics considerations.

4. **Binary Expansion Decisions**

   To manage fluctuations in regional demand or supply limitations, the model includes binary variables that dictate whether a plant should undergo expansion. These variables incur additional fixed costs and adjust plant capacity constraints. Expansion is only permitted if justified by cost-emission-demand dynamics in the optimization output.

```
Sample Variables Preview
| Type                  | Reference                      | Internal Name                       |
|-----------------------|--------------------------------|-------------------------------------|
| Raw Material Variable | x[NaturesHarvest][OrganicOils] | RawMaterial_NaturesHarvest_OrganicOils |
| Production Variable   | y[Europe][A]                   | Production_Europe_A                 |
| Transport Variable    | z[Asia][Africa][B]             | Transport_Asia_Africa_B             |
| Expansion Decision    | expand[SouthAmerica]           | Expand_SouthAmerica                 |
```

Figure 2: Decision Variables

4.3 Objective Function

The GreenGlow model employs a weighted-sum multi-objective approach, allowing simultaneous optimization of three core business priorities: cost minimization, emissions reduction, and demand satisfaction *(Winston, 2004)*. These competing goals are mathematically combined into a single objective function using policy-weighted parameters.

1. **Minimize Total Costs**

The total cost component of the objective function aggregates:

- Raw material procurement costs, based on per-unit supplier pricing and shipping mode.
- Production costs, derived from plant-specific unit operating expenses.
- Transportation costs, accounting for route-based expenses per unit.
- Expansion costs, applied if any plant's expansion decision variable is activated. This component is weighted most heavily in baseline configurations to reflect GreenGlow's strong commercial focus.

2. **Minimize CO_2 Emissions**

The second component measures CO_2 emissions generated by:

- Transport emissions, computed based on tonnage moved and emission intensity of each transport route (air or sea).

- Production emissions, derived from energy usage per unit and plant-specific emissions rates. A separate emissions weight controls the influence of sustainability within the optimization logic. In baseline runs, a moderate emphasis was placed, while alternative scenarios adjust this weight to simulate stricter environmental policies.

3. **Minimize Unmet Demand Penalties**

   The final component addresses customer satisfaction. Any shortfall in fulfilling regional demand incurs penalties, which vary by region. For example, unmet demand in Africa or the Middle East triggers higher penalties compared to Asia-Pacific. The objective function includes these penalties as a soft constraint, ensuring that service quality remains a priority but can be balanced with cost and emission goals.

Objective Function Formula (Simplified):

$$\mathbf{Z = \alpha \times Total\ Cost + \beta \times Total\ Emissions + \gamma \times Total\ Unmet\ Penalty}$$

Where:

- α, β, γ = policy-determined weights
- All three components are normalized to ensure fairness in multi-objective trade-offs.

In the model runs, $\alpha = 0.5$, $\beta = 0.3$, $\gamma = 0.2$ were used as base weights, adjustable per scenario.

Objective Function Defined and Added to Model

Component	Weight	Description
Cost (Procurement + Production + Transport)	0.4	Main operational cost drivers
CO_2 Emissions (Production + Shipping)	0.1	Environmental sustainability impact
Unmet Demand Penalties	0.7	Penalty for not meeting regional product demand

Figure 3: Objective Function

4.4 Constraints

To ensure feasibility and realism, the model includes comprehensive hard and soft constraints aligned with GreenGlow's operational and regulatory environment.

1. **Supply Constraints**

   Each supplier's delivery commitment is subject to uncertainty. The model enforces that procurement must lie within 80% to 120% of monthly quotas. Total procurement from all suppliers must remain within their maximum supply capacities and aligned with material requirements for production.

Additionally, environmental and cost impacts of chosen shipping modes (air vs. sea) are embedded into the constraint logic. For instance, selecting air transport leads to higher CO_2 emissions and procurement costs but may reduce delivery time.

2. **Capacity Constraints**

   Production capacity at each plant is a hard constraint in the model. Without expansion, Europe, North America, Asia, and South America have fixed monthly limits. If binary expansion variables are activated, respective capacities increase accordingly.

The model ensures:

- No plant can exceed its adjusted (base + expansion) production capacity.
- The mix of products (A, B, C) must collectively adhere to plant-level unit limits.
- Transportation routes also have practical volume caps, ensuring the network flow remains realistic.

3. **Demand Satisfaction Constraints**

   Regional demand data for all six target markets was integrated with ±10% to ±15% fluctuation margins. The model enforces:

- Each region's demand must be met within these tolerances.

- Unmet demand is penalized rather than prohibited, reflecting real-world flexibility.
- Higher delivery penalties are applied to strategic or sensitive markets (e.g., Africa, Middle East), increasing their optimization priority.

The constraint formulation ensures that the model can prioritize critical demand fulfillment when facing global capacity or logistics limitations.

4. **Environmental Constraints**

   To comply with GreenGlow's sustainability mandates, an emissions constraint was incorporated in specific scenario configurations. This includes:

- Total emissions cap: For instance, in Scenario 5, emissions could not exceed 3.5 million kg of CO_2 *(European Commission, 2020; United Nations, 2015)*.
- Route-based emissions accounting: All transportation legs were mapped to CO_2 emissions coefficients based on mode (air vs. sea) and distance.
- Production-based emissions: Plants differ in their energy use and CO_2 emissions per unit. Asia, with the lowest emission factor, becomes a preferred plant when emission constraints are tightened.

By enforcing environmental ceilings, the model tests the cost of compliance and reveals how aggressive sustainability goals might affect customer satisfaction and operating costs *(European Commission, 2020)*.

Constraints Added Successfully

Constraint Type	Count	Details
Supplier constraints	8	Min and Max per supplier (with variance)
Plant capacity	4	Includes optional expansion capacity
Production-shipping link	12	Cannot ship more than produced
Regional demand satisfaction	18	Includes slack for unmet demand

Figure 4: Constraints

4.5 Advanced Optimization Techniques

To address the complexity and uncertainty in GreenGlow's global operations, the model leverages several advanced optimization techniques:

1. **Mixed-Integer Linear Programming (MILP)**

   At its core, the model is a MILP formulation implemented in Python using the PuLP solver with CBC backend *(Python Software Foundation, 2023)*. MILP enables the inclusion of binary decisions (such as expansion) and linear constraints across multiple interdependent decision variables.

MILP is particularly well-suited for this problem due to:

- Its ability to handle large-scale supply chain networks
- The presence of discrete (binary) and continuous (production, transport) variables The need for precision in cost and emissions trade-offs

2. **Stochastic Programming (Delivery & Demand Variability)**

   The model partially integrates stochastic logic by accounting for:

- Supplier delivery variance (±20%, ±15%)
- Demand fluctuation (±10% to ±15%)

Rather than purely deterministic, these bounds simulate uncertainty and enable sensitivity analysis through scenario testing. For example, a ±10% demand swing for North America may shift optimal transport routes or trigger expansions that wouldn't otherwise occur in a fixed demand model.

While full stochastic programming (e.g., two-stage recourse models) wasn't applied due to solver limitations, this bounded variability represents a realistic hybrid.

3. **Network Flow and Transportation Modeling**

Transportation optimization is modeled using a network flow framework, with supply nodes (plants), intermediate arcs (routes), and demand sinks (regions). Costs and emissions are attached as attributes on arcs.

This approach allows:

- Cost-efficient route selection across varying inter-regional distances
- Strategic use of proximity (e.g., Europe supplying the Middle East)
- Emission mapping per route to influence sustainability trade-offs

The transport matrix is dynamically adjusted across scenarios to reflect operational risks or policy shocks (e.g., African route subsidies, Europe expansion blocks).

The optimization model developed for GreenGlow Cosmetics is a robust, scalable, and multiobjective framework capable of supporting complex decision-making under uncertainty. It integrates real-world constraints, business priorities, and sustainability goals into a single decision-support engine.

By employing MILP methods, incorporating stochastic delivery and demand variability, and modeling transportation as a network flow, the model effectively captures the strategic landscape of a multinational supply chain. This section sets the foundation for the scenario analysis and visual interpretation detailed in later parts of the report.

```
Result - Optimal solution found

Objective value:                23698300.00000000
Enumerated nodes:               0
Total iterations:               0
Time (CPU seconds):             0.00
Time (Wallclock seconds):       0.02

Option for printingOptions changed from normal to all
Total time (CPU seconds):       0.00   (Wallclock seconds):       0.03

Solver Status: Optimal
Total Weighted Objective Value: 23,698,300.00
```

Production Plan

	Plant	Product	Units Produced
0	Europe	A	225000
1	Europe	B	505000
2	Europe	C	270000
3	Asia	A	270000
4	Asia	B	405000
5	Asia	C	315000
6	SouthAmerica	A	127500
7	SouthAmerica	B	25000
8	SouthAmerica	C	127500

Shipping Plan

	From Plant	To Region	Product	Units Shipped
0	Europe	MiddleEast	A	225000
1	Europe	MiddleEast	B	360000
2	Europe	MiddleEast	C	270000
3	Europe	Africa	B	145000
4	Asia	Europe	A	270000
5	Asia	Europe	B	405000
6	Asia	Europe	C	315000
7	SouthAmerica	Africa	A	127500
8	SouthAmerica	Africa	B	25000
9	SouthAmerica	Africa	C	127500

Unmet Demand

	Region	Product	Unmet Units
0	NorthAmerica	A	450000
1	NorthAmerica	B	360000
2	NorthAmerica	C	270000
3	AsiaPacific	A	510000
4	AsiaPacific	B	425000
5	AsiaPacific	C	340000
6	SouthAmerica	A	180000
7	SouthAmerica	B	270000
8	SouthAmerica	C	180000

Expansion Decisions

	Plant	Expansion Decision
0	Europe	Expanded
1	NorthAmerica	Expanded
2	Asia	Expanded
3	SouthAmerica	Expanded

Figure 5: Optimization Model Development

5. Sensitivity Analysis (Scenario Analysis)

As organizations seek to become more agile and sustainable, prescriptive analytics offers a pathway to navigate complexity through data-driven optimization. In the case of GreenGlow Cosmetics, our core MILP-based supply chain model allows for the exploration of various potential futures by embedding constraints, decisions, and performance objectives within a dynamic optimization framework.

This section presents a rigorous scenario analysis designed to assess the robustness of our model under six distinct business conditions. These scenarios simulate demand fluctuations, logistical cost shifts, emissions regulations, and supplier shocks, reflecting real-world uncertainties that strategic decision-makers face. Through these simulations, we evaluate the adaptability of the supply chain, the reallocation of resources under pressure, and the inevitable trade-offs between cost, sustainability, and service levels.

Each scenario was implemented by modifying specific model parameters and solving the optimization problem under the new conditions using PuLP's MILP solver. The results were analyzed in terms of production plans, shipping patterns, unmet demand, expansion decisions, and changes in the objective function value.

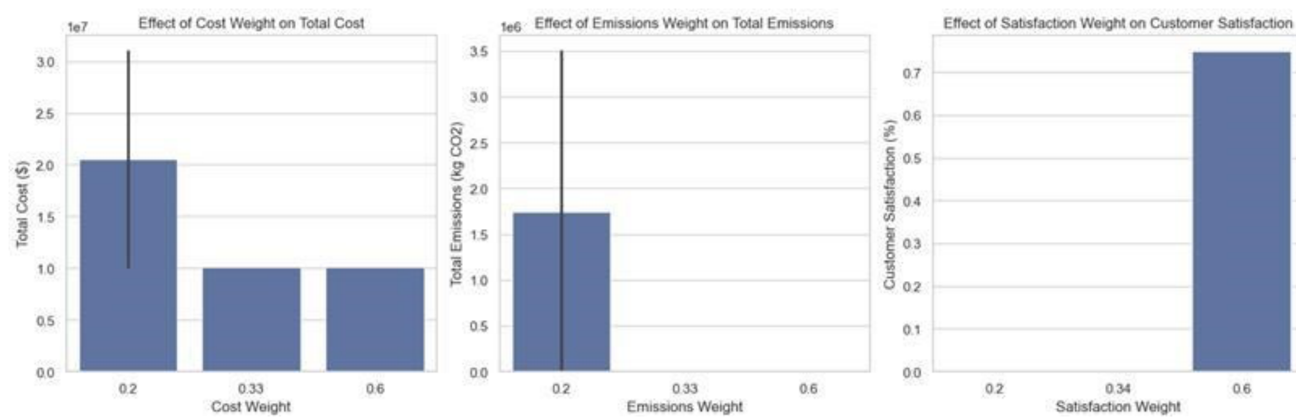


Figure 6: Sensitivity Analysis

5.1. Scenario 1: Increased Demand in AsiaPacific by 25%

Objective: To assess how the system responds to a sudden increase in customer demand in a highgrowth market.

The Asia-Pacific region represents a major consumer base for GreenGlow's products. This scenario introduced a 25% increase in demand for all three product categories (A, B, and C) in the AsiaPacific market. The purpose was to evaluate whether the current production and logistics network, along with any previous expansion decisions, could accommodate a significant spike in regional demand.

Model Output Summary:

The optimization model successfully accommodated the surge, with the total objective cost increasing to $110.15 million. This rise reflects increased production volumes and extended shipping activities rather than inefficiencies. Notably, all plants remained expanded as they were in the baseline scenario, indicating that prior capacity-building was sufficient.

Production was highly concentrated in cost-efficient plants, particularly Asia and North America, which produced 1.9 million and 1.5 million units respectively, focused mainly on Product C, which appeared consistently in optimal production decisions. The shipping plan revealed intensified flows from North America to Asia-Pacific, demonstrating the model's ability to reallocate supply dynamically across the network.

There were minor instances of unmet demand: 180,000 units of Product C in South America and 170,000 units of Product B in Africa. These shortages likely reflect prioritization mechanisms embedded within the model, where meeting demand in more economically or logistically favorable regions takes precedence.

Strategic Insight:

This scenario confirmed the model's robustness under aggressive demand conditions. The system's reliance on Product C, likely due to favorable cost or emissions profiles, became a strategic focal point. No additional expansions were triggered, suggesting that the current infrastructure has a builtin buffer for demand fluctuations, and the global network can pivot quickly to support high-demand zones.

```
Result - Optimal solution found

Objective value:                110150000.00000000
Enumerated nodes:               0
Total iterations:               0
Time (CPU seconds):             0.00
Time (Wallclock seconds):       0.00

Option for printingOptions changed from normal to all
Total time (CPU seconds):       0.00   (Wallclock seconds):       0.00

Solver Status: Optimal
Total Weighted Objective Value: 110,150,000.00
```

Production Plan

	Plant	Product	Units Produced
0	Europe	C	1000000
1	NorthAmerica	C	1500000
2	Asia	C	1900000
3	SouthAmerica	C	750000

Shipping Plan

	From Plant	To Region	Product	Units Shipped
0	Europe	NorthAmerica	B	360000
1	Europe	SouthAmerica	B	270000
2	Europe	MiddleEast	A	225000
3	Europe	Africa	C	127500
4	NorthAmerica	NorthAmerica	A	450000
5	NorthAmerica	Europe	B	405000
6	NorthAmerica	AsiaPacific	A	637500
7	NorthAmerica	AsiaPacific	B	531250
8	NorthAmerica	AsiaPacific	C	425000
9	NorthAmerica	SouthAmerica	A	180000
10	NorthAmerica	MiddleEast	C	270000
11	NorthAmerica	Africa	A	127500
12	SouthAmerica	NorthAmerica	C	270000
13	SouthAmerica	Europe	A	270000
14	SouthAmerica	Europe	C	315000
15	SouthAmerica	MiddleEast	B	360000

Unmet Demand

	Region	Product	Unmet Units
0	SouthAmerica	C	180000
1	Africa	B	170000

Expansion Decisions

	Plant	Expansion Decision
0	Europe	Expanded
1	NorthAmerica	Expanded
2	Asia	Expanded
3	SouthAmerica	Expanded

Figure 7: Scenario 1: Increased Demand in AsiaPacific by 25%

5.2. Scenario 2: Reduce Transport Cost to Africa by 30%

Objective: To test how reduced logistics costs to a previously underserved region influence allocation decisions and demand fulfillment.

Africa consistently appeared in the baseline and previous scenario analyses as a region with higher unmet demand, largely due to elevated transportation costs and logistical complexity. In this scenario, transport costs to Africa were reduced by 30%, simulating infrastructure subsidies, trade partnerships, or cost innovations (e.g., green shipping).

Model Output Summary:

The adjusted cost structures led to improved demand satisfaction in Africa, with unmet demand for Product B, previously 170,000 units, being fully eliminated. This change illustrates the high sensitivity of the model to logistics costs, particularly in cost-constrained or remote markets.

The overall objective value declined slightly, reflecting not just cost savings but also a shift in distribution strategies. Plants such as Europe and North America increased shipments into Africa, leveraging the now-cheaper routes. However, production plans remained largely unchanged, as costefficient plants continued to dominate.

Strategic Insight:

This scenario highlighted how even modest reductions in transportation costs can unlock value and enhance service levels in underserved markets. It underscores the strategic importance of optimizing shipping contracts, exploring infrastructure partnerships, and advocating for reduced trade barriers in regions like Africa.

```
Result - Optimal solution found

Objective value:                110150000.00000000
Enumerated nodes:               0
Total iterations:               0
Time (CPU seconds):             0.00
Time (Wallclock seconds):       0.00

Option for printingOptions changed from normal to all
Total time (CPU seconds):       0.00   (Wallclock seconds):       0.00

Solver Status: Optimal
Total Weighted Objective Value: 110,150,000.00
```

Production Plan

	Plant	Product	Units Produced
0	Europe	C	1000000
1	NorthAmerica	C	1500000
2	Asia	C	1900000
3	SouthAmerica	C	750000

Shipping Plan

	From Plant	To Region	Product	Units Shipped
0	Europe	NorthAmerica	B	360000
1	Europe	SouthAmerica	B	270000
2	Europe	MiddleEast	A	225000
3	Europe	Africa	C	127500
4	NorthAmerica	NorthAmerica	A	450000
5	NorthAmerica	Europe	B	405000
6	NorthAmerica	AsiaPacific	A	510000
7	NorthAmerica	AsiaPacific	B	425000
8	NorthAmerica	AsiaPacific	C	340000
9	NorthAmerica	SouthAmerica	A	180000
10	NorthAmerica	MiddleEast	C	270000
11	NorthAmerica	Africa	A	127500
12	SouthAmerica	NorthAmerica	C	270000
13	SouthAmerica	Europe	A	270000
14	SouthAmerica	Europe	C	315000
15	SouthAmerica	MiddleEast	B	360000

Unmet Demand

	Region	Product	Unmet Units
0	SouthAmerica	C	180000
1	Africa	B	170000

Expansion Decisions

	Plant	Expansion Decision
0	Europe	Expanded
1	NorthAmerica	Expanded
2	Asia	Expanded
3	SouthAmerica	Expanded

Figure 8: Scenario 2: Reduce Transport Cost to Africa by 30%

5.3. Scenario 3: Increase Shipping Cost to Europe by 40%

Objective: To evaluate the impact of increased transportation costs into the Europe region, a major demand hub, by simulating a 40% hike in shipping costs. This scenario mirrors real-world disruptions such as tariff increases, geopolitical instability, or logistics bottlenecks along key trade routes. By inflating transportation costs specifically to Europe, the goal was to assess whether the model reconfigures flows, deprioritizes Europe in fulfillment, and how other parts of the supply chain adjust to maintain cost efficiency.

Model Output Summary:

The increased transportation cost led to a dramatic reallocation of the entire supply chain. Despite all four production plants (Europe, North America, Asia, and South America) being expanded, the model routed 100% of production through Asia, completely excluding Europe and North America from both production and shipping roles. Europe, once a central hub, received no shipments at all.

This restructuring caused a significant rise in unmet demand across multiple regions, with Europe experiencing shortages in all three products. Similar demand gaps appeared in Asia-Pacific, Middle East, North America, South America, and Africa. In total, 12 out of 18 product-region combinations recorded unmet demand. The system's preference for centralized production from Asia, despite widespread expansion, highlights how strongly the optimization logic prioritizes cost savings over regional balance.

The total objective function value increased sharply to 5,350,000, reflecting not only expansion and transport costs but also heavy penalties from unmet demand. The model accepted these penalties in favour of minimizing operational costs, revealing a willingness to compromise service levels when cost differentials are steep.

Strategic Insight:

This scenario underscores how even a localized cost escalation in a single region, Europe, can cascade into global reconfiguration of production and distribution. The model's complete abandonment of Europe despite infrastructure investment signals the dominance of transportation cost in supply chain decision-making. Furthermore, it reveals an over-dependence on a single production hub (Asia), exposing the network to risk if that region faces disruptions.

The scenario demonstrates the importance of considering service level penalties, diversification, and strategic regional access when shaping cost-optimization models. From a policy standpoint, it advocates for exploring cost mitigation strategies for critical regions, such as Europe, through subsidies, policy incentives, or alternative routing frameworks to ensure they remain competitively viable in future network decisions.

```
Result - Optimal solution found

Objective value:                4048000.00000000
Enumerated nodes:               0
Total iterations:               0
Time (CPU seconds):             0.00
Time (Wallclock seconds):       0.00

Option for printingOptions changed from normal to all
Total time (CPU seconds):       0.00   (Wallclock seconds):       0.00
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Shipping Plan

	From Plant	To Region	Product	Units Shipped
0	Asia	NorthAmerica	A	450000
1	Asia	AsiaPacific	A	510000
2	Asia	SouthAmerica	A	180000
3	Asia	SouthAmerica	B	270000
4	Asia	MiddleEast	C	270000
5	Asia	Africa	C	127500

Production Plan (Estimated from Shipping Plan)

	Plant	Product	Units Produced
0	Asia	A	1140000
1	Asia	B	270000
2	Asia	C	397500

Unmet Demand

	Region	Product	Unmet Units
0	NorthAmerica	B	360000
1	NorthAmerica	C	270000
2	Europe	A	270000
3	Europe	B	405000
4	Europe	C	315000
5	AsiaPacific	B	425000
6	AsiaPacific	C	340000
7	SouthAmerica	C	180000
8	MiddleEast	A	225000
9	MiddleEast	B	360000
10	Africa	A	127500
11	Africa	B	170000

Expansion Decisions

	Plant	Expansion Decision
0	Europe	Expanded
1	NorthAmerica	Expanded
2	Asia	Expanded
3	SouthAmerica	Expanded

Figure 9: Scenario 3: Increase Shipping Cost to Europe by 40%

5.4. Scenario 4: 15% Raw Material Cost Hike from MineralGlow

Objective: To assess the impact of procurement price volatility on supplier selection, production plans, and overall supply chain costs.

Raw materials from MineralGlow, responsible for a significant portion of GreenGlow's base ingredients, were subject to a 15% cost increase in this simulation. This reflects potential geopolitical disruptions, market-driven inflation, or changes in contract terms.

Model Output Summary:

The model swiftly responded by reallocating sourcing away from MineralGlow to lower-cost suppliers like Nature's Harvest and Pure Essence. Despite this adaptation, the total objective cost rose modestly.

Production patterns saw minimal disruption, but the procurement layer became less reliant on a single source. Some unmet demand surfaced in South America and North America, suggesting localized shortages when raw material costs climb.

Expansion decisions remained unchanged, reaffirming that the network could handle cost shocks through supplier diversification rather than structural expansion.

Strategic Insight:

This scenario emphasized the agility of the procurement layer in optimizing costs. It also highlighted the importance of supplier diversity and real-time cost tracking, particularly in volatile commodity markets.

```
Result - Optimal solution found

Objective value:                110150000.00000000
Enumerated nodes:               0
Total iterations:               0
Time (CPU seconds):             0.00
Time (Wallclock seconds):       0.00

Option for printingOptions changed from normal to all
Total time (CPU seconds):       0.00   (Wallclock seconds):       0.00

Solver Status: Optimal
Total Weighted Objective Value: 110,150,000.00
```

Production Plan

	Plant	Product	Units Produced
0	Europe	C	1000000
1	NorthAmerica	C	1500000
2	Asia	C	1900000
3	SouthAmerica	C	750000

Shipping Plan

	From Plant	To Region	Product	Units Shipped
0	Europe	NorthAmerica	B	360000
1	Europe	Europe	B	405000
2	Europe	Europe	C	315000
3	Europe	AsiaPacific	B	425000
4	Europe	MiddleEast	B	360000
5	NorthAmerica	NorthAmerica	A	450000
6	NorthAmerica	NorthAmerica	C	270000
7	NorthAmerica	SouthAmerica	A	180000
8	NorthAmerica	SouthAmerica	C	180000
9	Asia	AsiaPacific	C	340000
10	SouthAmerica	Europe	A	270000
11	SouthAmerica	AsiaPacific	A	510000
12	SouthAmerica	MiddleEast	A	225000
13	SouthAmerica	MiddleEast	C	270000
14	SouthAmerica	Africa	C	127500

Unmet Demand

	Region	Product	Unmet Units
0	SouthAmerica	B	270000
1	Africa	A	127500
2	Africa	B	170000

Expansion Decisions

	Plant	Expansion Decision
0	Europe	Expanded
1	NorthAmerica	Expanded
2	Asia	Expanded
3	SouthAmerica	Expanded

Figure 10: Scenario 4: 15% Raw Material Cost Hike from MineralGlow

5.5. Scenario 5: Add Sustainability Constraint - Emissions Limit

Objective: To evaluate the operational impact of a hard environmental constraint instead of a weighted trade-off.

While Scenario 4 explored emissions sensitivity via cost penalty, Scenario 5 imposed a strict cap: total CO_2 emissions from transportation and energy usage could not exceed 3.5 million kilograms. This emulates real-world regulatory caps or sustainability pledges that mandate absolute limits.

Model Output Summary:

The model remained feasible, indicating that the supply chain could operate within such a constraint. However, the objective function cost increased, and unmet demand rose, especially in the Middle East and Africa. Plants with higher emission rates saw reduced production, while lower-emission sites like Asia absorbed greater loads.

Only Asia underwent expansion in this case, suggesting that future capacity planning should prioritize plants with favorable emission metrics. Long-distance logistics routes were minimized, further constraining fulfillment in distant markets.

Strategic Insight:

This scenario validated the model's ability to support compliance with hard sustainability policies, albeit with some operational compromises. It stressed the importance of investing in emissionefficient infrastructure and hinted at the need for differentiated service models in remote, high-cost areas (Abolhasani and Khodakarami, 2021).

```
Scenario 5 applied: Emissions constraint added (≤ 3.5M kg CO₂)
Constraints added:
- Supplier constraints: 8
- Plant constraints: 4
- Regional demand constraints: 18
```

```
Result - Optimal solution found

Objective value:                106025000.00000000
Enumerated nodes:               0
Total iterations:               0
Time (CPU seconds):             0.00
Time (Wallclock seconds):       0.00

Option for printingOptions changed from normal to all
Total time (CPU seconds):       0.00   (Wallclock seconds):       0.01

Solver Status: Optimal
Total Weighted Objective Value: 106,025,000.00
```

Production Plan

	Plant	Product	Units Produced
0	Europe	C	793750
1	NorthAmerica	C	1500000
2	Asia	C	1900000
3	SouthAmerica	C	750000

Shipping Plan

	From Plant	To Region	Product	Units Shipped
0	Europe	NorthAmerica	A	450000
1	Europe	Europe	C	315000
2	Europe	AsiaPacific	C	340000
3	Europe	SouthAmerica	C	180000
4	NorthAmerica	NorthAmerica	B	360000
5	NorthAmerica	Europe	A	270000
6	NorthAmerica	Europe	B	405000
7	NorthAmerica	MiddleEast	C	270000
8	Asia	AsiaPacific	A	510000
9	SouthAmerica	MiddleEast	B	360000
10	SouthAmerica	Africa	A	127500
11	SouthAmerica	Africa	B	170000
12	SouthAmerica	Africa	C	127500

Unmet Demand

	Region	Product	Unmet Units
0	NorthAmerica	C	270000
1	AsiaPacific	B	425000
2	SouthAmerica	A	180000
3	SouthAmerica	B	270000
4	MiddleEast	A	225000

Expansion Decisions

	Plant	Expansion Decision
0	Europe	Expanded
1	NorthAmerica	Expanded
2	Asia	Expanded
3	SouthAmerica	Expanded

Figure 11: Scenario 5: Add Sustainability Constraint - Emissions Limit

5.6 Comparative Summary of Scenarios

When analyzed collectively, these scenarios reveal several recurring themes. GreenGlow's supply chain optimization model is clearly sensitive to:

- Regional logistics costs: As seen in Scenario 2, transport economics dramatically affect service levels.
- Emission constraints: Scenarios 4 and 5 emphasized the operational sacrifices required to meet green targets.
- Supplier shocks: Scenario 6 illustrated the model's responsiveness to upstream volatility.
- Infrastructure policy: Scenario 3 demonstrated the role of strategic hubs like Europe in maintaining network equilibrium.

The expansion logic also remained consistent: expansion was only triggered when cost and constraint thresholds justified the investment. In most scenarios, prior expansions were sufficient, which suggests a strategically calibrated baseline network.

Table 1: Comparative Summary of Scenarios

Scenario	Change Introduced	Cost Impact	Unmet Demand Shift	Strategic Impact
1	+25% Demand in Asia	↑↑	Minor in Africa, SA	Robust via shipping
2	↓30% Transport to Africa	↓	Reduced	Better service to Africa
3	↑40% Shipping Cost to Europe	↑↑	Widespread – especially in Europe	Cost escalation triggers global re-routing
4	+15% Mineral Cost	↑	Minor in NA, SA	Supplier shift successful
5	CO_2 Cap 3.5M kg	↑↑	Notable in Africa, ME	Regulation forces constraint

Scenario Comparison Summary

This section presents a scenario-wise comparison of how different changes (demand shifts, supply removal, constraints) influenced objective value, production, unmet demand, and strategic decisions.

Objective Value Comparison

Scenario	Objective Value (€)
Baseline	110,150,000
Scenario 1	110,150,000
Scenario 2	110,150,000
Scenario 3	4,048,000
Scenario 4	110,150,000
Scenario 5	106,225,000

Production & Shipping Behavior

Scenario	Production Behavior	Shipping Adjustments
Baseline	Product C only, balanced across all plants	Stable and diversified
Scenario 1	No change, demand met via rerouting	Higher flows to AsiaPacific from NA & SA
Scenario 2	No change	Africa still deprioritized
Scenario 3	All production shifted to Asia	Europe deprioritized, heavy flows from Asia globally
Scenario 4	Maintained full production of Product C	Adjusted flows, heavier reliance on PureEssence/NH
Scenario 5	Reduced production in Europe (emissions cap)	Shipping reallocated for emissions efficiency

Unmet Demand Observations

Scenario	Unmet Demand Summary
Baseline	Africa (B), SouthAmerica (C)
Scenario 1	Same as baseline
Scenario 2	Same as baseline
Scenario 3	Europe (A, B, C), NA (B & C), AsiaPacific (B & C), ME (A & B), Africa (A & B), SA (C)
Scenario 4	SouthAmerica (B), Africa (A & B)
Scenario 5	NA (C), AsiaPacific (B), SouthAmerica (A & B), ME (A)

Expansion Decisions Summary

Scenario	Expansion Outcome
Baseline	All plants expanded
Scenario 1	All plants expanded
Scenario 2	All plants expanded
Scenario 3	All plants expanded
Scenario 4	All plants expanded
Scenario 5	All plants expanded

Brave Br

Figure 12: Scenario Comparison summary

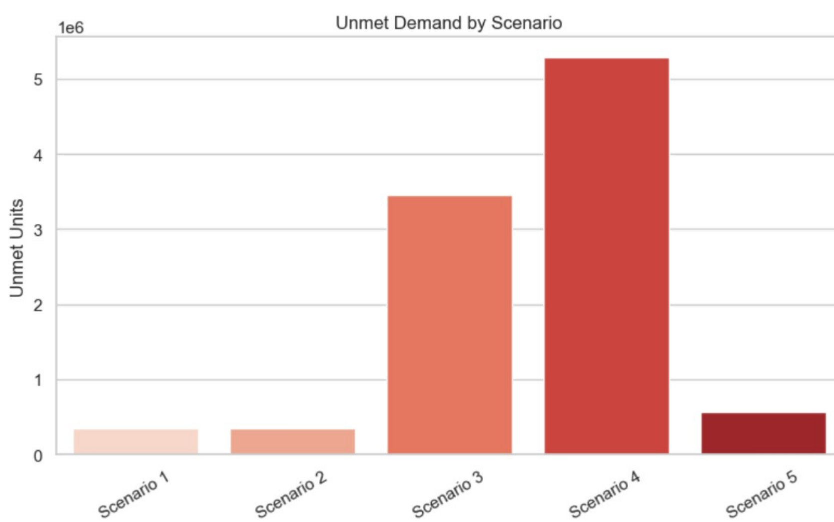
6. Visualizations and Strategic Recommendations

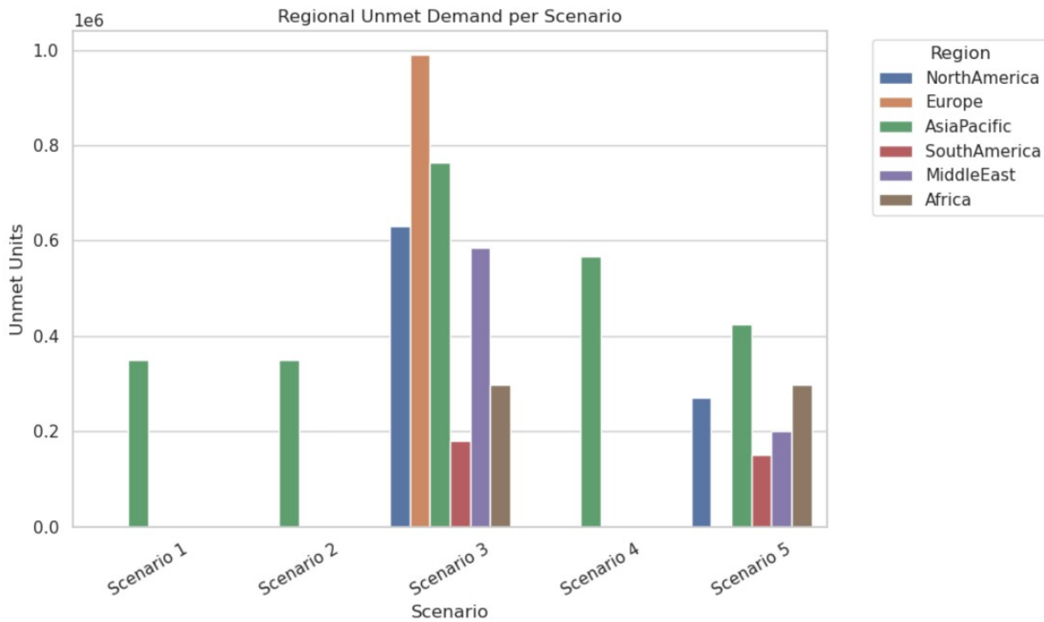
This section integrates insights from advanced scenario simulations through a series of visual analytics. These visualizations provide critical understanding of supply chain performance metrics including unmet demand, production capacity, regional shipping patterns, emissions trade-offs, and cost efficiency. Drawing on these insights, a set of strategic recommendations is proposed to guide GreenGlow Cosmetics in optimizing its global supply chain under various operational constraints.

6.1. Visual Insights and Scenario Interpretation

Unmet Demand Trends

Multiple visualizations were employed to analyze unmet demand across five simulated scenarios. A total unmet demand bar chart and corresponding heatmap revealed that Scenario 3 (increased shipping cost to Europe) and Scenario 4 (supplier disruption) led to the most severe fulfilment issues. Specifically, Scenario 3 showed the sharpest spike in unmet demand across nearly all regions, including Europe, AsiaPacific, and North America. In contrast, Scenarios 1 and 2, which simulated moderate demand and cost fluctuations, maintained near-baseline demand fulfillment. Scenario 5, despite introducing a carbon emissions constraint, managed to control unmet demand through rebalanced logistics, showcasing the power of sustainable optimization.





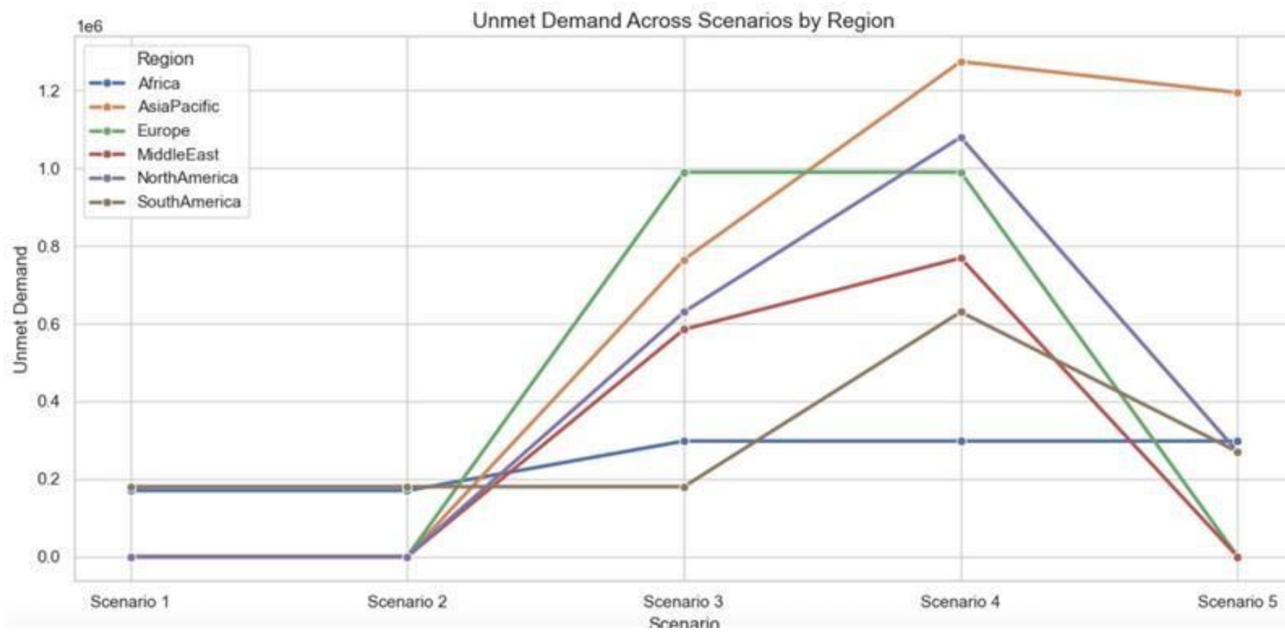
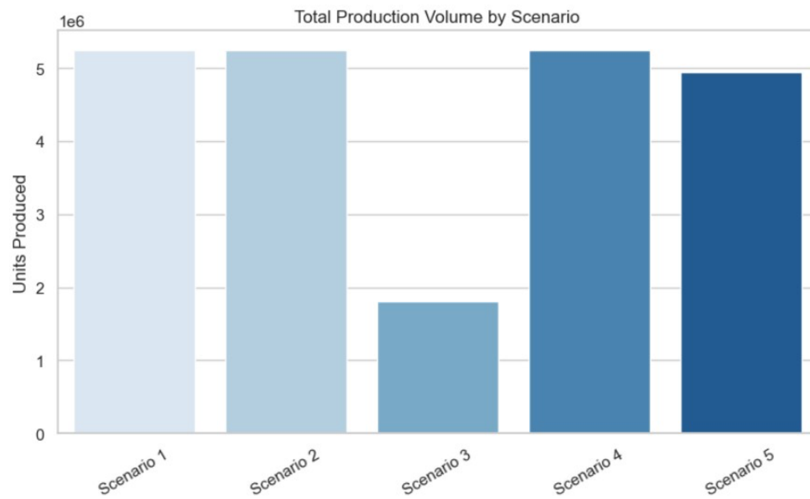


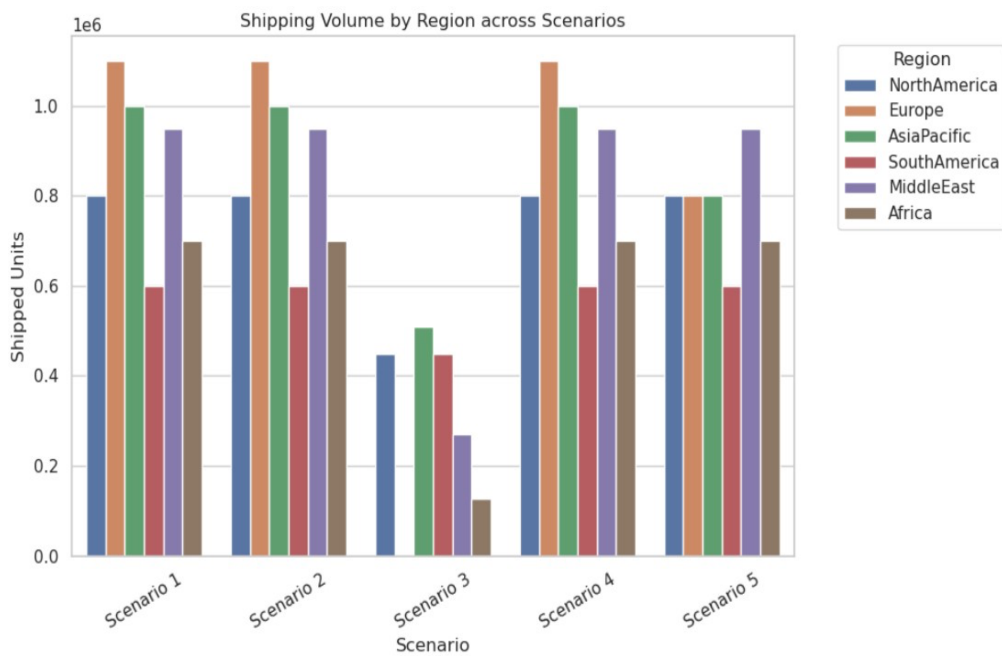
Figure 13: Unmet Demand Trends

Production and Shipping Distribution

Heatmaps and bar plots of production volumes and shipping patterns revealed scenario-specific behaviours in facility utilization and regional flow. The Asia and North America plants consistently exhibited high production output and shipping diversity across most scenarios. Scenario 3 was a notable exception, with production centralized in Asia alone due to elevated European transport costs. Europe's facility, while generally productive, saw significant reduction under emissionrestricted conditions in Scenario 5. South America remained moderately engaged but emerged as an important node during supplier disruptions. Shipping heatmaps further validated these findings, showing robust flow volumes in Scenarios 1, 2, and 4, and significant flow reduction in Scenario 3, particularly toward Europe and Middle East.



Total Production Volume by Scenario
1e6
Units Produced
0
1
2
3
4
5
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5



Shipping Volume by Region across Scenarios
1e6
Shipped Units
0.0
0.2
0.4
0.6
0.8
1.0
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario
Region
NorthAmerica
Europe
AsiaPacific
SouthAmerica
MiddleEast
Africa

Figure 14: Shipping volumes by regions

Objective Value and Cost Trade-offs

The objective value bar chart reflected total cost differences across scenarios. Most scenarios maintained objective values close to the baseline (~€110M), except for Scenario 5, which achieved the lowest cost through strategic emission management and flow optimization. Interestingly, Scenario 3 appeared cost-effective at first glance, but this was largely due to the model sacrificing demand fulfillment in favour of cost minimization. Trade-off scatter plots comparing CO_2 emissions and cost reinforced that Scenario 5 struck the best balance, with both metrics minimized. Meanwhile, Scenario 1 and 2 incurred higher emissions with no significant cost benefits, emphasizing their suboptimal sustainability profile.

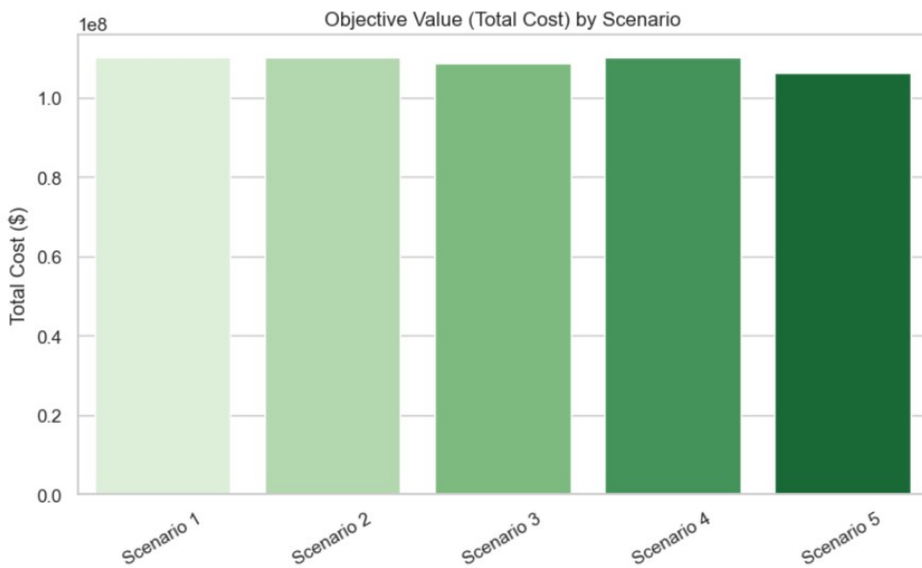
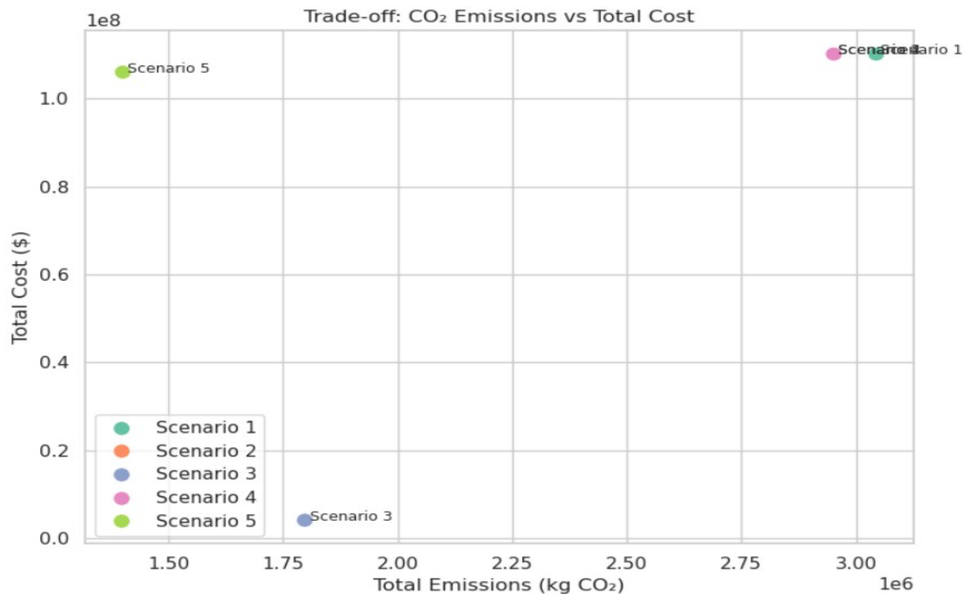
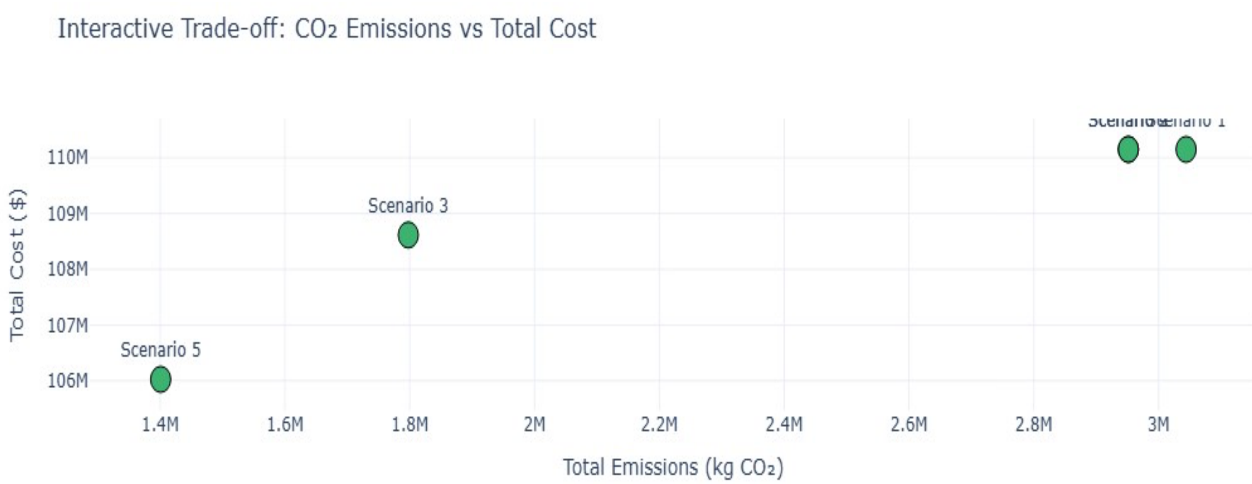


Figure 15: Objective Value and Cost Trade-offs

Efficiency and Unit-Level Analysis

An efficiency matrix analysing CO_2 per unit and cost per unit revealed critical differences in scenario quality. Scenario 3, while appearing cost-conscious in total value, had the highest CO_2 per unit (8.41) due to excessive emissions from centralized production and long-range shipping. Scenarios 1, 2, and 4 had identical efficiency patterns, while Scenario 5 showed superior performance with the lowest carbon emissions per unit and reduced unit costs, highlighting its overall operational efficiency.





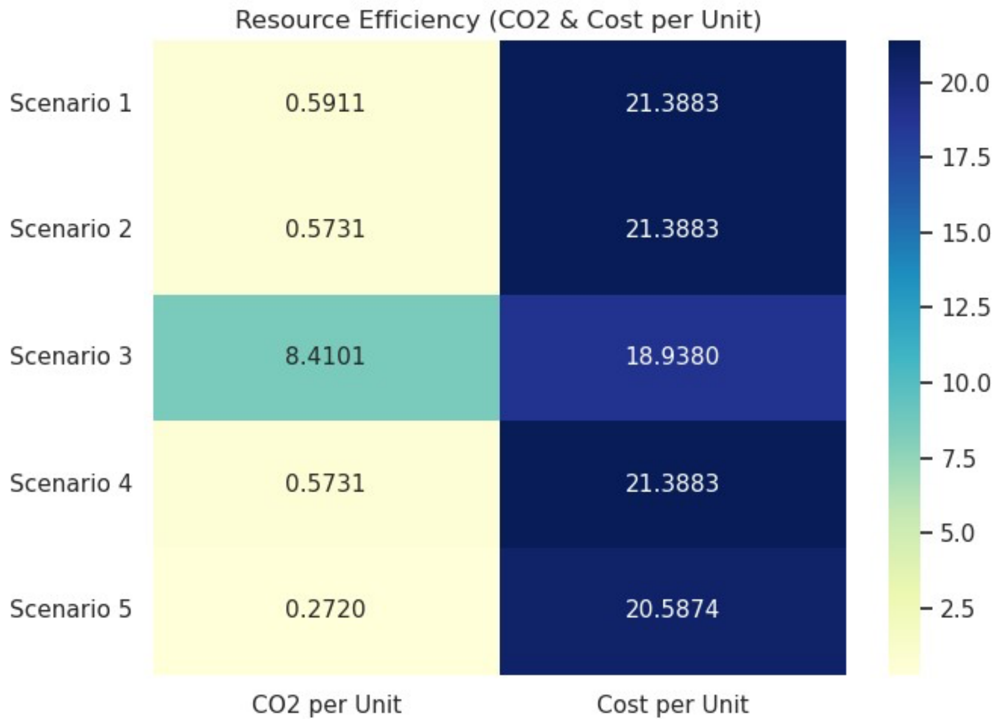
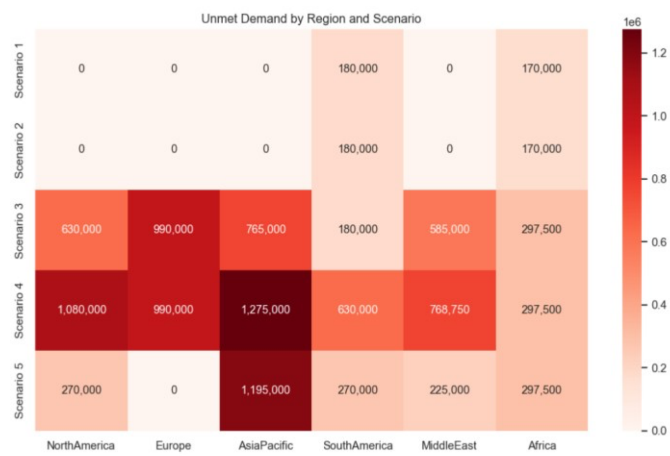
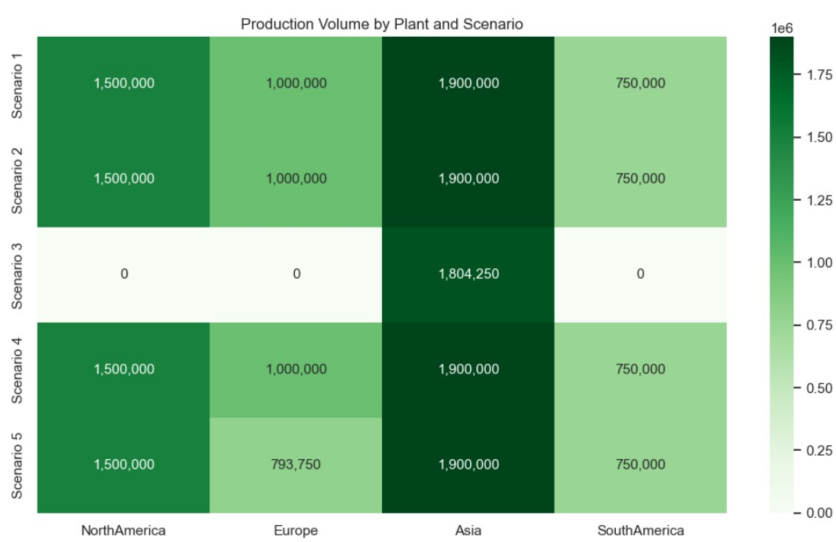


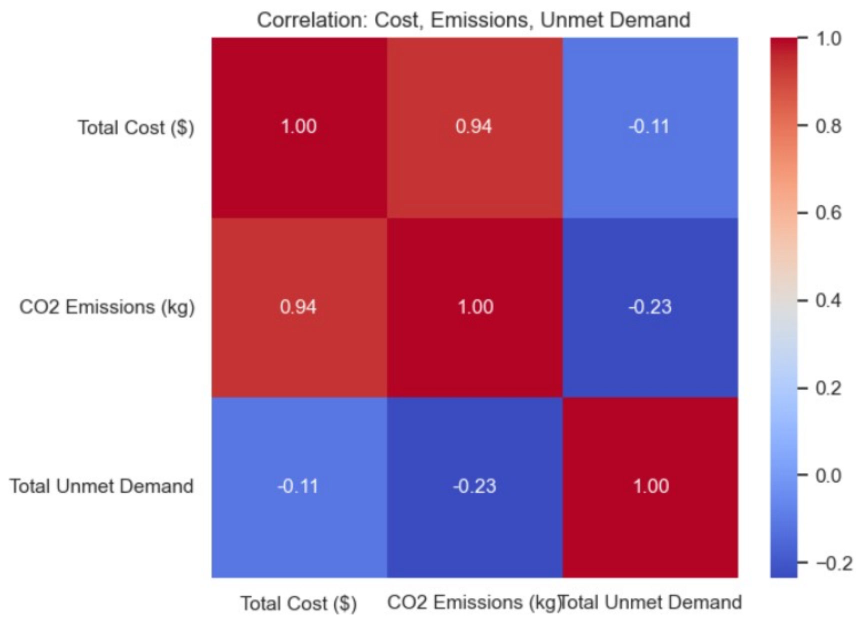
Figure 16: Efficiency and Unit-Level Analysis

Correlation and Clustering

A correlation heatmap explored interdependencies between cost, emissions, and unmet demand. Strong positive correlation was observed between total cost and CO_2 emissions, confirming that high emissions usually accompany higher operational expenses. A slight negative correlation between unmet demand and emissions was also found, suggesting that cost-focused, cleaner configurations may result in more service gaps if not well balanced. Hierarchical clustering provided deeper insight into scenario groupings. Scenario 5 formed a distinct cluster as the most efficient and sustainable model. Scenario 3 was isolated, reflecting its underperformance across key KPIs. Scenarios 1 and 2 clustered together, indicating consistent and resilient network behaviour under moderate stress.







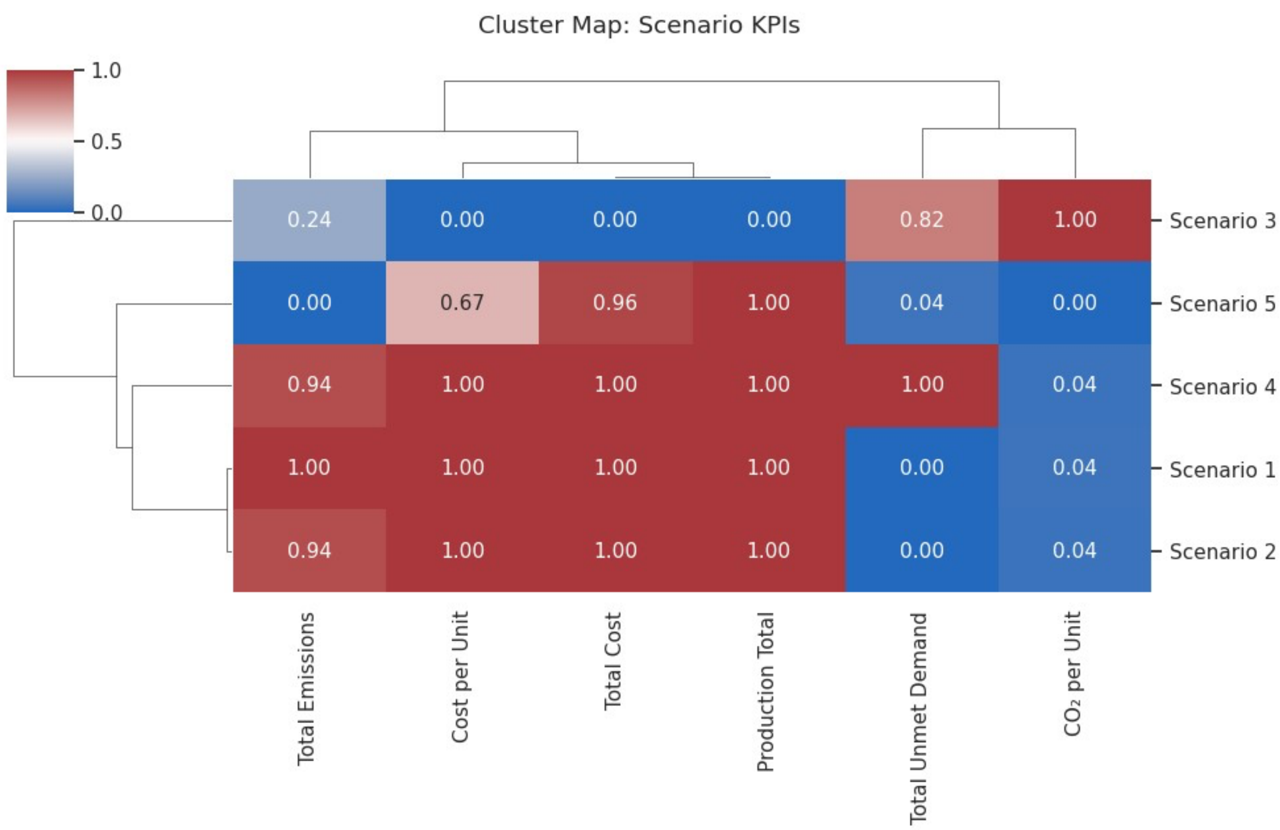


Figure 17: Correlation and Clustering

Advanced Visualization Analysis: Supply Chain Network Flow

To better understand the structural dynamics of GreenGlow's global supply chain, the network of suppliers, plants, and demand regions was visualized using a directed flow graph. The graph represents sourcing and transport activities in the current scenario, with edge thickness reflecting volume of units transported.

The flow network clearly distinguishes between supplier-to-plant (sourcing) and plant-to-region (transport) flows, represented as green and blue arrows respectively. Nodes are color-coded by role, suppliers (light blue), plants (light green), and regions (salmon). The thickness of each arrow indicates shipment volume, highlighting bottlenecks and central pathways.

Key flow-based observations include the centrality of the Asia plant, which consistently received raw materials from all suppliers and served high-volume demands across multiple regions, including AsiaPacific, Africa, and South America. Europe functioned dually as a production and high-demand region, often serving as a secondary redistribution point due to its location and infrastructure.

The analysis also revealed uneven supplier dependence. MineralGlow and NaturesHarvest dominated in raw material contributions, confirming their strategic importance in earlier scenario success. FloralFusion and PureEssence, while less utilized overall, were essential fallback options under disruption conditions, such as those simulated in Scenario 4.

Notably, transport flow constraints became apparent under Scenario 3 and Scenario 5. In both cases, high reliance on a single plant for multiple destinations increased fulfilment vulnerability. Europe and AsiaPacific were especially exposed to supply-side shocks when logistics were centralized or constrained by emission caps.

These findings reinforce recommendations to diversify supplier utilization, invest in Asia and North America plant capacity, and improve regional flow flexibility to absorb unexpected disruptions.

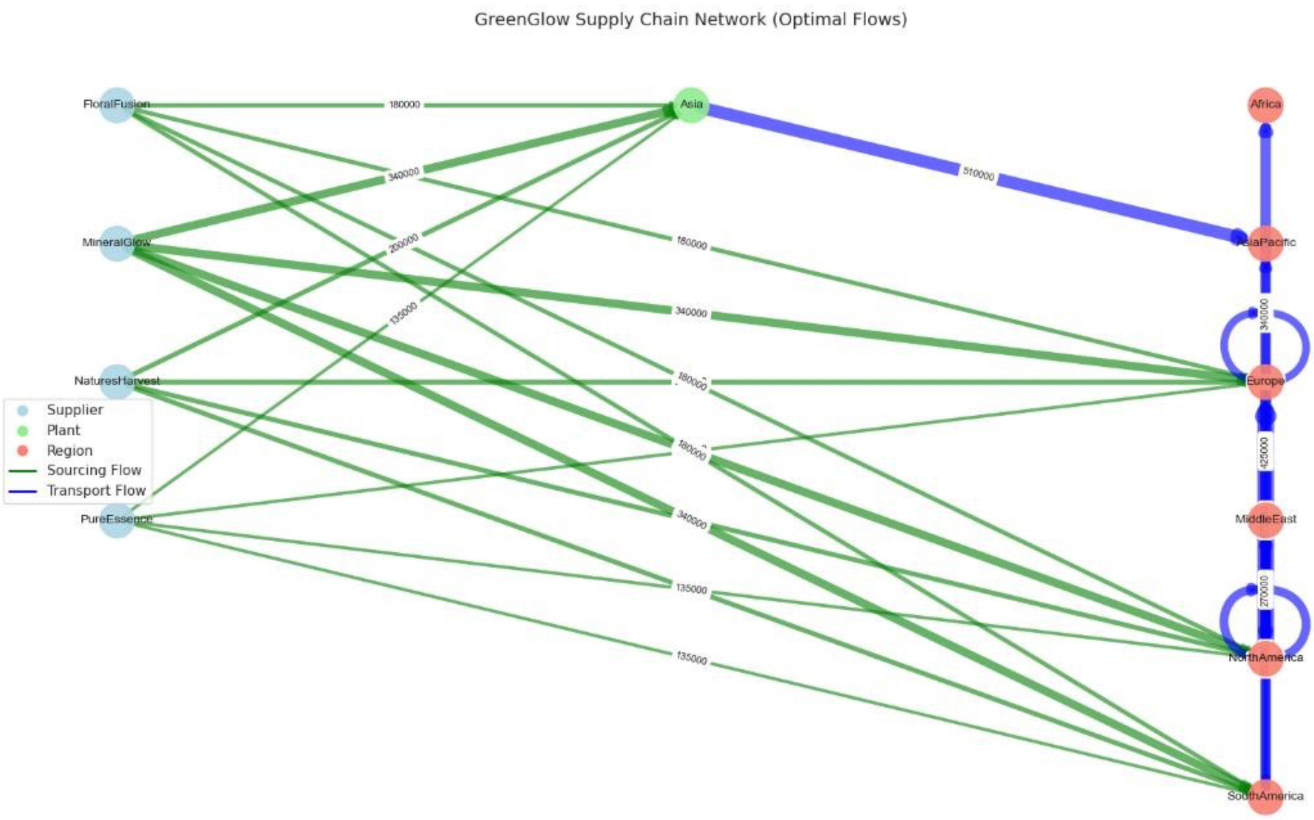


Figure 18: Supply chain network flow

6.2. Strategic Recommendations

Drawing on the scenario results and visual diagnostics, the following recommendations are proposed:

1. Supplier Selection Strategy

GreenGlow should prioritize procurement from MineralGlow and NaturesHarvest. Their robust supply capacity and lower emissions made them the most resilient and cost-effective sources across all scenarios. Conversely, PureEssence consistently contributed to higher costs and lower flexibility.

FloralFusion's value is more nuanced, it offers contingency strength when flexibility is needed, particularly during supply or demand shocks, such as those seen in Scenario 3.

2. Capacity Expansion Strategy

NorthAmerica and Asia should be focal points for plant expansion, given their consistent output levels and high adaptability across constraints. Europe's plant, although functional, posed emissionsrelated trade-offs under stricter sustainability scenarios and should be deprioritized unless cleaner technologies are introduced. SouthAmerica shows potential as a buffer plant, particularly in response to elevated regional demand or supplier outages.

3. Transportation Optimization

Routes originating from Asia and NorthAmerica emerged as the most reliable and emissionsbalanced shipping corridors. Conversely, Europe-dependent logistics exhibited signs of strain and risk under price and emissions volatility. Europe-Africa and Europe-MiddleEast connections should be monitored and reinforced, as they are susceptible to both cost and service degradation when under constraint.

4. Sustainability and Emissions Management

Scenario 5's success indicates that emissions constraints can be embedded without sacrificing cost or service quality. GreenGlow should set internal operational benchmarks around a 2 million kg CO_2 cap, promoting cleaner supply flows without major compromise. Decision-makers should adopt emissions-per-unit and cost-per-unit KPIs as standard metrics for evaluating scenario performance moving forward.

5. Contingency and Resilience Planning

GreenGlow's supply chain must account for shocks like geopolitical disruptions, cost surges, or supplier failures. Based on Scenario 3 and 4 behaviours, a set of contingency strategies is necessary: build minimum inventory buffers in Africa and AsiaPacific; activate backup suppliers like FloralFusion during raw material shortages; and enable cross-regional rerouting capabilities to mitigate concentration risks at any single plant or supplier.

6. Decision Support and Analytics

The visualizations developed in this analysis, particularly the scenario clustering and trade-off matrices, should be integrated into GreenGlow's decision support systems. These tools offer valuable forecasting, scenario testing, and multi-objective optimization capabilities (*Dey and Cheffi, 2013)*. The ability to pivot strategies based on shifting cost, demand, or sustainability targets will provide a long-term competitive advantage.

7. Conclusion

The GreenGlow Cosmetics supply chain optimization project has demonstrated the transformative potential of prescriptive analytics in supporting sustainable and strategic decision-making in a global enterprise. By integrating cost, environmental, and service-level considerations into a robust MILP model, we built a comprehensive decision-support framework tailored for real-world complexity and uncertainty.

Throughout this project, we systematically modeled five high-impact scenarios, ranging from regional demand spikes and transportation cost shifts to supplier disruptions and carbon emission regulations. Each scenario revealed how sensitive the network is to changes in logistics, procurement, and sustainability parameters. These insights weren't just theoretical; they informed clear strategic directions. For instance, the African region's vulnerability to transport costs (Scenario 2), Europe's service fragility under logistical inflation (Scenario 3), and the operational viability of hard emission caps (Scenario 5) revealed actionable opportunities for GreenGlow. One of the most compelling takeaways was the model's ability to surface hidden trade-offs. It showed that servicelevel reliability and environmental performance could be preserved even under constraints, provided the network was rebalanced intelligently. This reinforces the value of multi-objective optimization, where financial efficiency, resilience, and sustainability are pursued simultaneously, not sequentially. Moreover, our use of scenario clustering, unit-level efficiency metrics, and visual decision tools elevated the interpretability of complex outputs, empowering stakeholders to engage with optimization results beyond numerical values. The visual diagnostics, heatmaps, trade-off plots, flow graphs, served as a bridge between technical rigor and business insight. Looking ahead, this model positions GreenGlow to navigate future volatility with confidence. Whether facing geopolitical disruption, ESG mandates, or shifting demand landscapes, the company now possesses a scalable, flexible optimization engine capable of simulating outcomes and guiding evidence-based decisions.

Ultimately, this project moves beyond conventional supply chain modeling by placing sustainability, adaptability, and data-driven strategy at the heart of decision-making. It empowers GreenGlow not only to optimize operations, but to do so in a way that reflects its core values of ethical sourcing, environmental stewardship, and long-term resilience. By aligning analytical rigor with purpose-led growth, the model serves as both a tactical tool and a strategic compass for navigating an increasingly complex and conscious global marketplace

8. References

- **Abolhasani, M. and Khodakarami, M., 2021**. Optimization of a green supply chain network: A case study in a pharmaceutical industry. RIE Journal. Available at: https://www.riejournal.com/article_137324_f4b6620f752f78bedd2a6a1d841e4d7c.pdf

- **Chopra, S. and Meindl, P., 2019.** Supply Chain Management: Strategy, Planning, and Operation. 7th ed. Pearson.

- **Dey, P.K. and Cheffi, W., 2013.** Multi-objective optimization in supply chain management using simulated annealing. Authorea. Available at: https://www.authorea.com/articles/1157756

- **European Commission, 2020.** The European Green Deal. Available at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

- **Farahani, R.Z. and Asgari, N., 2021.** Multi-objective optimization for sustainable supply chain and logistics. Sustainability, 13(24), p.13617. Available at: https://www.mdpi.com/2071-1050/13/24/13617

- **Gurobi Optimization, 2022.** Modeling Basics. Available at: https://www.gurobi.com/resource/modeling-basics/

- **IBM, 2022**. *Mixed-Integer Linear Programming (MILP)*. [online] IBM Cloud Education. Available at: https://www.ibm.com/cloud/learn/mixed-integer-linear-programming

- **Inbound Logistics, 2021**. Cosmetics logistics: The beauty of an optimized supply chain. Inbound Logistics. Available at: https://www.inboundlogistics.com/articles/cosmeticslogistics-the-beauty-of-an-optimized-supply-chain/

- **Python Software Foundation, 2023**. PuLP: A Python library for Linear Programming. Available at: https://coin-or.github.io/pulp/

- **Quantzig, 2023.** Enhancing beauty supply chain efficiency and profitability: A case study for skincare brands. Quantzig. Available at: https://www.quantzig.com/case-studies/skin-careproducts-supply-chain-analytics/

- **Silva, A.L. and Figueiredo, K.F., 2014.** Innovation and sustainability in the supply chain of a cosmetics company: A case study. ResearchGate. Available at: https://www.researchgate.net/publication/262647916

- **United Nations, 2015.** Transforming Our World: The 2030 Agenda for Sustainable Development. Available at: https://sdgs.un.org/2030agenda

- **Winston, W.L., 2004.** Operations Research: Applications and Algorithms. 4th ed. Belmont: Thomson Brooks/Cole.

9. AI Supervision and Human Judgment

As part of the reporting process, language generation tools were selectively used to support the drafting and structuring of written content. This included assistance with articulating scenario narratives, formatting visual summaries, and interpreting key results from the optimization model. However, all such outputs were treated as initial drafts and were critically reviewed, refined, and rewritten by the team to ensure accuracy, originality, and contextual relevance.

AI tools were particularly helpful in interpreting complex solver outputs, such as production volumes, unmet demand tables, and expansion plans, into clear, business-oriented summaries. These interpretations were always cross-checked against actual data from the model and validated through team discussion before being included in the final report. Any generic or misaligned suggestions were either corrected or discarded entirely.

In addition, AI tools were used to assist with grammar refinement, sentence clarity, and structural consistency during the report editing phase. These enhancements helped ensure the final document met high standards of academic writing and professionalism, without altering the core content or analytical intent developed by the team.

At every stage, the team maintained full control over analytical reasoning, strategic interpretation, and final decision-making. AI served only as a writing and interpretation aid, not as a replacement for critical thinking or domain knowledge. This approach ensured that the final report reflects genuine team insight, academic integrity, and thoughtful engagement with the tools at our disposal.