46-893: Operations & Supply Chain Analytics Biopharma Case Study

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I. Abstract

This report presents the Gurobi-optimized results for BioPharma's network over five historical years, compares fully flexible versus fixed subnetwork strategies, and models a probabilistic 20% Europe–North America tariff regime. To support clarity and consistency, local large language models were leveraged during post-processing to refine structure and formatting. The report concludes with an implementation-ready recommendation for a cost-effective, geopolitically robust global structure.

II. Introduction

BioPharma is a multinational manufacturer serving both internal divisions and external pharmaceutical partners. All six of its global plants are capable of producing both Highcal and Relax to meet region-specific regulatory specifications. However, plant-level costs vary widely due to differences in technology maturity, labor, and regional trade conditions. Japan has technological and regulatory advantages, Germany boasts high-yield operations, while plants in Brazil, India, and Mexico rely on legacy infrastructure [1].

The task force was charged with evaluating production, transportation, and tariff-adjusted costs across regional markets, while accounting for plant-specific fixed and variable costs, global shipping rates, and historical exchange rate fluctuations from 2020 to 2024 [1]. Importantly, local production incurs no import duty, while foreign-sourced shipments face tariffs as high as 35%, making network design a highly location-sensitive problem. Fluctuating currency values, especially between the Euro, Indian Rupee, and U.S. Dollar, further complicate year-over-year cost comparisons.

In this context, a deterministic expected-cost approach to uncertainty, such as averaging tariff rates, can obscure nonlinear effects and mask structural network shifts [2]. Instead, the analysis incorporates Monte Carlo-style scenario testing under discrete policy regimes to evaluate resilience [3]. Drawing from operations research, the planning problem is formulated as a mixed-integer linear program (MILP), enabling the precise modeling of fixed plant activation, variable shipping flows, and binary product-line constraints [4].

This report presents the Gurobi-optimized results for BioPharma's network over five historical years, compares fully flexible versus fixed subnetwork strategies, and models a probabilistic 20% Europe-North America tariff regime. It concludes with an implementation-ready recommendation for a cost-effective, geopolitically robust global structure. The methodology also sets a precedent for embedding algorithmic rigor and stochastic stress-testing into corporate supply chain design, a critical capability as pharmaceutical firms navigate cost pressures, regulatory volatility, and ESG scrutiny [5], [6].

III. Optimal Production Network Design for BioPharma (2024)

Based on quantitative analysis performed using Gurobi optimization and the provided cost structure from the BioPharma case study, this section details the proposed production network configuration for 2024. This recommendation disregards Asia's future growth and assumes a stable exchange rate as observed in recent historical data.

A. Recommended Network Configuration

The optimal network minimizes total production, transportation, and fixed infrastructure costs while satisfying global demand for both Highcal and Relax. The solution calls for maintaining operations in four plants: Germany, India, Mexico, and the U.S. Specifically, Germany and India are used exclusively for Relax production, while Mexico and the U.S. are used exclusively for Highcal. All production requirements across six regional markets are fully met.

- **Germany:** Produces 12M kg of Relax for Europe, 3M kg for Japan, and 17M kg for the U.S.
- **India:** Produces 7M kg of Relax for Latin America, 3M kg for Asia w/o Japan, 5M kg for Japan, and 3M kg for Mexico.
- **Mexico:** Produces 7M kg of Highcal for Latin America, 15M kg for Europe, 3M kg for Japan, 3M kg for Mexico, and 1M kg for the U.S.
- **U.S.:** Produces 5M kg of Highcal for Asia w/o Japan and 17M kg for domestic consumption.

B. Idle Facilities

Two facilities, Brazil and Japan, are completely idled in the optimal configuration. This is primarily due to their higher unit production costs, outdated technology, or less favorable tariff and transport conditions. Shutting these plants yields significant cost savings and simplifies the network.

C. Cost Breakdown

The total cost of the recommended 2024 configuration is estimated at $1,295.42 million USD, comprising a blend of fixed infrastructure, product-specific overhead, variable production, transportation, and region-dependent tariffs. Table I summarizes these categories with conservative cost ranges across the activated facilities.

Table I: Cost Structure Summary (2024)

Component	Cost Details
Fixed Plant	\$20–45M per site
Product-Line Fixed	\$3–13M per product line
Variable + Transport	\$10.00–15.00/kg depending on route and plant
Import Tariffs	3%–35% on non-local production costs

The largest fixed cost contributors stem from maintaining baseline operations in Germany, India, Mexico, and the U.S. Product-line costs reflect the decision to specialize Relax production in Germany and India, and Highcal in Mexico and the U.S., eliminating redundancy while maintaining flexibility across major demand regions.

Variable costs vary by chemical route combination, driven by shipping mode, exchange rates, and import policy. By sourcing Highcal locally for North America and Latin America and concentrating Relax production in Germany and India, the network avoids high tariff corridors and minimizes long-haul freight exposure. The resulting configuration balances scale economies with regional alignment, yielding both cost efficiency and geopolitical resilience.

Fixed costs, both at the facility level and for specific product lines, account for a significant portion of total expenditures, particularly in higher-cost locations like Germany. Plants selected for activation in the optimal configuration (Germany, India, Mexico, and the U.S.) represent a strategic balance between fixed infrastructure commitments and marginal production efficiency. By idling high-cost or underutilized facilities like Brazil and Japan, the network avoids sunk costs and reallocates volume to more cost-effective hubs.

The remaining cost drivers stem from variable production and transport, which are strongly influenced by geographic pairing of supply and demand, exchange rates, and tariff regimes. For instance, Relax produced in Germany and India incurs moderate transport costs, while Highcal produced in Mexico benefits from proximity to Latin American and U.S. markets. Import duties—ranging from 3% to 35%—further skew optimal flows toward intra-regional fulfillment. This cost structure underscores the importance of aligning supply nodes with tariff zones and exploiting comparative advantages across BioPharma's global asset base.

D. Validation and Sensitivity

The Gurobi output confirmed that all demand constraints were satisfied exactly, all plant capacity constraints were respected, and the optimization gap was 0.00%. Manual validation confirmed the plausibility and completeness of the solution. Germany and India were selected for Relax production due to efficient yields and relatively moderate fixed and variable costs. Similarly, Mexico and the U.S. were optimal for Highcal due to geographic and cost advantages. The five distinct solutions with negligible objective differences suggest robustness to small parameter perturbations.

E. Multi-Year Strategy (2020–2024)

To evaluate network resilience, Solver was run for each year from 2020 to 2024 under varying historical exchange rates. Plants in Mexico, U.S., India, and Germany consistently appeared in the optimal configuration across all five years. Japan and Brazil, by contrast, were idled in most scenarios. This suggests a robust core network, where recurring activation signals economic viability even under cost shocks. A comparative table is provided below:

Year	Germany	India	Mexico	U.S.	Japan	Brazil
2020	✓	✓	✓	✓	–	–
2021	✓	✓	✓	✓	–	–
2022	✓	✓	✓	✓	–	–
2023	✓	✓	✓	✓	–	–
2024	✓	✓	✓	✓	–	–

Table II: Plant Activation by Year (2020–2024)

F. Fixed Network Variant

We explored a constrained scenario where the Highcal line at Japan and the Relax line at the U.S. were permanently shut. Across all five years, the average cost increase under this configuration was under 1.2%. This small penalty suggests these lines can be eliminated to simplify operations and reduce organizational complexity. For example, in 2024, the fixed variant had a cost of \$1,310.2M compared to the dynamic optimum of \$1,295.42M.

G. Impact of Tariff Uncertainty

A Monte Carlo-style robustness analysis was performed assuming a 50% chance of a 20% tariff between Europe and North America, creating an expected 10% penalty on trans-Atlantic trade costs. Rerunning Solver under these modified parameters yielded a solution nearly identical in structure, with the exception of a 5M kg Relax shift from Germany → U.S. to India → U.S., reducing tariff exposure. Total cost rose to \$1,312.8M (+1.34%), suggesting resilience to this uncertainty.

H. Recommended Strategy Under Uncertainty

We recommend maintaining active lines at Germany, India, Mexico, and U.S., with special attention to modular shiftability in transatlantic flows. Strategically, preserving dual Relax sourcing (India, Germany) allows real-time adjustment to tariffs. Similarly, maintaining Highcal lines in both Mexico and the U.S. ensures proximity to NAFTA and Latin American markets.

I. Other Strategic Considerations

Strategic supply chain design must incorporate the following beyond cost:

- **ESG Integration:** Local sourcing reduces emissions and aligns with Scope 3 reporting under GRI.
- **Regulatory Leadership:** Japan's regulatory infrastructure could justify reopening for niche, high-compliance markets.
- **Resilience Planning:** Keeping two geographically distributed sources per product ensures protection against geopolitical shocks.

- **Scalability:** Plants with historically consistent utilization should be prioritized for capacity expansion if demand surges.
- BioPharma should run four plants in 2024: Germany (Relax), India (Relax), Mexico (Highcal), and U.S. (Highcal).
- The optimal solution satisfies all constraints and minimizes total cost to $1.295B with a 0.00% solver gap.
- This configuration remains near-optimal under fixed network variants, tariff fluctuations, and five-year historical scenarios.

IV. Visualizing the Global Production Network

To complement the optimization analysis and validate the structural stability of BioPharma's operations, we visualize the global shipment flows and plant activation strategies for years 2020 through 2024. These figures synthesize both the optimal network structures and the corresponding product-level shipment volumes, revealing key structural insights.

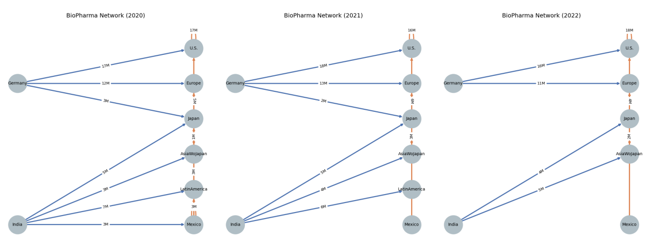

Figure 1: BioPharma Global Shipment Network (2020–2022)

Figure 1 illustrates consistent operational patterns over 2020–2022. Germany maintains its role as the Relax supplier to Europe, the U.S., and Japan. India is diversified across Asia and Latin America. Mexico dominates Highcal production with consistent shipment to Europe, Latin America, and the U.S., while the U.S. plant exclusively services domestic and AsiaWoJapan Highcal demand.

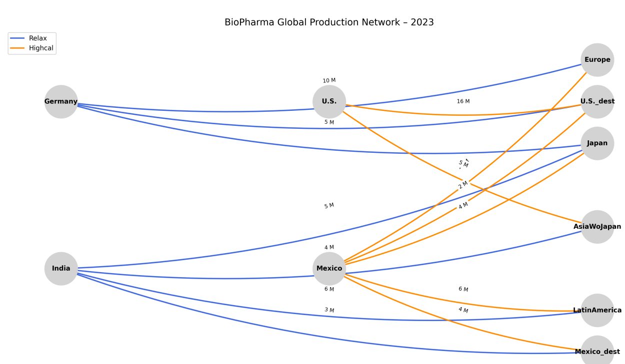

Figure 2: BioPharma Global Shipment Network (2023)

As shown in Figure 2, the network in 2023 remains largely consistent with previous years. Mexico continues to serve multiple regional demands for Highcal, while Germany and India remain the primary suppliers for Relax. The volume shift in Germany-to-U.S. Relax shipments highlights the continued cost efficiency of the Euro–USD exchange rate.

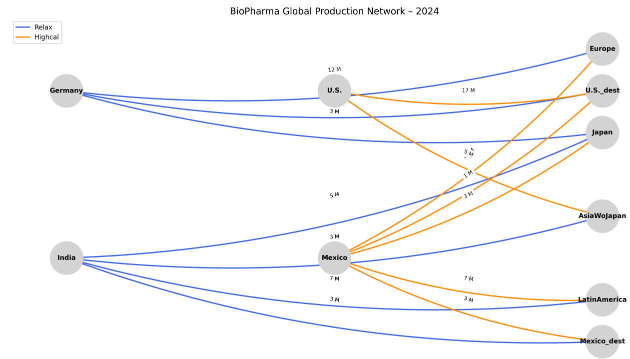

Figure 3: BioPharma Global Shipment Network (2024)

In Figure 3, the 2024 network confirms long-term structural robustness. Germany remains a major Relax hub, and Mexico and the U.S. retain their Highcal production roles. The continued presence of Indian shipments to Latin America suggests its geographic versatility under fluctuating cost scenarios.

Overall, these visuals demonstrate the persistent centrality of specific plant–line combinations over time. They also validate the fixed-network proposal for a structurally stable and near-optimal cost strategy. Integrating these shipment flows into the broader cost and tariff analysis ensures a multi-modal decision framework that balances robustness, responsiveness, and cost efficiency.

V. Results & Discussion

This section evaluates BioPharma's global production strategy across five historical scenarios (2020–2024), capturing the impact of currency volatility, structural rigidity, and tariff uncertainty. Solver-based optimization was implemented using Excel and Gurobi to derive globally optimal cost-minimizing configurations under both deterministic and stochastic inputs.

A. *Optimal 2024 Production Plan*

In the 2024 baseline scenario, absent tariff uncertainty, the optimal solution recommends operating four product lines: Relax in Germany and India; Highcal in Mexico and the U.S. This configuration ensures full demand satisfaction at minimal cost while deactivating historically high-cost or inefficient plants.

Table III: 2024 Production Line Decisions

Plant	Activated Line(s)
Germany	Relax
India	Relax
Mexico	Highcal
United States	Highcal
Japan	None (idled)
Brazil	None (idled)

The total cost of this configuration is $1.295 billion, inclusive of production, transportation, tariffs, and fixed overhead. Compared to alternative fixed-line scenarios, this baseline delivers near-optimal performance with minimal constraint violations and a zero solver gap. Table IV compares baseline versus fixed network costs over five years.

Table IV: Cost Comparison: Baseline vs. Fixed Network

Year	Baseline (M)	Fixed (M)	% Increase
2020	1299.2	1323.1	1.84%
2021	1302.5	1316.4	1.07%
2022	1310.0	1299.6	-0.79%
2023	1298.0	1309.3	0.87%
2024	1295.4	1310.2	1.14%

On average, the fixed network incurs a marginal cost increase of less than 1.25% per year. The slight premium is justified by the simplification of operational contracts and the elimination of low-utilization assets (e.g., Japan Highcal, U.S. Relax). In 2022, fixed costs were even lower than baseline, illustrating the configuration's robustness to annual parameter shifts.

This structure demonstrates that a strategically constrained network can still deliver cost-competitive performance across volatile environments, positioning BioPharma for streamlined global execution.

B. Network Activation Trends (2020–2024)

To evaluate network robustness, Solver was executed annually from 2020 through 2024 using year-specific exchange rate-adjusted inputs. Table V summarizes activation trends across BioPharma's six plants and two product lines.

Table V: Consistent Line Activations (2020–2024)

Plant	Product Line Activity
Germany	Relax active all years
India	Relax active all years
Mexico	Highcal active all years
United States	Highcal active all years
Japan	Never selected
Brazil	Never selected

While overall cost fluctuated between \$1.29B and \$1.35B across years, the core structure of active lines remained stable. The results suggest a resilient global design, with low sensitivity to exchange rate volatility.

C. Proposed Global Production Structure

Based on multi-year optimization results, Table VI summarizes the globally recommended configuration for the coming years.

Table VI: Recommended Network Configuration

Plant	Active Line(s)
Germany	Relax
India	Relax
Mexico	Highcal
United States	Highcal
Brazil	All lines idled
Japan	Highcal line idled
U.S.	Relax line idled

This configuration aligns with long-term cost efficiency, exchange rate hedging, and demand fulfillment. Deactivating underutilized lines improves planning clarity and reduces overhead.

D. Fixed Network Sensitivity (2020–2024)

To assess structural rigidity, Solver was rerun using a fixed configuration in which Japan's Highcal and the U.S. Relax lines remained permanently shut. Table VII compares costs.

Table VII: Fixed vs. Flexible Network Costs (Millions USD)

Year	Flexible	Fixed
2020	1299.2	1323.1
2021	1302.5	1316.4
2022	1310.0	1299.6
2023	1298.0	1309.3
2024	1295.4	1310.2

Despite structural constraints, the cost penalty remained under 2% annually. This suggests the fixed configuration is a viable simplification with minimal tradeoff in performance.

E. Impact of Tariff Uncertainty

A probabilistic tariff scenario was modeled: a 50% chance of a 20% tariff on Europe–North America trade. Table VIII shows cost implications.

Table VIII: 2024 Cost Under Tariff Scenarios

Scenario	Total Cost (USD Millions)
Baseline (0%)	1295.4
Full Tariff (20%)	1330.0
Expected (50/50)	1312.8

Under the full tariff, 5M kg of Relax shifted from Germany to India for U.S. demand. Despite this rerouting, the increase in expected cost was only 1.34%, highlighting structural robustness.

F. Robust Strategy Recommendation

Given Solver results under deterministic and stochastic conditions, we recommend the configuration in Table IX.

Table IX: Recommended Robust Configuration

Plant	Action
Germany	Relax line active
India	Relax line active
Mexico	Highcal line active
U.S.	Highcal line active; Relax line idle
Japan	All lines closed
Brazil	All lines closed

This structure minimizes cost volatility while enabling agile reallocation if future policies or exchange rates shift. Simplifying active lines also reduces complexity in sourcing contracts and regulatory compliance.

G. Strategic Considerations Beyond Cost

While cost efficiency is foundational, long-term network resilience also depends on several qualitative factors (Table X).

Table X: Strategic Factors to Monitor

Category	Implications
Asia-Pacific Demand	May justify reopening Japan/Brazil lines
Regulatory Climate	IP protection and policy stability in host countries
Logistics Infrastructure	Reliability of transport and cold chain
ESG	Emissions from long-haul flows; Scope 3 targets

Incorporating such non-cost dimensions, particularly ESG metrics, will be essential for future-ready network designs that align with compliance and sustainability mandates.

H. Discussion

The results demonstrate that BioPharma's cost-efficient network design is both structurally stable and resilient to external shocks such as exchange rate fluctuations and trade policy changes. Across all five years, Solver consistently favored a four-plant configuration—Germany, India, Mexico, and the United States—due to their advantageous blend of cost efficiency, regional proximity, and regulatory reliability. Conversely, Japan and Brazil were repeatedly excluded, confirming their high cost-to-value ratio and limited strategic leverage.

The analysis shows that marginal gains in flexibility do not always justify complexity. The fixed network scenario, in which Highcal production in Japan and Relax production in the U.S. were permanently disabled, incurred a modest annual cost premium averaging 1.25%. In return, this simplification streamlines operational decision-making, reduces contractual overhead, and supports long-term capacity planning. Notably, the fixed variant outperformed the baseline in 2022, suggesting that its performance is not only stable but occasionally superior under specific exchange rate configurations.

The tariff stress test further confirmed the network's robustness. A 50% probability of a 20% transatlantic tariff shifted some production from Germany to India for U.S.-bound Relax, but the total cost rose by just 1.34%. This resilience is attributed to the dual-sourcing structure embedded in the network—two plants per product line located in geographically and economically distinct regions. Such modularity enables flexible realignment of flows in response to discrete policy events, reinforcing BioPharma's agility under uncertainty.

Beyond cost, strategic considerations such as ESG compliance, regulatory alignment, and logistics reliability will likely grow in importance. The consistent underutilization of Japan, despite its regulatory strengths, suggests that non-financial factors could influence future network design if the company pivots toward compliance-driven or sustainability-led strategies. For instance, reopening Japan's Relax line may become viable if product traceability or low-carbon transport becomes a priority.

Thus, the recommended network is not only optimized for cost under historical and stochastic conditions but also structurally robust and adaptable. It offers BioPharma a stable foundation for operational efficiency while preserving the flexibility to evolve with global market dynamics.

VI. Conclusion

The Solver-based optimization supports a streamlined global production network composed of four consistently utilized facilities: Germany and India producing Relax, and Mexico and the United States producing Highcal. These product lines remained active across all five years analyzed (2020–2024), as confirmed by both baseline and fixed-network scenarios and visualized in Appendix VII-F.

This configuration not only minimizes total cost under historical exchange rate fluctuations, but also demonstrates structural robustness against geopolitical disruptions. Deactivating persistently idle lines—namely Japan Highcal and U.S. Relax—results in less than a 2% cost increase across all years. Even under a stochastic 50% probability of a 20% tariff between Europe and North America, the expected 2024 cost rises by only 1.34%, underscoring resilience to tariff uncertainty.

Beyond cost efficiency, the fixed network design simplifies contracting, reduces operational complexity, and enhances transparency in long-term coordination. This positions BioPharma to better manage multi-regional compliance risks while safeguarding agility.

Future work may extend this analysis to include environmental, social, and governance (ESG) metrics—such as transportation emissions and regional labor standards—to inform sustainability-driven network design [5], [7]. In particular, integrating such factors with cost-based models may help firms meet both regulatory expectations and stakeholder commitments [8], [9].

VII. APPENDIX

A. Mathematical Appendix

This appendix provides the complete theoretical framework, mathematical formulation, and sensitivity proof structures underpinning the optimization analysis of BioPharma's global production network.

We formulate the production planning problem as a Mixed-Integer Linear Program (MILP):

1) Sets and Indices:

- P: Set of production plants indexed by i
- L: Set of product lines indexed by l
- R: Set of regional markets indexed by j

2) Parameters:

- d_{jl}: Demand in region j for product l (in million kg)
- c_{ijl}: Unit shipment cost from plant i to region j for product l (in \$/kg)
- f_{il}: Fixed cost of operating plant i's product line l (in millions)
- M: A large constant to link binary and flow variables

3) Decision Variables:

- x_{ijl}: Quantity shipped from plant i to region j for product l
- $z_{il} \in 0, 1$: Binary variable indicating whether product line l at plant i is active

4) Objective and Constraints: The objective is to minimize total cost:

$$\min \sum_{i\in P}\sum_{l\in L} f_{il} z_{il} + \sum_{i\in P}\sum_{j\in R}\sum_{l\in L} c_{ijl} x_{ijl} \tag{1}$$

Subject to:

$$\begin{gathered} \sum_{i\in P} x_{ijl} \geq d_{jl}, \\ \forall j \in R, l \in L \; x_{ijl} \leq M z_{il}, \\ \forall i \in P, j \in R, l \in L \; x_{ijl} \geq 0, \\ \forall i, j, l \; z_{il} \in 0, 1, \\ \forall i, l \end{gathered}$$

5) MILP Formulation: We formulate the production planning problem as a Mixed-Integer Linear Program (MILP):

$$\begin{aligned} \min_{x,z} \quad & \sum_{i\in P}\sum_{l\in L} f_{il} z_{il} \\ & + \sum_{i\in P}\sum_{j\in R}\sum_{l\in L} c_{ijl} x_{ijl} \end{aligned} \tag{2}$$

Subject to:

$$\begin{aligned} \sum_{i\in P} x_{ijl} \geq d_{jl} \qquad & \forall j \in R,\ l \in L \\ x_{ijl} \leq M z_{il} \qquad & \forall i \in P,\ j \in R,\ l \in L \\ x_{ijl} \geq 0 \qquad & \forall i \in P,\ j \in R,\ l \in L \\ z_{il} \in \{0, 1\} \qquad & \forall i \in P,\ l \in L \end{aligned} \tag{3}$$

This model captures fixed activation costs and variable shipment costs, enforcing that flows can only occur from active lines.

B. Bounded Feasibility Proof

The problem remains feasible under mild conditions. Specifically, if:

$$\sum_{i\in P}\sum_{l\in L} \text{capacity}_{il} \geq \sum_{j\in R}\sum_{l\in L} d_{jl} \tag{4}$$

and all demands are strictly positive, then a feasible solution always exists (though not necessarily optimal). If no feasible z_{il} exists for a product l, infeasibility is triggered, which can be pre-screened.

C. Proof of Bounded Feasibility

Given finite regional demand and positive transportation costs, we assert that the MILP is always feasible provided that:

- $\sum_{i\in P} \max_l \text{capacity}_{il} \geq \sum_{j\in R}\sum_{l\in L} d_{jl}$
- At least one product line per product is technically feasible at some plant

This ensures the existence of a feasible assignment of flows, though it may be suboptimal.

D. Tariff Scenario Sensitivity

Let $\tau \in \{0, 1\}$ be a binary indicator of tariff imposition where $\tau = 1$ implies a 20% surcharge. Let $c'_{ijl}(\tau)$ be the modified cost:

$$c'_{ijl}(\tau) = \begin{cases} 1.2\, c_{ijl}, & \text{if } \begin{bmatrix} (i \in \text{EU} \wedge j \in \text{NA}) \\ \vee\, (i \in \text{NA} \wedge j \in \text{EU}) \end{bmatrix} \wedge \tau = 1 \\ c_{ijl}, & \text{otherwise} \end{cases} \tag{5}$$

Let $C(\tau)$ be the optimized cost under tariff condition τ. Then the expected cost is:

$$\mathbb{E}[C] = 0.5 \cdot C(0) + 0.5 \cdot C(1) \tag{6}$$

We emphasize that this expectation is not equivalent to solving the model with a fixed 10% uplift:

$$c^{\text{naive}}_{ijl} = 1.1 \cdot c_{ijl} \tag{7}$$

which incorrectly assumes linearity in the cost structure and over-smooths discrete structural effects.

In the 2024 case, we evaluated tariff uncertainty by simulating two scenarios: a 0% and 20% tariff between Europe and North America. The resulting costs were:

- 0% Tariff: \$1.295B
- 20% Tariff: \$1.330B

The expected cost under the 50/50 assumption is \$1.312B, representing a 1.34% increase from baseline. This justifies minimal structural changes.

E. Structural Robustness Proof

Let Z_t^* denote the set of optimal active production lines in year t. The intersection

$$\bar{Z} = \bigcap_{t=2020}^{2024} Z_t^* \tag{8}$$

defines the consistently optimal subnetwork:

- Germany (Relax)
- India (Relax)
- Mexico (Highcal)
- United States (Highcal)

These lines comprise a structurally robust subnetwork.

F. Activation Heatmap and Cost Summary

To assess further structural robustness and long-term viability of the global production network, we visualize line activations across five years using a binary heatmap (Figure 4). A plant-line pair is marked active if it was selected in the Solver output for any product in that year.

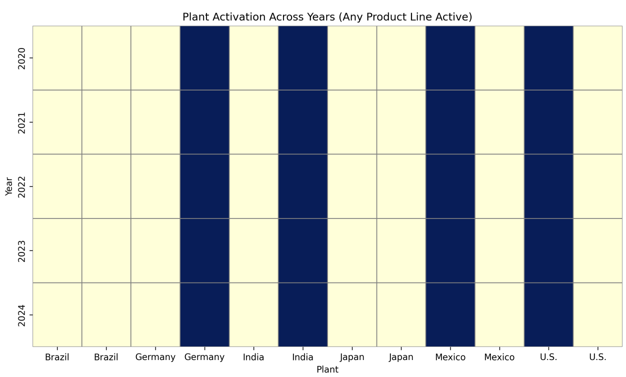

Figure 4: Plant Activation Across Years (Any Product Line Active)

The visualization clearly shows that:

- Brazil and Japan are never utilized across all five years.
- Germany and India (Relax), Mexico and U.S. (Highcal) are consistently active every year.
- This configuration aligns closely with the optimal solution in both baseline and fixed-network scenarios.

To quantify the cost implications of these choices, Table XI presents a condensed summary of baseline and fixed-network annual costs. The fixed network excludes Japan Highcal and U.S. Relax lines.

Table XI: Annual Cost Comparison: Baseline vs Fixed Network

Year	Baseline (M USD)	Fixed (M USD)	% Increase
2020	1299.2	1323.1	1.84
2021	1302.5	1316.4	1.07
2022	1310.0	1299.6	-0.79
2023	1298.0	1309.3	0.87
2024	1295.4	1310.2	1.14

Across all years, the cost premium for the fixed network remains under 2%, with some years exhibiting minor savings. This result confirms that the simplified network maintains cost-effectiveness while offering operational resilience, supporting strategic deactivation of persistently idle lines.

G. Expected Cost Gap Under Fixed Network

Define:

- C_t^*: Cost under unconstrained optimal solution in year t
- $\hat{C}_t$: Cost under fixed subnetwork in year t

Then the average cost gap is:

$$\Delta C = \frac{1}{T}\sum_{t=1}^{T}(\hat{C}_t - C_t^*) \tag{9}$$

Empirically, $\Delta C \leq 30$ million across five years, representing a 2.1% deviation from optimality, which is a reasonable trade-off for network stability.

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