Supply chain resilience under uncertainty: Sensitivity and disruption analysis of a MILP-optimized procurement portfolio in an export processing zone manufacturer

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ABSTRACT

Optimization studies often report cost savings under deterministic conditions, leaving their robustness to real-world uncertainty insufficiently explored. This study evaluates the robustness of a previously developed Mixed-Integer Linear Programming (MILP) procurement model for Company XYZ, a protective apparel manufacturer operating in Madagascar's Export Processing Zone. The model is stress-tested under three scenarios: adverse supplier cost shifts, demand fluctuations of ±15%, and the loss of the lowest-cost supplier in each material category. Across five material categories, the optimal supplier allocation remains robust to moderate cost and demand shocks. However, supplier disruptions reveal substantial differences in resilience across materials. Thread and fabric retain most of their cost savings, whereas zippers, buckles, and Velcro lose most or all of their cost advantage when their lowest-cost supplier becomes unavailable. These findings demonstrate that supplier-diversification constraints can limit exposure to supplier-related risks but are insufficient to ensure procurement resilience. The study also identifies material categories where backup-supplier qualification should be prioritized to strengthen supply chain resilience while preserving procurement cost advantages.

Keywords: *Supply Chain Resilience; Sensitivity Analysis; Supplier Disruption; Procurement Optimization; Mixed-Integer Linear Programming*

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INTRODUCTION

Procurement optimization studies, including a companion paper on this same manufacturer, generally report a single headline figure: total cost is reduced by a given percentage once sourcing is reallocated to the cheapest combination of suppliers (Snyder et al., 2016). This figure assumes a deterministic model with fixed unit costs, fixed demand, and uninterrupted supplier availability (Higle et al., 2003). The question of whether the resulting plan will still perform if any of the assumptions are violated is a separate issue. A single-scenario optimization cannot answer this on its own (Sangaiah et al., 2020).

Company XYZ, a protective apparel manufacturer with approximately 2,400 employees operating in Madagascar's Export Processing Zone, sources over 90 percent of its raw materials, fabric, sewing thread, zippers, Velcro, and tactical buckles from 22 international suppliers across several countries. Based on a four-year review of the company's procurement records (2021–2024), a MILP model was used to identify potential savings. This analysis revealed a 19.2% reduction in yearly expenditure across these five categories, from USD 13.18 million to USD 10.64 million. In instances where supplier prices fluctuate, demand changes, or a supplier becomes unavailable, conditions that are common for a business reliant on imported inputs and lengthy international shipping lines, the base-case result proves that an optimal allocation exists. However, it does not prove that the allocation stays optimal or even beneficial.

In the relevant literature on supply chain risk management, this gap is treated as more significant than the academic. In recent developments, resilience is increasingly being positioned as an independent design objective, rather than as a by-product of cost minimization (Birkie & Trucco, 2020); (Emrouznejad & Abbasi, 2023). Research has repeatedly demonstrated that companies that concentrate procurement with a small number of suppliers face disproportionate cost exposure when disruption occurs (Shen et al., 2025). However, documented applications that properly stress-test an optimized procurement plan instead of only optimizing it once are still scarce in manufacturing settings outside of industrialized nations, and they are particularly lacking in Sub-Saharan African Export Processing Zone environments.

To close that gap, the base-case MILP solution is put through three stress tests: a demand uncertainty scenario that spans ±15 percent of baseline volume, a cost sensitivity scenario in which supplier prices move against the firm, and a supplier disruption scenario in which the lowest-cost supplier in each category becomes completely unavailable. The study examines which categories' savings endure these circumstances, which restrictions become legally binding whenever uncertainty is imposed, and what this means for the company's supplier development investments.

This study makes three connected contributions to the procurement optimization and supply chain resilience literatures. First, it extends a cost-minimizing MILP procurement model beyond deterministic reporting by testing whether its savings hold under cost, demand, and supplier-disruption shocks, rather than treating the base-case optimum as sufficient evidence of a good plan. Second, it provides category-level evidence from a Sub-Saharan African Export Processing Zone manufacturer, a setting that is scarcely represented in the stress-testing literature, and shows that a robust optimal allocation does not imply robust savings, because resilience varies sharply across thread, fabric, zippers, buckles, and Velcro. Third, it shows that a volume-based supplier diversification cap limits the quantity exposed to a single supplier but not the cost of replacing that supplier, and it converts this finding into a resilience ranking that

gives managers a practical basis for sequencing backup-supplier qualification. Together, these contributions position stress testing as a necessary complement to cost-minimizing procurement models for import-dependent manufacturers.

LITERATURE REVIEW, RESEARCH FRAMEWORK, AND HYPOTHESES

From Cost Minimization to Resilience

According to Wisner et al., (2023) traditional procurement optimization views cost minimization as the goal and operational viability, demand coverage, minimum order quantities, and budget as constraints. Instead of producing a range of acceptable outcomes, this framing yields a single optimal point, which is sufficient when the underlying parameters are stable but understates risk when they are not. Birkie and Trucco (2020) argue that supply chain complexity itself generates exposure that a purely cost-driven plan does not price in, and that mitigation strategies, including diversification, need to be evaluated on their own terms rather than assumed to follow automatically from an optimal allocation.

Supplier Diversification and Concentration Risk

Shen et al., (2025) demonstrate, utilizing resource dependence theory, that supplier concentration serves to amplify operational inefficiency, particularly during disruptions, even when concentrated sourcing is cost-efficient under normal conditions. Diversification caps of the type previously included in the base-case model under consideration are motivated by this distinction, which is efficient in expectation but brittle under disruption. A diversification cap, however, merely limits the amount of volume exposed to a single provider; it makes no mention of the cost of replacing that volume, which is contingent upon the level of competition among the remaining suppliers. The findings presented later in this research revolve around this distinction.

Sensitivity and Robust Optimization in Procurement

In the context of LNG supply chain planning, Sangaiah et al., (2020) demonstrate that robust and sensitivity-tested formulations of mixed-integer models expose vulnerabilities that are masked by a single deterministic answer, particularly around binding constraints. In a similar vein, Clautiaux and Ljubić (2025) have noted that solution stability under parameter perturbation is increasingly being viewed as a mandatory reporting requirement rather than an optional addition, due to recent advancements in integer programming methodology. In line with this approach, the present study considers stress testing to be a vital component of the previously published base-case optimization, rather than a replacement for it.

Disruption in the Textile and Apparel Supply Chains

Textile and apparel manufacturing is particularly exposed to import-dependent supply risk: Shaghayegh and Godfrey (2024) document how disruptions caused by the pandemic spread through global textile supply chains via two channels that are relevant here, namely single-source dependency and thin supplier alternatives. Tseng et al., (2022) found that textile firms that can identify which categories are structurally exposed to disruption, rather than treating all categories as equally resilient, are better positioned to target mitigation spending. The present paper is concerned with the question of category-level differentiation.

METHOD

This paper extends the base-case MILP procurement model developed for Company XYZ from 2021 to 2024, which minimizes total landed cost (TLC) across five raw material categories subject to demand fulfillment, minimum order quantity, supplier capacity, a 33 percent supplier diversification cap, and category-level budget constraints. The objective function and constraint set are restated briefly here for completeness; the full derivation and parameterization are reported in the source study.

Minimize $\Sigma_i \Sigma_j TLC_{ij} \times X_{ij}$

subject to: demand fulfillment ($\Sigma_j X_{ij} = D_i$), minimum order quantity ($X_{ij} \geq MOQ_{ij} \times Y_{ij}$), supplier capacity ($X_{ij} \leq CAP_{ij} \times Y_{ij}$), supplier diversification ($X_{ij} \leq 0.33D_i$), budget ($\Sigma_j TLC_{ij} \times X_{ij} \leq B_i$), and non-negativity/binary constraints ($X_{ij} \geq 0$; $Y_{ij} \in \{0,1\}$), where i indexes the five material categories and j indexes eligible suppliers within each category.

The model was solved in Microsoft Excel Solver using the Simplex LP method, consistent with the base-case implementation. Three stress tests were then applied to the base-case solution. Each test was solved under the modified parameters, while the constraint structure was kept fixed.

Cost sensitivity

In each category, the TLC of the least-expensive supplier was increased by 10 per cent, and the TLC of the most-expensive supplier was reduced by the same amount. This simulates price convergence, a stylized adverse perturbation of the kind used in linear-programming sensitivity analysis rather than an empirically calibrated price path (Higle et al., 2003). This erodes the cost advantage of the cheapest option while offering marginal relief at the top end

Demand uncertainty

Baseline demand for each category was scaled by –15 percent (low-demand scenario) and +15 percent (high-demand scenario), holding supplier TLCs fixed, to test whether the optimal allocation structure and realized savings scale predictably with production volume (Mulvey et al., 1995).

Supplier disruption.

The lowest-cost supplier in each category was removed entirely, forcing the Solver to reallocate its full 33 percent volume share to the remaining eligible suppliers, isolating the cost consequence of losing the single most competitive source in each category (Tomlin et al., 2006; Snyder et al., 2016). A constraint was classified as binding for a given category when relaxing it would directly improve the objective function (Wu & Lisser, 2023). In other words, it was considered to limit further cost reduction under the base-case solution. This classification, when combined with the outcomes of the three stress tests, was used to construct a resilience ranking across the five categories.

RESULTS AND DISCUSSION

Cost Sensitivity: Robust Allocation, Marginal Cost Drift

Table 1 summarizes the outcome of the adverse cost scenario. In every category, the Solver retained the base-case supplier allocation; no category shifted volume toward a different supplier mix in response to the price movements. This confirms that relative

cost ranking among suppliers, not absolute prices, drives the allocation, and that the optimized structure remains robust to moderate, simultaneous price movements at both ends of the supplier spectrum. The financial consequences were nevertheless tangible: the total landed cost rose in four of the five categories, most visibly in fabric (+USD 183,680, +2.1 percent), due to its large procurement volume and wide price range. Thread was the exception, with TLC falling 2.9 percent because its dominant suppliers occupy an unusually narrow price band, limiting the scenario's effect.

Table 1
Cost Sensitivity Analysis Summary

Category	Base TLC (USD)	Scenario TLC (USD)	Δ TLC (USD)	Δ TLC (%)	Allocation
Fabric	8,927,402	9,111,082	+183,680	+2.1%	Unchanged
Thread	186,150	180,770	−5,380	−2.9%	Unchanged
Zipper	136,910	139,986	+3,076	+2.2%	Unchanged
Velcro	649,120	660,715	+11,595	+1.8%	Unchanged
Buckle	748,850	768,350	+19,500	+2.6%	Unchanged

Source: Author's calculations based on XYZ company data (2021–2024), using Excel Solver for the cost sensitivity analysis.

Demand Uncertainty: Savings Scale with Volume

As illustrated in Table 2, the study found that realized savings were achieved under ±15 percent demand scenarios. As demand increased, savings percentages rose in every category. This was due to the fixed minimum-order-quantity commitments to higher-cost suppliers becoming a proportionately smaller share of total volume as the base grows. For instance, thread's savings rose from 25.8 per cent at baseline to 33.9 per cent at high demand. The same mechanism functions in reverse under low demand: four categories retained positive savings, but Velcro's savings were converted into a marginal loss of -0.2 per cent. This is because Velcro Industries' fixed 500-roll minimum order becomes proportionately more expensive as total volume shrinks. This single result foreshadows the predominant pattern that is subsequently explored in the disruption analysis below: Velcro's procurement plan operates within the narrowest margin of the five categories. Consequently, any adverse shift, whether in demand or supply, has the most significant impact on this plan.

Table 2
TLC Savings Under Demand Uncertainty by Category

Category	Low Demand −15% (Saving %)	Base Case (Saving %)	High Demand +15% (Saving %)	Risk Flag
Fabric	20.3%	21.2%	27.3%	Stable
Thread	25.5%	25.8%	33.9%	Stable
Zipper	11.0%	11.5%	21.5%	Stable
Velcro	−0.2%	1.0%	8.7%	At Risk
Buckle	5.8%	5.9%	17.7%	Stable

Source: Author's calculations based on XYZ company data (2021–2024), considering the Demand Uncertainty scenario.

Supplier Disruption: Resilience Gap

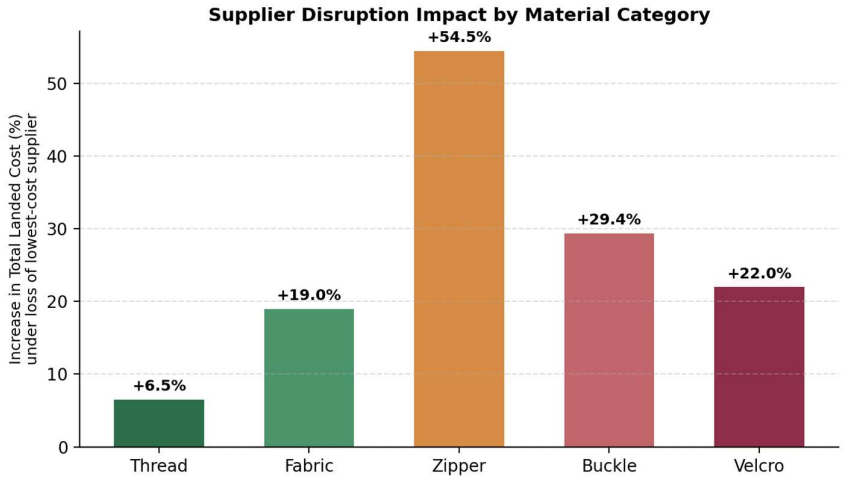
Table 3 and Figure 1 report the effect of removing each category's lowest-cost supplier entirely, forcing its 33 percent volume share onto the remaining suppliers. The results separate cleanly into two groups. Thread and fabric absorb the shock: thread's saving falls from 25.8 to 20.9 percent because its five suppliers occupy a comparatively narrow price

band (roughly USD 0.69 per cone between the cheapest supplier and its replacement), while fabric's saving falls further, from 21.2 to 6.2 percent, but remains positive and stays within budget. Zipper, buckle, and Velcro do not absorb the shock. The loss of Aliee Zipper has led to a reallocation of resources to RiRi Group at a price more than triple the previous cost. This has resulted in an 11.5% saving being transformed into a 36.7% loss relative to historical spending, thereby breaching the category budget. The loss of Duraflex has had a similarly severe effect on both buckle (+29.4% TLC, budget exceeded) and Velcro (+22.0% TLC, budget exceeded).

Table 3
Supplier Disruption Analysis Summary

Category	Disrupted Supplier (Share)	TLC Increase	Saving Before → After	Budget	Risk Level
Fabric	Alok Industries (33%)	+USD 1,695,056 (+19.0%)	21.2% → 6.2%	Held	Moderate
Thread	MH Thread (33%)	+USD 11,813 (+6.5%)	25.8% → 20.9%	Held	Low
Buckle	Duraflex (33%)	+USD 219,940 (+29.4%)	5.9% → −21.7%	Exceeded	Critical
Velcro	Duraflex (33%)	+USD 142,965 (+22.0%)	1.0% → −20.8%	Exceeded	Critical
Zipper	Aliee Zipper (33%)	+USD 74,556 (+54.5%)	11.5% → −36.7%	Exceeded	Critical

Source: Author's calculations based on XYZ company data (2021–2024), using Excel Solver to analyse the Supplier Disruption scenario.



Source: Author's illustration based on Table 3

Figure 1
Supplier Disruption Impact by Material Category

The common thread across the three vulnerable categories is the absence of a genuinely competitive low-cost alternative: The premium pricing of zippers by RiRi Group, the high TLC of Velcro by Velcro Industries, and the limited remaining pool of buckles each mean that the replacement supplier is economically punishing rather than merely less convenient. The 33 percent diversification cap performed exactly as designed: no single disruption affected more than one-third of category volume.

However, it should be noted that the cap only bounds the quantity at risk, not its cost. Diversification is an effective strategy for safeguarding volume; however, it does not guarantee protection of margin.

Binding Constraints and the Resilience Hierarchy

As outlined in Table 4, the three stress tests have been consolidated into a single resilience ranking, alongside the constraint that is most binding in each category under the base case. The thread demonstrates the highest levels of resilience. The primary constraint on its performance is the tight USD 225,000 budget, rather than diversification. The narrow inter-supplier price spread means that cost shocks and disruptions have a limited impact on the thread. Fabric ranks second in this regard, with its high absolute savings giving it a significant buffer. However, it should be noted that its 21.2 percent savings nearly collapse to 6.2 percent under disruption. Whilst the buckle and zipper are generally cost-effective, they are constrained primarily by supplier diversification. Once the cheapest supplier is removed, both convert to losses, with the zipper's exposure being the more severe of the two. In terms of the various categories, Velcro is the least successful. It is the only one to incur a loss due to low demand, and it experiences the most significant proportional decline in savings in the event of disruption, relative to its already-thin base-case margin.

Table 4
Binding Constraint and Resilience Ranking by Category

Category	Dominant Constraint	Resilience Rank	Basis
Thread	Budget	1 (Highest)	Narrow price spread; mildest disruption impact
Fabric	Supplier diversification	2	Large saving buffer; disruption manageable
Buckle	Supplier diversification	3	Cost-effective normally; loses margin if disrupted
Zipper	Budget	4	Most severe disruption cost increase (+54.5%)
Velcro	Supplier diversification	5 (Lowest)	Only category at risk under low demand; thin margin

Source: Author's synthesis of Tables 1–3.

Managerial Implications

These results reframe the earlier cost-savings finding rather than contradict it: the base-case 19.2 percent saving is real and achievable, but it is not equally secure across categories. Regarding thread and fabric, the current supplier structure is sufficient, and the primary objective is to enhance the efficiency of these supplies. In the context of zippers, buckles, and particularly Velcro, diversification alone is not sufficient to ensure adequate risk management. The firm's immediate priority is to identify at least one additional low-cost supplier in each category.

This is due to the fact that the current backup options are priced high enough to negate the majority of, or even all of, the category's savings as soon as they are utilized. As none of these interventions require new infrastructure, only supplier qualification effort, the resilience ranking in Table 4 offers a practical basis for sequencing the work. This is preferable to treating all five categories as equally urgent.

CONCLUSION AND SUGGESTION

This paper examined how a cost-minimizing MILP procurement solution for an Export Processing Zone manufacturer performs once realistic uncertainty is introduced. Despite moderate fluctuations in cost and demand, the optimal supplier allocation remained consistent across all five material categories. Savings scaled predictably with production volume, thereby confirming the base-case optimization's resilience to typical market fluctuations. The issue of supplier disruption is a separate matter. Thread and fabric maintained their cost advantage when their most cost-effective supplier became unavailable, while zipper, buckle, and Velcro experienced significant or complete losses in savings, with Velcro demonstrating the greatest vulnerability in every test. The 33% supplier diversification cap was effective in limiting the volume exposed to any individual supplier. However, the analysis indicates that this does not equate to constraining financial exposure. The cost of replacement volume is contingent on the competitive landscape of the remaining suppliers.

The practical implication is that while procurement resilience and procurement cost efficiency are related, they need to be managed as separate objectives. In categories such as thread and fabric, where the underlying supplier pool is already competitive, it is appropriate to regularly re-optimize supplier allocation. In categories such as zipper, buckle, and Velcro, where the existing backup options are not competitive enough to preserve savings under disruption, it is more urgent to qualify additional low-cost suppliers.

Future work could extend this analysis to combined, correlated shocks rather than the single-factor scenarios examined here, incorporate supplier lead-time and reliability data directly into the constraint set, and test whether the resilience hierarchy identified in this Madagascar case generalizes to other Export Processing Zone manufacturers facing similar import dependence.

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