Blockchain-Enabled Multi-Objective Construction Supply Chain Optimization

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ABSTRACT

Construction procurement decisions inherently trade off cost, transportation and holding expenses, supplier reliability, and delivery lead time a structure well suited to multi-objective optimization, yet rarely modeled with the genuine nonlinear mechanisms (quantity discounts, capacity congestion, reliability degradation under load) that characterize real supplier behavior. This paper formulates a five-objective, mixed-integer nonlinear procurement model for a construction supply chain in Zelten, Libya, incorporating blockchain-enabled sourcing as a per-supplier adoption decision with an explicit adoption cost, genuine multi-period inventory dynamics, and a reliability service-level constraint. We report a practical finding relevant to similarly constrained problems: NSGA-II, despite being standard practice for this problem class, twice failed to maintain solution diversity under tightly binding constraints, collapsing to near-single-point Pareto sets; a weighted-sum sweep using multi-start Sequential Quadratic Programming (fmincon) recovered a genuine, wide Pareto front in both cases. Results show that blockchain-enabled sourcing does not merely shift average performance, but shifts the achievable trade-off frontier toward lower unreliability and shorter lead times: blockchain-enabled solutions reach lower unreliability (minimum 244 vs. 363) and shorter lead times (minimum 7,370 vs. 9,237 supplier-days) than the best baseline solutions, at a higher minimum procurement cost (353,040 vs. 342,360 LYD), even after accounting for adoption costs and the model's added operational realism. The case study combines verified project quantities with documented assumptions and is illustrative.

Keywords: Blockchain technology; Construction supply chain; Multi-objective optimization; Supplier reliability; Procurement optimization

1. INTRODUCTION

Construction supply chains are characterized by fragmented, multi-tier supplier networks, long and variable lead times, and procurement decisions made under incomplete information about supplier reliability. These conditions contribute to well-documented cost overruns and schedule delays across the construction industry, with recent empirical work continuing to identify inaccurate cost estimation, delivery delays, and procurement-related risks among the most significant and recurring contributors (Julca-Varas et al., 2025). Blockchain technology has been proposed as a mechanism to address several of these frictions directly: by enabling verifiable, tamper-resistant records of transactions and material provenance, blockchain-based systems can reduce administrative overhead, improve the verifiability of supplier performance claims, and accelerate payment and confirmation cycles (Hamledari & Fischer, 2021a, 2021b).

This paper studies the procurement allocation problem for a real construction project (the Zelten branch project, Libya), formulated as a multi-objective optimization problem across five objectives: procurement cost, transportation cost, inventory holding cost, supplier unreliability, and delivery lead time. Blockchain adoption is modeled as a binary, per-supplier decision that reduces administrative cost, improves reliability, and shortens lead time, but carries a real one-time integration cost making adoption a genuine trade-off rather than a strictly dominant choice.

Beyond the applied contribution, this paper reports a methodological finding of independent interest: across two versions of this model (a linear formulation and an extended nonlinear formulation with inventory dynamics and a reliability constraint), the standard multi-objective solution method for this problem class NSGA-II repeatedly failed to maintain population diversity under tightly binding constraints, converging to degenerate, near-single-point Pareto sets. A multi-start, gradient-based weighted-sum approach recovered ge-

nuine, wide Pareto fronts in both cases. We report this as a practical caution for similarly constrained supply chain optimization studies, alongside the substantive result that blockchain-enabled sourcing achieves lower unreliability and lead time than baseline solutions of comparable cost, although not at the lowest-cost end of the range.

The remainder of this paper is organized as follows: Section 2 reviews related work in multi-objective construction and supply chain optimization. Section 3 presents the mathematical model. Section 4 describes the solution methodology, including the NSGA-II diversity-collapse finding and the switch to a multi-start fmincon approach. Section 5 presents results, and Section 6 concludes with limitations and directions for future work.

2. RELATED WORK

Multi-objective evolutionary algorithms, particularly the Non-Dominated Sorting Genetic Algorithm (NSGA-II), have become the standard tool for construction and supply chain optimization problems involving competing objectives such as cost, time, and quality (Deb et al., 2002). Jayarathna et al. (2021) review the broader literature on multi-objective optimization for sustainable supply chain and logistics problems, noting that cost-service-risk trade-offs of the type modeled in this paper are among the most common formulations in the field, typically solved via NSGA-II or related Pareto-based metaheuristics.

Within construction specifically, NSGA-based methods have been applied extensively to time-cost-quality trade-off problems (see, e.g., the NSGA-III literature on construction scheduling) and, more recently, to construction supply chain sourcing and production decisions. Bharadwaj et al. (2025) apply NSGA-III to a responsible-sourcing construction supply chain problem incorporating environmental, cost, and social-responsibility objectives, reporting Pareto-efficient trade-offs of a similar character to those found in this paper, though without a blockchain-adoption dimension or the nonlinear supplier-behavior mechanisms (quantity discounts, congestion, reliability degradation) introduced here.

The application of blockchain technology to construction supply chains has grown into an active research area, recently synthesized in a scientometric review of 145 publications on blockchain-enabled construction supply chain management (Pittri et al., 2026), which identifies adoption barriers and persistent gaps between conceptual proposals and practical implementation. Hamledari & Fischer (2021a) examine blockchain-based crypto assets for integrating physical and financial supply chains in construction and engineering, while Hamledari & Fischer (2021b) study blockchain-enabled smart contracts combined with robotic reality-capture technologies for construction payment automation. Closer to the reliability mechanism modeled in this paper, Kim et al. (2023) develop a blockchain-enabled coordination system for off-site construction that uses Bayesian updating to estimate supplier plan reliability, directly motivating the reliability-improvement effect of blockchain adoption used here. Most directly relevant to this paper's treatment of adoption as a genuine cost/benefit decision, Zhong et al. (2025) use a game-theoretic model to show that blockchain adoption meaningfully alters contractors' optimal pricing and quality-effort strategies in competitive construction markets reinforcing that blockchain adoption should be modeled as a strategic decision with real trade-offs, not a costless, uniformly beneficial upgrade. None of these works, however, embed blockchain's cost, reliability, and lead-time effects within a multi-objective supplier-allocation optimization framework, which is the contribution of the present work.

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This paper differs from the reviewed literature in three respects: (1) it models blockchain adoption as a per-supplier decision with an explicit adoption cost, rather than a costless or industry-wide assumption; (2) it incorporates genuine multi-period inventory dynamics and nonlinear supplier-behavior mechanisms (quantity discounts, capacity congestion, reliability degradation) rather than static per-unit rates; and (3) it reports and analyzes a solution-method diversity failure under NSGA-II a practical finding largely undiscussed in the applied construction optimization literature, which typically reports NSGA-II results without diagnostic verification of Pareto-front completeness.

3. MATHEMATICAL MODEL

3.1 Sets and Indices

Symbol	Description
$i \in \{1, \dots, 9\}$	Suppliers
$t \in \{1, \dots, 5\}$	Time periods
$m \in \{1,2,3\}$	Materials (1 = Concrete, 2 = Steel, 3 = Cement)
$M(i)$	Material produced by supplier i

3.2 Decision Variables

Symbol	Description
$X_{i,t} \geq 0$	Quantity ordered from supplier i in period t
$b_i \in \{0,1\}$	Blockchain adoption decision for supplier i
$I_{m,t} \geq 0$	End-of-period inventory of material m carried at the end of period t

Unlike a simplified period-matching formulation, $X_{i,t}$ is not forced to sum exactly to that period's demand suppliers may be ordered ahead of or below immediate need, with the difference carried as inventory $I_{m,t}$.

3.3 Parameters

Project data and documented assumptions (see the data provenance note after the tables):

Symbol	Description
p_i, C_i, d_i, w_i	Price, capacity, distance, unit weight
$R_i, L_i^0, D_{m,t}$	Baseline reliability, lead time, demand
τ, h_i, c_o	Transport rate, holding rate, order cost
α, β, γ	Blockchain admin/reliability/lead-time factors (0.30, 0.05, 0.20)
δ_i, κ_i	Quantity-discount and congestion factors (0.15, 0.30)
c_i^{adopt}	One-time blockchain adoption cost (6,000 LYD)

New parameters for the nonlinear extensions (documented assumptions, not measured project data introduced to make the model genuinely nonlinear; open to revision if better estimates become available):

Symbol	Meaning	Value
ϕ_i	Max bulk-shipping discount fraction	0.10
S_m	Site storage capacity per material	1.5× peak period demand
ψ_m	Storage-congestion penalty factor	0.25
v_m	Reference unit value per material	mean supplier price
λ_i	Reliability degradation under load	0.15
R_{min}	Minimum demand-weighted delivered reliability	0.80

Data provenance. Demand D_{m,t} comes from the project's verified bill of quantities (concrete 632.4 m3, steel 393.7 quintal); the cement quantity (1,500 bags) is an assumption. Steel and cement prices and supplier

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distances were provided by the project team. The following are documented assumptions: concrete prices (200 and 210 LYD/m3); supplier capacities (180 m3, 120 quintal and 350 bags per period), set so that no single supplier can cover a period's demand; the pairing of reliability values with steel and cement suppliers, arranged so that cheaper, more distant suppliers are less reliable; and baseline lead times, computed as L_i^0 = 2 + 4·d_i/125 days. Storage capacity S_m is 1.5 times each material's peak period demand, and inventory is bounded above by η·S_m with η = 1.5. The blockchain factors α, β and γ and the adoption cost are also scenario assumptions: the literature (Hamledari & Fischer, 2021a, 2021b; Kim et al., 2023) motivates the direction of each effect, not its magnitude. The case study is therefore illustrative of the model's behaviour and is not a calibrated representation of the project.

3.4 Objective Functions

F1 — Procurement Cost (concave quantity discount, a standard procurement pricing mechanism (Dolan, 1987) + admin cost + one-time adoption cost):

$$F_1 = \sum_{i,t} X_{i,t}\ p_i \left(1 - \delta_i \frac{X_{i,t}}{C_i}\right) + \sum_i (1 - \alpha b_i)\, c_o\, U_i + \sum_i b_i\ c_i^{adopt}$$

F2 — Transportation Cost (concave bulk-shipping discount):

$$F_2 = \tau \sum_{i,t} X_{i,t}\ w_i\, d_i \left(1 - \phi_i \frac{X_{i,t}}{C_i}\right)$$

F3 — Inventory Holding Cost (convex storage-congestion penalty on genuine carried inventory, extending the classical economic order quantity holding-cost formulation (Harris, 1913)):

$$F_3 = \sum_{m,t} I_{m,t}\ v_m\, h_m \left(1 + \psi_m \left(\frac{I_{m,t}}{S_m}\right)^2\right)$$

F4 — Weighted Unreliability (convex reliability degradation under utilization):

$$F_4 = \sum_{i,t} X_{i,t}\ \max\left(1 - R_i + \lambda_i \left(\frac{X_{i,t}}{C_i}\right)^2 - \beta b_i,\ 0\right)$$

F5 — Weighted Lead Time (convex congestion effect):

$$F_5 = \sum_{i,t} X_{i,t}\ L_i^0 (1 - \gamma b_i) \left(1 + \kappa_i \left(\frac{X_{i,t}}{C_i}\right)^2\right)$$

Optimization sense (all five objectives minimized simultaneously):

$$\min[F_1,\ F_2,\ F_3,\ F_4,\ F_5]$$

3.5 Constraints

Inventory balance:

$$I_{m,t} = I_{m,t-1} + \sum_{i:\, M(i)=m} X_{i,t} - D_{m,t} \qquad \forall m, t \qquad (I_{m,0} = 0)$$

$$I_{m,t} \geq 0 \qquad \forall m, t$$

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Supplier capacity:

$$0 \le X_{i,t} \le C_i \qquad \forall i,t$$

Storage capacity (hard upper bound with η = 1.5; the convex penalty in F3 grows as inventory approaches S_m):

$$I_{m,t} \le \eta\, S_m \qquad \forall m,t$$

Reliability service-level floor:

$$\sum_{i,t} X_{i,t}\left(1 - \max\left(1 - R_i + \lambda_i\left(\frac{X_{i,t}}{C_i}\right)^2 - \beta b_i, 0\right)\right) \;\ge\; R_{min}\sum_{m,t} D_{m,t}$$

Blockchain adoption decision:

$$b_i \in \{0,1\} \qquad \forall i$$

3.6 Nonlinear Structure Summary

Term	Location	Type	Effect
Quantity-discount pricing	F1	Concave	Bigger single-supplier orders cost less per unit
Bulk-shipping discount	F2	Concave	Larger shipments amortize fixed freight costs
Storage congestion	F3	Convex	Holding cost rises as inventory nears site capacity
Reliability degradation	F4	Convex	Suppliers pushed near capacity become less reliable
Congestion-based lead time	F5	Convex	Lead time worsens disproportionately near capacity

This is a mixed-integer nonconvex nonlinear program (MINLP): 9 binary variables, 60 continuous variables (45 allocation + 15 inventory), with nonconvexity arising from concave discount terms in F1/F2, convex congestion/degradation terms in F3/F4/F5, and a nonlinear reliability constraint.

4. SOLUTION METHODOLOGY

4.1 Model Justification

The model follows the structure used in blockchain-enabled supply chain literature: a multi-period, multi-supplier procurement allocation problem in which blockchain adoption is represented as a per-supplier decision modifying cost, reliability, and lead-time parameters. This is motivated by Hamledari & Fischer (2021a, 2021b), who document blockchain's effect on reducing administrative/payment friction, improving information verifiability, and accelerating transaction cycles in construction supply chains.

4.2 Why Five (Nonlinear) Objectives

The five objectives map to three managerially distinct decision dimensions: economic (F1 procurement, F2 transport, F3 holding kept separate rather than aggregated so the results show where cost differences originate), risk (F4 unreliability), and schedule (F5 lead time). Each was extended with a literature-grounded nonlinear mechanism (Section 3.6) so that all five objectives, not only cost, reflect realistic diminishing or worsening returns rather than being fixed per-unit rates.

4.3 Solver Selection: From NSGA-II to Multi-Start fmincon

The extended model was first solved using NSGA-II (gamultiobj), consistent with standard practice for multi-objective problems of this type, and with the binary adoption variables b_i handled natively via integer constraints. However, the resulting Pareto set showed a clear diversity failure: F2 and F3 returned identical

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values across every reported non-dominated solution in the baseline scenario, indicating the population had converged onto a single allocation and inventory profile, varying only the blockchain-adoption bits rather than genuinely exploring the allocation space.

A direct verification solving for the true minimum achievable procurement cost under the reliability constraint via nonlinear programming confirmed that procurement cost alone can be reduced to approximately 322,000 LYD in the baseline scenario (best of 20 random starts), well below the single point contained in NSGA-II's reported solution set (360,069 LYD). The Pareto sets in Table 1 cover the non-dominated solutions found by the weighted-sum sweep, which does not reach such single-objective extremes. This is consistent with a known limitation of penalty-based nonlinear constraint handling in genetic algorithms: a tightly binding nonlinear constraint, combined with a larger mixed-integer search space (69 decision variables), can collapse population diversity onto a narrow "safely feasible" region. Premature convergence and diversity loss of this kind are documented limitations of standard NSGA-II under constrained or high-dimensional conditions in the broader optimization literature (Ma & Liu, 2025), independent of this paper's specific application domain. These observations apply to the solver settings used in this study. We did not conduct an exhaustive parameter-tuning study, so the diversity loss should be read as an observation for this setting, not as a general property of NSGA-II.

Consequently, the extended model was instead solved via a weighted-sum sweep (Marler & Arora, 2004) using fmincon, an implementation of Sequential Quadratic Programming (SQP) (Boggs & Tolle, 1995), with multiple random restarts per weight vector. Unlike gamultiobj, fmincon enforces nonlinear constraints exactly rather than via penalty, and multi-start restarts mitigate the local-optima risk introduced by the model's concave cost terms. For the blockchain-adoption scenario, the binary variables were relaxed to $[0,1]$ during the joint search, then rounded to binary and the allocation/inventory variables re-optimized (polished) with adoption fixed at the rounded values, a common heuristic for mixed-integer nonlinear problems. The polishing step enforces all constraints, so the reported solutions are feasible; the optimality gap of the heuristic relative to enumerating adoption patterns was not quantified.

This experience NSGA-II failing to maintain solution diversity under tightly constrained, nonconvex conditions on two separate occasions in this study, while multi-start gradient-based methods succeeded both times is itself a modest methodological finding, suggesting population-based heuristics may require substantially more careful tuning or hybridization when applied to tightly constrained supply chain optimization problems of this type.

4.4 Scenarios

- **Scenario A (Baseline):** $b_i = 0$ for all suppliers (no blockchain)
- **Scenario B (Blockchain-optimized):** b_i jointly optimized per supplier, since adoption now carries a real one-time cost and is no longer automatically optimal

5. RESULTS

5.1 Pareto-Front Spread

Table 1 reports the minimum and maximum value of each objective across the non-dominated solution set for both scenarios, confirming genuine trade-off space was recovered by the fmincon-based solution method in clear contrast to the degenerate single-point result obtained under NSGA-II.

Table 1: Pareto-set range comparison, extended nonlinear model, baseline vs. blockchain-enabled.

Objective	Baseline (min – max)	Blockchain-enabled (min – max)
F1 – Procurement Cost (LYD)	342,360 – 390,395	353,040 – 463,468

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Objective	Baseline (min – max)	Blockchain-enabled (min – max)
F2 – Transport Cost (LYD)	20,574 – 32,609	20,855 – 27,831
F3 – Holding Cost (LYD)	2,081 – 9,430	668 – 8,723
F4 – Unreliability	363 – 501	244 – 454
F5 – Lead Time (supplier-days)	9,237 – 12,770	7,370 – 11,319

5.2 Trade-off Structure

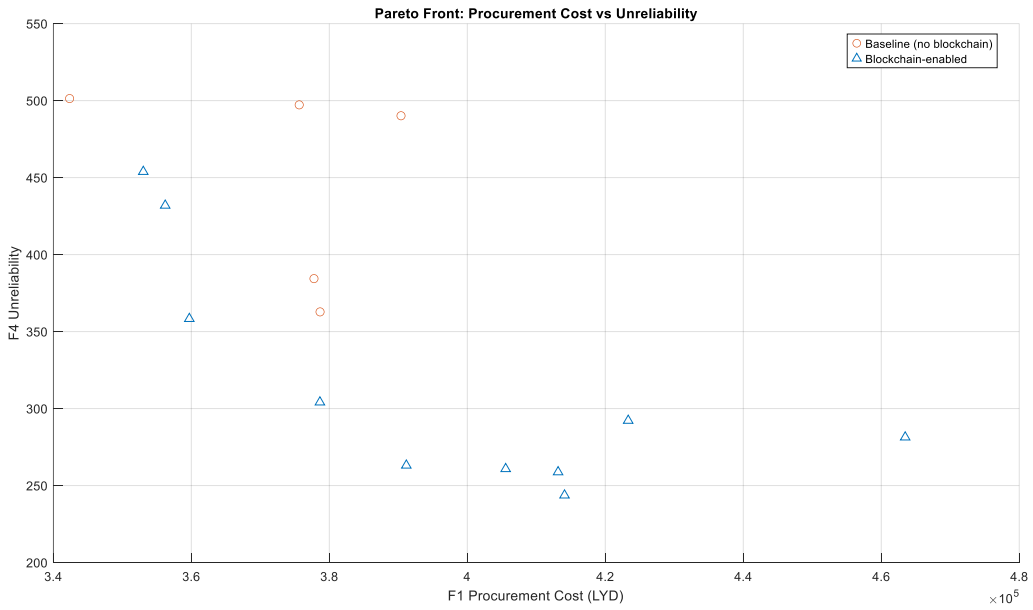


Figure 1. Pareto front: procurement cost vs. unreliability (baseline vs. blockchain-enabled).

The Procurement Cost vs. Unreliability front shows a clear downward-sloping trade-off for the blockchain-enabled scenario: lower-cost solutions correspond to higher unreliability and vice versa, consistent with a genuine Pareto-efficient front. The blockchain-enabled front sits below and to the left of the baseline solutions across most of the comparable cost range for similar procurement cost, blockchain-enabled sourcing achieves materially lower unreliability. The baseline's best-case unreliability (363) still exceeds the blockchain scenario's midrange values, while the blockchain scenario reaches unreliability levels as low as 244 that no baseline solution approaches at any tested cost.

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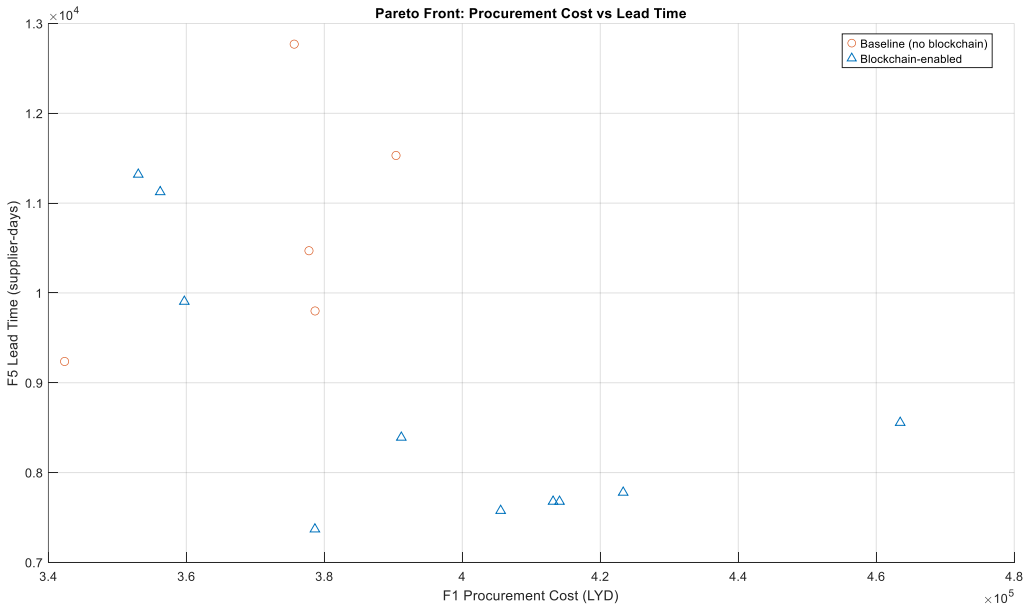


Figure 2. Pareto front: procurement cost vs. lead time (baseline vs. blockchain-enabled).

A parallel pattern holds for lead time: the blockchain-enabled front reaches lead times as low as 7,370 supplier-days, roughly 20% below the baseline's best achievable lead time (9,237 supplier-days), with the gap widening further among similar-cost solutions.

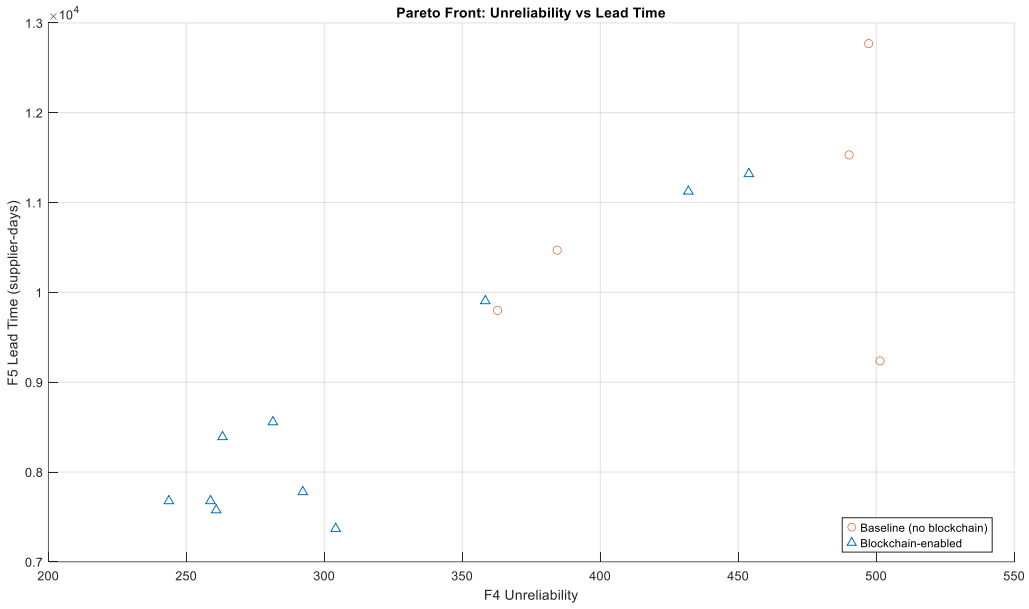


Figure 3. Pareto front: unreliability vs. lead time (baseline vs. blockchain-enabled).

The Unreliability vs. Lead Time plot shows the two scenarios occupying largely separated regions of the objective space, with the blockchain-enabled cluster consistently closer to the origin (simultaneously better on both dimensions) suggesting that blockchain adoption improves reliability and speed together rather than trading one for the other.

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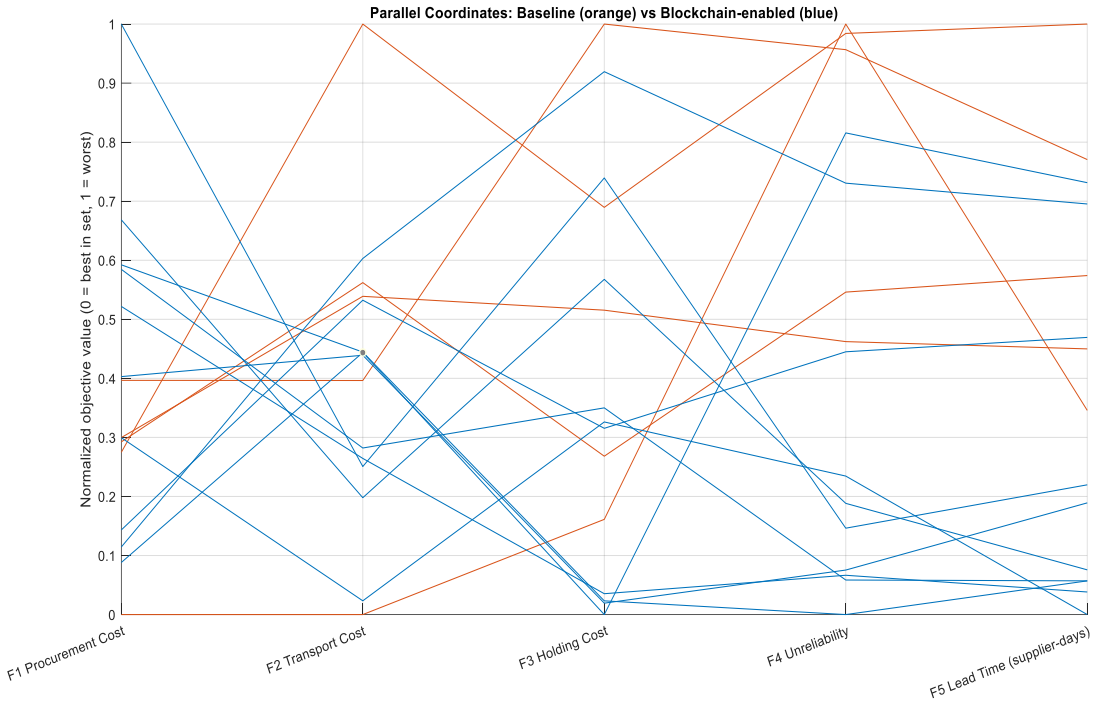


Figure 4. Parallel coordinates across all five objectives (baseline vs. blockchain-enabled).

The parallel-coordinates plot illustrates this across all five objectives simultaneously: both scenarios show genuine within-scenario variation on every axis (confirming the solution method explored a real trade-off surface), while blockchain-enabled solutions visibly cluster toward better values on the F4 and F5 axes relative to baseline. These comparisons are graphical; formal multi-objective indicators such as hypervolume and coverage are left for future work.

5.3 Interpretation

These results reinforce the central finding from the earlier, simpler nonlinear model: blockchain-enabled sourcing does not merely shift the mean of key performance measures, but shifts the achievable frontier: a more favorable reliability and lead-time trade-off space becomes available once blockchain adoption is permitted, at the cost of a higher minimum procurement cost, even after accounting for adoption costs, quantity-discount pricing dynamics, multi-period inventory carrying costs, and reliability degradation under high supplier utilization. The extended model's added realism did not overturn this conclusion; the blockchain-enabled front's reliability and lead-time advantages persist under the additional operational constraints introduced in this formulation.

6. CONCLUSION

This paper presented a five-objective, mixed-integer nonlinear procurement model for a construction supply chain, incorporating blockchain-enabled sourcing as a costed, per-supplier adoption decision, genuine multi-period inventory dynamics, and nonlinear supplier-behavior mechanisms across all five objectives. Applied to the Zelten (Libya) case study, the model shows that blockchain-enabled sourcing shifts the achievable Pareto frontier, and not merely the average outcome, toward lower unreliability and shorter lead times at comparable procurement cost, a materially stronger result than a mean-comparison alone would suggest.

A secondary contribution is methodological: NSGA-II, despite being the standard solution method for problems of this type, was found to collapse population diversity under tightly binding constraints on two separate model variants in this study, producing degenerate near-single-point Pareto sets that a naive reading of the solver output would not reveal without direct verification. A weighted-sum sweep using multi-start Sequential Quadratic Programming (fmincon) reliably recovered genuine, wide Pareto fronts in both cases. We recommend that future applied work in this problem class include an explicit diversity check (e.g., verifying that reported objectives

vary meaningfully across the solution set, not merely across the adoption/binary dimensions) before accepting NSGA-II output as representative of the true Pareto front.

Limitations and future work: the blockchain adoption cost, storage congestion, and reliability degradation parameters introduced in the extended model are documented assumptions rather than measured quantities, and should be recalibrated against real supplier data where available. The reliability floor constraint ($R_{min} = 0.80$) was fixed rather than treated as a sensitivity parameter; future work should explore how the achievable frontier shifts as this threshold is relaxed or tightened. Finally, the multi-start fmincon approach, while effective here, offers no formal global-optimality guarantee under the model's concave cost terms; a hybrid approach seeding NSGA-II with fmincon-derived solutions, or an exact branch-and-bound-based MINLP method (Grossmann, 2002), would be a natural next step for a journal-length extension of this work. The blockchain factors, adoption cost and several supplier inputs (Section 3.3) are assumptions, not measurements. The order-count term U_i in F1 is piecewise constant in the order quantities, so the gradient-based solver treats it as flat; multi-start restarts mitigate this but offer no guarantee. Repeated independent runs with performance indicators (hypervolume, IGD), a sensitivity analysis of adoption cost, reliability threshold and nonlinear parameters, and validation of the relax-and-round heuristic against enumeration of adoption patterns are left for future work.

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