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PROJECT REPORT

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Multi-Objective Goal Programming for Hazardous Facility Relocation Under Uncertainty

GABES PHOSPHATE CASE

المجمع الكيميائي التونسي
GROUPE CHIMIQUE TUNISIEN

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ABSTRACT

This study addresses the demand for urgent relocation of the Gabès phosphate processing facility in Tunisia, a move urged due to severe environmental degradation and escalating public health risks. The decision-making process involves evaluating an initial pool of 24 candidate sites, lowest-density municipality in each governorate, filtered through stochastic screening to a final set of six feasible locations. Each site presents distinct trade-offs between population safety, economic costs, water resource availability, and environmental quality.

We develop a multi-objective goal programming model utilizing lexicographic priorities. The model assigns the highest weight to the minimization of population exposure, followed by water availability, cost efficiency, and environmental quality. To ensure operational viability, the model incorporates hard constraints on budget (750 million TND), minimum water requirements (2.0 Mm^3/y), and environmental quality thresholds (6.0/10). Monte Carlo simulation with 1,000 iterations per site is employed to address parameter uncertainty, utilizing probability distributions derived from engineering benchmarks and regional data.

The analysis identifies Boughrara (Medenine) as the optimal site. It achieves a 97% reduction in population exposure while maintaining full compliance with all technical and environmental constraints. Although the optimal solution requires a 506 million TND cost increase over the status quo, the lexicographic framework demonstrates that the substantial public health benefits significantly outweigh the fiscal deviation. Sensitivity analysis confirms the stability of this result, as Boughrara remains the optimal choice across five of six weight scenarios and all tested parameter variations (±20%).

The findings indicate that continued operations at the Gabès site are mathematically and ethically unsupportable under modern standards. Relocation to Boughrara represents a robust, policy-aligned solution that prioritizes public safety without compromising operational feasibility. This research provides a transparent methodology for complex industrial relocation problems, although real-world implementation should follow field data validation and expert consultation to supplement the simulated parameters.

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INTRODUCTION

While the phosphate industry in Gabès is a pillar of Tunisia's industrial exports and a 3% contributor to the national GDP, its legacy is defined by a severe socio-environmental crisis. Decades of intensive operations have resulted in significant marine pollution and hazardous air emissions, affecting approximately 8,500 local residents. As environmental mandates and constitutional health rights evolve, the status quo is no longer tenable, necessitating a strategic relocation of the industrial complex.

Relocating such a facility is a "wicked problem" requiring the reconciliation of conflicting objectives: minimizing human hazard exposure, containing fiscal costs, ensuring water security in an arid climate, and preserving ecological integrity. These decisions are further complicated by parameter uncertainty, where data for capital outlays and hydrogeological capacities are often indicative rather than absolute.

This study develops a robust decision-support framework to optimize site selection from a nationwide pool of candidates. The model utilizes Multi-Objective Goal Programming (MOGP) integrated with stochastic Monte Carlo simulation to minimize deviations from four primary goals: Population Safety, Economic Feasibility, Water Security, and Environmental Integrity. By adopting a lexicographic hierarchy, the study explicitly quantifies the trade-offs between public safety and expenditure, providing a transparent path toward sustainable industrial development.

The primary aim of this paper is to provide a mathematically rigorous justification for relocation. To achieve this, the project addresses **three central research questions:**

1. Which candidate site emerges as the robust optimal choice under a safety-first, non-compensatory policy?
2. How resilient is the optimal solution to shifts in fiscal priorities or resource variations?
3. What is the quantified "price of safety" when balancing population risk reduction against capital investment?

By placing the right to health at the apex of a lexicographic hierarchy, this research provides a transparent mechanism for policy-makers to navigate the transition from industrial pollution toward sustainable development.

The remainder of this report is organized as follows. **Section 2** reviews the theoretical foundations of facility location and multi-objective optimization. **Section 3** details the MOGP methodology and the Monte Carlo simulation workflow. **Section 4** presents the site-specific data and parameter estimation for the feasible candidates. **Section 5** delivers the optimization results and comparative visualizations. Finally, **Section 6** discusses managerial implications and limitations, followed by concluding recommendations in **Section 7**.

LITERATURE REVIEW

2.1 Facility Location and Obnoxious Facilities

Facility location problems form a foundational domain in operations research, traditionally prioritizing cost and distance minimization (Weber, 1909). A critical subset addresses "obnoxious" facilities, those generating pollution, health hazards, or environmental degradation, requiring objectives that maximize separation from populations (Erkut & Neuman, 1989). Early hazardous waste siting models employed maximin approaches to maximize minimum distance from residential areas (Church & Garfinkel, 1978). Industrial relocation in chemical processing frequently arises from legacy pollution, necessitating systematic evaluation balancing economic viability, public safety, environmental quality, and resource constraints.

2.2 Multi-Objective Optimization Approaches

Industrial siting inherently involves conflicting objectives. Contemporary approaches favor Pareto frontier methods, particularly evolutionary algorithms like NSGA-II, which generate diverse non-dominated solution sets (Ehrgott, 2005). Recent applications include chemical plant layout optimization (Lin et al., 2022) and facility relocation with life-cycle environmental assessment (Ma et al., 2024).

However, Pareto methods assume continuous tradeability between objectives, implying economic gains can compensate for increased hazard exposure. This compensatory logic contradicts regulatory frameworks establishing non-negotiable safety thresholds. Weighted-sum scalarization suffers similar limitations, imposing fixed exchange rates between incommensurable objectives.

2.3 Goal Programming for Non-Compensatory Decisions

Goal Programming (GP), formulated by (Charnes & Cooper, 1961), minimizes deviations from aspirational targets rather than optimizing objectives directly. Through preemptive (lexicographic) weighting, GP enforces hierarchical prioritization where higher-priority objectives dominate before lower-priority criteria influence solutions (Romero, 1991). This satisficing approach ensures non-compensatory decision structures, public health cannot be traded against economic efficiency.

GP's deviation variables quantify precisely how alternatives fall short of ideal targets, providing transparency essential for policy decisions. Applications include industrial waste disposal (Zografos & Samara, 1989) and semi-obnoxious infrastructure location (Zare et al., 2025). The method proves particularly effective for discrete problems with rigid objective hierarchies where policy alignment and interpretability supersede exhaustive Pareto enumeration (Oksuz & Satoglu, 2024).

2.4 Uncertainty Quantification in Facility Location

Real-world facility location faces substantial parameter uncertainty in costs, resource availability, and environmental assessments (Snyder, 2006). While stochastic programming addresses uncertainty through scenario-based formulations, these approaches require analytical tractability often incompatible with discrete multi-objective models.

Monte Carlo simulation offers a complementary approach, propagating input uncertainty through deterministic models without convexity assumptions (Raychaudhuri, 2008). For GP applications, simulation solves the deterministic model across parameter realizations sampled from specified distributions, generating probability distributions of optimal selections and quantifying decision robustness. Recent applications demonstrate effectiveness under uncertainty (Chang et al., 2021). This integration preserves GP's non-compensatory structure while addressing parameter variability, a critical gap in existing literature.

2.5 The Gabès Case and Resource Constraints

The Gabès phosphate complex (operated by Groupe Chimique Tunisien since the 1970s) exemplifies industrial-environmental crises necessitating systematic relocation. Daily phosphogypsum discharges (14,000 tons) containing heavy metals and radioactive materials have created a marine dead zone (El Zrelli et al., 2015). (Robert, 2024) documents sustained civil opposition, demonstrating that politically expedient solutions without systematic optimization prove untenable.

(Abdenneji et al., 2023) provide epidemiological evidence linking atmospheric pollution to respiratory disease severity (SO_2: $p = 0.019$; PM: $p = 0.023$), validating population exposure minimization as a paramount, non-compensatory objective and supporting residential proximity as a quantifiable health risk proxy.

Water scarcity introduces binding constraints absent from facility location models developed for industrialized settings. Phosphoric acid production requires 4 m^3 water per ton output (Becker, 1989). The World Bank (2018) documents severe water stress across southern Tunisia, where withdrawal exceeds renewable supply. Tunisia's Water Code (Law 75-16, 1975) prioritizes human consumption over industrial uses, rendering water availability a primary feasibility constraint. This distinction is critical for arid-region facility siting yet remains underexplored in existing literature.

2.6 Research Contribution

This study addresses three simultaneous gaps: **(1)** operationalizing non-compensatory public health priorities mandated by constitutional frameworks (Tunisia's 2014 Constitution, Article 38) into optimization models; **(2)** treating water scarcity as a binding feasibility constraint in resource-limited contexts; **(3)** systematically quantifying decision robustness under parameter uncertainty in multi-objective siting problems.

The methodological contribution integrates goal programming with Monte Carlo simulation for the Gabès facility relocation, preserving GP's lexicographic priority structure while generating probabilistic performance metrics. This provides decision-makers with both a modal site recommendation and uncertainty quantification, a framework applicable to industrial siting in water-scarce developing regions where health protections cannot be compromised for economic efficiency.

METHODOLOGY

3.1 Model Type

This study uses a Multi-Objective Goal Programming (MOGP) model with preemptive priority weighting and binary decision variables to select alternative locations for the Gabès phosphate facility. The choice reflects the problem's hierarchical and non-compensatory objectives, where public health and regulatory compliance must be met before economic efficiency. Weighted-sum methods require trade-offs between incommensurable objectives, and Pareto approaches can allow unacceptable compromises. MOGP enforces the priority order directly. The problem also requires satisficing: feasible alternatives must meet all critical thresholds rather than optimizing a single measure. Multi-attribute methods like AHP or TOPSIS assume compensatory trade-offs, whereas MOGP minimizes deviations from aspiration levels to ensure essential criteria are satisfied. It also provides transparent, interpretable performance measures for each objective, making MOGP the most suitable method for this context.

3.2 Model Formulation

3.2.1 Indices

$$i \in I = \{1, 2, \dots, 6\}$$

where i indexes the final set of six feasible candidate sites obtained after stochastic feasibility screening. These sites correspond to Sidi Boubaker (Gafsa), Boughrara (Médenine), Gabès (status quo), Batten Ghazal (Sidi Bouzid), Bouaguereb (Sfax), and Rjim Maatoug (Kébili). The initial candidate pool consisted of 24 sites, representing the lowest-density municipality in each governorate; infeasible sites were eliminated through Monte Carlo simulation as described in Section 3.3.

3.2.2 Decision Variables

Primary binary variable:

$$x_i = \begin{cases} 1 & \text{if site } i \text{ is selected,} \\ 0 & \text{otherwise} \end{cases}$$

Deviation variables:

$$\begin{aligned}
d_1^+ &\geq 0 \quad \text{(over-achievement of zero population exposure)} \\
d_2^+ &\geq 0 \quad \text{(budget overrun)} \\
d_3^- &\geq 0 \quad \text{(water shortfall)} \\
d_4^- &\geq 0 \quad \text{(environmental quality shortfall)}
\end{aligned}$$

3.2.3 Parameters

Site-specific:

- P_i: population within 3 km radius (persons)
- C_i: capital cost (million TND)
- o_i: unit operating cost (TND/ton; constant at 150)
- d_i: road distance from Gafsa mining basin (km)
- W_i: annual water supply (Mm^3/yr)

- E_i: environmental quality score (0–10, the higher the better)

System-wide:

- Q = 500,000 t/yr (annual production)
- τ = 0.20 TND/t-km (transport cost)
- α: 7.5: present value annuity factor for 10-year horizon at 6% discount rate
- B = 750 M TND (budget)
- W^{req} = 2.0 Mm³/yr (water requirement)
- $E^{\min}$ = 6.0 (environmental threshold)

Total cost function:

$$TC_i = C_i + \alpha \times Q \times (o_i + \tau \times d_i) \qquad (3.1)$$

Equation 3.1. Total Cost Function

where operating and transport costs are converted from TND to Million TND (divided by 1,000,000).

3.2.4 Objective Function

$$\min Z = w_1 d_1^+ + w_2 d_3^- + w_3 d_2^+ + w_4 d_4^- \qquad (3.2)$$

Equation 3.2. Objective Function

with lexicographic ordering $w_1 \gg w_2 > w_3 > w_4$. Base-case weights $(100, 20, 10, 5)$ reflect order-of-magnitude priority differences (detailed in Section 3.6).

3.2.5 Constraints

1. **Site selection:** Ensures that exactly one candidate site is selected for facility relocation. The model assumes a single, indivisible relocation decision rather than distributed or phased development.

$$\sum_i x_i = 1 \qquad (3.3)$$

Equation 3.3. Single-site selection constraint

2. **Safety goal:** The target population exposure is zero (ideal scenario with no residential population near the facility). Any actual exposure becomes a positive deviation d_1^+, which is heavily penalized in the objective function. This formulation treats population exposure as a continuous harm rather than a threshold effect.

$$\sum_i P_i x_i = d_1^+ \qquad (3.4)$$

Equation 3.4. Population exposure (safety) goal

3. **Budget goal:** The total project cost should not exceed the budget constraint B. If the selected site's total cost exceeds the budget, the overage is captured by the positive deviation d_2^+. This formulation allows the model to select over-budget sites if they offer substantial safety or technical advantages, but with an explicit penalty:

$$\sum_i TC_i x_i - d_2^+ = B \qquad (3.5)$$

Equation 3.5. Budget constraint

4. **Water availability:** The selected site must provide adequate water supply to meet production requirements (W^{req}). Phosphoric acid production requires approximately 4 m³ of water per ton of output for chemical reactions, cooling, and waste processing. Sites with insufficient natural water availability require supplementary sources (e.g., desalination), implicitly captured in capital costs. Any shortfall below W^{req} is penalized via the negative deviation d_3^-:

$$\sum_{i} W_i x_i + d_3^- \geq W^{\text{req}} \tag{3.6}$$

Equation 3.6. Water availability constraint

5. **Environmental quality:** The selected site must meet or exceed a minimum environmental quality threshold ($E^{\min}$), reflecting regulatory standards established by Tunisia's Environmental Protection Law (1992)[1]. The environmental score E_i is a composite index incorporating baseline air quality, proximity to protected ecosystems, soil contamination risk, and topographical factors affecting pollutant dispersion. Any under-achievement of the threshold is penalized via d_4^-:

$$\sum_{i \in I} E_i x_i + d_4^- \geq E^{\min} \tag{3.7}$$

Equation 3.7. Environment Score constraint

6. **Variable domains**: The site selection variables are binary, making this a Mixed Integer Linear Program (MILP). All deviation variables are continuous and non-negative.

$$x_i \in \{0, 1\}, \quad d_j^+, d_j^- \geq 0 \tag{3.8}$$

Equation 3.8. Binary decision and non-negativity constraints

3.3 Parameter Estimation and Uncertainty

Site-specific parameters are estimated from public and engineering sources. Uncertainty is addressed via Monte Carlo simulation (1,000 iterations) over an initial set of 24 candidate sites, using a log-normal distribution for population exposure and normal distributions for all other parameters.

Monte Carlo simulation is used exclusively for feasibility screening, eliminating sites that fail minimum water, environmental, or cost plausibility conditions. This yields six feasible sites. Median parameter values for these sites are then used as deterministic inputs in the goal programming model, ensuring a robust solution for a one-time, safety-dominated relocation decision.

3.4 Assumptions

The model rests on the following assumptions:

1. Only a finite set of pre-identified locations is considered; continuous location choices are ignored.
2. Deterministic parameters: Costs, population, water, and production requirements are treated as known constants.
3. Capital, operating, and transport costs are linear; no economies/diseconomies of scale are modeled.
4. The model assumes a one-time relocation without future expansion.
5. Population within a 3 km radius as a proxy for health risk exposure.
6. Each site can access sufficient water; costs are included in capital estimates.
7. A simplified metric aggregates environmental indicators for regulatory screening.
8. Political acceptability, land acquisition negotiations, and community opposition are excluded from the optimization model, requiring separate policy analysis.

These assumptions promote transparency and align with the model's strategic decision-support role.

[1] https://pce.tn/wp-content/uploads/2022/08/Loi-92-72-du-28-Janvier-1992.pdf

3.5 Solution Procedure

The mixed-integer linear program is implemented in Python using the PuLP modeling framework with the CBC solver. The solution procedure consists of:

1. Monte Carlo simulation for parameter uncertainty and feasibility screening.
2. Extraction of median parameter values for surviving sites.
3. Base-case goal programming optimization.
4. Sensitivity and scenario analysis.
5. Diagnostic visualization.

Given the small final set, solutions are obtained instantaneously with guaranteed global optimality.

3.6 Rationale for Weight Selection

- **Safety ($w_1 = 100$).** Safety is the highest priority, reflecting the non-compensatory principle that public health risks cannot be offset by economic gain. This aligns with Article 38 of the 2014 Tunisian Constitution[2], guaranteeing the right to health, and Article 45, mandating pollution reduction.
- **Water availability ($w_2 = 20$).** As a binding feasibility constraint in arid southern Tunisia, water security is documented as critical by the World Bank[3]. While the Water Code (Law 75-16) prioritizes essential use, this weight ensures technical viability while remaining subordinate to safety.
- **Economic cost ($w_3 = 10$).** Cost is assigned a moderate weight to acknowledge fiscal constraints and budget targets without compromising safety or technical feasibility.
- **Environmental quality ($w_4 = 5$).** Modeled as a threshold-based criterion, this factor follows Law 91-1992[4] standards. Once regulatory compliance is met, further improvements are considered secondary to safety and cost drivers.

The 100:20:10:5 ratio enforces a strict lexicographic hierarchy. Sensitivity analysis confirms that the optimal solution remains robust across alternative weighting structures.

3.7 Methodological Scope and Limitations

While this model serves as a stylized decision-support tool, it establishes a transparent framework for industrial relocation by operationalizing constitutional priorities through a lexicographic structure. By integrating goal programming with probabilistic estimation, the study provides a simplified but rigorous mechanism for quantifying the trade-offs between safety, cost, and resource availability.

However, the model's real-world applicability is constrained by its deterministic assumptions and the indicative nature of the underlying data. In practice, industrial relocation requires high-fidelity field data, dynamic multi-period planning, and non-linear cost modeling that go beyond the scope of this static optimization. Consequently, this study should be viewed as a methodological template for structured decision-making rather than a final implementation plan.

[2] https://www.constituteproject.org/constitution/Tunisia_2014.pdf

[3] World Bank (2018), *Beyond Scarcity: Water Security in the Middle East and North Africa.* https://openknowledge.worldbank.org/entities/publication/62f75eb4-5488-50dc-9bb5-b54b12a32ac0

[4] https://faolex.fao.org/docs/pdf/tun2106.pdf

DATA DESCRIPTION

4.1 Candidate Sites

Candidate sites are derived through a two-stage screening process. An initial pool of 24 locations was constructed by selecting the lowest-density municipality in each Tunisian governorate. These sites were then subjected to Monte Carlo-based feasibility screening (Section 3.3) to eliminate locations that systematically violate minimum water availability, environmental, or cost plausibility requirements.

This process yielded a final set of six feasible candidate sites, including the current Gabès location retained as a status quo benchmark. Table 4.1 summarises the final sites and their geographic context.

Table 4.1. Final Candidate Sites and Geographic Context

Site	Governorate	Type	Rationale
S1: Sidi Boubaker	Gafsa	Peri-urban interior	Mining proximity
S2: Boughrara	Medenine	Remote coastal	Pristine environment
S3: Gabès	Gabès	Urban coastal	Status quo baseline
S4: Batten Ghazal	Sidi Bouzid	Rural interior	Balanced profile
S5: Bouaguereb	Sfax	Industrial coastal	Existing infrastructure
S6: Rjim Maatoug	Kebili	Remote interior	Deep south option

4.2 Parameter Definitions and Sources

4.2.1 Site-Specific Parameters

- **Population Exposure (P_i):** Measures residents within a 3 km hazard radius (Carter et al., 1995), derived from 2014 INS census data via spatial buffer analysis. Values reflect the gradient from high-density urban coastal zones (Gabès) to remote interior sites.

- **Capital Cost (C_i):** Relocation and infrastructure investment estimated via factorial methods (Seider et al., 2016). Costs scale international phosphate benchmarks (European Fertilizer Manufacturers Association, 2000) by site-specific multipliers (1.2×–2.8×) accounting for greenfield development and logistical remoteness.

- **Transport Distance (d_i):** Routing distance from the Gafsa mining basin. Gabès utilizes existing SNCFT rail infrastructure; all relocation alternatives rely on road transport network routing (OpenStreetMap) to account for grade limitations and heavy vehicle accessibility for bulk rock transport.

- **Water Availability (W_i):** Sustainable annual supply based on regional hydrogeological assessments. Capacities range from high-volume coastal reverse osmosis to restricted arid-zone aquifers, modeled with a ±20% variance to reflect extraction uncertainty.

- **Environmental Quality (E_i):** A composite index (0–10) aggregating air quality, ecosystem sensitivity, and soil integrity via AHP multi-criteria scoring (Saaty et al., 2022). It benchmarks sites from severely degraded industrial zones to pristine coastal environments.

4.2.2 System-Wide Parameters

Table 4.2 reports parameters common to all sites.

Table 4.2. System Parameters

Parameter	Value	Source/Justification
Production (Q)	500,000 t/yr	GCT historical output
Operating cost (o_i)	150 TND/t	Industry benchmark (constant)
Transport cost (τ)	0.20 TND/t-km	Bulk mineral freight rates
Present value factor (α)	7.5	10-year horizon, 6% discount
Budget (B)	750 M TND	Fiscal constraint
Water requirement (W^{req})	2.0 Mm^3/yr	4 m^3/t standard
Environmental threshold (E^{min})	6.0	Regulatory minimum

4.3 Data Preparation and Final Estimates

Monte Carlo simulation (1,000 iterations per site) is used to generate parameter distributions and perform feasibility screening. Correlations between key variables (e.g., population ↔ environment at −0.60) are incorporated using Cholesky decomposition, and distributions are truncated to physically plausible ranges.

For the six feasible sites, median values are extracted to form a deterministic dataset for the base-case goal programming model. The resulting parameter set is reported in Table 4.3. Total lifecycle cost (TC_i) is calculated as:

$$TC_i = C_i + \alpha \times Q \times (o_i + \tau \times d_i) \tag{4.1}$$

Equation 4.1. Total lifecycle cost

where the variable cost component captures the present value of 10 years of operating and transport costs:

$$\text{Variable Cost}_i = \alpha \times Q \times (o_i + \tau \times d_i) \tag{4.2}$$

Equation 4.2. Variable Cost

with parameters $\alpha = 7.5$ (present value factor), $Q = 500$ kt/yr (annual production), $o_i = 150$ TND/t (unit operating cost), and $\tau = 0.20$ TND/t-km (unit transport cost).

4.3.1 Cost Structure Interpretation

The lifecycle cost analysis highlights a significant financial barrier to relocation, with all alternatives requiring a 25–79% premium over the status quo.

- **Status Quo Baseline (Gabès):** At 733 M TND, Gabès is the least expensive option due to zero CAPEX, despite the longest transport route (227 km). This establishes a minimum 185 M TND "relocation barrier."
- **Infrastructure-Led Efficiency (Bouaguereb):** The most competitive alternative (919 M TND). It minimizes the relocation premium to 25% by leveraging existing industrial infrastructure (308 M CAPEX) and short 64 km highway routing. It represents the fiscally rational relocation choice.
- **Balanced Interior Profile (Batten Ghazal):** A middle-ground option (1,009 M TND; 38% premium). It offers a superior cost-safety-environment balance, providing low exposure (580 persons) and high environmental quality (7.6) for a 276 M TND increase over baseline.
- **Capital vs. Proximity (Sidi Boubaker):** Despite the shortest haul (45 km) and lowest OPEX, high greenfield CAPEX (428 M) pushes total costs to 1,024 M TND (40% premium). This proves that mine adjacency cannot offset high infrastructure costs.

Table 4.3. Final Median Parameter Set with Cost Breakdown

Site	Pop.	Capital	Distance	Water	Env.	Variable Cost	Total Cost
	P_i	C_i	d_i	W_i	E_i	(M TND)	TC_i (M TND)
	(persons)	(M TND)	(km)	(Mm³/yr)	(0–10)		
Sidi Boubaker	1,100	428	45	0.75	5.7	596.3	1,024.3
Boughrara	280	518	212	2.88	8.7	721.5	1,239.5
Gabès	8,500	0	227†	2.88	2.1	733.1	733.1
Batten Ghazal	580	388	78	1.60	7.6	621.0	1,009.0
Bouaguereb	2,600	308	64	2.88	5.7	610.5	918.5
Rjim Maatoug	280	578	225	0.75	7.6	731.3	1,309.3

†Railway distance via CFT line; all others road transport from Gafsa mines.

- **Remote Safety Extremes:** Boughrara (1,240 M TND) and Rjim Maatoug (1,309 M TND) incur the highest premiums (69–79%). While achieving maximum safety (280 exposure), they are penalized by extreme capital requirements and long-haul transport.

In summary, **Bouaguereb is the least disruptive relocation option** (185 M TND premium), though it maintains higher population exposure. For decision-makers prioritizing health, **Batten Ghazal** offers a balanced 38% cost premium, while **Boughrara** provides maximum safety at a 69% premium.

4.4 Data Limitations and Validation

Due to significant data constraints and a lack of public cost estimates, model parameters are indicative rather than absolute. The analysis prioritizes structured comparison under uncertainty over precise engineering prediction, utilizing 2014 census data and regional environmental records.

Logistics distances represent actual routing, using the CFT railway for Gabès and road networks for alternatives, validated via OpenStreetMap and SNCFT infrastructure maps. A uniform transport cost is applied for consistency, though this likely underestimates the reliability and economies of scale inherent to rail. Future refinements to mode-specific costs could reveal additional savings for the Gabès baseline or justify new rail development for high-volume remote sites.

To ensure robustness, Monte Carlo simulations filter infeasible outcomes while median values provide a transparent baseline. International benchmarking and sensitivity analysis confirm that site rankings remain stable across parameter fluctuations. Bouaguereb consistently emerges as the most cost-competitive relocation choice, while Gabès maintains a persistent cost advantage. The significant cost gaps (185–576 M TND) ensure that these fundamental hierarchies and strategic conclusions remain valid even under varying assumptions.

RESULTS AND ANALYSIS

5.1 Optimal Solution and Comparison with Status Quo

Under base-case lexicographic weights $(w_1, w_2, w_3, w_4) = (100, 20, 10, 5)$, the goal programming model selects **Boughrara** as the optimal relocation site. The results highlight the non-compensatory priority of public safety, quantify key trade-offs, and demonstrate robustness to weight, parameter, and stochastic variations.

Boughrara minimizes the weighted objective (Z = 28,000) relative to the Gabès status quo (Z = 850,020), but at a substantial economic cost. Its lifecycle cost of 1,240 M TND represents a 506 M TND premium (69%) over Gabès' 733 M TND baseline. Table 5.1 summarizes the main performance differences.

Table 5.1. Optimal Solution (Boughrara) vs. Gabès Status Quo

Criterion	Boughrara	Gabès
Population Exposure (P_i, persons)	280	8,500
Total Cost (TC_i, M TND)	1,240	733
Water Availability (W_i, Mm^3/yr)	2.88	2.88
Environmental Quality (E_i, 0–10)	8.7	2.1
Objective Value (Z)	28,000	850,020

Boughrara delivers a **97% reduction in population exposure**, the dominant goal, while fully satisfying water and environmental constraints. The 506 M TND cost increase, equivalent to a 490 M TND deviation from the 750 M TND budget target, is accepted because the safety benefit ($w_1 \times 8{,}220 = 822{,}000$) overwhelmingly exceeds the financial penalty ($w_3 \times 490 = 4{,}900$). This illustrates the core trade-off: achieving world-class safety and environmental performance requires a cost premium equal to 65% of the budget constraint.

5.2 Overall Site Ranking and Trade-offs

Table 5.2 ranks the six feasible candidates by their objective values.

Table 5.2. Site Ranking by Objective Value

Rank	Site	P_i (persons)	TC_i (M TND)	Z
1	Boughrara	280	1,240	28,000
2	Rjim Maatoug	280	1,309	28,000
3	Batten Ghazal	580	1,009	58,900
4	Sidi Boubaker	1,100	1,024	110,240
5	Bouaguereb	2,600	919	260,190
6	Gabès (Status Quo)	8,500	733	850,000

Analysis of the ranking reveals several key trade-offs and strategic insights:

- **Safety Dominance:** Rankings are primarily driven by population exposure. Boughrara and Rjim Maatoug achieve identical minimal exposure (280 persons), proving that maximum safety is achievable at multiple locations.
- **Cost as Tie-breaker:** Among the safest alternatives, cost becomes the differentiator. Boughrara outperforms Rjim Maatoug by 69 M TND (5% savings), though both require 506–576 M TND premiums (69–79%) over Gabès.
- **Economic Undervaluation:** Bouaguereb (rank 5) is the most affordable relocation option (919 M TND; 25% premium) but ranks low because the lexicographic model prioritizes safety. Shifting weights toward fiscal efficiency () would make it the preferred choice.

- **Compromise Options:** Batten Ghazal (rank 3) and Sidi Boubaker (rank 4) offer 87–93% exposure reductions for 38–40% cost premiums. These serve as viable middle grounds between Gabès' high risk and Boughrara's high cost.
- **Water Constraints:** Scarcity acts as a hard filter, eliminating several interior candidates. Surviving sites like Boughrara and Bouaguereb (desalination) or Batten Ghazal (aquifers) demonstrate superior hydrogeological resilience.
- **Status Quo Domination:** Gabès is mathematically dominated on safety (30× worse) and environment (4.1× worse). While it offers the lowest cost, its 185–576 M TND relocation premium poses significant fiscal feasibility challenges for Tunisia.

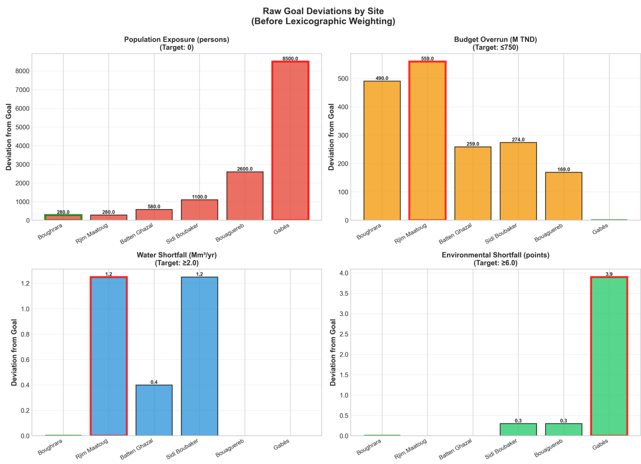

Figure 5.1. Raw deviations by site across the four primary objectives

Figure 5.1 illustrates objective trade-offs and the core policy dilemma. Gabès meets budget and water targets but exhibits a massive population exposure deviation (8,500 persons) and the worst environmental shortfall (3.9 points). Conversely, Boughrara and Rjim Maatoug minimize exposure to near-zero but incur the highest budget overruns (490–559 M TND), confirming the high opportunity cost of prioritizing safety over fiscal constraints.

Boughrara and Rjim Maatoug define the safety-priority extreme, while Batten Ghazal and Sidi Boubaker occupy intermediate positions with moderate deviations across all categories. Although Gabès excels in fiscal adherence, its extreme safety and ecological failures suggest it is a poor holistic choice, effectively dominated by more balanced profiles like Bouaguereb.

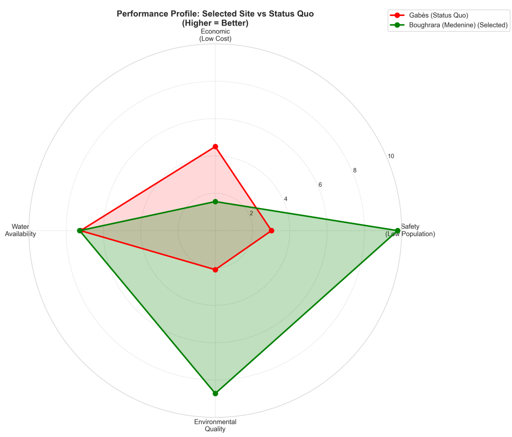

Figure 5.2. Radar Performance Comparison: Boughrara vs. Gabès Status Quo

The radar plot in Figure 5.2 highlights the profound environmental and safety gains provided by Boughrara, while starkly visualizing the cost penalty. While relocation necessitates substantial fiscal sacrifice (506 M TND premium), this trade-off delivers transformational improvements: 97% exposure reduction (8,500 → 280 persons) and restoration of pristine environmental conditions (2.1 → 8.7 index). The question for Tunisian policymakers becomes whether these non-monetary benefits justify a 69% increase in lifecycle costs. 18

5.3 Robustness and Sensitivity Analysis

5.3.1 Weight Sensitivity

Sensitivity scenarios (Table 5.3) demonstrate that site selection is highly sensitive to priority assumptions, with distinct strategic regimes emerging.

Table 5.3. Weight Sensitivity Analysis Scenarios

Scenario	Weights (w_1, w_2, w_3, w_4)	Optimal Site
Base (Lexicographic)	100, 20, 10, 5	Boughrara
Equal Weights	25, 25, 25, 25	Boughrara
Fiscal Austerity (Cost)	10, 10, 100, 5	Bouaguereb
Strict Safety	1000, 20, 10, 5	Boughrara/Rjim Maatoug
Water Priority	100, 200, 10, 5	Boughrara
Environmental Focus	100, 20, 10, 50	Boughrara

- **Safety-dominant regime (5 of 6 scenarios):** Boughrara remains optimal whenever population exposure receives dominant weight ($w_1 \geq 4w_3$). This includes base lexicographic priorities, equal weighting, and scenarios emphasizing water or environment. Under extreme safety prioritization (1000×), Boughrara and Rjim Maatoug tie, as both achieve minimal exposure (280 persons).
- **Cost-dominant regime (fiscal austerity):** When cost weight exceeds safety weight by 10×, **Bouaguereb** emerges as optimal. This represents the "economically rational" solution, accepting 9× higher exposure (2,600 vs. 280 persons) to save 321 M TND (26% cost reduction) relative to Boughrara. Notably, even under fiscal dominance, the model does not revert to Gabès, confirming that the status quo is unacceptable even to cost-obsessed decision frameworks.
- **Regime transition threshold:** The critical threshold lies near $w_3/w_1 \approx 5$. Above this ratio, cost considerations override safety; below it, population protection dominates. This threshold provides a quantitative benchmark for assessing whether Tunisia's stated policy priorities genuinely reflect decision-making weights.

5.3.2 Parameter and Stochastic Sensitivity

The model was subjected to ±20% variations in parameter thresholds, and cost estimates. Results confirm two-tier robustness:

- **Ranking Stability:** Under base weights, Boughrara remained optimal across all perturbations. The 506 M TND (69%) cost differential vs. Gabès is large enough that 20% estimation errors (±150–250 M TND) do not reverse the safety-cost trade-off under lexicographic priorities.
- **Budget Violations:** At the pessimistic cost boundary (+20%), Boughrara's lifecycle cost reaches 1,488 M TND, exceeding the 750 M TND target by 98%. This suggests the fiscal constraint is systematically violated under uncertainty, necessitating either a budget revision to 1,200–1,500 M TND or the acceptance of sub-optimal sites.
- **Risk Profiles:** Monte Carlo simulations (1,000 iterations) confirm Boughrara maintains adequate water supply even at the 10th percentile (2.30 Mm^3/yr). A cost coefficient of variation ($CV \approx 6.4\%$) indicates low volatility around the 1,240 M TND median.

DISCUSSION

6.1 Managerial and Practical Implications

The central managerial implication is the clear dominance of **Boughrara (Medenine)** when public safety is treated as a non-negotiable objective. The model demonstrates that a **97% reduction in population exposure** is achievable, but only by accepting a substantial **506 M TND safety premium** relative to the Gabès status quo. This cost is not a modeling artifact but the quantified price of aligning industrial siting decisions with modern health and environmental standards.

Crucially, the framework makes trade-offs explicit. Lower-cost alternatives, such as Bouaguereb or Batten Ghazal, reduce expenditure but retain materially higher residual exposure, in some cases an order of magnitude larger than Boughrara. Managers can therefore use the model to justify higher capital commitments by demonstrating that cost minimization directly translates into elevated public risk, rather than abstract efficiency gains.

6.2 Robustness and Validity

The recommendation is supported by a rigorous, multi-stage screening process that reduced 24 initial candidates to 6 feasible sites. Across sensitivity tests, **Boughrara remains optimal in 5 of 6 weight configurations**, losing dominance only under extreme fiscal prioritization. Monte Carlo analysis further confirms feasibility under pessimistic cost and water availability realizations, indicating that the solution is structurally stable rather than parameter-driven.

6.3 Limitations and Potential Improvements

The model is inherently **static**, evaluating a single relocation decision rather than a phased transition that could smooth fiscal impacts. In addition, all constraints are treated as **hard thresholds**, whereas real-world negotiations may allow temporary or conditional relaxations. Finally, reliance on adjusted 2014 census data introduces demographic uncertainty that could be reduced using higher-resolution spatial population datasets.

6.4 Extensions and Future Research

Future work should extend the framework to **multi-period optimization** to capture transition dynamics and overlapping operations. Integrating **GIS-based site generation** would allow identification of optimal greenfield locations beyond administrative boundaries. Expanding the environmental dimension to include **life-cycle assessment (LCA)** would also enable evaluation of carbon trade-offs associated with relocation-induced transport changes.

CONCLUSION

This research formulated a decision-support framework for the strategic relocation of the Gabès phosphate facility, addressing conflicting priorities and data uncertainty. By integrating stochastic screening of 24 candidates with a lexicographic Multi-Objective Goal Programming (MOGP) model, the study demonstrates a transition from cost-centric industrial planning to a model centered on human safety and environmental resilience.

Summary of Insights and Recommendations

The analysis yields three critical insights for industrial governance:

- **The Primacy of Safety: Boughrara (Medenine)** is the optimal site, enabling a 97% reduction in population hazard exposure. The 506 M TND "safety premium" over the status quo is mathematically justified by the lexicographic priority of public health.
- **Obsolescence of the Status Quo:** The current Gabès location is a "dominated" solution in all scenarios. It fails to meet modern environmental and safety thresholds, making continued operations indefensible regardless of fiscal savings.
- **Stability Under Uncertainty:** Monte Carlo simulations confirm that Boughrara remains the optimal choice even under pessimistic cost and resource percentiles, establishing it as a robust long-term strategic recommendation.

Future Applications and Scalability

The methodology provides a scalable template for "NIMBY" infrastructure challenges, offering a rigorous tool for decision-makers in several areas:

- **Infrastructure Siting:** Applicable to waste-to-energy plants, chemical hubs, and desalination facilities requiring the reconciliation of technical feasibility with community health.
- **Policy Calibration:** The model allows agencies to "stress-test" policy weights, visually demonstrating the consequences of prioritizing fiscal austerity over environmental quality.
- **Data-Poor Environments:** The integration of Monte Carlo methods provides a blueprint for optimization in regions lacking precise public data, offering a statistically defensible path forward despite information gaps.

In conclusion, the framework proves that the relocation of the Gabès complex *is the only viable path* to aligning Tunisia's industrial growth with its constitutional mandates for health and environmental protection.

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APPENDICES

Appendix A: Core Implementation

The complete analysis is implemented in Python 3.12. This appendix presents the critical functions underlying the framework: correlated parameter sampling, the optimization solver, and the sensitivity analysis logic.

A.1 Correlated Monte Carlo Parameter Simulation

This function generates 1,000 samples per site using Cholesky decomposition to impose realistic dependencies between conflicting parameters (e.g., urbanization vs. environmental baseline).

```python
def simulate_site_parameters(site_id: str, n_sim: int = 1000) -> pd.DataFrame:
    """
    Generate correlated parameters:
    - Capital cost vs Water: +0.50 (infrastructure access)
    - Population vs Environment: -0.60 (urban impact)
    """
    profile = SITE_PROFILES[site_id]

    # Pearson Correlation Matrix [Cost, Pop, Water, Env]
    corr_matrix = np.array([
        [1.00,  0.30,  0.50, -0.20],
        [0.30,  1.00, -0.10, -0.60],
        [0.50, -0.10,  1.00,  0.20],
        [-0.20, -0.60,  0.20,  1.00],
    ])

    # Cholesky decomposition for multivariate sampling
    L = np.linalg.cholesky(corr_matrix)
    uncorr = np.random.randn(n_sim, 4)
    corr_samples = uncorr @ L.T
    uniform_samples = stats.norm.cdf(corr_samples)

    # 1. Capital cost (Normal)
    cdist = CAPITAL_COST_DISTS[profile['capital_type']]
    capital = stats.norm.ppf(uniform_samples[:, 0], cdist['mean'], cdist['std'])
    capital = np.clip(capital, cdist['min'], cdist['max'])

    # 2. Population (Log-normal to handle demographic skewness)
    pdist = POPULATION_DISTS[profile['population_type']]
    mu_log = np.log(pdist['mean']**2 / np.sqrt(pdist['mean']**2 + pdist['std']**2))
    sig_log = np.sqrt(np.log(1 + (pdist['std']**2 / pdist['mean']**2)))
    population = stats.lognorm.ppf(uniform_samples[:, 1], s=sig_log, scale=np.exp(mu_log))
    population = np.clip(population, pdist['min'], pdist['max'])

    # 3. Water availability (Normal)
    wdist = WATER_DISTS[profile['water_type']]
    water = np.clip(stats.norm.ppf(uniform_samples[:, 2], wdist['mean'], wdist['std']),
                    wdist['min'], wdist['max'])

```

```
    # 4. Environmental quality (Normal)
    edist = ENV_QUALITY_DISTS[profile['env_type']]
    environment = np.clip(stats.norm.ppf(uniform_samples[:, 3], edist['mean'], edist['std
        ']),
                          edist['min'], edist['max'])

    return pd.DataFrame({
        'site_id': site_id,
        'P_i': population.astype(int),
        'C_i': capital.round(1),
        'W_i': water.round(2),
        'E_i': environment.round(2),
    })
```

Listing 9.1. Correlated parameter sampling with truncated distributions

A.2 Goal Programming Optimization Solver

Implements the lexicographic goal programming model as a Mixed Integer Linear Program (MILP) using the PuLP interface.

```
def solve_gp(sites: Dict, weights: Dict = None, system_params: Dict = None) -> Dict:
    """
␣␣␣␣Minimizes␣weighted␣deviations␣from␣target␣goals:
␣␣␣␣d1+:␣Population␣over-achievement␣(Safety)
␣␣␣␣d2+:␣Budget␣overrun␣(Economics)
␣␣␣␣d3-:␣Water␣shortfall␣(Feasibility)
␣␣␣␣d4-:␣Quality␣shortfall␣(Compliance)
␣␣␣␣"""
    weights = weights or BASE_WEIGHTS
    params = system_params or SYSTEM_PARAMS

    model = LpProblem("Gabes_Relocation_GP", LpMinimize)

    # Binary selection variables
    x = {sid: LpVariable(f"x_{sid}", cat='Binary') for sid in sites}

    # Deviation variables (non-negative)
    d1_pos = LpVariable("d1_pos", lowBound=0)
    d2_pos = LpVariable("d2_pos", lowBound=0)
    d3_neg = LpVariable("d3_neg", lowBound=0)
    d4_neg = LpVariable("d4_neg", lowBound=0)

    # Objective: Lexicographic weighted minimization
    model += (weights['w1'] * d1_pos + weights['w2'] * d3_neg +
              weights['w3'] * d2_pos + weights['w4'] * d4_neg)

    # Constraints
    model += lpSum([x[sid] for sid in sites]) == 1
    model += lpSum([sites[sid]['P_i'] * x[sid] for sid in sites]) == d1_pos
    model += lpSum([sites[sid]['TC_i'] * x[sid] for sid in sites]) - d2_pos == params['B'
        ]
    model += lpSum([sites[sid]['W_i'] * x[sid] for sid in sites]) + d3_neg >= params['
```

```
        W_req']
    model += lpSum([sites[sid]['E_i'] * x[sid] for sid in sites]) + d4_neg >= params['
        E_min']

    model.solve(PULP_CBC_CMD(msg=0))
    selected = [sid for sid in sites if value(x[sid]) == 1][0]

    return {'selected_site': selected, 'objective': value(model.objective)}
```

Listing 9.2. Goal programming solver with deviation variables

Appendix B: Software Environment and Reproducibility

The analysis is implemented in **Python 3.12** using the following scientific stack:

- **NumPy & SciPy**: Stochastic sampling and statistical distributions.
- **Pandas**: Data manipulation and simulation result aggregation.
- **PuLP**: Linear programming interface using the COIN-OR CBC solver.
- **Matplotlib & Seaborn**: Visualization of Pareto fronts and radar charts.

Full execution (24,000 iterations and 48 sensitivity scenarios) completes in approximately 12–15 seconds on a standard workstation. The random seed is fixed at 42 to ensure deterministic reproducibility of the Monte Carlo results.