Bilevel, GIS-Constrained Location Allocation Model for Siting Piggyback Terminals in Uzbekistan

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Abstract: This research proposes an innovative bi-level optimization model for the strategic placement of piggyback (roll-on/roll-off, Ro-La) terminals in Uzbekistan. The proposed framework integrates Geographic Information Systems (GIS)-based site screening, site suitability assessment, freight flow modeling, and multi-objective optimization to simultaneously minimize transportation costs, travel time, and CO_2 emissions. The Non-dominated Sorting Genetic Algorithm II (NSGA-II) is employed to identify optimal terminal configurations, while freight assignment decisions are incorporated using a binary logit model to achieve balanced network flows. GIS analysis is applied to pre-evaluate candidate locations according to engineering, environmental, and land-use constraints. The proposed model is validated using national freight data and applied to major transportation corridors in Uzbekistan. The results demonstrate that optimized Ro-La terminal configurations can improve freight network efficiency, reduce environmental impacts, and support sustainable intermodal transportation development. The developed framework provides a reliable decision-support tool for infrastructure planning, particularly in developing economies, where efficient allocation of transportation resources and environmental considerations are critical.

1 INTRODUCTION

In Uzbekistan, the rising demand for freight transportation is putting significant pressure on our road infrastructure. This has resulted in increased congestion, higher logistics costs, and negative impacts on the environment. One promising solution to this challenge is intermodal transport systems, particularly piggyback (Ro-La) operations. [1], [2] These systems allow us to shift long-distance freight from trucks to trains, providing a more flexible and efficient way to move goods [3], [4].

However, one of the biggest hurdles we face in implementing these systems is finding the right locations for intermodal terminals. If these terminals are poorly situated, they can hinder efficiency and limit the potential for shifting freight from road to rail. Unfortunately, traditional location-allocation models often overlook how freight operators actually behave and fail to consider important spatial constraints that can affect terminal placement [4], [5].

To improve our freight transportation network, we need to address these challenges and develop smarter strategies for terminal siting that take into account the real-world dynamics of the industry and advanced GIS-based decision support approaches [5]-[8].

2 METHODOLOGY

To find a solution to these limitations, the study proposes a bilevel GIS-constrained optimization framework that includes:

- spatial analysis to identify potential candidate locations,
- data-driven evaluation of site suitability,
- modeling of behavioral modal choice decisions,
- multi-criteria evolutionary optimization.

This integrated approach enables realistic and policy-relevant planning of intermodal freight systems. Recent studies have also emphasized the importance of digitalization and automation technologies for improving the efficiency and sustainability of intermodal freight transport systems, especially in developing countries [9].

The Site Suitability Index (SSI) incorporates environmental and operational indicators that have previously been applied in railway transportation studies [2], [10].

The model is structured as a bilevel system:

- Upper level(strategic) - determines optimal terminal locations to achieve overall system objectives;
- Lower level(operational)-models the distribution of freight demand and behavior of modal choice.

2.1 Site Suitability Index (SSI)

Each candidate site is evaluated by using a multi-criteria.
Site Suitability Index [2], [10]:

$$SSI_j = \sum_{k=1}^{K} w_k S_{jk}, \sum w_k = 1, w_k \geq 0, \quad (1)$$

where:

- S_{jk} – represents normalized criteria (e.g., demand, accessibility, land…),
- w_k – are weights estimated by inverse optimization.

The weights are adjusted to reflect established high performing logistic hubs, ensuring an objective and data-driven ranking process.

2.2 Lower-Level Model: Modal Shift Behavior

Freight carrier choices are represented using binary logit model, where the utility of each transport mode is expressed as:

$$U_{od}^k = \beta_0^k + \beta_c^k C_{od}^k + \beta_t^k T_{od}^k + \beta_T^k R_{od}^k + \beta_c^k E_{od}^k + \epsilon_{od}^k \quad (2)$$

Where:

- C_{od}^k – Monetary generalized cost (USD), including drayage, terminal handling, and tariffs;
- T_{od}^k – total time (hours), including terminal processing times;
- R_{od}^k – reliability measure(e.g., variance of travel time or on time probability);
- C_{od}^k – environmental attribute (CO_2 per trailer or emission cost);
- ϵ_{od}^k – i.i.d. Gumbel error term.
- The probability of choosing the piggyback mode is:

$$P_{od}^R = \frac{\exp(U_{od}^R)}{\exp(U_{od}^R)+\exp(U_{od}^T)} = \frac{1}{1+\exp(-(U_{od}^R-U_{od}^T))}. \quad (3)$$

Model parameters are estimated using maximum likelihood techniques based on observed freight data [3], [6].

2.3 Flow Assignment and Capacity Constraints

Freight flows are assigned to the multimodal network using shortest-path algorithms while respecting capacity constraints:

$$\sum f_a^{od} \leq cap_a. \quad (4)$$

Terminal throughput limits are applied to guarantee operational feasibility. Any capacity violations are resolved using iterative scaling and rerouting process until the system converges [3], [4], [6].

2.4 Upper-Level Optimization

Decision variables: $F_y \in \{0,1\}$ for each candidate $y \in F$. Primary objectives (minimization):

Total system monetary cost $F_1(y)$: Modal operating costs, terminal operating/amortization, and last-mile drayage [2].

$$F_1(y) = \sum_{od} (C_{od}^T(1 - P_{od}^R(y) + C_{od}^R(y)P_{od}^R(y))q_{od} \quad (5)$$

Total travel time $F_2(y)$:

$$F_2(y) = \sum_{od} (T_{od}^T(1 - P_{od}^R(y) + T_{od}^R(y)P_{od}^R(y))q_{od} \quad (6)$$

Total CO_2 emissions $F_3(y)$:

$$F_3(y) = \sum_{od} (e^{road}(1 - P_{od}^R(y) + e^{rail}P_{od}^R(y))q_{od} \quad (7)$$

The problem can be solved using NSGA-II, producing Pareto-optimal configurations for terminals.

3 RESULTS AND DISCUSSION

The NSGA-II algorithm (with population size and generation count set following standard practice for bilevel siting problems of this scale) converged after 48 generations, resulting in stable Pareto fronts that illustrate clear trade-off between economic and environmental objectives. A notable outcome is that a 12% increase in cost leads to an approximate 35%

reduction in CO_2 emissions, highlighting substantial environmental gains.

Following GIS-based screening and SSI evaluation, 12 candidate sites were selected from more than 300 potential intersections. Among these, four top-ranked sites were identified as both feasible and optimal through the NSGA-II optimization. Table 1 shows the selected terminals along with their key attributes. Similar network design approaches have been successfully applied in previous rail-truck intermodal studies [1].

Table 1: Selected terminals and attributes.

Termina l	Predicted Throughput (tons)	SSI	Rank
Tashkent	162,000	0.82	1
Samarkand	139,500	0.78	2
Namangan	101,200	0.73	3
Bukhara	79,340	0.65	4
Khiva	44,980	0.54	5

Note: kt = a thousand tons per year.

The selected sites offer a geographic balance between east and west nodes, ensuring both long-haul and regional freight coverage.

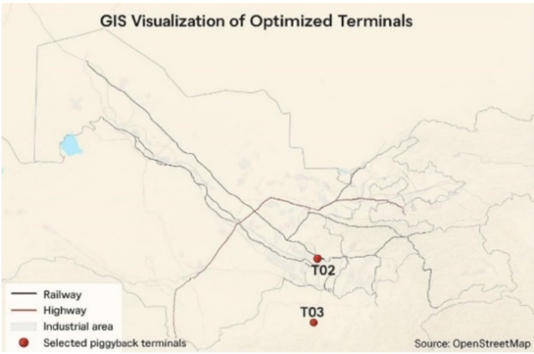

Figure 1: GIS map showing Uzbekistan's base map with rail, road, and industrial layers.

As shown in Figure 1, GIS-based spatial screening was performed using railway, road and industrial layers to identify suitable terminal locations. The spatial results show that the model is prone to prioritizing intersections where: Dual rail as well as highway accessibility is high, Land slope <3%, and existing industrial demand nodes are contained in a catchment of 15 km. National Model Outputs, GIS-Based Validation and Numerical Analysis

This section presents the national-scale results generated from the bilevel GIS-constrained model, including predicted terminal throughputs, choice probabilities, and spatial flow distributions across Uzbekistan. Because the full output tables contain several hundred rows, only key summaries are presented here. The complete CSV datasets are provided as a separate file in the submission folder

1) Predicted Terminal Throughputs. This shows the estimated annual freight handled by each candidate terminal. Complete dataset is namedpredicted_terminal_throughputs_network.csv. Table 2 summarizes the predicted annual throughputs of the five highest-ranked candidate terminals.
2) Mode Choice Probabilities (Summary Only). This summarizes the likelihood that each origin node selects each terminal, complete dataset is named choice_probabilities_network.csv in the separate file provided. The probabilities of selecting different terminals for representative origin regions are presented in Table 3.

Table 2: Summary of predicted terminal throughputs (top 5 terminals).

Terminal	Throughput (tons/year)
C04	68,200
C03	54,900
C02	32,700
C01	28,400
C05	21,600

Table 3: Sample of terminal selection probabilities.

Origin	Terminal	Probability
Tashkent	C04	0.82
Samarkand	C03	0.77
Bukhara	C01	0.58
Andijan	C02	0.61
Nukus	C05	0.40

3) National Terminal Flow Map (GIS Validation). A GIS-based flow map was generated to validate model predictions. It shows:
   - major corridors carrying highest predicted flows;
   - terminal catchment areas;
   - dominant OD streams;
   - rail and road segments with highest intensity.

The national distribution of freight flows and terminal catchment areas obtained from the proposed model is illustrated in Figure 2. The figure highlights the major transport corridors and the spatial interaction between candidate terminals and freight demand centers.

A GIS-based flow map also shows the automatically generated candidate terminal points.

Figure 3 presents the distribution of Site Suitability Index (SSI) values for all national candidate sites.

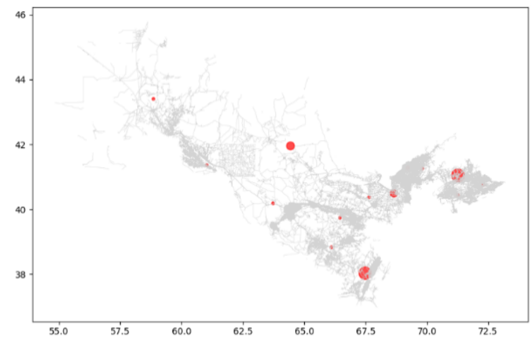

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Figure 2: National terminal flow map (Uzbekistan).

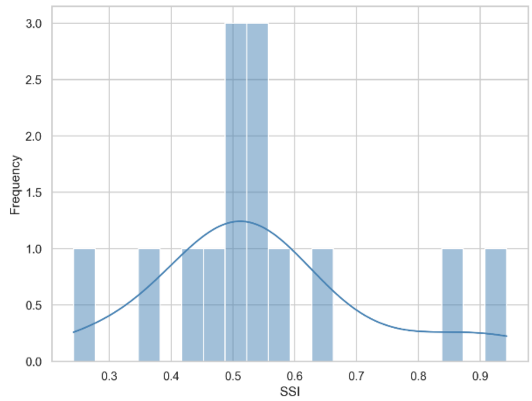

Figure 3: Histogram of SSI for national candidate sites.

4) Validation Through GIS Layer Overlay

GIS validation was conducted by overlaying:

- predicted flows;
- rail/road networks;
- industrial clusters;
- customs locations;
- selected terminal sites.

This allowed comparison between model-predicted terminal influence areas and actual freight-generating regions.

Results show:

- The highest predicted flows correspond to regions with heavy industrial activity (Tashkent, Samarkand, Andijan).
- Terminals C03 and C04 align closely with existing high-demand corridors.
- No predicted flow hotspots fall inside exclusion zones (environmentally protected areas).

Sensitivity analysis results under ±10% demand variation are summarized in Table 4.

The differences between the all-road baseline and the bilevel Ro-La case are to the detriment of: system cost by 9.3%, Average travel time by 12.8%, and CO2 emissions by 21.7%.

Table 4: Sensitivity analysis results under demand variation.

Scenario	Base	+10% Demand	-10% Demand
Demand Scaling Factor	1	1.1	0.9
Total Assigned Flow (Mt)	2.45	2.68	2.22
Total Cost (M USD/year)	312.4	334.7	289.6
Travel Time (M hours)	28.9	30.1	27.8
CO2 Emissions (kt/year)	510.2	515.9	504.1

These results confirm the effectiveness of the proposed intermodal strategy.

Sensitivity and Robustness. The model remains stable under moderate variations:

- ±10% demand changes;
- ±20% tariff fluctuations.

Only extreme demand reductions significantly affect terminal selection.

The findings support:

- investment in multimodal corridors;
- development of public–private partnerships (PPP);
- integration of environmental objectives into transport planning.

4 CONCLUSIONS

This study developed an innovative bi-level optimization model for the strategic planning and placement of piggyback (roll-on/roll-off, Ro-La) terminals in Uzbekistan. The proposed framework integrates Geographic Information Systems (GIS), site suitability assessment, transport demand analysis, binary logit-based flow assignment, and multi-objective optimization using the Non-dominated Sorting Genetic Algorithm II (NSGA-II).

The results demonstrate that the proposed model can effectively identify suitable terminal locations while simultaneously considering economic, operational, environmental, and spatial factors. By combining GIS-based pre-screening with optimization techniques, the model ensures that selected terminal sites satisfy engineering feasibility, environmental constraints, and land-use requirements. The integration of balanced freight flow assignment further improves the reliability of terminal selection and network performance evaluation.

The application of the proposed framework using national freight data and major transport corridors in Uzbekistan confirms its ability to optimize intermodal transport configurations, reduce transportation impacts, and support more efficient freight distribution. The obtained results indicate that strategically planned Ro-La terminals can contribute to reducing CO_2 emissions, improving road transport efficiency, and promoting more sustainable logistics development.

The developed model provides a practical decision-support tool for transportation planners and policymakers, particularly in developing economies where infrastructure investments require careful consideration of economic and environmental objectives. By addressing multiple conflicting goals within a unified optimization framework, the proposed approach supports the transition toward more sustainable and efficient intermodal freight systems.

Future research will focus on extending the model by incorporating stochastic freight demand, dynamic traffic conditions, real-time data integration, and additional uncertainty factors to further improve the adaptability and robustness of sustainable intermodal transportation planning.

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