Humanitarian Aid Warehouse Network Optimization for Disaster Response in Turkey

A Mixed Integer Programming Approach to Emergency Supply Chain Design

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Executive Summary

Turkey faces significant natural disaster risks, particularly in the Aegean and Marmara regions where seismic activity, industrial density, and coastal vulnerabilities create compound risks, this project develops a warehouse placement system for humanitarian aid distribution across Turkey's disaster-prone regions.

1. Problem Statement

Following recent catastrophic events (e.g., the 2023 Kahramanmaraş earthquakes and the 2021 Izmir earthquake), efficient disaster response planning has become critical. A humanitarian aid foundation sought to establish an optimal network of emergency supply warehouses to store and rapidly distribute:

- **Tents** (3 storage units each)
- **Blankets** (1 storage unit each)
- **Sleeping bags** (1 storage unit each)

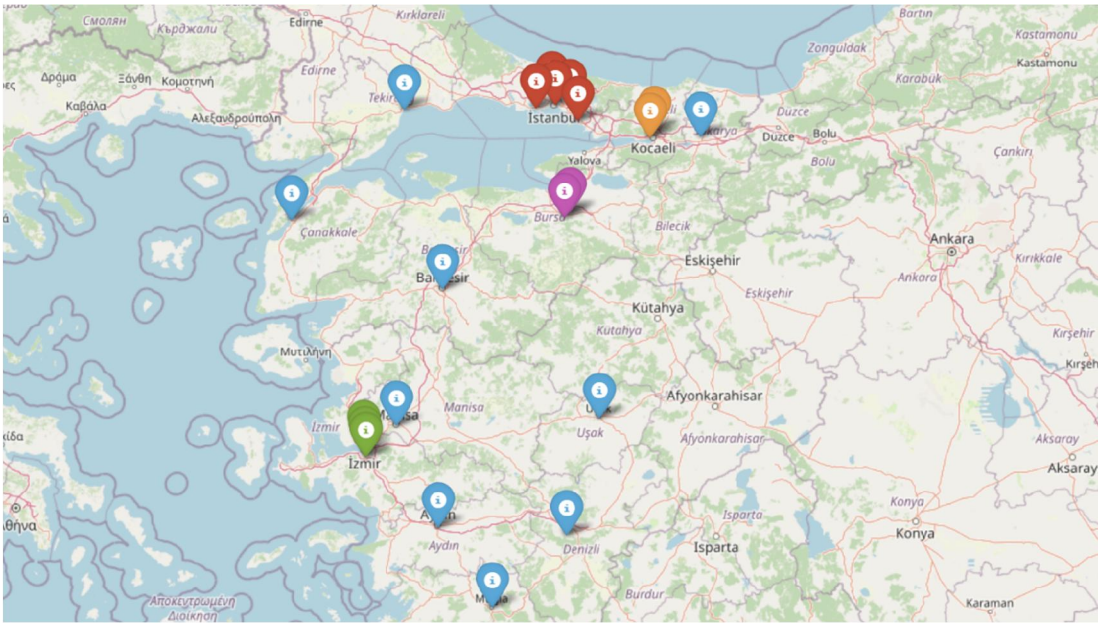
The aim is to determine optimal warehouse locations, sizes, and service assignments while balancing cost efficiency with response time requirements, particularly for high-risk areas.

Geographic Scope

The project focused on 14 key cities:

- Istanbul (Europe & Asia) – High-risk mega-city
- Bursa – Industrial hub with seismic risk
- Balıkesir – Coastal area with flood/earthquake risk
- Çanakkale – Earthquake-prone

- Kocaeli – Industrial zone with high seismic risk
- Sakarya – Earthquake risk
- Tekirdağ – Moderate risk
- İzmir – Major city with high earthquake risk
- Aydın – Earthquake and flood risk
- Denizli – Moderate seismic risk
- Manisa – Earthquake risk
- Muğla – Coastal flood risk
- Uşak – Lower risk



Warehouse Location & Sizing

- There are potential warehouse locations where warehouse will be built and used to serve the cities
- Three warehouse sizes with varying costs and capacities:

Size	Capacity (unit)	Cost (million TL)
Large	2.200.000	25
Medium	1.500.000	20
Small	1.250.000	17

Project Objective

This project addresses the strategic planning problem of optimizing the humanitarian aid warehouse network across 14 major Turkish cities, encompassing 21 distinct districts. The goal is to create a mathematically optimal solution that:

- Minimizes total system costs (construction and operational)
- Prioritizes rapid response to high-risk areas
- Ensures adequate coverage for vulnerable populations
- Maintains operational efficiency and resource utilization

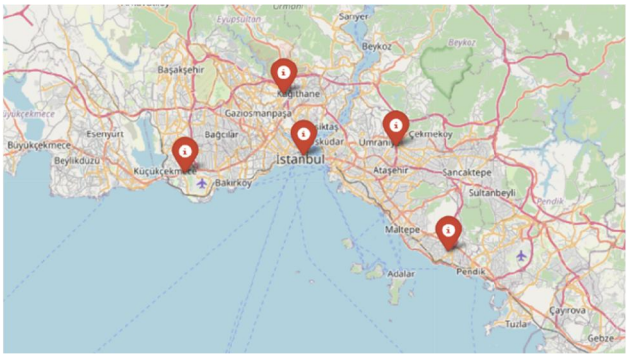
2. Data Foundation and Methodology

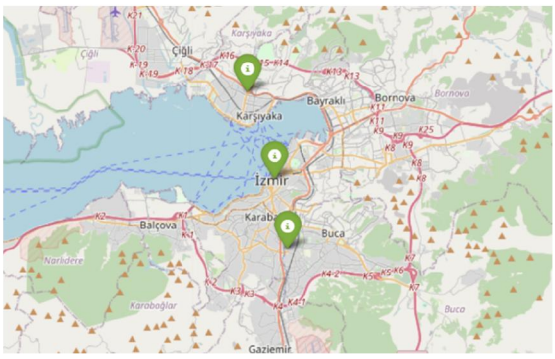
2.1 City/District Structure:

The model operates at the district level. Cities are subdivided into districts to better represent population distribution and logistical considerations, resulting in 21 potential warehouse locations across the study area. Major cities are divided into multiple districts, each acting as a potential warehouse location and a distinct demand point.

Example District Divisions:

- Istanbul divided into 5 districts (Europe North/Central/South, Asia North/Central)
- İzmir divided into 3 districts (Central, Karşıyaka, Konak)





2.2 Data Collection and Processing

Population & Risk:

Population data and risk scores are assigned at the parent city level and then distributed proportionally to their constituent districts. With populations based on 2024 estimates and risk scores (1-10) derived from:

- Proximity to North Anatolian Fault and other seismic zones
- Historical earthquake frequency and intensity
- Industrial density and infrastructure vulnerability
- Flood risk and secondary disaster potential

Distance Calculations:

Distances are calculated between the geographic centroids of all districts, using a factor of **1.4** to approximate real-world driving distances from straight-line coordinates.

2.3 Demand Estimation:

Demand is calculated based on affected population ratios, foundation coverage targets, and a household-based unit requirement. The model assumes that during a major disaster, 25% of the population will require humanitarian aid, and this foundation will serve 30% of those affected individuals.

Average Household Size: The average household size in Turkey is approximately 3.2 people.

Units Per Person Calculation:

- Blankets: 1 unit per person.
- Sleeping Bags: 1 unit per person.
- Tents: 1 tent per family (3.2 people). Since a tent requires 3 storage units, the per-person unit cost for tents is 3 / 3.2 = 0.9375.

Total Storage Units per Person: 1 (blanket) + 1 (sleeping bag) + 0.9375 (tent) = 2.9375 units.

*Demand Formula = Population * 0.25 (Affected) * 0.30 (Coverage) * 2.9375 (Units/Person)*

2.4 Technical Approach

Risk and Priority Modeling:

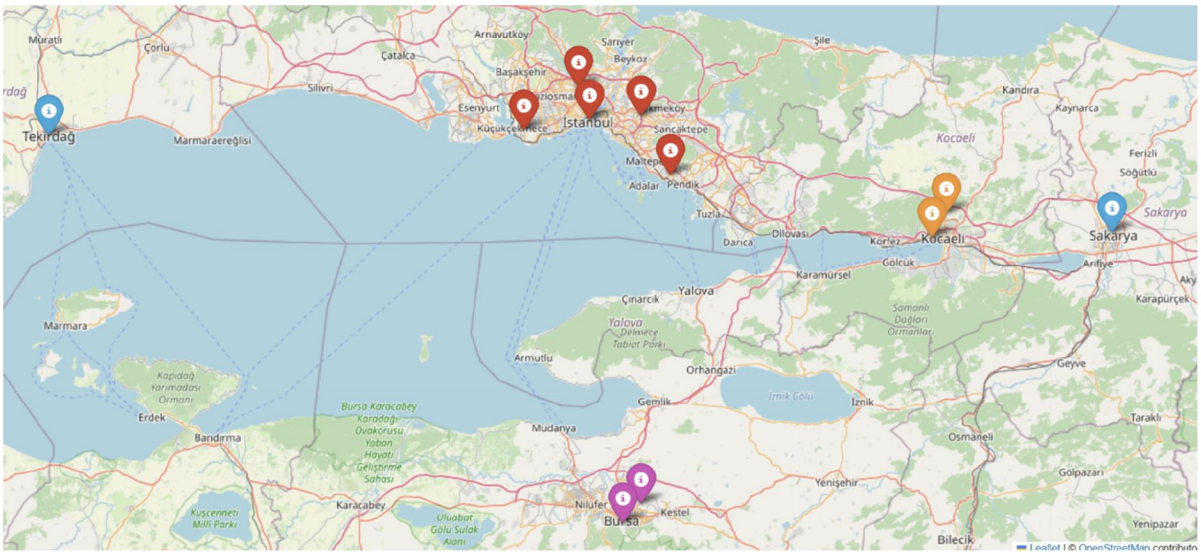
The model incorporates seismic risk scores (1-10 scale) directly into the objective function, creating natural incentives to position warehouses closer to high-risk areas without requiring overly restrictive constraints. The risk-weighted transportation cost component alongside maximum distance constraints ensure that high-risk districts incur heavier distance penalties and transportation costs in the objective therefore they must have priority access to nearby warehouses, this approach also reduces transportation time.

Note: because these risk scores act as unitless penalty multipliers, that component of the objective isn't strictly measured in Turkish Lira. In future versions, one could introduce a conversion factor or scaling parameter to normalize all cost terms into the same currency units.

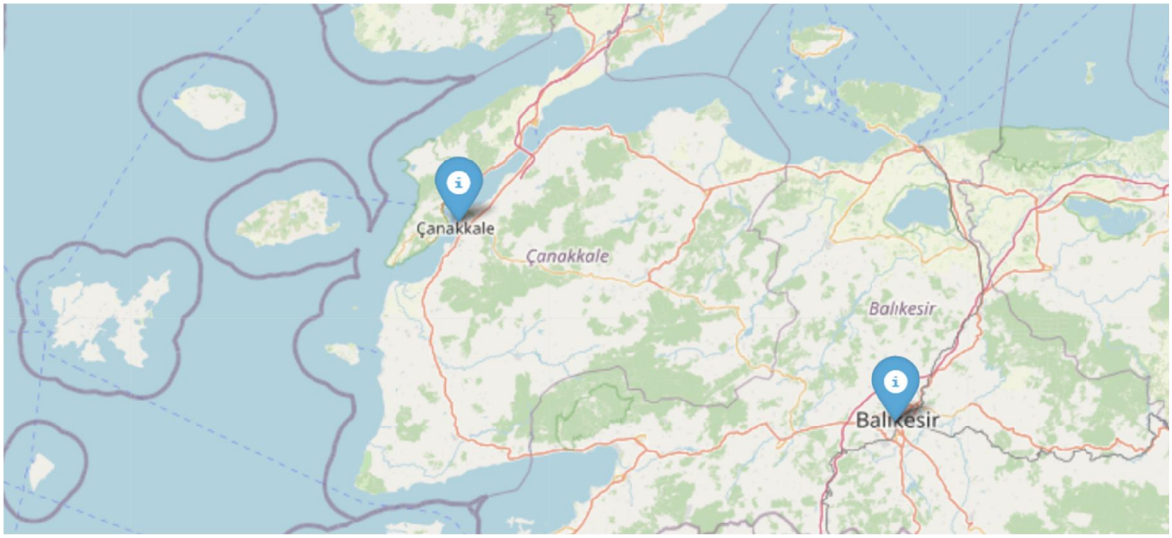
Operational Efficiency:

The minimum utilization constraint prevents expensive, nearly-empty warehouses. **Region & city quotas** guarantee strategic geographic coverage. **Separation constraint** stops clustering of too-many depots in very tight neighborhoods (except İstanbul, where urban density requires exceptions). The decision of allocating larger warehouses to higher-risk cities isn't explicitly implemented, it's left as the model's choice.

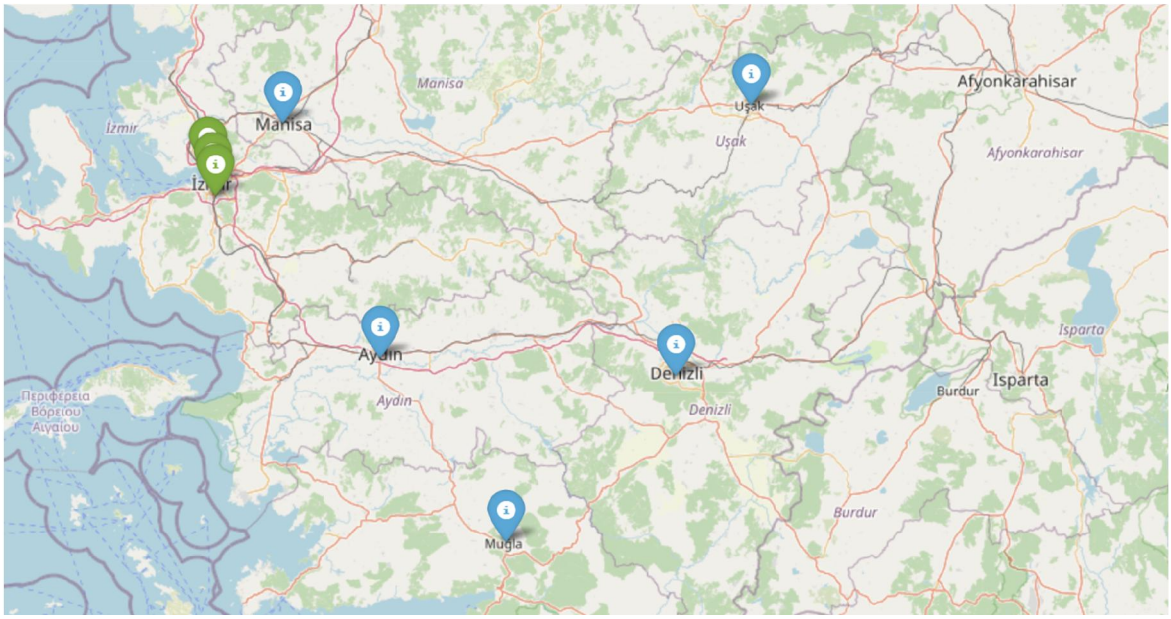
The Marmara region:



The Northwest region:



The Aegean region:



Assignment:

The model prioritizes initial disaster response capability, where each district's demand must be served by exactly one warehouse. Secondary support arrangements are considered beyond the scope of this model.

3. Mathematical Model Formulation

3.1 Sets and Indices

I: Set of potential warehouse locations (districts) where warehouses can be established

J: Set of demand districts requiring humanitarian aid services (identical to set I)

S: Set of warehouse size options = {Small, Medium, Large}

C: Set of cities = {Istanbul, Bursa, İzmir, Kocaeli, Balıkesir, Çanakkale, Sakarya, Tekirdağ, Aydın, Denizli, Manisa, Muğla, Uşak}

R: Set of geographic regions = {Marmara, Aegean, Northwest}

3.2 Parameters

demand_j: Estimated demand for relief supplies in district j (storage units)

population_j: Population of district j based on 2024 data distributed proportionally within cities

risk_j: Composite disaster risk score for district j (scale 1-10)

dist_{ij}: Driving distance approximation between districts i and j (kilometers)

capacity_s: Storage capacity for warehouse size s (storage units)

cost_s: Fixed establishment and annual operating cost for warehouse size s (million TL)

DISTANCE_WEIGHT: Cost penalty factor per unit of risk-weighted distance = 0.01

MIN_UTILIZATION: Minimum required warehouse utilization ratio = 0.50

MIN_TOTALWAREHOUSE: Minimum total warehouse number = 6

MIN_DISTANCE: Minimum separation distance between warehouses = 20 km

MIN_MARMARA: Minimum required warehouse number in Marmara region = 3

MIN_AEGEAN: Minimum required warehouse number in Aegean region = 2

MIN_NORTHWEST: Minimum required warehouse number in Northwest region = 1

MIN_IST: Minimum required warehouse number in Istanbul = 2

MAX_WAREHOUSES_PER_CITYc: Maximum allowed warehouses per city c

- Istanbul: 4 (mega-city requiring multiple facilities)
- İzmir: 2 (major urban center)
- All other cities: 1

MAX_DISTANCE_BY_RISK: Maximum allowable service distance based on district risk

- Risk 10: 90 km maximum
- Risk 9: 120 km maximum
- Risk 8: 150 km maximum
- Risk 7: 200 km maximum
- Risk ≤6: 230 km maximum

3.3 Decision Variables

$y_{is} \in \{0,1\}$: Binary warehouse establishment variable

- y_{is} = 1 if a warehouse of size s is built at district i; 0 otherwise

$x_{ij} \in \{0,1\}$: Binary assignment variable

- x_{ij} = 1 if district j is assigned to receive service from warehouse at district i; 0 otherwise

3.4 Objective Function

$\text{Min } Z = \Sigma_i \Sigma_s \text{cost}_s \times y_{is} + \text{DISTANCE\_WEIGHT} \times \Sigma_i \Sigma_j (\text{dist}_{ij} \times \text{risk}_j \times x_{ij})$

The objective minimizes total system cost comprising two components:

- **Fixed costs:** Capital and operating expenses for warehouse establishment
- **Risk-weighted transportation costs:** Penalty for serving high-risk districts from distant warehouses

3.5 Constraints

1. Unique Assignment Constraint: $\Sigma_i\ x_{ij} = 1\ \forall j \in J$

Every district must be assigned to exactly one primary warehouse for initial disaster response.

2. Assignment Enabling Constraint: $x_{ij} \leq \Sigma_s\ y_{is}\ \forall i \in I, j \in J$

Districts can only be assigned to warehouses that have been established.

3. Warehouse Capacity Constraint: $\Sigma_j\ demand_j \times x_{ij} \leq \Sigma_s\ capacity_s \times y_{is}\ \forall i \in I$

Total demand assigned to a warehouse cannot exceed its capacity.

4. Minimum Utilization Constraint: $\Sigma_j\ demand_j \times x_{ij} \geq MIN\_UTILIZATION \times \Sigma_s\ capacity_s \times y_{is}\ \forall i \in I$

Warehouses must operate at minimum 50% capacity to ensure efficiency.

5. Unique Size Constraint: $\Sigma_s\ y_{is} \leq 1\ \forall i \in I$

At most one warehouse (of one specific size) can be built per district.

6. City-Level Capacity Constraints: $\Sigma_{i \in Ic}\ \Sigma_s\ y_{is} \leq MAX\_WAREHOUSES\_PER\_CITY_c\ \forall c \in C$

Where Ic represents the set of districts within city c.

7. Istanbul Minimum Requirement: $\Sigma_{i \in}\ IIstanbul\ \Sigma_s\ y_{is} \geq MIN\_IST$

Istanbul requires an at least warehouses constraint due to its size and critical importance.

8. Minimum Distance Separation (Non-Istanbul): $y_{is1} + y_{js2} \leq 1$
$\forall i \neq j$ where $dist_{ij} < MIN\_DISTANCE, i,j \notin$ Istanbul, $s_1,s_2 \in S$

Prevents redundant warehouse placement outside Istanbul while allowing dense coverage within Istanbul.

9. Risk-Based Maximum Service Distance: $dist_{ij} \times x_{ij} \leq MAX\_DISTANCE\_BY\_RISK_j\ \forall i \in I, j \in J$

High-risk districts must be served by relatively nearby warehouses to ensure rapid response.

10. Minimum Total Warehouses: $\Sigma_i \Sigma_s y_{is} \geq$ MIN_TOTALWAREHOUSE

Ensures adequate geographic distribution across the study area.

11. Regional Coverage Requirements:

- **Marmara Region:** $\Sigma_{i \in I\text{Marmara}} \Sigma_s y_{is} \geq$ **MIN_MARMARA**
- **Aegean Region:** $\Sigma_{i \in I\text{Aegean}} \Sigma_s y_{is} \geq$ **MIN_AEGEAN**
- **Northwest Region:** $\Sigma_{i \in I\text{Northwest}} \Sigma_s y_{is} \geq$ **MIN_NORTHWEST**

Guarantees minimum coverage levels across all major geographic regions.

4. Implementation and Solution

4.1 Technical Implementation

The model was implemented using:

- Pyomo: Python-based optimization modeling framework
- GLPK: Open-source linear programming solver
- NumPy/Pandas: Data preprocessing and analysis
- Python 3.x: Core implementation language

For full code implementation, detailed results, and additional documentation, please visit the GitHub repository or contact me directly.

4.2 Baseline Solution Results

Model is solved and the results are:

```
Total demand across all districts: 7,169,630 units

Solving model...

Solver Status: ok
Total Optimal Cost: 181.75 million (unitless)
Fixed Cost Component: 113.00 million (TL)
Transport Cost Component: 68.75 million (unitless)

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WAREHOUSE LOCATIONS BY CITY
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Istanbul (2 warehouses):
  → Istanbul_Europe_South: Medium warehouse
     Cost: 20 million TL, Capacity: 1,500,000 units
     Utilization: 94.3% (1,414,142 units)
  → Istanbul_Asia_North: Large warehouse
     Cost: 25 million TL, Capacity: 2,200,000 units
     Utilization: 96.4% (2,121,213 units)

Izmir (1 warehouses):
  → Izmir_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 80.9% (1,011,234 units)

Kocaeli (1 warehouses):
  → Kocaeli_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 93.4% (1,167,877 units)

Canakkale (1 warehouses):
  → Canakkale_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 52.3% (654,328 units)

Denizli (1 warehouses):
  → Denizli_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 64.1% (800,836 units)

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DISTRICT ASSIGNMENT SUMMARY
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Warehouse at Istanbul_Europe_South (Medium) serves 2 districts:
  - Istanbul_Europe_Central: 707,071 units, 21km, risk 10
  - Istanbul_Europe_South: 707,071 units, 0km, risk 10

Warehouse at Istanbul_Asia_North (Large) serves 3 districts:
  - Istanbul_Europe_North: 883,839 units, 22km, risk 10
  - Istanbul_Asia_North: 707,071 units, 0km, risk 10
  - Istanbul_Asia_Central: 530,303 units, 21km, risk 10

Warehouse at Izmir_Central (Small) serves 4 districts:
  - Izmir_Central: 274,950 units, 0km, risk 9
  - Izmir_Karsiyaka: 240,581 units, 8km, risk 9
  - Izmir_Konak: 171,844 units, 6km, risk 9
  - Manisa_Central: 323,859 units, 48km, risk 6

Warehouse at Kocaeli_Central (Small) serves 5 districts:
  - Bursa_Central: 326,327 units, 135km, risk 8
  - Bursa_Industrial: 139,854 units, 127km, risk 8
  - Kocaeli_Central: 277,594 units, 0km, risk 10
  - Kocaeli_Industrial: 185,062 units, 9km, risk 10
```

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  - Sakarya_Central: 239,039 units, 58km, risk 8

Warehouse at Canakkale_Central (Small) serves 3 districts:
  - Balikesir_Central: 277,594 units, 192km, risk 6
  - Canakkale_Central: 123,375 units, 0km, risk 7
  - Tekirdag_Central: 253,359 units, 182km, risk 4

Warehouse at Denizli_Central (Small) serves 4 districts:
  - Aydin_Central: 253,359 units, 154km, risk 5
  - Denizli_Central: 233,531 units, 0km, risk 4
  - Mugla_Central: 231,328 units, 124km, risk 3
  - Usak_Central: 82,617 units, 145km, risk 1

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SOLUTION SUMMARY
============================================================
Total Warehouses Built: 6
Total System Demand: 7,169,630 units
Total System Capacity: 8,700,000 units
Overall System Utilization: 82.4%
Districts Served: 21

Warehouse Distribution by City:
  Istanbul: 2/4 warehouses
  Bursa: 0/1 warehouses
  Izmir: 1/2 warehouses
  Kocaeli: 1/1 warehouses
  Balikesir: 0/1 warehouses
  Canakkale: 1/1 warehouses
  Sakarya: 0/1 warehouses
  Tekirdag: 0/1 warehouses
  Aydin: 0/1 warehouses
  Denizli: 1/1 warehouses
  Manisa: 0/1 warehouses
  Mugla: 0/1 warehouses
  Usak: 0/1 warehouses

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MODEL EXECUTION COMPLETE
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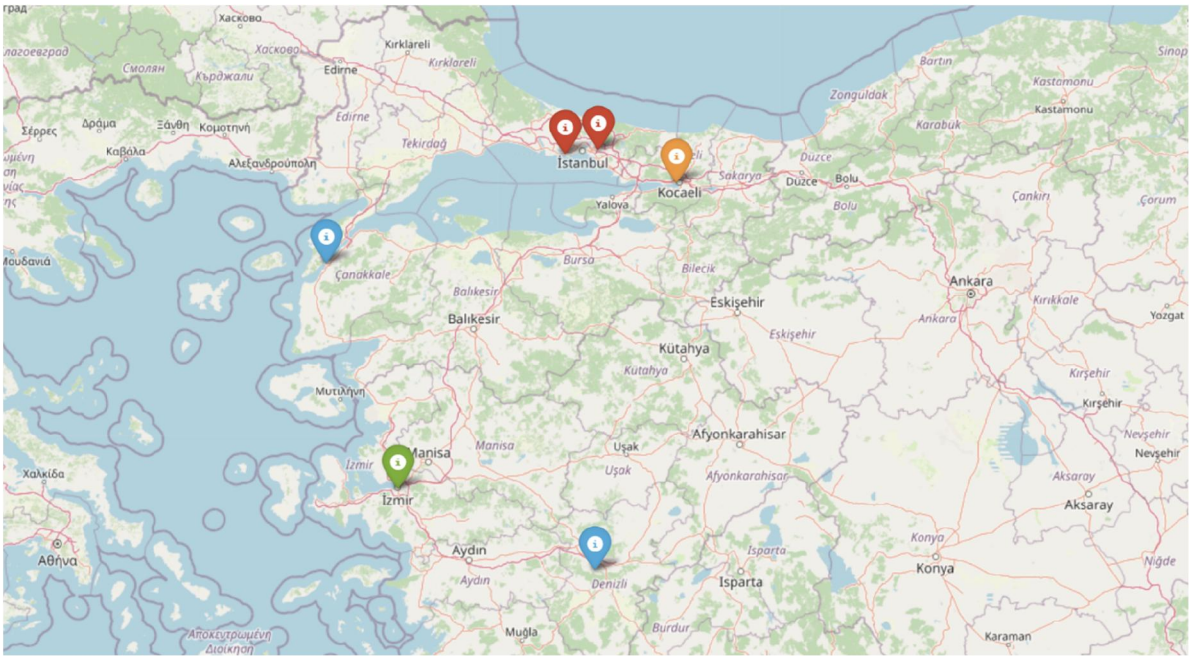
Results interpretation:

The baseline optimization scenario, using initial parameters (25% affected ratio, 30% coverage ratio, 50% minimum utilization, and moderate transportation penalties), identified an optimal warehouse network configuration with the following key outcomes:

Key Metric	Result
Total demand	7.17 M units
Warehouses built	6 (Istanbul 2, İzmir 1, Kocaeli 1, Çanakkale 1, Denizli 1)
System capacity	8.70 M units → 82.4% utilised
Total cost	181.75 M TL · 113 M fixed (62%) + 68.8 M transport (38%)
Max service distance	192 km (Balıkesir → Çanakkale)

- **Total Demand:** 7,169,630 units
- **Total Optimal Cost:** 181.75 million TL
  - **Fixed Costs:** 113.00 million TL (62.2%)
  - **Transportation Costs:** 68.75 million TL (37.8%)
- **Total Warehouses Built:** 6
- **Overall Utilization:** 82.4%
- **Maximum Service Distance:** 192 km (Balikesir → Canakkale)

Warehouse Distribution:



- **Istanbul:** Two strategically placed warehouses (one medium, one large) operating at high utilization (>94%), efficiently covering all five Istanbul districts, ensuring service within 22 km for risk-10 districts.
- **Izmir:** One small warehouse with utilization at 80.9%, serving four districts efficiently.
- **Kocaeli:** One small warehouse at high utilization (93.4%), efficiently serving five districts, including Bursa and Sakarya.

Canakkale and Denizli: Each with a small warehouse, effectively covering wider regional areas with utilization rates of 52.3% and 64.1%, respectively, providing latent surge capacity.

The baseline provides a balanced solution, optimizing cost while ensuring effective coverage, particularly prioritizing high-risk districts.

5. Scenario Analysis

5.1 Scenario 1: Demand Surge

Preparing for an extreme disaster event causing a surge in demand for aid and/or serve more of the affected population at higher cost.

Adjustments:

- Affected population: 25% → 30%
- Coverage ratio: 30% → 33%

Results:

```
Total demand across all districts: 9,463,911 units

Solving model...

Solver Status: ok
Total Optimal Cost: 201.34 million (unitless)
Fixed Cost Component: 138.00 million (TL)
Transport Cost Component: 63.34 million (unitless)

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WAREHOUSE LOCATIONS BY CITY
============================================================

Istanbul (3 warehouses):
  → Istanbul_Europe_North: Large warehouse
     Cost: 25 million TL, Capacity: 2,200,000 units
     Utilization: 95.5% (2,100,001 units)
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  → Istanbul_Europe_South: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 89.4% (1,117,941 units)
  → Istanbul_Asia_Central: Large warehouse
     Cost: 25 million TL, Capacity: 2,200,000 units
     Utilization: 93.8% (2,064,085 units)

Izmir (1 warehouses):
  → Izmir_Central: Medium warehouse
     Cost: 20 million TL, Capacity: 1,500,000 units
     Utilization: 89.0% (1,334,829 units)

Kocaeli (1 warehouses):
  → Kocaeli_Industrial: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 74.1% (926,238 units)

Canakkale (1 warehouses):
  → Canakkale_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 69.1% (863,713 units)

Denizli (1 warehouses):
  → Denizli_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 84.6% (1,057,103 units)

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DISTRICT ASSIGNMENT SUMMARY
============================================================

Warehouse at Istanbul_Europe_North (Large) serves 2 districts:
  - Istanbul_Europe_North: 1,166,667 units, 0km, risk 10
  - Istanbul_Europe_Central: 933,334 units, 11km, risk 10

Warehouse at Istanbul_Europe_South (Small) serves 2 districts:
  - Istanbul_Europe_South: 933,334 units, 0km, risk 10
  - Bursa_Industrial: 184,608 units, 125km, risk 8

Warehouse at Istanbul_Asia_Central (Large) serves 3 districts:
  - Istanbul_Asia_North: 933,334 units, 21km, risk 10
  - Istanbul_Asia_Central: 700,000 units, 0km, risk 10
  - Bursa_Central: 430,751 units, 113km, risk 8

Warehouse at Izmir_Central (Medium) serves 4 districts:
  - Izmir_Central: 362,934 units, 0km, risk 9
  - Izmir_Karsiyaka: 317,567 units, 8km, risk 9
  - Izmir_Konak: 226,834 units, 6km, risk 9
  - Manisa_Central: 427,494 units, 48km, risk 6

Warehouse at Kocaeli_Industrial (Small) serves 3 districts:
  - Kocaeli_Central: 366,424 units, 9km, risk 10
  - Kocaeli_Industrial: 244,282 units, 0km, risk 10
  - Sakarya_Central: 315,532 units, 53km, risk 8
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Warehouse at Canakkale_Central (Small) serves 3 districts:
  - Balikesir_Central: 366,424 units, 192km, risk 6
  - Canakkale_Central: 162,855 units, 0km, risk 7
  - Tekirdag_Central: 334,434 units, 182km, risk 4

Warehouse at Denizli_Central (Small) serves 4 districts:
  - Aydin_Central: 334,434 units, 154km, risk 5
  - Denizli_Central: 308,261 units, 0km, risk 4
  - Mugla_Central: 305,353 units, 124km, risk 3
  - Usak_Central: 109,055 units, 145km, risk 1

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SOLUTION SUMMARY
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Total Warehouses Built: 7
Total System Demand: 9,463,911 units
Total System Capacity: 10,900,000 units
Overall System Utilization: 86.8%
Districts Served: 21

Warehouse Distribution by City:
  Istanbul: 3/4 warehouses
  Bursa: 0/1 warehouses
  Izmir: 1/2 warehouses
  Kocaeli: 1/1 warehouses
  Balikesir: 0/1 warehouses
  Canakkale: 1/1 warehouses
  Sakarya: 0/1 warehouses
  Tekirdag: 0/1 warehouses
  Aydin: 0/1 warehouses
  Denizli: 1/1 warehouses
  Manisa: 0/1 warehouses
  Mugla: 0/1 warehouses
  Usak: 0/1 warehouses

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MODEL EXECUTION COMPLETE
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5.2 Scenario 2: Economic Efficiency Focus

Maximize operational efficiency and cost-effectiveness (continuing with the high demand parameters).

Adjustments:

- Minimum utilization: 50% → 70%

Results:

```
Total demand across all districts: 9,463,911 units

Solving model...

Solver Status: ok
Total Optimal Cost: 207.75 million (unitless)
Fixed Cost Component: 152.00 million (TL)
Transport Cost Component: 55.75 million (unitless)

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WAREHOUSE LOCATIONS BY CITY
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Istanbul (3 warehouses):
  → Istanbul_Europe_Central: Large warehouse
     Cost: 25 million TL, Capacity: 2,200,000 units
     Utilization: 95.5% (2,100,001 units)
  → Istanbul_Europe_South: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 74.7% (933,334 units)
  → Istanbul_Asia_Central: Large warehouse
     Cost: 25 million TL, Capacity: 2,200,000 units
     Utilization: 74.2% (1,633,334 units)

Bursa (1 warehouses):
  → Bursa_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 76.0% (949,794 units)

Izmir (1 warehouses):
  → Izmir_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 72.6% (907,335 units)

Kocaeli (1 warehouses):
  → Kocaeli_Industrial: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 74.1% (926,238 units)

Balikesir (1 warehouses):
  → Balikesir_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 76.5% (956,773 units)

Denizli (1 warehouses):
  → Denizli_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 84.6% (1,057,103 units)

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DISTRICT ASSIGNMENT SUMMARY
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Warehouse at Istanbul_Europe_Central (Large) serves 2 districts:
  - Istanbul_Europe_North: 1,166,667 units, 11km, risk 10
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  - Istanbul_Europe_Central: 933,334 units, 0km, risk 10

Warehouse at Istanbul_Europe_South (Small) serves 1 districts:
  - Istanbul_Europe_South: 933,334 units, 0km, risk 10

Warehouse at Istanbul_Asia_Central (Large) serves 2 districts:
  - Istanbul_Asia_North: 933,334 units, 21km, risk 10
  - Istanbul_Asia_Central: 700,000 units, 0km, risk 10

Warehouse at Bursa_Central (Small) serves 3 districts:
  - Bursa_Central: 430,751 units, 0km, risk 8
  - Bursa_Industrial: 184,608 units, 9km, risk 8
  - Tekirdag_Central: 334,434 units, 222km, risk 4

Warehouse at Izmir_Central (Small) serves 3 districts:
  - Izmir_Central: 362,934 units, 0km, risk 9
  - Izmir_Karsiyaka: 317,567 units, 8km, risk 9
  - Izmir_Konak: 226,834 units, 6km, risk 9

Warehouse at Kocaeli_Industrial (Small) serves 3 districts:
  - Kocaeli_Central: 366,424 units, 9km, risk 10
  - Kocaeli_Industrial: 244,282 units, 0km, risk 10
  - Sakarya_Central: 315,532 units, 53km, risk 8

Warehouse at Balikesir_Central (Small) serves 3 districts:
  - Balikesir_Central: 366,424 units, 0km, risk 6
  - Canakkale_Central: 162,855 units, 192km, risk 7
  - Manisa_Central: 427,494 units, 169km, risk 6

Warehouse at Denizli_Central (Small) serves 4 districts:
  - Aydin_Central: 334,434 units, 154km, risk 5
  - Denizli_Central: 308,261 units, 0km, risk 4
  - Mugla_Central: 305,353 units, 124km, risk 3
  - Usak_Central: 109,055 units, 145km, risk 1

============================================================
SOLUTION SUMMARY
============================================================
Total Warehouses Built: 8
Total System Demand: 9,463,911 units
Total System Capacity: 11,900,000 units
Overall System Utilization: 79.5%
Districts Served: 21

Warehouse Distribution by City:
  Istanbul: 3/4 warehouses
  Bursa: 1/1 warehouses
  Izmir: 1/2 warehouses
  Kocaeli: 1/1 warehouses
  Balikesir: 1/1 warehouses
  Canakkale: 0/1 warehouses
  Sakarya: 0/1 warehouses
  Tekirdag: 0/1 warehouses
  Aydin: 0/1 warehouses
  Denizli: 1/1 warehouses
```

```
  Manisa: 0/1 warehouses
  Mugla: 0/1 warehouses
  Usak: 0/1 warehouses

============================================================
MODEL EXECUTION COMPLETE
============================================================
```

5.3 Scenario 3: Rapid Response Priority

Emphasis on fast emergency response (continuing with the high demand parameters).

Adjustments:

- Distance weight increased to 0.03
- Minimum 8 warehouses required
- Reduced minimum utilization to 30%

Results:

```
Total demand across all districts: 9,463,911 units

Solving model...

Solver Status: ok
Total Optimal Cost: 277.99 million (unitless)
Fixed Cost Component: 172.00 million (TL)
Transport Cost Component: 105.99 million (unitless)

============================================================
WAREHOUSE LOCATIONS BY CITY
============================================================

Istanbul (3 warehouses):
  → Istanbul_Europe_North: Large warehouse
     Cost: 25 million TL, Capacity: 2,200,000 units
     Utilization: 95.5% (2,100,001 units)
  → Istanbul_Europe_South: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 74.7% (933,334 units)
  → Istanbul_Asia_Central: Large warehouse
     Cost: 25 million TL, Capacity: 2,200,000 units
     Utilization: 74.2% (1,633,334 units)

Bursa (1 warehouses):
  → Bursa_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 78.5% (981,783 units)

Izmir (1 warehouses):
```

```
  → Izmir_Central: Medium warehouse
     Cost: 20 million TL, Capacity: 1,500,000 units
     Utilization: 89.0% (1,334,829 units)

Kocaeli (1 warehouses):
  → Kocaeli_Industrial: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 74.1% (926,238 units)

Canakkale (1 warehouses):
  → Canakkale_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 39.8% (497,289 units)

Aydin (1 warehouses):
  → Aydin_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 51.2% (639,788 units)

Denizli (1 warehouses):
  → Denizli_Central: Small warehouse
     Cost: 17 million TL, Capacity: 1,250,000 units
     Utilization: 33.4% (417,316 units)

============================================================
DISTRICT ASSIGNMENT SUMMARY
============================================================

Warehouse at Istanbul_Europe_North (Large) serves 2 districts:
  - Istanbul_Europe_North: 1,166,667 units, 0km, risk 10
  - Istanbul_Europe_Central: 933,334 units, 11km, risk 10

Warehouse at Istanbul_Europe_South (Small) serves 1 districts:
  - Istanbul_Europe_South: 933,334 units, 0km, risk 10

Warehouse at Istanbul_Asia_Central (Large) serves 2 districts:
  - Istanbul_Asia_North: 933,334 units, 21km, risk 10
  - Istanbul_Asia_Central: 700,000 units, 0km, risk 10

Warehouse at Bursa_Central (Small) serves 3 districts:
  - Bursa_Central: 430,751 units, 0km, risk 8
  - Bursa_Industrial: 184,608 units, 9km, risk 8
  - Balikesir_Central: 366,424 units, 164km, risk 6

Warehouse at Izmir_Central (Medium) serves 4 districts:
  - Izmir_Central: 362,934 units, 0km, risk 9
  - Izmir_Karsiyaka: 317,567 units, 8km, risk 9
  - Izmir_Konak: 226,834 units, 6km, risk 9
  - Manisa_Central: 427,494 units, 48km, risk 6

Warehouse at Kocaeli_Industrial (Small) serves 3 districts:
  - Kocaeli_Central: 366,424 units, 9km, risk 10
  - Kocaeli_Industrial: 244,282 units, 0km, risk 10
  - Sakarya_Central: 315,532 units, 53km, risk 8
```

```
Warehouse at Canakkale_Central (Small) serves 2 districts:
  - Canakkale_Central: 162,855 units, 0km, risk 7
  - Tekirdag_Central: 334,434 units, 182km, risk 4

Warehouse at Aydin_Central (Small) serves 2 districts:
  - Aydin_Central: 334,434 units, 0km, risk 5
  - Mugla_Central: 305,353 units, 116km, risk 3

Warehouse at Denizli_Central (Small) serves 2 districts:
  - Denizli_Central: 308,261 units, 0km, risk 4
  - Usak_Central: 109,055 units, 145km, risk 1

============================================================
SOLUTION SUMMARY
============================================================
Total Warehouses Built: 9
Total System Demand: 9,463,911 units
Total System Capacity: 13,400,000 units
Overall System Utilization: 70.6%
Districts Served: 21

Warehouse Distribution by City:
  Istanbul: 3/4 warehouses
  Bursa: 1/1 warehouses
  Izmir: 1/2 warehouses
  Kocaeli: 1/1 warehouses
  Balikesir: 0/1 warehouses
  Canakkale: 1/1 warehouses
  Sakarya: 0/1 warehouses
  Tekirdag: 0/1 warehouses
  Aydin: 1/1 warehouses
  Denizli: 1/1 warehouses
  Manisa: 0/1 warehouses
  Mugla: 0/1 warehouses
  Usak: 0/1 warehouses

============================================================
MODEL EXECUTION COMPLETE
============================================================
```

6. Comparative Strategic Analysis

6.1 Overall Interpretation

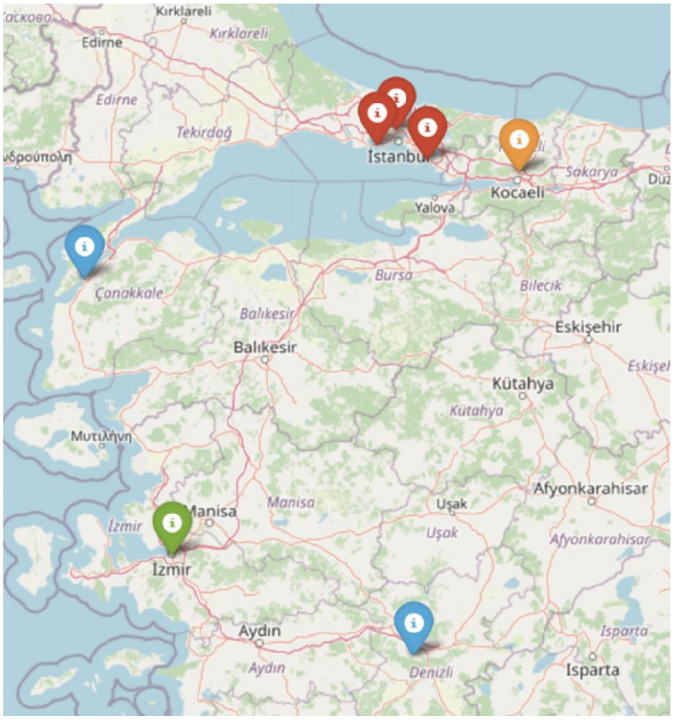
High-Demand Base: 9.46 M units (AFFECTED = 30%, COVERAGE = 33%)

Scenario	Demand Surge	Economic Efficiency	Rapid Response
Warehouses built	**7**	8	9
System capacity	10.9	11.9	13.4
System utilization	86.8%	79.5%[1]	70.6%
Total cost	201.34	207.75	277.99
Fixed / Transport split	138 / 63	152 / 56	172 / 106
Max service distance	192 km	222 km	182 km
Risk-10 max distance	53 km	53 km	53 km

[1] Higher MIN_UTIL forces additional warehouses but creates capacity redundancy → lower average utilization

Scenario 1: Demand Surge

This scenario considers a significant increase in the affected population (to 30%) and coverage ratio (to 33%) to prepare for extreme disaster events:



Total Demand: 9,463,911 units (32% increase from baseline)

Total Optimal Cost: 201.34 million TL (+19.59 million TL from baseline)

Fixed Costs: 138.00 million TL (68.6%)

Transportation Costs: 63.34 million TL (31.4%)

Total Warehouses Built: 7 (one additional warehouse)

Overall Utilization: 86.8%

Maximum Service Distance: 192 km

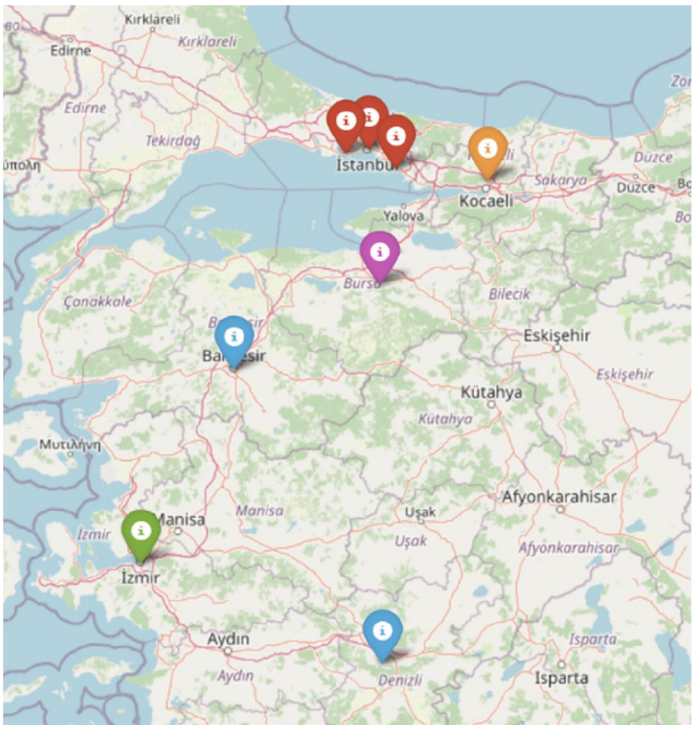
Risk-10 Maximum Distance: 53 km

Key Insights:

- An additional small warehouse in Istanbul ensures sufficient capacity, maintaining high utilization (>89%) and short service distances.
- Izmir upgraded to medium warehouse to accommodate increased demand efficiently.
- This proactive approach effectively absorbs demand surges with moderate additional cost, primarily infrastructure-driven.

Scenario 2: Economic Efficiency Focus

To maximize economic efficiency by raising minimum utilization requirements to 70%, this scenario aimed at optimizing cost-effectiveness:



Total Demand: 9,463,911 units

Total Optimal Cost: 207.75 million TL (+26.00 million TL from Scenario 1)

Fixed Costs: 152.00 million TL (73.2%)

Transportation Costs: 55.75 million TL (26.8%)

Total Warehouses Built: 8

Overall Utilization: 79.5%

Maximum Service Distance: 246 km

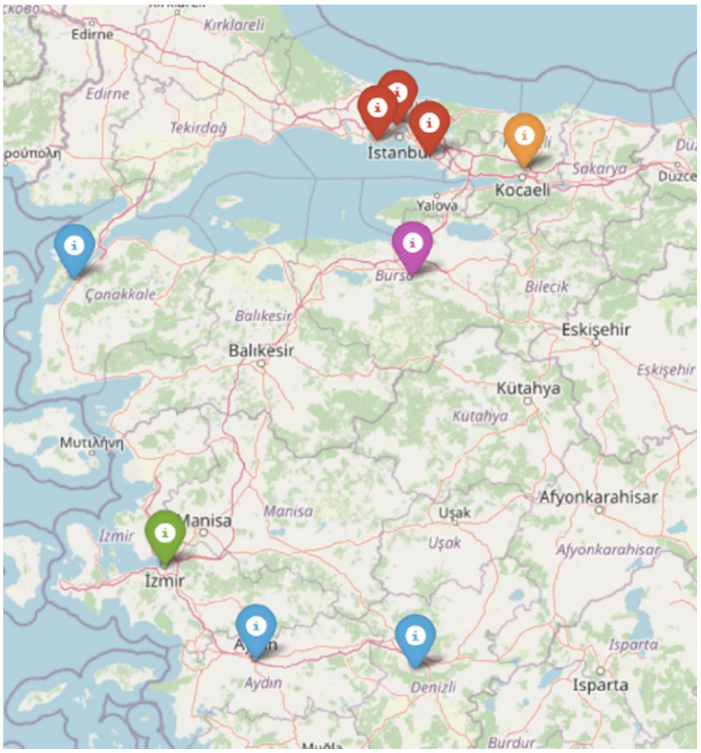
Risk-10 Maximum Distance: 58 km

Key Insights:

- Higher minimum utilization requirement leads to additional warehouses in Bursa and Balikesir, reducing transport costs significantly.
- Increased fixed infrastructure investment to maintain high depot-level efficiency.
- Extended service distances acceptable within lower-risk districts, demonstrating a balance between efficiency and response time.

Scenario 3: Rapid Response Priority

Focusing on rapid emergency response, this scenario significantly increased the transportation penalty, reduced minimum utilization (to 30%), and mandated a higher warehouse count:



Total Demand: 9,463,911 units

Total Optimal Cost: 277.99 million TL (+70.24 million TL from Scenario 2)

Fixed Costs: 172.00 million TL (61.9%)

Transportation Costs: 105.99 million TL (38.1%)

Total Warehouses Built: 9

Overall Utilization: 70.6%

Maximum Service Distance: 182 km

Risk-10 Maximum Distance: 53 km

Key Insights:

- Increased warehouse density, especially in high-risk urban areas, significantly reduces transportation distances and improves emergency response.
- Higher fixed costs due to expanded infrastructure, with under-utilized warehouses acting as critical forward staging posts for rapid deployment.
- Emphasis on responsiveness over economic efficiency, suitable for high-risk areas requiring immediate resource availability.

6.2 Cost-Performance Matrix & Strategic Recommendations

Each scenario highlights different strategic priorities:

Optimization Focus	Cost Efficiency	Service Quality	Emergency Readiness	Recommended Use
Baseline	Excellent (181.8 M)	Good (192km max)	Standard	Normal operations
Demand Surge	Very Good (201.3 M)	Good (192km max)	Enhanced	**Primary recommendation**
Economic Efficiency	Good (207.8 M)	Reduced (222km max)	Standard	Budget-constrained scenarios
Rapid Response	Poor (278.0 M)	Excellent (182km max)	Superior	High-risk periods

- **Baseline Scenario:** Optimal for routine preparedness, balancing cost-efficiency and effective coverage.
- **Scenario 1 (Demand Surge):** Suitable for anticipating significant disaster events, managing increased demand efficiently at moderate cost.
- **Scenario 2 (Economic Efficiency):** Ideal for budget-sensitive planning, emphasizing operational efficiency and minimizing long-term transport costs.
- **Scenario 3 (Rapid Response Priority):** Recommended for areas prioritizing immediate response capability, accepting higher infrastructure investment for minimized response times.

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*This project was completed as part of my graduate studies **in Optimization & Decision Modeling Course** at **Istanbul Technical University**.*

Data Sources:

https://www.citypopulation.de/

https://www.macrotrends.net/

https://en.wikipedia.org/

https://en.afad.gov.tr/

https://worldpopulationreview.com/

https://www.distancecalculator.net/

https://www.distancefromto.net/

Project Links:

- *GitHub Repository:*

  github.com/AysanPak/aid-warehouse-mip

Contact:

- LinkedIn: linkedin.com/in/aysan-pak
- Email: aysanpakmanesh@gmail.com