Two-Stage Stochastic–Robust Optimization of Sustainable Logistics Networks

Carbon-Constrained, Energy-Efficient Routing Under Uncertainty

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The Research Story: From Fragile Plans to Resilient Green Logistics

Act I: Why Current Logistics Plans Fail

- **Background:** Balancing freight growth with carbon limits.
- **Problem Statement:** Why static, penalty-based plans break down.
- **Aim & Objectives:** Building an integrated, uncertainty-resilient model.
- **Literature Gaps:** Bridging location, routing, and hybrid uncertainty.

Act II: How Our Model Solves It in Lagos

- **Formulations:** Deterministic $\rightarrow$ Stochastic $\rightarrow$ Stochastic–Robust.
- **Lagos Case Study:** 25 nodes tested across Dry, Moderate & Heavy Rain.
- **Key Findings:** Cost composition, carbon savings, and 100% service reliability.
- **Conclusion:** Actionable takeaways for sustainable freight networks.

Background & Problem Statement

Definition of a Logistics Network

A logistics network is a system of interconnected facilities, customers, and transportation links through which goods flow from supply points to demand locations.

Sustainable Logistics Drivers

- Freight transport drives economic trade but increases fuel use and CO_2 emissions.
- Traffic congestion and severe weather disrupt travel times and demand.
- Requires balancing **cost**, **emissions**, and **resilience**.

Problem Statement

- Deterministic models assume fixed demand and travel times.
- Emissions are treated as soft penalties rather than hard limits.
- Facility location and energy routing are modelled separately.
- Pure stochastic models fail under worst-case extremes; pure robust models are overly conservative.

Aim and Specific Objectives

Aim

To develop and evaluate a two-stage stochastic–robust optimization framework for sustainable logistics network design and energy-efficient routing under demand and travel-time uncertainty with carbon emission limits.

- Review state-of-the-art literature on green logistics network design and energy-efficient routing.
- Formulate deterministic and two-stage stochastic logistics network and routing models.
- Develop a two-stage stochastic–robust optimization framework.
- Design and implement efficient solution methods, including decomposition and matheuristic/metaheuristic enhancements.
- Experimentally evaluate deterministic, stochastic, and stochastic–robust models.
- Analyse trade-offs in cost, service level, robustness, energy use, and carbon emissions.

Building on Prior Research in Green & Uncertain Logistics

- **Fahimnia et al. (2015):** Showed that sustainable supply chain design must integrate economic efficiency with environmental performance.
- **Demir et al. (2014):** Established that road freight emissions depend on fuel consumption, vehicle load, speed, and travel distance.
- **Moghdani et al. (2021):** Demonstrated that energy-efficient vehicle routing lowers fuel use and emissions.
- **Govindan et al. (2017) & Qiu et al. (2019):** Highlighted stochastic and p-robust optimization for handling supply chain uncertainty.
- **Bertsimas & Sim (2004):** Introduced budgeted robust optimization (Γ) to protect models against worst-case deviations without excessive conservatism.

Literature Gap Analysis

Author(s)	Contribution	Limitation	Gap Identified
Fahimnia et al. (2015)	Green supply chain sustainability	Strict carbon limits not enforced	Need explicit carbon constraints
Demir et al. (2014)	Road freight emission modelling	Weak link with network design	Need routing–network integration
Moghdani et al. (2021)	Green vehicle routing models	Routing separated from facilities	Need joint facility & routing model
Govindan et al. (2017); Qiu et al. (2019)	Supply chain uncertainty & p-robust models	Limited energy/routing integration	Need integrated sustainability & uncertainty
Bertsimas & Sim (2004)	Budgeted robust optimization	Pure robust can be overconservative	Need controlled uncertainty protection

Overall Research Gap

Need for an integrated framework combining **network design**, **energy-efficient routing**, **hybrid stochastic–robust uncertainty**, and **hard carbon limits**.

Methodology Overview: Six-Step Modelling Workflow

1. Define the sustainable logistics network problem.
2. Develop a deterministic MILP baseline model.
3. Extend into a two-stage stochastic model.
4. Add budgeted robust optimization (Γ_d, Γ_τ).
5. Integrate hard carbon and energy constraints.
6. Compare deterministic, stochastic, and stochastic–robust models.

Two-Stage MILP Decision Architecture

- **Stage 1 (Strategic):** Select distribution centres (x_i) before uncertainty is known.
- **Uncertainty:** Demand (d_j) and travel time (τ_{ij}) vary across weather scenarios & bounds.
- **Stage 2 (Operational):** Optimize freight flows (q_{ij}^s) and routing under strict CO_2 limits.

Proposed Formulations: Deterministic & Two-Stage Stochastic

1. Deterministic Baseline Objective Function

$$\min Z_0 = \sum_{i \in I} F_i x_i + \sum_{(i,j) \in A} c_{ij} q_{ij} + \omega \sum_{(i,j) \in A} u_{ij}$$

F_i : Fixed cost of opening facility i
x_i : Binary facility-opening decision ($x_i \in \{0, 1\}$)
c_{ij}, q_{ij} : Unit transport cost and freight flow on arc (i, j)
ω, u_{ij} : Unit energy cost and energy consumed on arc (i, j)

2. Two-Stage Stochastic Objective Function

$$\min Z_1 = \sum_{i \in I} F_i x_i + \sum_{s \in S} p_s Q(x, \xi_s)$$

p_s : Probability that weather scenario $s \in S$ occurs
$Q(x, \xi_s)$: Second-stage recourse routing cost under scenario s
d_j^s, τ_{ij}^s : Customer demand and travel time in scenario s
q_{ij}^s, u_{ij}^s : Scenario freight flow and energy consumed on (i, j)

Proposed Formulations: Budgeted Robust & Integrated Model

3. Budgeted Uncertainty Set (Bertsimas & Sim)

$$d_j = \bar{d}_j + \hat{d}_j z_j, \quad \sum_{j \in J} z_j \leq \Gamma_d$$

$$\tau_{ij} = \bar{\tau}_{ij} + \hat{\tau}_{ij} v_{ij}, \quad \sum_{(i,j) \in A} v_{ij} \leq \Gamma_\tau$$

$\bar{d}_j, \bar{\tau}_{ij}$: Nominal demand and nominal travel time
$\hat{d}_j, \hat{\tau}_{ij}$: Maximum demand and travel-time deviations
z_j, v_{ij} : Scaled uncertainty deviation variables $\in [0, 1]$
Γ_d, Γ_τ : Uncertainty budgets for demand and travel time

4. Integrated Two-Stage Stochastic–Robust Objective Function

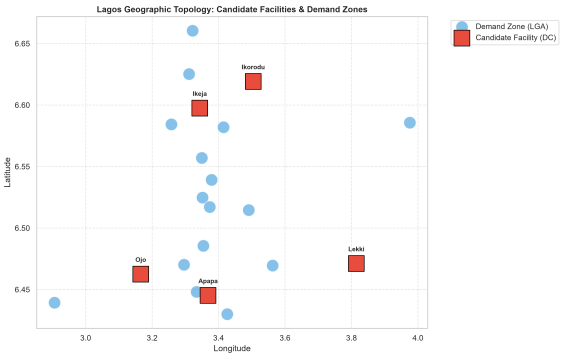
$$\min Z_2 = \sum_{i \in I} F_i x_i + \sum_{s \in S} p_s \left[\sum_{(i,j) \in A} c_{ij} q_{ij}^s + \omega \sum_{(i,j) \in A} u_{ij}^s \right]$$

Subject to robust capacity constraints (Γ_d, Γ_τ) and hard carbon emission limits ($C_{\max}$)

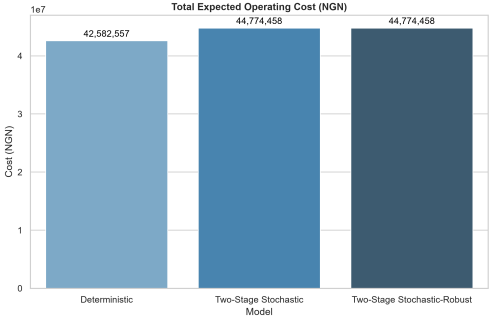
Testing the Model on a Real-World Lagos Logistics Network

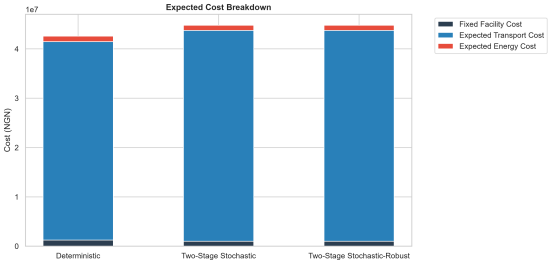
25-Node Network & Data Sources

- **Network:** 5 candidate DCs (Ikeja, Apapa, Lekki, Ojo, Ikorodu) & 20 LGA demand zones ($\sim$ 100 OD pairs).
- **Nominatim & OSRM:** Node coordinates, road distances, and travel times.
- **WorldPop & World Bank API:** Zone demand, fuel prices, and economic indicators.
- **Open-Meteo:** Weather data defining *Dry*, *Moderate Rain*, and *Heavy Rain* scenarios.



Finding 1: Resilience Costs Very Little, and Routing Drives Spend

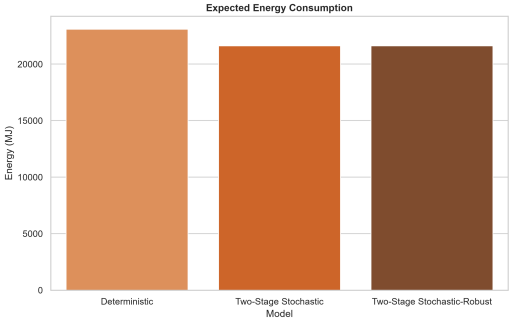


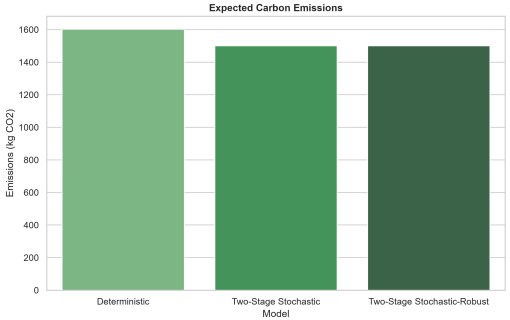


Key Finding: Economic Performance & Cost Drivers

While the deterministic model has the lowest nominal cost (**NGN 42,582,557**), accounting for uncertainty in the stochastic and stochastic–robust models (**NGN 44,774,458**) adds worst-case protection without extra expected cost over the stochastic baseline. Across all models, **transportation cost** dominates total spend, making routing efficiency the primary cost lever.

Finding 2: Planning for Uncertainty Cuts Energy Use and CO_2

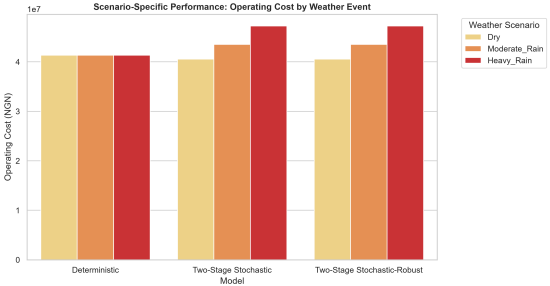


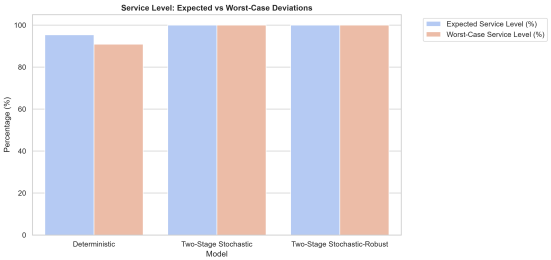


Key Finding: Sustainability Benefit of Uncertainty Modelling

Both the stochastic and stochastic–robust models lower expected energy use from **23,000 MJ to 21,500 MJ** and reduce carbon emissions from **1,600 kg to 1,500 kg CO_2** ($\sim 6.25\%$ reduction) while strictly respecting carbon-constrained operations.

Finding 3: Guaranteed 100% Service Even in Heavy Rain





Key Finding: Weather Adaptability & Service Protection

As weather worsens from *Dry* to *Heavy Rain*, routing costs rise to absorb traffic delays. Unlike the deterministic plan—whose service level drops to **90%** under worst-case deviations—the stochastic–robust model preserves **100% customer fulfillment**.

Conclusion & Recommendations

Conclusion

- Developed an integrated two-stage stochastic–robust optimization framework for sustainable network design and energy-efficient routing.
- Jointly optimizes facility opening, freight flow, energy consumption, and hard carbon emission caps.
- Cuts expected emissions by $\sim 6.25\%$ and guarantees 100% service resilience against severe weather disruptions.

Recommendations

- Adopt joint facility location and energy-efficient routing in urban logistics planning.
- Use stochastic–robust optimization to protect delivery reliability against demand and travel-time uncertainty.
- Enforce hard carbon emission limits alongside energy constraints.
- Integrate live traffic feeds and electric vehicle (EV) fleets in future large-scale networks.

Thank You

Questions & Discussion

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