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Multi-objective optimization of cost and time in freight transportation along the Apapa-Agbara industrial corridor

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Abstract: This study examined freight transportation optimization within a typical global South industrial corridor (Apapa-Agbara industrial corridor) in Nigeria by simultaneously minimizing the total cost and the total time for freight delivery. A Multi-Objective Mixed-Integer Linear Programming (MOMILP) framework based on the weighted-sum approach was developed to evaluate freight allocation across road, waterway, and intermodal transport systems. The model structure comprises six variables and six constraints. Unconstrained single-mode analysis of the 255-ton weekly demand highlighted the inherent supply chain trade-off where the road mode was fastest at 1.59 hours but most expensive at ₦363,158 and the waterway mode was the cheapest at ₦226,248 but slowest at 2.84 hours. The optimal solution was an intermodal approach combining road and waterway transport. This strategy achieved a total cost of ₦291,826.09 and a total delivery time of 2.11 hours, yielding a combined objective value of 0.5419. The study conclusively reiterated that the choice of intermodal transport option was effective in balancing the trade-off between cost and time by avoiding the high costs associated with the sole road mode and also reducing the substantial time delays associated with transit peculiar to the waterway mode.

Keywords: supply chain, intermodal transport, optimization, freight transportation, trade-off.

Sustainable Development Goals (SDGs): SDG 9: Industry, Innovation and Infrastructure; **SDG 11:** Sustainable Cities and Communities

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1. Introduction

In Nigeria's evolving economic landscape, efficient freight transportation remains imperative to supply-chain efficacy and national competitiveness. Although Nigeria's freight and logistics market valued at approximately USD 15.45 billion in 2024, is one of the biggest in sub-Sahara Africa (SSA), the sector is bedeviled by critical infrastructural challenges (International Trade Administration, 2023; Oxford Business Group, 2024). These persistent challenges adversely affect business operations and overall economic productivity. Existing statistics further underscore this reality, as Nigeria ranked 131st out of 190 countries in the Ease of Doing Business Index and 110th in the Logistics Performance Index in 2020 (International Trade Administration, 2023)

Apart from the perennial problem of infrastructural deficits associated with Nigeria's freight system, the country's urban freight transportation is particularly characterized by negative externalities such as environmental impacts (air pollution and greenhouse gases (GHGs), water pollution), social impacts (congestion and noise pollution) and economic impacts (road traffic crashes, loss of lives, and property. The Apapa-Agbara industrial corridor serves as a critical nexus for Nigeria's manufacturing and maritime trade; however, freight transport within the corridor is peculiarly dependent on road transport, which has resulted in a number of critical problems militating against the attainment of the sustainable freight distribution goal. Some of the identified challenges, as established from extant research, include the inability of the present road infrastructure to accommodate the volume of trucking traffic, over-reliance on the unimodal structure (road network), weak regulatory framework to guide trucking operations (Ajayi, 2016; Nnadi, 2023; Oni, 2024). In recent times, to curb some of these challenges, most cities in Africa now consider investing in intermodal transport systems for both intercity and intracity freight distribution.

Intermodal paradigms, amalgamating road and water modalities, offer lower costs, higher throughput, and improved environmental sustainability. However, its adoption and impact in developing economies like Nigeria remain under-explored (Oni et al., 2023). The Apapa-Agbara corridor is one of the few industrial corridors in the Nigerian milieu where there is an identifiable intermodal transport structure that provides a linkage between the Nigerian flagship seaport and industrial parks (Agbara and Abule-Osun, Kirikiri/Satellite town). There is a paucity of research that examines the performance of the corridor in optimizing transport demand and enhancing sustainability among industrial entities that utilize it.

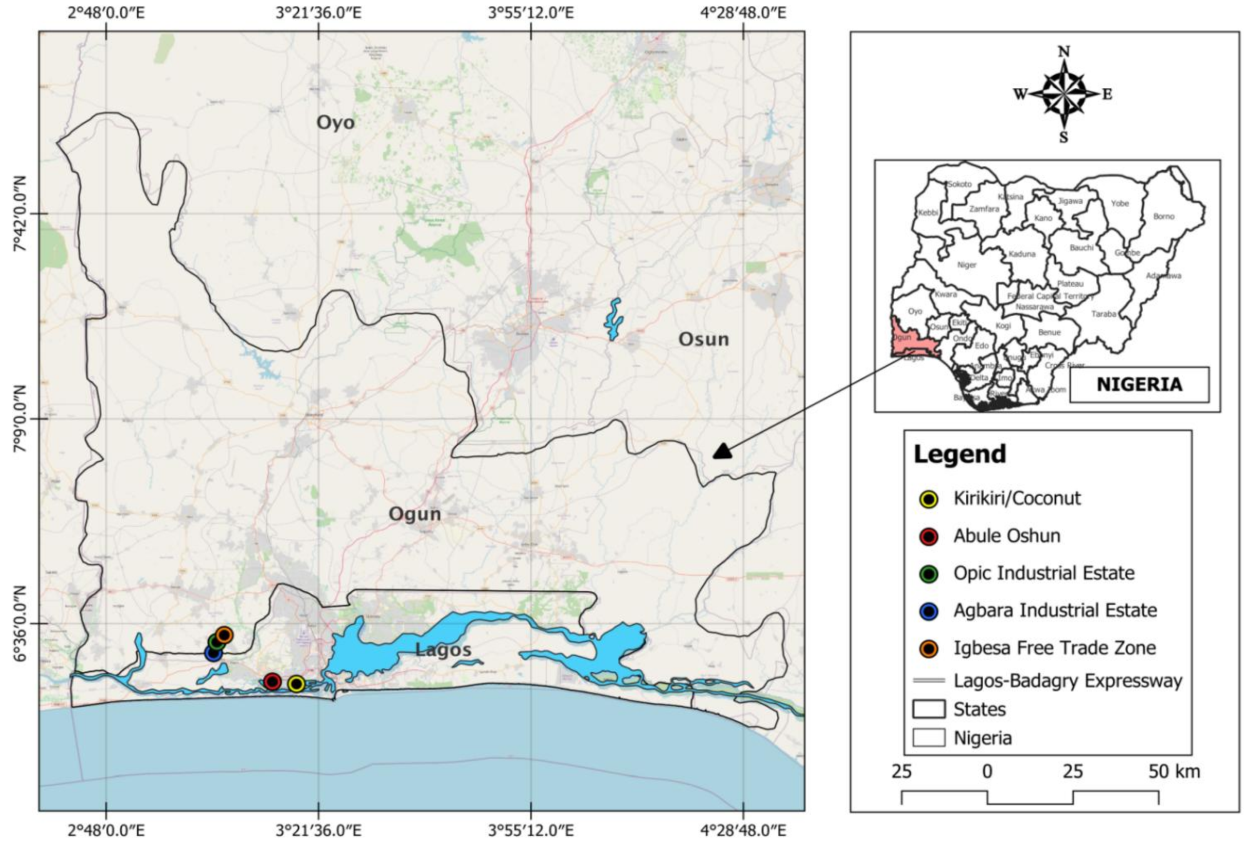
Though intermodal transport is linked to supply chain efficiency, its specific impact on delivery time, flexibility, and cost in congested corridors like Apapa-Agbara lacks empirical validation. Past studies such as (Nze et al., 2018; Oluwakoya, 2021) indicate that the current transport system negatively impacts key supply chain performance metrics, affecting the competitiveness and profitability of industries. Such studies fail to quantify the impact of intermodal transport on supply chain performance and demonstrate its potential benefits. Furthermore, existing optimization model studies carried out in similar Global South countries such as (Lebedeva, 2020) often generalize supply chain outcomes or focus on regional transit without providing empirical validation for specific, highly congested industrial corridors. This study, however, fills a gap by applying a dual-objective framework that uniquely prioritizes the cost-time trade-off. This study aims to provide an empirical analysis of cost and time optimization in freight transportation along apapa-agbara industrial corridor.

1.1. Hypothesis

Ho: There is no significant difference in the overall cost-time efficiency between unimodal and intermodal freight transportation options along the Apapa-Agbara industrial corridor.

Hi: Integrated intermodal scheduling optimizes the trade-off between cost and time among industrial entities in the Apapa-Agbara corridor.

Figure 1: Map showing Apapa-Agbara industrial corridor



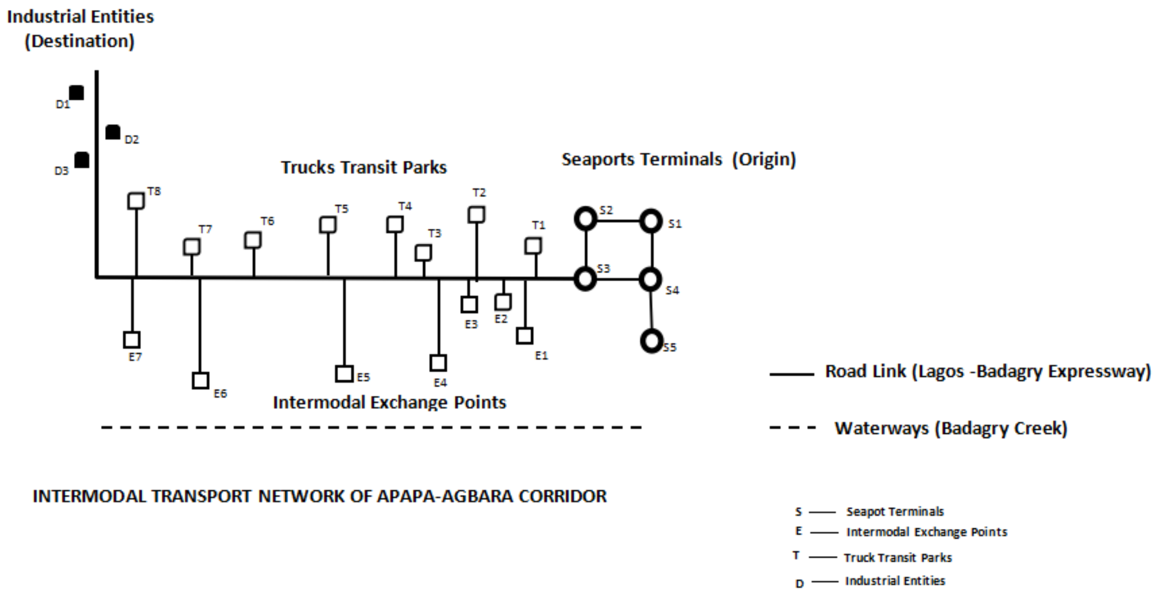
Source: Researcher (2026)

1.2. System context and problem description

The classical transportation problem is represented by a set of industrial entities' locations on the Agbara axis, seaport terminals on the Apapa axis, intermodal exchange points, and truck transit parks along the Lagos Badagry expressway (see Figure 2). While multiple nodes exist, this study models the dominant Apapa–Agbara trunk route, which accounts for the bulk of freight movement. Three freight transport options currently operate within the corridor.

The first option involves the direct movement of cargo units from the seaport terminals (origins) to the industrial establishments (destinations) using a single transport mode (trucks). The second option adopts an intermodal approach, where cargo is first conveyed from the seaports to a determined intermodal exchange terminal located along the Badagry Expressway, after which it is trans-shipped by road (trucks) to complete the last-mile delivery. The third option entails transporting cargo units from the seaports (origin) to destinations located along the Badagry creeks using only waterborne transport. A Multi-Objective Mixed-Integer Linear Programming (MOMILP) approach was used for the analysis to develop an optimization model for freight transportation in Apapa-Agbara industrial corridor.

Figure 2: Intermodal transport network of Apapa-Agbara industrial corridor



Source: Researcher (2026)

2. Literature review

2.1. Intermodal transportation

The European Conference of Ministers of Transport (1993), define the concept of intermodal freight transport as the movement of a single freight unit using two or more transportation modes. Intermodal transport is the basis of global trade in the modern world. In contrast to traditional transportation systems, which function independently for each mode of transportation, intermodal transportation combines many modes and services to increase the effectiveness of the entire supply chain process (Crainic and Kim 2007). This enables the possibility of easy transfer of the freight from one transport mode to another, involving containers that can easily interchange from one transport means to the next. Consequently, intermodal transportation enhances transport efficiency, cost-effectiveness, and environmental sustainability.

Intermodal transport in Nigeria is also an integrated system whereby the transfer of goods or persons occurs between different transport modes without handling the cargo directly, and standardized containers can improve efficiency (Onokala et al., 2020). The main concepts lie in integrating modes, sustaining the future, and economic viability. Its adoption is driven by the need to control the prevalence of road transport, which now stands at 90% of the inland transport sector and has been found to be associated with a high incidence of accidents and significant environmental pollution (Aworemi & Ajayi, 2013). The concept of modal shift aims to transport goods from roads to rail and waterways for long-distance journeys, resulting in significant cost savings of around 35% and reduced emissions (Onyemechi et al., 2021).

2.2. Multi-objective optimization in freight and intermodal transport

In freight transportation optimization, minimization of cost and travel time simultaneously are researchers imperatives sobjective. Current and Min (1986) showed that the Pareto frontier is superior to any single-objective optimum. Their model, formulated as a bi-criteria mixed-integer program, anticipated the MOMILP structure used in this study by several decades and established the intellectual precedent for dual-objective freight routing.

Previous work by Crainic (2000) also contributed to the theoretical framework on which the service network design of freight transportation can be built, incorporating the limitations of capacity and multi-modal operations, and expressing the interaction between the decisions on fleet management and the optimization of cost and time objectives in an integer programming model, which in turn motivated the structure of the Big-M linking constraint used in the present model.

In the intermodal freight transport sector, in particular, Macharis and Bontekoning (2004) made a pioneering review and highlighted the scarcity of real multi-objective models that could simultaneously address the cost, time and environmental externalities in the intermodal network. In their review, they noted that most of the intermodal OR studies at the time were single objective cost minimizations, and later researchers attempted to fill in this void. Bontekoning, Macharis, and Trip (2004) agreed with this criticism, saying that the emerging research area of intermodal transport needed specific multi-criteria models that could reflect the complexity of transport modal choice decisions.

The issue of multimodal routing was studied by Lozano and Storchi (2001) who proposed the shortest viable path algorithm for multi-modal networks with time window constraints. They showed that the interactions between the transshipment penalties (wait times at exchange terminals) and modal speed differentials, which are multiplicative, make intermodal routing problems structurally more complicated than unimodal routing problems by leading to a different Pareto frontier. In a similar fashion, Barnhart and Ratliff (1993) also represented intermodal service options as a series of arc-flow decisions in a mixed-integer program, this time formalizing the network-thematic foundations around which MOMILP formulations for intermodal problems, including the current problem, have been built.

SteadieSeifi et.al (2014) conducted a systematic review of the existing literature on multimodal freight transportation planning, organizing models according to the objective structure, decision horizon, and solution methodology. They found that the most common structure in multimodal freight optimization is bi-objective cost-time formulations, and that in real-life logistics contexts, the weighted sum and constraint methods are the most commonly used scalarization methods. Critically, SteadieSeifi et al. (2014) found that there was a strong geographical bias in favour of studies carried out in corridors in Europe and North America while industry corridors in the North and South of the globe, especially those located in sub-Saharan Africa, were under-represented in the optimization literature. This observation directly corroborates the contribution of the present study whose aim was to investigate the Apapa-Agbara freight corridor through an empirical MOMILP analysis, thus filling a gap in the geographic span of freight optimization research noted.

These works form a consistent theory of development from Pareto (1896) to Cohon (1978), Current and Min (1986), Macharis and Bontekoning (2004) and SteadieSeifi et al. (2014) which validates the MOMILP approach used in this study. The normalized weighted-sum scalarization and the Big M linking constraint are both directly linked to the existing multi-objective optimization and intermodal freight literature, respectively.The normalized weighted-sum scalarization and the Big-M linking constraint are both directly related to the existing multi-objective optimization and intermodal freight literature, respectively.

3. Research method

3.1. Sample population and sample size

This study sampled 4 major industrial clusters operating within the Apapa-Agbara corridor. A multistage sampling technique was used to determine the sample size. In the first stage, industrial entities were selected using a systematic sampling technique from a parent population of 833 registered industrial entities operating within the corridor. In the second stage, structured questionnaires were administered using a simple random sampling technique to a total of 416 supply chain/logistics officers representing individual industrial entities. Out of the 416 questionnaires administered, 371 were successfully retrieved and subsequently analysed for the study. Details of the study population and sample size are presented in Table 1.

Table1: Study population / sample size

S/N	Zone	Industrial Settlement	Numbers of Industrial Entities in Clusters	Numbers of Registered Supply Chain/Logistics Officers	Sample Size
1	Zone A	Agbara Industrial Estate	39	216	108
2	Zone B	Opic Industrial Estate	42	235	117
3	Zone C	Abule Osun	31	185	92
4	Zone D	Coconut/Kirikiri	35	197	98
Total			**147**	**833**	**416**

Source: Manufacturers Association of Nigeria (MAN) and the author's analysis, 2026

To ensure the reliability of the parameters defined in Table 3, the triangulation method was applied. Survey responses were cross-referenced with available transit data from secondary sources, including the Nigerian Ports Authority (NPA), the Barge Operators Association of Nigeria (BOAN) and the Nigerian Association of Road Transport Owners (NARTO). Outliers in reported costs or times were excluded to establish the static average values used in the model.

3.2. Research design and data analysis

This study adopts a quantitative research approach, utilizing only primary data collected through the use of a structured survey. Parameters used in the optimization model were derived from a primary data collection exercise conducted during the two months the study lasted, ensuring that the findings accurately reflect the current and contemporary economic realities of the corridor.

The questionnaire in this study was designed to collect some qualitative data using the Likert scale and some quantitative data using the open-ended numerical scale. Moreover, the static averages used in the MOMILP model reflect the exact average values obtained from the responses of the survey sample, which were validated. The model was formulated and solved in Python 3.11 using the PuLP library PuLP (version 2.7.0), which is a modeler for Multi-Objective Mixed-Integer Linear Programming (MOMILP).

3.3. Assumptions and limitations

The assumptions behind the MOMILP model in this study simplify a very complex logistics system into one that is computationally tractable. This model applies a single route - Apapa-Agbara and multiple relay nodes linking it Also, the model is developed under a blanket of static parameters, where all inputs (cost, speed, wait time, demand, and capacity) are fixed and are average values. The model relies on these simplifying mathematical premises, which assume linear relationships in both the objective functions and the constraints. This means that total cost is strictly proportional to volume.

Furthermore, the model makes the assumption that cargo is a continuous variable; i.e., it can be divided and transported in any fraction or quantity. And, in order to enforce the relationship between a continuous variable (freight volume) and a binary decision (mode selection), the structure uses the Big M method. Lastly, the model is designed to optimize both cost (λ_{cost} and λ_{time}), but it fixes the final solution by using empirically derived weights (the λ values) derived from an initial, pre-defined efficiency rating. This approach forces the complex trade-off into a single, predetermined optimal outcome.

The sets and indices used in the model are shown in Table 2.

Table 2: Sets and indices

Index	Description
m	Set of available transport Modes (e.g., Road, Waterway, Combination).
r	Set of origin-destination Routes in the Apapa-Agbara corridor.

Source: Researcher (2026)

The input parameters and decision variables for the optimization model are summarized in Table 3 and 4.

Table 3: Parameters (input coefficients)

Parameter	Source/Description (from Questionnaire)	Unit
Costton-km,m	Estimate cost per ton-km for Mode m.	NGN / (ton . km)
Distancer	Average distance for route r.	Km
Energy Costm,r	The cost component is derived from the average fuel or energy consumed by machinery at the loading and unloading terminals.	NGN
Speedm	Average speed of freight using Mode m.	km/h
Wait Timer	Non-travel time (e.g., Long waiting times at ports) for route r.	Hours
Demandavg	Average freight volume transported weekly (total system demand).	tons
Capacitym	Fleet size/capacity limit for Mode m.	Tons
Max Cost	Maximum acceptable total delivery cost per tonnage (ideal requirement).	NGN
Max Time	Maximum acceptable delivery time (ideal requirement).	Hours
Accessibilitym, r	Binary indicator of Route Availability / functional terminals (1 if accessible, 0 otherwise).	Binary
Big-M	Big-M constant for linking constraint (300 tons)	tons

Source: Researcher (2026)

Table 4: Decision variables

Variable	Type	Description
Xm, r	Binary ∈ {0, 1}	1 if transport Mode of Transport m is selected for route r; 0 otherwise.
Fm, r	Continuous ≥ 0	The volume of freight (in tons) transported using mode m on route r.

Source: Researcher (2026)

3.3. Mathematical model

The core objective is the simultaneous minimization of Total Freight Cost (ZCost) and Total Delivery Time (ZTime).

3.3.1. Objective aggregation (weighted sum approach)

Two conflicting objectives (Cost and Time) are combined into one scalar objective using the Weighted Sum Method. The objectives are then normalized according to the ideal requirements (Max Cost and Max Time) for each of them to obtain comparable objectives, even when they are in different units (Naira vs. Hours). The combined objective function is given by the following:

$$\min Z = \lambda_{\text{cost}} \cdot \left(\frac{Z_{Cost}}{Max\ Cost}\right) + \lambda_{\text{time}} \cdot \left(\frac{Z_{Time}}{Max\ Time}\right), \quad (1)$$

where:
λ_{cost} and λ_{time} are the relative weights assigned to cost and time efficiency (where λ_{cost} and $\lambda_{\text{time}} = 1$)
Z_{Cost} and Z_{Time} are the calculated total cost and time for a specific mode or combination.

The weighting coefficients were empirically derived from the efficiency ratings provided by the 371 surveyed respondents.

The Multi-Objective Mixed-Integer Linear Programming (MOMILP) framework incorporates a normalized weighted sum formula to aggregate cost and time objectives into a value defined as Min ZTotal = λcost (Zcost/Max Cost) + λtime (Ztime/Max Time). Final weights are derived from the survey as described in Table 5 below.

Table 5: Derivation of objective weights from survey efficiency ratings

Criterion	Average Likert Score (n=371)	Normalized Weight (λ)
Cost	7.35	0.489
Time	7.67	0.511
Total	15.02	1.000

Source: Researcher (2026)

3.3.2. Objective functions

1. Total freight cost minimization (Z_{cost})

Energy Cost is here defined as supplementary energy surcharges (cost component derived from the average fuel or energy used by machinery at the loading and unloading terminals) not captured in the standard ton-km rate.

$$\min Z_{cost} = \sum_{m\in M} \sum_{r\in R} \left(\left(Cost_{m,r} \cdot F_{m,r} \right) + EnergyCost_{m,r} \right). \quad (2)$$

2. Total delivery time minimization (Z_{Time})

This function accounts for both transit time (distance divided by speed) and fixed delays (waiting times).

$$\min Z_{time} = \sum_{m\in M} \sum_{r\in R} \left(\frac{Distance_r}{Speed_m} + Wait\ Time_r \right) X_{m,r} \quad (3)$$

3. Aggregated weighted objective function

To resolve the multi-objective nature, a normalized weighted sum approach is used:

$$\min Z_{Total} = \lambda_{cost} \left(\frac{Z_{cost}}{Max\ Cost} \right) + \lambda_{time} \left(\frac{Z_{time}}{Max\ Time} \right), \quad (4)$$

where $\lambda_{cost} + \lambda_{time} = 1$. The denominators (Max Cost and Max Time) are used to normalize the values into a dimensionless scale between 0 and 1.

3.3.3. Constraints

The following constraints ensure the model remains within the physical and economic realities of the corridor:

Constraint 1: Demand satisfaction

$$\sum_{m\in M} F_{m,r} = Demand_{avg} \quad \forall_r \in R \quad (5)$$

(This ensures that the entire 255-ton weekly freight demand is satisfied.)

Constraint 2: Fleet/Capacity Limit

$$F_{m,r} \le Capacity_m \cdot X_{m,r} \quad \forall_{m,r} \quad (6)$$

Constraint 3 & 4: Ideal Requirements (Bounds)

$$Z_{cost} \leq \text{max Cost} \quad (7)$$

$$Z_{time} \leq \text{max Time} \quad (8)$$

Constraint 5: Accessibility/Route Availability

$$X_{m,r} \leq Accessibility_{m,r} \quad \forall_{m,r} \quad (9)$$

(Ensures a mode is only selected if the infrastructure is functional.)
Constraint 6: Variable Restrictions

$$F_{m,r} \leq M.\, X_{m,r} \quad \forall_{m,r} \quad \text{(Non-negative)} \quad (10)$$

where M is a sufficiently large constant, i.e., freight is only assigned to a mode if that mode is accessible.

$$X_{m,r} \leq \{0,1\} \quad \forall_{m,r} \quad \text{(Binary Selection)} \quad (11)$$

3.3.4. The Big-M linking constraint

This constraint mathematically links the continuous freight volume ($F_{m,r}$) to the binary decision variable ($X_{m,r}$), ensuring that freight is only allocated to a mode if that mode has been activated or selected.

The linking constraint is formulated as follows:

$$F_{m,r} \leq Capacitym \cdot X_{m,r} \; and \; FX_{m,r} \leq X_{m,r} \quad (12)$$

(The Big-M constraint establishes a logical relationship between freight allocation and modal selection.) where: M is a sufficiently large positive constant (representing the maximum possible capacity or a value significantly higher than the total weekly demand of 255 tons). The Big-M constant was set to 300 tons, approximately 18% larger than the total weekly demand.
If $X_{m,r}$ = 0 (mode not selected), then $F_{m,r}$ is forced to 0.
If $X_{m,r}$ = 1 (mode selected), then $F_{m,r}$ is allowed to take any value up to the capacity limit.

Table 6 presents the freight allocation across three transport modes for the 255-ton weekly demand along the Apapa-Agbara corridor. The optimal solution allocates 76.5 tons (30%) to road mode, 76.5 tons (30%) to waterway mode, and 102 tons (40%) to the combination (Intermodal) mode. This mixed allocation reflects the MOMILP model's attempt to balance cost and time objectives through a diversified intermodal strategy as shown in Table 6

Table 6: Freight allocation

Mode	Volume (tons)	Percentage	Cost/Ton (₦)	Total Cost (₦)	Total Time (hrs)	Speed (km/h)
Road	76.5	30%	1,424.15	108,947.48	1.59	35.27
Waterway	76.5	30%	887.25	67,874.63	2.84	22.3
Combination	102	40%	1,127.49	115,003.98	2.11	28.26

Source: Researcher (2026)

4. Results

4.1. Model performance metrics-feasibility check

Table 7 outlines the cost and time components for transporting the total freight demand of 255 tons using single modes and the optimal combination mode.

An initial analysis of the three transport options, namely road, water, and the combination, has been carried out to establish baseline performance, considering the implied freight demand of 255 tons for the Apapa-Agbara corridor. Road mode was the fastest, with a total time of 1.59 hours, by combining a low travel time of 1.29 hours with a minimal wait time of 0.3 hours. This speed came at the highest economic cost, i.e., A cost per ton of ₦1,424.15, therefore yielding a total cost of ₦363,158.25 and water mode had the lowest cost per ton of ₦887.25, with a corresponding total cost of ₦226,248.75. However, it faced a time disadvantage, yielding the longest total time of 2.84 hours because of a higher travel time of 2.04 hours and the longest waiting time of 0.8 hours. Lastly, the combination of road and water modes provided an intermediate, balanced solution, with a total time of 2.11 hours and a total cost of ₦291,826.09, positioning intermodal option as a strategic trade-off between the speed of road transportation and the cost efficiency of waterway transportation.

Table 7 outlines the cost and time components for the three transport modes.

Table 7: Mode performance metrics

Mode	Cost per Ton (N)	Total Cost (N)	Travel Time (hours)	Wait Time (hours)	Total Time (hours)
Road	1,424.15	363,158.25	1.29	0.3	1.59 (Fastest)
Waterway	887.25	226,248.75 (Cheapest)	2.04	0.8	2.84
Combination	1,127.49	287,509.95	1.61	0.5	2.11

Source: Researcher (2026)

Table 8 presents a summary of the performance of the unconstrained single-mode optimal solutions and the feasibility analysis of the overall optimization problem against the maximum allowable budgets. The analysis established that the problem is feasible and identified the range of performance for the available single transport modes. The single-Mode Optimal Solutions identified these trade-offs: the absolute cheapest solution was the Waterway, with a cost of ₦226,248.75, while the absolute fastest solution was the Road mode, with a time of 1.59 hours. The cost constraint is viable since the minimum possible cost is ₦226,248.75 and the maximum allowed cost is ₦578,850.00, giving a slack value of 352,601.25 as shown in Table 8. In addition, the time constraint is also viable since the minimum feasible time is 1.59 hours and the maximum allowed time is 3.65 hours, resulting in a slack value for the slack as 2.06 hours.

A summary of the single-mode optimal solutions and feasibility analysis is presented in Table 8.

Table 8: Single-mode optimization solution

Constraint / Metric	Description	Value	Status	Slack
Single-Mode Optimal	Cheapest Solution	₦226,248.75 (Waterway)	N/A	N/A
	Fastest Solution	1.59 hours (Road)	N/A	N/A
Cost Constraint	Minimum Achievable Cost	₦226,248.75	FEASIBLE	₦352,601.25
	Maximum Allowed Cost	₦578,850.00	N/A	N/A
Time Constraint	Minimum Achievable Time	1.59 hours	FEASIBLE	2.06 hours
	Maximum Allowed Time	3.65 hours	N/A	N/A

Source: Researcher (2026)

4.2. Optimal solution summary

The aim of this optimization process is to find the optimal freight allocation strategy that minimizes both total cost and total time simultaneously for the 255-ton weekly demand along the 45.50 km Apapa-Agbara corridor route. The entire analysis was conducted on a cost per ton basis. All required data, including the specific parameters for the three modes: Road, Waterway, and Combination, were successfully loaded into the model. As shown in Table 6, the solution allocated 30% of the weekly freight demand to the road mode, 30% to the waterways mode, and 40% to the combination mode. According to these parameters that defined the operating environment, the model reveals road mode was the fastest, with a total time of 1.59 hours, while the waterway mode was the least expensive at ₦887.25/ton

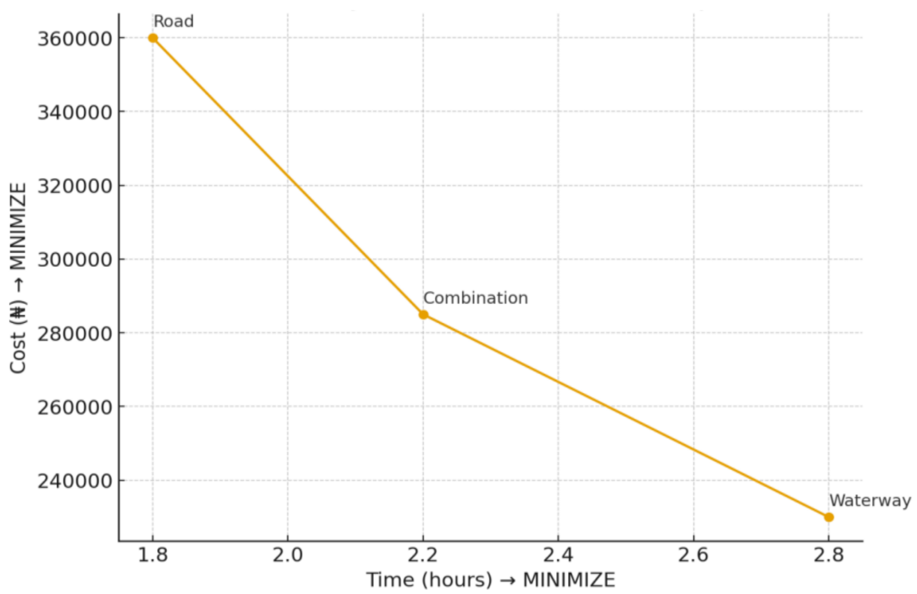
The combination mode (Intermodal) presented a balanced intermediate profile at ₦1,127.49/ton and 2.11 hours, as shown in Table 7. A feasibility pre-check confirmed that the problem was well constrained but solvable: the minimum achievable time of 1.59 hours and the minimum achievable cost (₦226,248.75) were far below the generous maximum allowable limits of 3.65 hours and ₦578,850.00 respectively. This indicates significant slack in both budgetary and time constraints. The MOMILP model was formulated with a dual minimization objective, utilizing a weighted-sum approach that prioritized time slightly (λ_{time} = 0.511 or 51.1%) over cost (λ_{cost} = 0.489 or 48.9%).

The solver reached an optimal status, yielding a final combined objective value of 0.5419. The optimal solution achieved a minimized total time of 2.11 hours and a total cost of ₦291,826.09. While this cost is 29.0% higher than the absolute cheapest single-mode option (waterway), and the time is 32.7% longer than the fastest single-mode option (road), the result represents the most efficient trade-off, given the prescribed objective weights.

The MOMILP model prescribed a comprehensive allocation strategy, showing that all the defined constraints for the Apapa-Agbara corridor were fully satisfied. According to the MOMILP's balance between the cost and time objectives (λcost = 48.9%, λtime = 51.1%), this model found that the most efficient strategy was to assign 40% (102 tons) of the 255-ton weekly freight demand to the combination mode. This resulted in a final total cost of ₦291,826.09 and a total time of 2.11 hours (precisely 2.10777 hours). The combination mode operates at a cost per ton of ₦1,127.49 and achieves an effective speed of 28.3 km/h over the 45.5 km route, which includes a 0.5-hour wait time at the transfer point. The solution utilized only part of the maximum allocated budgets, showing significant resource slack. The total cost of the optimum plan used only 50.4% of the maximum allowable cost budget (₦578,850.00), while the total time of 2.11 hours utilized 57.8% of the maximum allowable time budget of 3.65 hours.

Figure 3 illustrates the multi-objective trade-off between cost and time.

Figure 3: Multi-Objective Trade-off Graph



Source: Researcher (2026)

4.3. Impact of weight variation (λ_{cost} vs λ_{time})

The baseline model utilized the empirically derived weights (λ_{cost} = 0.489, λ_{time} = 0.511), which slightly prioritize time over cost in line with the survey respondents' ratings. For comparative purposes, a perfectly balanced scenario (λ_{cost} = 0.5, λ_{time}= 0.5) was also evaluated and produced the same optimal intermodal solution. As shown in Table 8, when the model is shifted to a time-dominant scenario ($\lambda_{cost} \geq 0.8$), the optimal solution reverts to sole road transport despite the higher costs required to meet urgent delivery windows. Furthermore, in a cost-dominant scenario ($\lambda_{cost} \geq 0.8$), the model strictly favors the waterway mode. The stability of the intermodal (combination) solution across the 0.4 to 0.6 weight range confirms its effectiveness as a reliable middle-ground strategy for the Agbara industrial cluster. Table 9 proves the model's logic by showing how the optimal mode changes based on the priority assigned to cost versus time.

The results of the sensitivity analysis on weight variations are summarized in Table 9.

Table 9: Sensitivity analysis summary

Scenario	λ_{cost} (Weight)	λ_{time} (Weight)	Optimal Mode	Combined Z-Value
Cost-Prioritized	0.9	0.1	Waterway	0.4296
Derived Baseline (Balanced Equal Weights)	0.489	0.511	Intermodal	0.5419
Time-Prioritized	0.1	0.9	Road	0.4548

Source: Researcher (2026)

5. Discussion

The results from the model reveal that the road transport option is the fastest mode, with a delivery time of 1.59 hours, but also the most expensive, incurring a total cost of ₦363,158.25. Conversely, the waterway mode is the least costly option, with a total cost of ₦226,248.75, but it records the longest delivery time at 2.84 hours. An optimal solution was achieved with a total transportation cost of ₦291,826.09 and a delivery time of 2.11 hours by adopting a combined (Intermodal) transport mode.

Freight allocation yields a total cost that is 29.0% higher than the waterway option but 19.6% lower than the road option, while achieving a delivery time that is 32.7% longer than road transport but 25.7% shorter than the waterway alternative. The combined objective function value of 0.541928 reflects a balanced trade-off between the cost and time objectives. Overall, the solution attains a cost efficiency of 49.6% and a time efficiency of 75.4%, utilizing only 50.4% of the available cost budget and 57.8% of the allowable time budget. These findings position the combination (Intermodal Transport) mode as the most balanced and sustainable choice, avoiding road's high costs and waterway's delays. These findings align with (Vigier et al., 2021) who argue that sustainable freight transportation cannot rely on incremental road improvements but requires a structural shift toward intermodal integration.

The findings of the study reject the null hypothesis (H_0) and support the alternative hypothesis (H_1). Integrated intermodal scheduling optimizes the trade-off between cost and time among industrial entities in the Apapa-Agbara corridor.

6. Conclusions

This study developed a Multi-Objective Mixed-Integer Linear Programming (MOMILP) model using static averages from a questionnaire administered to 371 respondents representing individual industrial entities Apapa–Agbara corridor. The optimization results reveal that prioritizing the intermodal transport option provides the most balanced trade-off between cost and delivery time, outperforming single-mode alternatives. This finding empirically validates intermodal transport as the most cost-efficient and time-reliable means of freight distribution strategy for congested industrial corridors in Nigeria.

6.1. Areas for future research

While this study employs a deterministic MOMILP model using static average weekly demand figures to optimize delivery time and cost, future iterations should adopt or incorporate stochastic modeling to account for the inherent volatility in industrial supply chains. Furthermore, to align with global shifts toward sustainable freight distribution, future models should integrate the inclusion of environmental externalities (carbon costing), i.e., Transitioning from a bi-objective to a tri-objective optimization (cost, time, and CO_2 emissions) would provide a more holistic assessment of sustainable freight distribution strategies, particularly when evaluating the environmental trade-offs of switching from road to inland waterways.

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Conflicts of interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly to improve language quality and ChatGPT to optimize visualization code. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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