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Optimization of Multi-Stage Multimodal Fixed Cost Transportation Network: A Case Study in Paper Mill in Bangladesh

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Abstract

Efficient transportation planning is essential for improving supply chain performance, particularly in multi-stage networks where transport mode and route selection significantly affect total logistics cost. This study develops a Linear Programming (LP) model to minimize fixed transportation costs across a three-stage multimodal supply chain of a paper mill in Bangladesh. Using real data on supply, demand, and fixed route costs, the model optimizes shipment allocation from suppliers to the factory, from the factory to distribution centers, and from distribution centers to retailers using road, rail, or a combined mode. Results indicate that while rail transport offers lower unit costs, limited rail connectivity prevents full demand fulfillment; in contrast, the combined mode selecting the lowest-cost option per route satisfies all demand and reduces total fixed transportation cost by 18.4% compared to road-only transport. Overall, the findings demonstrate that integrating road and rail transport significantly improves cost efficiency in developing-country logistics networks and provides a practical, easily implementable framework for optimizing fixed-cost transportation decisions in the paper mill supply chain.

Key words
Fixed-cost optimization, multimodal transportation, supply chain logistics, linear programming, transport network design.

1.Introdcution
A supply chain is a network of suppliers, manufacturers, and distribution facilities that transforms raw materials into finished products and delivers them to customers through multiple distribution stages. Transportation plays a critical role in enhancing the efficiency, responsiveness, and cost-effectiveness of these interconnected systems. As supply chains grow more complex especially across global and urban contexts minimizing transportation costs becomes increasingly vital.

The classical transportation problem (TP) addresses the allocation of goods from sources to destinations while satisfying supply and demand constraints. When a fixed cost is introduced for using a route regardless of the shipment quantity, the problem evolves into the Fixed-Charge Transportation Problem (FCTP). FCTP incorporates fixed charges such as loading fees, terminal access costs, and infrastructure use charges that are incurred once a route is activated (Vinay V. Panicker 2019). Balinski formally introduced FCTP as a distinct optimization class, and earlier contributions by Hirsch and Dantzig . laid the groundwork with approximate solution methods (Mahmoud M. El-Sherbiny 2021).

In modern logistics, multimodal transportation—also known as intermodal transportation has become a strategic approach for achieving flexibility, sustainability, and cost-effectiveness. It integrates different transportation modes such as road, rail, water, and air within a single delivery network (Tvsscs, 2023a). This approach enables goods to reach remote or infrastructure-limited regions by seamlessly switching between transport modes, such as from road to rail or road to air. It also facilitates better accountability through unified contract management, ensuring easier resolution of issues such as shipment delays or damage (Staff 2024).

In regions like Bangladesh, multimodal networks are increasingly relevant for reducing congestion, lowering costs, and enhancing overall connectivity (Tvsscs, 2023b). By capitalizing on the unique strengths of each mode, such systems provide scalable logistics solutions despite infrastructure disparities. Effective multimodal planning not only reduces operational bottlenecks but also contributes to environmental sustainability and economic resilience.

However, the current logistics and transportation planning frameworks still heavily rely on traditional cost models that often underrepresent the role of fixed costs. Additionally, standard tools like the Level of Service (LOS) index, which are often car-centric, fail to reflect the complexity of modern multimodal transport systems. Updated models must account for dynamic, interconnected transport hubs and support decision-making through analytical data and performance metrics (Urban Mobility Review, n.d.).

This research addresses a notable gap in existing literature by focusing on fixed-cost-only optimization in a multi-stage, multimodal transportation setting. Through the development and application of a linear programming model, this study aims to enhance decision-making in logistics networks where fixed costs are the dominant concern.

Objective of research:

1. To construct a Linear Programming (LP) model for a multimodal transportation network.
2. To minimize the total fixed transportation **costs** across all stages of the supply chain.
3. To identify the optimal transportation routes that yield the lowest total fixed cost while meeting supply and demand constraints.

2. Literature Review

Different attention to fixed costs and stage-wise route selection is required in multimodal transport systems. Unlike traditional models that emphasize variable operational costs such as distance or fuel, this study focuses on stable cost patterns to minimize overall transportation expenses. Effective route selection across multiple stages—road, rail, or combined modes—requires flexibility to adapt to infrastructure limitations, particularly in cost-sensitive sectors like the paper industry in Bangladesh.

Most multimodal transport optimization literature has concentrated on variable costs, leaving fixed costs underexplored despite their significant influence on network performance. Fixed expenses such as terminal usage fees, equipment acquisitions, and transshipment setup play a vital role in total logistics costs. (Liu 2023) explicitly incorporated carbon cost penalties as a fixed element, showing their effect on route selection, while (Okyere, Yang et al. 2022) and (Liu 2023) highlighted that the lack of standardized fixed cost accounting reduces comparability across studies. Unequal terminal distribution also increases fixed operational costs, a problem especially evident in Bangladesh, where logistic hubs are unevenly developed.

Several algorithmic frameworks have been developed to improve stage-wise multimodal route selection (Yang, Zhang et al. 2023) used fuzzy adaptive genetic algorithms to determine optimal routes considering uncertainties, while (Li and Tian 2016) introduced a two-level neighborhood search to balance local and global route optimization (Naim, Adnan et al. 2022) utilized GIS-based routing suitable for the regional variations in Bangladesh's infrastructure. However, many models still overlook regulatory and physical limitations such as bridge load restrictions and road accessibility.(Guo, Du et al. 2021)further proposed resilience-based routing approaches, embedding backup routes to improve network reliability.

In fixed-cost optimization, several computational approaches have been explored. (Lucic and Teodorovic 2003) proposed a queen bee evolution algorithm to balance environmental and financial objectives, while (Dumez, Lehuédé et al. 2021) used neighborhood search to minimize fixed facility and route costs. (Akkerman, Mes et al. 2025) demonstrated the use of reinforcement learning for adaptive routing under dynamic conditions. Hybrid frameworks, such as those by (Li, Liu et al. 2021) combining kernel search and dynamic programming, have shown promise in multimodal transportation systems. However, computational efficiency and the integration of real-time data remain major challenges (Li, Liu et al. 2021, Xu, Li et al. 2024).

Studies on multimodal transport cost trade-offs have shown that high fixed-cost modes, such as rail, become more cost-effective over longer distances when terminal costs are distributed over larger shipment volumes. (Ferguson, Sharmin et al. 2025) confirmed this relationship, while (Hao, Jia et al. 2024) emphasized the need to consider resilience along with cost in route design. High fixed-cost systems like rail offer reliability and efficiency, especially in stable, high-volume supply chains such as paper manufacturing. (Gbadegoye, Camur et al. 2025) suggested balancing cost, capacity, and reliability through batching and consolidation techniques. However, many studies fail to account for the effects of return load planning and reverse logistics, which can substantially reduce per-unit fixed costs.

Infrastructure and institutional factors play a decisive role in multimodal optimization. (Okyere, Yang et al. 2022) noted that underdeveloped intermodal hubs and low digitalization raise marginal costs and discourage multimodal integration. (Aleman-Castilla 2025) and (Biton, Reovan et al. 2019) highlighted the impact of fragmented transport policies and inconsistent regulations between rail and road systems, which create fixed cost unpredictability. Few studies isolate fixed costs as the main decision variable or analyze the long-term depreciation of transport assets. Furthermore, the potential of shared investment models such as Public-Private Partnerships (PPPs) remains underexplored. In Bangladesh, where integrated terminals are limited, fixed costs vary significantly due to infrastructure gaps. Context-specific models using local data, e-logistics platforms, and digital scheduling can enhance fixed asset utilization and cost efficiency.

Despite the growing body of research, there remain significant gaps in the literature. Few studies have developed fixed-cost-only optimization models for multi-stage multimodal transport networks, particularly in developing countries. Existing models rarely combine empirical data validation with linear programming or incorporate infrastructure constraints specific to Bangladesh. Moreover, there is a lack of context-specific, data-driven frameworks that minimize fixed transportation costs while ensuring full supply and demand satisfaction. This study aims to address these gaps by developing a linear programming-based multimodal optimization model tailored to the logistics conditions of Bangladesh's paper industry.

3. Methodology

This research employs a deterministic linear programming (LP) framework to address the optimization of a multi-stage, multimodal fixed-cost transportation problem. The model is developed and validated through a case study of a paper mill supply chain in Bangladesh, with the primary objective of minimizing total fixed transportation costs across a three-echelon network.

3.1 Model Formulation

The problem is formulated as a fixed-charge transportation problem (FCTP) structured across three sequential stages:

- Stage 1 (Upstream): Transportation of raw materials from a set of m suppliers (i = 1,2,...,m) to a central manufacturing facility.
- Stage 2 (Midstream): Distribution of finished goods from the factory to a set of n distribution centers (j = 1,2,...,n).
- Stage 3 (Downstream): Last-mile delivery from distribution centers to a set of k retailers.

For each stage, the optimization is performed under three distinct modal scenarios: Road-only, Rail only, and a Combined mode selecting the minimum-cost option per route. The core LP formulation for a generic stage is defined as follows:

Objective Function: Minimize total transportation cost: $$\text{Min } Z = \sum_{i=0}^{m} \sum_{j=0}^{n} C_{ij} X_{ij} \quad (1)$$

Subjective to constraints: Supply Constraints: $$\sum_{j=1}^{n} x_{ij} \leq S_i \quad \forall I \quad (2)$$

Demand Constraints: $\sum_{i=1}^{m} x_{ij} \leq S_i \quad \forall j$ **(3)**

Non-negativity: $X_{ij} \geq 0 \quad \forall I, j$ **(4)**

Where:

- X_{ij}: Decision variable representing the quantity shipped from origin i to destination j.
- C_{ij}: Fixed unit transportation cost from i to j for a specific mode.
- S_i: Supply capacity at origin i.
- D_j: Demand at destination j.

3.2 Data Acquisition and Case Context

The model parameters were instantiated with empirical data from a paper mill with its factory in Narayanganj. The network comprises seven upstream supplier zones (e.g., Rangamati, Khulna) and seven downstream distribution points (e.g., Tejgaon, Agrabad). Fixed-cost data for road and rail trans port, alongside capacity and demand Figures 1,2,3,4,5 were sourced directly from company logistics records and validated through structured interviews with supply chain managers.

4. Result & Discussion

The capacity and demand table specifies availability of supplies from seven source locations and demand needs at seven destination points. When an even total of 100 units for supply and for demand is achieved, the table presents the fundamental data for resolving the transportation problem. It allows determining those sources which can address the needs of particular regions at the most cost-effective rate at the same time across the whole network (Table 1-Table19).

Table 1. Capacity and Demand Table

Sources	Capacity	Manufacturer (Naraynganj)	Demand	Distribution center	Demand	Retailers	Demand
Rangamati	30	Section (Liu)	15	Agrabad	15	Reazuddin Bazar	13
Bandarban	15	Section (Akkerman, Mes et al.)	15	City Gate	12	Dewanhat + Station Road	10
Khagrachhari	5	Section (Liu)	15	Tejgaon	35	Karwan + Nilkhet Market	34
Bagerhat	20	Section (D)	15	Tongi	12	Tongi Bazar	12
Khulna	8	Section (E)	15	BSCIC	8	Chashara Market	7
Hobigonj	12	Section (Liu)	15	Kadamtoli	13	Sadarghat	13
Moulovibazar	10	Section (G)	10	Rangpur	5	Rangpur New Market	5
Total	100		100		100		94

4.1 STAGE 01; Sources to Manufacturer Factory For Road Transportation Only

Table 2. Data for unit transportation costs ROAD ONLY (Taka per unit shipments in Thousands)

Sources/Factory	Factory A	Factory B	Factory C	Factory D	Factory E	Factory F	Factory G	Capacity
Rangamati	65	65	65	65	65	65	65	30
Bandarban	60	60	60	60	60	60	60	15
Khagrachhari	68	68	68	68	68	68	68	5
Bagerhat	35	35	35	35	35	35	35	20

Khulna	30	30	30	30	30	30	30	8
Hobiganj	50	50	50	50	50	50	50	12
Moulovibazar	48	48	48	48	48	48	48	10
Demand	15	15	15	15	15	15	10	**100**

This table presents the costs of transporting units (in thousand of Taka) from each source to factories A-G using the road. Cost is uniform across destinations from each source with total supply and demand each at 100 units ensuring a balanced transportation model.

Table 3. Data table for shipment quantities (Optimum allocation) for ROAD transportation

Sources/Factory	**Factory A**	**Factory B**	**Factory C**	**Factory D**	**Factory E**	**Factory F**	**Factory G**	**Capacity**
Rangamati	0	0	0	12	15	3	0	30
Bandarban	0	0	12	3	0	0	0	15
Khagrachhari	0	2	3	0	0	0	0	5
Bagerhat	7	13	0	0	0	0	0	20
Khulna	8	0	0	0	0	0	0	8
Hobiganj	0	0	0	0	0	2	10	12
Moulovibazar	0	0	0	0	0	10	0	10
Demand	15	15	15	15	15	15	10	**100**

Total cost For ROAD Transport = 5210 tk (thousands)

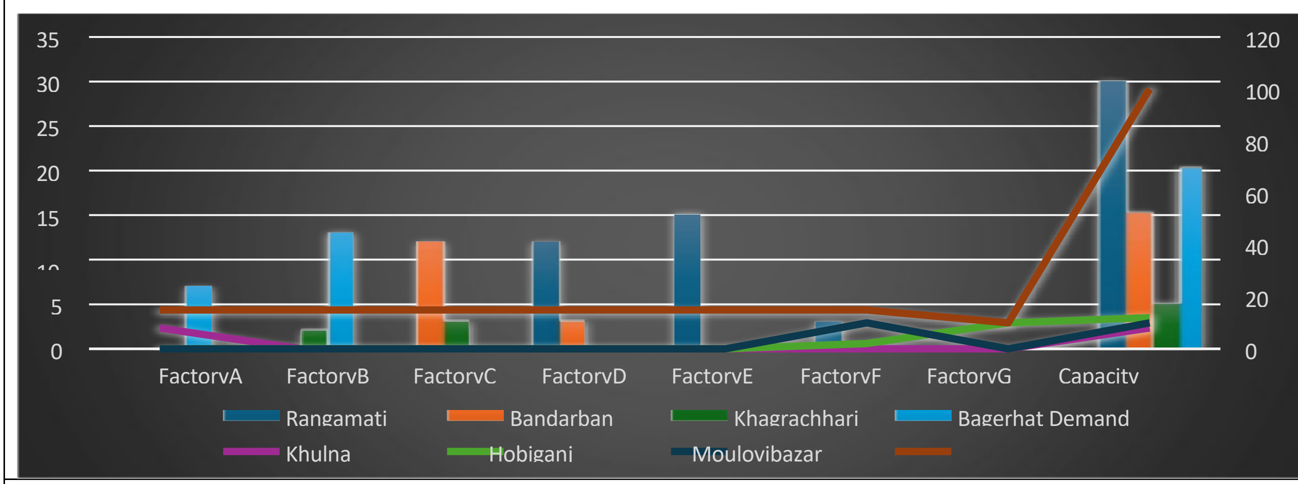

Figure 1. Combo chart for Data table for shipment quantities (Optimum allocation) for ROAD transportation

The following table shows the best quantities of shipments from sources to factories delivered through road transport. The laying is consistent with all of the supply and demand restrictions; a total of 100 units are moved. The lowest cost for transport cost realized is Tk 5,210 (in thousands).

For RAIL Transportation Only;

Table 4. Data for unit transportation costs RAIL ONLY (Taka per unit shipments in Thousands)

Sources/Factory	**Factory A**	**Factory B**	**Factory C**	**Factory D**	**Factory E**	**Factory F**	**Factory G**	**Capacity**
Rangamati	50	50	50	50	50	50	50	30
Bandarban	48	48	48	48	48	48	48	15
Bagerhat	25	25	25	25	25	25	25	20
Khulna	22	22	22	22	22	22	22	8
Hobiganj	38	38	38	38	38	38	38	12
Moulovibazar	36	36	36	36	36	36	36	10
Demand	15	15	15	15	15	10	10	**G5**

Unit transportation costs (in units of Taka thousand) from sources to factories A–G using rail transport are shown in this table. Costs are the same for destinations, for each source, from Tk 22,000 (Khulna), to Tk 50,000 (Rangamati). There is total supply of 95 units because there is no rail route from Khagrachari.

Table 5. Data table for shipment quantities (Optimum allocation) for RAIL transportation

Sources/Factory	**Factory A**	**Factory B**	**Factory C**	**Factory D**	**Factory E**	**Factory F**	**Factory G**	**Capacity**
Rangamati	0	0	2	15	13	0	0	30
Bandarban	0	2	13	0	0	0	0	15
Bagerhat	7	13	0	0	0	0	0	20
Khulna	8	0	0	0	0	0	0	8
Hobiganj	0	0	0	0	0	2	10	12
Moulovibazar	0	0	0	0	2	8	0	10
Demand	15	15	15	15	15	10	10	**G5**

total cost for RAIL Transportation = 3712 tk (thousands) (5 unit shortage for Khagrachari norail route)

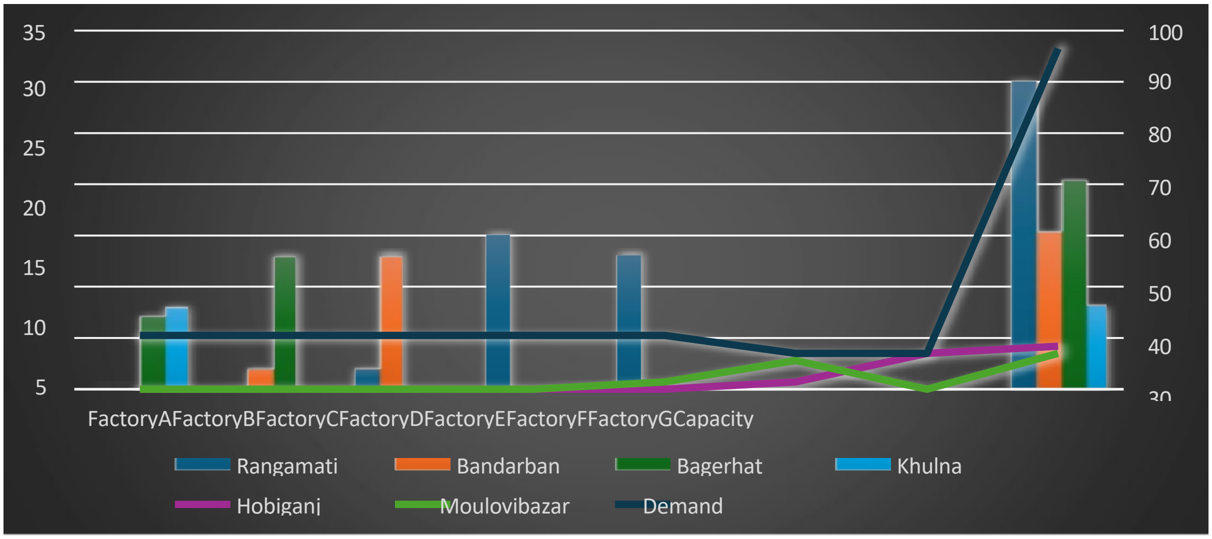

Figure 2. Combo chart for Data table for shipment quantities (Optimum allocation) for RAIL transportation.

This table presents the best distribution of products from sources to factories through railway. Total 95 units are shipped with 5 unit shortage because Khagrachari has no rail access. The collective transport cost is Tk 3,712 (thousands).

For COMBINED Transportation (ROAD + RAIL):

Table 6. Data for unit transportation costs COMBINED (ROAD + RAIL) (Taka per unit shipments in Thousands)

Sources/Factory	Factory A	Factory B	Factory C	Factory D	Factory E	Factory F	Factory G	Capacity
Rangamati	50	50	50	50	50	50	50	30
Bandarban	48	48	48	48	48	48	48	15
Khagrachhari	68	68	68	68	68	68	68	5
Bagerhat	25	25	25	25	25	25	25	20
Khulna	22	22	22	22	22	22	22	8
Hobiganj	38	38	38	38	38	38	38	12
Moulovibazar	36	36	36	36	36	36	36	10
Demand	15	15	15	15	15	15	10	**100**

This table presents unit transportation costs (in thousands of Taka) from source to factories A– G giving the cheapest mode between road and rail. The rates are different according to the source, with Khulna lowest (Tk 22,000 per unit), and Khagrachari highest (Tk 68,000). In the overall supply and demand are both 100 units, maintaining

Table 7. Data table for shipment quantities (Optimum allocation) for COMBINED (ROAD + RAIL) transportation.

Sources/Factory	**Factory A**	**Factory B**	**Factory C**	**Factory D**	**Factory E**	**Factory F**	**Factory G**	**Capacity**
Rangamati	0	0	0	12	15	3	0	30
Bandarban	0	0	12	3	0	0	0	15
Khagrachhari	0	2	3	0	0	0	0	5
Bagerhat	7	13	0	0	0	0	0	20
Khulna	8	0	0	0	0	0	0	8
Hobiganj	0	0	0	0	0	2	10	12
Moulovibazar	0	0	0	0	0	10	0	10
Demand	15	15	15	15	15	15	10	**100**

total cost for Combined transportation = 4052 tk (thousands). This Table 7 shows the optimal shipment plan from sources to factories using both road and rail transport. All 100 units of supply and demand are satisfied efficiently. The total transportation cost achieved through this combined mode is **Tk 4,052 (in thousands)**.

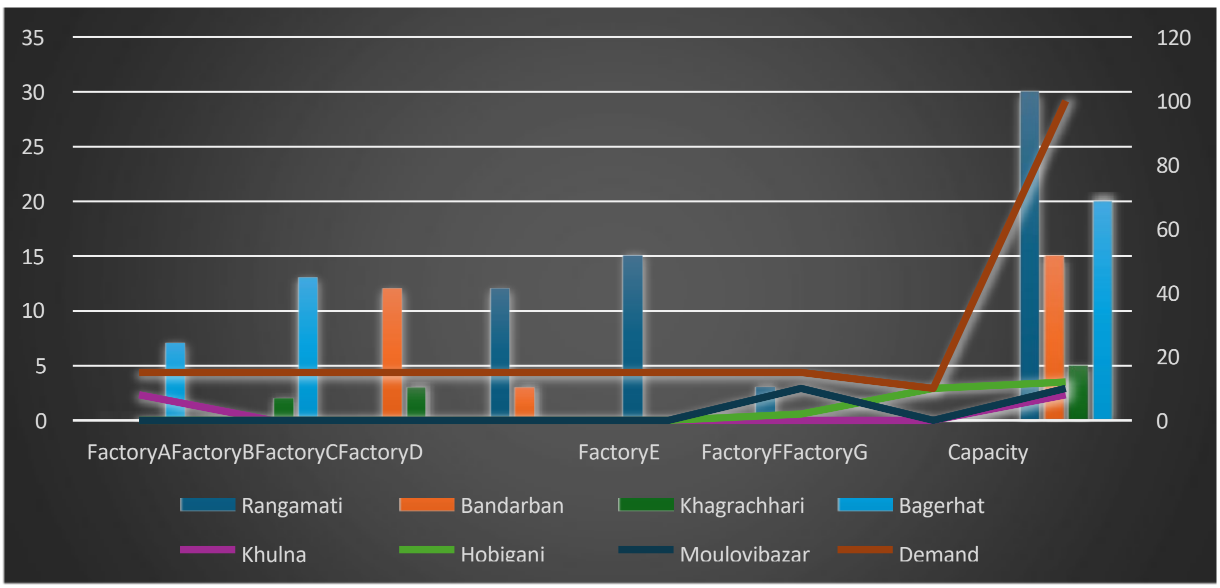

Figure 3. Combo chart for Data table for shipment quantities (Optimum allocation) for COMBINED (ROAD + RAIL) transportation.

Table 8. Per unit avarage cost after optimal allocation

Mode	**TotalCost**	**Demand**	**Costperunit**
ROAD	5210	100	52.1
RAIL	3712	95	39.07368421
COMBINED	4052	100	40.52

Table 9. Optimal modals for different routes

Sources	ROAD	RAIL	COMBINED
Rangamati	**not select**	**Select**	**Select**
Bandarban	**not select**	**Select**	**Select**
Khagrachhari	**select**	**not select**	**not select**
Bagerhat	**not select**	**Select**	**Select**
Khulna	**not select**	**not select**	**Select**
Hobiganj	**not select**	**Select**	**not select**
Moulovibazar	**not select**	**Select**	**Select**

This table compares the per unit average transportation cost for each mode. Road transport costs Tk 52.1k, rail transport costs Tk 39.07k, and the combined mode offers the lowest cost at Tk 40.52k per unit, highlighting the efficiency of using a mixed transport approach.

4.1 Stage 02; Factory to Distribution Center FOR ROAD TRANSPORTATION ONLY;

Table 10. Data for unit transportation costs ROAD ONLY (Taka per unit shipments in Thousands)

Factory/ Distribution	Agrabad	City Gate	Tejgaon	Tongi	BSCIC	Kadamtoli	Rangpur	Capacity
Factory A	55	53	18	20	8	10	65	15
Factory B	55	53	18	20	8	10	65	15
Factory C	55	53	18	20	8	10	65	15
Factory D	55	53	18	20	8	10	65	15
Factory E	55	53	18	20	8	10	65	15
Factory F	55	53	18	20	8	10	65	15
Factory G	55	53	18	20	8	10	65	10
Demand	15	12	35	12	8	13	5	**100**

In this stage goods are carried by road from factories to distribution centers. The model integrates diverse fixed cost such as distance based transport costs, fuel consumption and fixed charges per trip. It provides for efficient utilization of shipments by making allowance for the capacity limitations in vehicular capacities and pursuit of the minimum road transport expense .For a factory to the allocated distribution center.

Table 11. Data table for shipment quantities (Optimum allocation) for ROAD transportation

Factory/ Distribution	Agrabad	City Gate	Tejgaon	Tongi	BSCIC	Kadamtoli	Rangpur	Capacity
Factory A	0	0	2	12	1	0	0	15
Factory B	0	0	15	0	0	0	0	15
Factory C	0	0	15	0	0	0	0	15
Factory D	0	12	3	0	0	0	0	15
Factory E	15	0	0	0	0	0	0	15
Factory F	0	0	0	0	0	10	5	15
Factory G	0	0	0	0	7	3	0	10
Demand	15	12	35	12	8	13	5	**100**

Total Cost for ROAD Transportation = 2850 tk (thousands)
Table 12 below shows ideal amounts of shipment from each factory to each of the distribution centers using roads. The allocation guarantees all distribution center needs are covered without disturbing the capacity of the factories. Deals of note include Factory A which mostly serves Tongi, Factory D to City Gate, Factory E to Agrabad and factories F and G serving Kadamtoli and BSCIC. The optimized allocation gives a total transportation cost totalling 28,50 thousand Taka ($336,625).

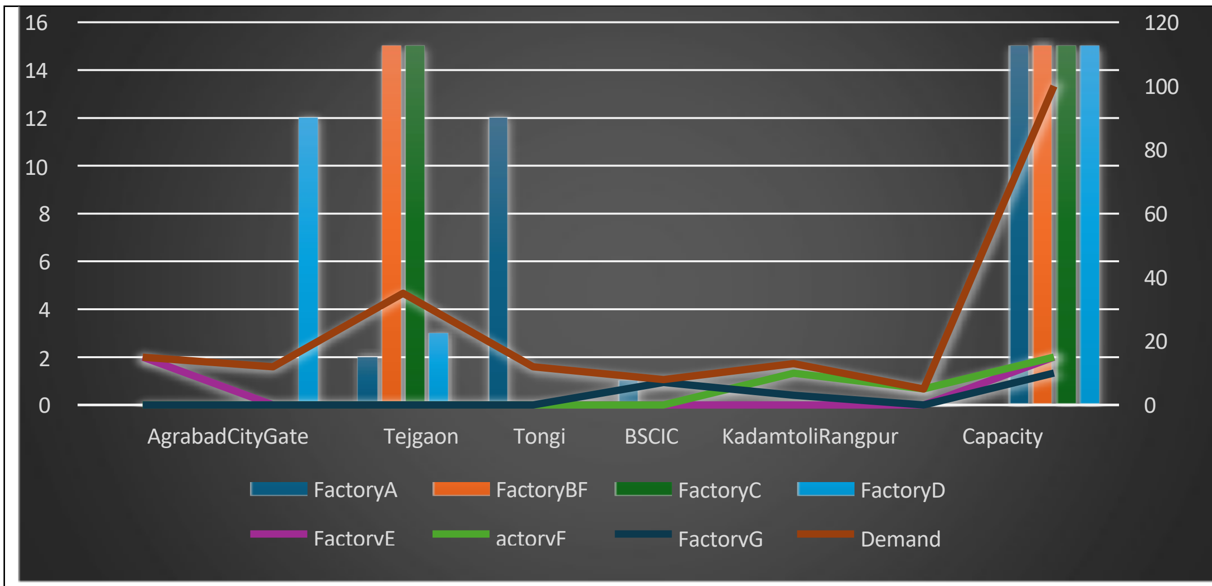

Figure 4. Combo chart for Data table for shipment quantities (Optimum allocation) for ROAD transportation.

For RAIL Transportation Only;

Table 12. Data for unit transportation costs RAIL ONLY (Taka per unit shipments in Thousands)

Factory/ Distribution	Agrabad	City Gate	Tejgaon	Tongi	Rangpur	Capacity
Factory A	42	40	20	17	68	15
Factory B	42	40	20	17	68	12
Factory C	42	40	20	17	68	12
Factory D	42	40	20	17	68	10
Factory E	42	40	20	17	68	10

Factory F	42	40	20	17	68	10
Factory G	42	40	20	17	68	10
Demand	15	12	35	12	5	**7G**

This Table 13 lists unit rail transport costs (in thousands of Taka) from factories to distribution centers. Costs are consistent across factories, with lowest rates to City Gate (40) and highest to Rangpur (68), guiding cost-efficient shipment planning.

Table 13. Data table for shipment quantities (Optimum allocation) RAIL transportation

Factory/ Distribution	Agrabad	City Gate	Tejgaon	Tongi	Rangpur	Capacity
Factory A	0	0	15	0	0	15
Factory B	0	0	12	0	0	12
Factory C	0	7	5	0	0	12
Factory D	5	5	0	0	0	10
Factory E	10	0	0	0	0	10
Factory F	0	0	0	5	5	10
Factory G	0	0	3	7	0	10
Demand	15	12	35	12	5	**7G**

Total Cost RAIL Transportation = 2354 tk (thousands)

This Table 14 provides the maximum shipment of the factories to distribution centers by rail. Outlined key allocations include Tejgaon, with largest share (35 units), mostly from Factories A, B and C, Agrabad and City Gateлу supplied Factories D and E. The total transport cost stands at 2,354 thousand Taka.

For COMBINED Transportation (ROAD + RAIL):

Table 14. Data for unit transportation costs COMBINED (ROAD + RAIL) (Taka per unit shipments in Thousands)

Factory/ Distribution	Agrabad	City Gate	Tejgaon	Tongi	BSCIC	Kadamtoli	Rangpur	Capacity
Factory A	42	40	18	17	8	10	65	15
Factory B	42	40	18	17	8	10	65	15
Factory C	42	40	18	17	8	10	65	15
Factory D	42	40	18	17	8	10	65	15
Factory E	42	40	18	17	8	10	65	15
Factory F	42	40	18	17	8	10	65	15
Factory G	42	40	18	17	8	10	65	10
Demand	15	12	35	12	8	13	5	**100**

The Table 15 below shows both the transport costs of units from factories to distribution centers via road and rail (in thousands of Taka). It represents the lowest cost available on any particular route, species of both modes—low costs to others (8) and higher costs to Rangpur (65).

Table 15. Data table for shipment quantities (Optimum allocation) for COMBINED transportation

Factory/ Distribution	Agrabad	City Gate	Tejgaon	Tongi	BSCIC	Kadamtoli	Rangpur	Capacity
Factory A	0	0	2	12	1	0	0	15
Factory B	0	0	15	0	0	0	0	15
Factory C	0	0	15	0	0	0	0	15
Factory D	0	12	3	0	0	0	0	15
Factory E	15	0	0	0	0	0	0	15

Factory F	0	0	0	0	0	10	5	15
Factory G	0	0	0	0	7	3	0	10
Demand	15	12	35	12	8	13	5	**100**

Total Cost Combined transportation = 2463 tk (thousands)

The optimized allocation of shipments from factories to distribution centers via both roads and rail is provided in this table. The distribution reflects the most economical paths, i.e. Factories A, B and C ply Tejgaon, Factory E services Agrabad. The total combined TTC is 2,463 thousand Taka.

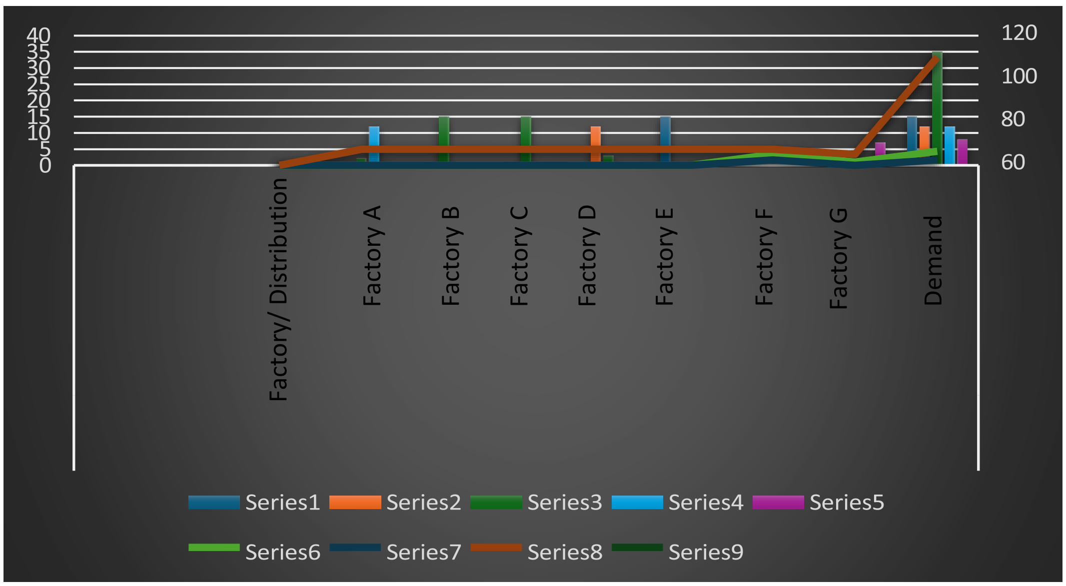

Figure 5. combined chart for Data table for shipment quantities (Optimum allocation) for COMBINED transportation

Table 16. Per unit avarage cost after optimal allocation

Mode	Total Cost	Demand	Cost per unit
ROAD	2850	100	28.5
RAIL	2354	79	29.79746835
COMBINED	2463	100	24.63

Table 17. Optimal modals for different routes (Factory to Distribution)

Distribution	ROAD	RAIL	Combined
Agrabad	Not select	select	select
City Gate	Not select	select	select
Tejgaon	select	Not select	Not select
Tongi	Not select	select	select
BSCIC	select	Not select	select

Kadamtoli	select	Not select	Not select
Rangpur	select	Not select	select

This table above compares the per-unit average costs in transportation as follows: Road: 28.5, Rail: 29.80 and Combined: 24.63 in thousands of Taka. The most efficient multimodal transport optimization is shown by the combined mode which incurs the least average cost.

4.3. STAGE 03; distribution to retailers

Table 18. Data Table for Last Mile Shipment Quantities, ROAD only (Taka per unit shipments in Thousands)

Distribution Center	DCCapacity	Retailers	Re. Demand	ROAD Cost	Total Cost
Agrabad	15	Reazuddin Bazar	13	4	52
City Gate	12	Dewanhat	10	5	50
Tejgaon	35	Nilkhet +Karwan Bazar	34	3	102
Tongi	12	Tongi Bazar	12	3	36
BSCIC	8	Chashara	7	2	14
Kadamtoli	13	Sadarghat	13	4	52
Rangpur	5	Rangpur New market	5	5	25

This table illustrates allocation of road only shipments to distribution centers to retailers. Each of the centers fully satisfies its own retailer's demand – e.g., Tejgaon fulfills 34 units for Karwan and Nilkhet Markets, Kadamtoli supplies 13 units to Sadarghat; the total last mile cost of 33.

4.4 Discussion

The present research study has the goal to create and verify the optimal structure of a multiphase, multimodal, fixed-cost transport network for realistic supply chain of a paper mill in Bangladesh. Solution was deployed for Excel Solver across three stages of transportation, from suppliers to factory, from factory to distribution centers and from distribution centers to retailers, assessed over road, rail and combined mode. The following discussion details the comparative results and strategic judgments made possible by the optimized allocation tables and cost analyses.

The transportation assessment throughout the three phases shows that multimodal integration greatly lowers total logistics expenses while guaranteeing complete demand satisfaction. In Stage 1 (Sources → Manufacturing Facility), rail transport offered the most affordable fixed cost (Tk. 3,712 thousand) but could not satisfy overall demand because there was no rail connection in Khagrachhari, resulting in a 5-unit shortfall. Road transport provided all 100 units, albeit at an increased expense (Tk. 5,210 thousand), while the combined method accomplished full distribution at a significantly reduced cost (Tk. 4,052 thousand) by employing rail for long-distance, economical routes (Rangamati, Bandarban) and utilizing road transport when rail was not accessible. In Stage 2 (Factory → Distribution Centers), rail once more provided a cheaper option (Tk. 2,354 thousand) but was able to provide only 79 units because of restricted terminal access, whereas road transport fulfilled the entire 100-unit requirement at a greater expense (Tk. 2,850 thousand. The unified model (Tk. 2,463 thousand) improved distribution by employing rail for significant long-distance locations (Agrabad, City Gate) and road for shorter or congested paths (Tejgaon, Kadamtoli), lowering the cost per unit to Tk. 24.63. Ultimately, in Stage 3 (Distribution → Retailers), road transport was the sole viable option as rail does not reach retail areas; all retailer requirements were met at an overall cost of Tk. 331 thousand, with increased expenses on congested urban routes like Tejgaon to Karwan/Nilkhet and reasonable costs for regions such as Sadarghat and Reazuddin Bazar

Comparative Summary of All Stages

- The combined transport model achieved maximum cost savings while fulfilling 100% demand at all stages.
- It outperformed road-only by Tk. 1,545 thousand and mitigated the demand shortfall in the rail-only model.

Table 19. Comparative Summary of All Stages

Mode	Stage 1 Cost (Tk '000)	Stage 2 Cost (Tk '000)	Stage 3 Cost (Tk '000)	Total Cost (Tk '000)
Road Only	5,210	2,850	331	8,391
Rail Only	3,712 (95 units only)	2,354 (79 units only)	–	Not fully satisfied
Combined	4,052	2,463	331	6,846

5. Conclusion

The research offers a verified linear programming model that effectively determines the most cost-efficient fixed-cost transportation approach within a three-stage multimodal network. The analytical comparison indicates that while rail transport offers the lowest fixed cost per unit, its insufficient network coverage hinders complete utilization—resulting in a 5-unit deficit in Stage 1 and a 21-unit deficit in Stage 2. Road transport, although entirely viable at all phases, consistently incurs the greatest overall fixed cost because of elevated modal fees and congestion-related routes, particularly in extended upstream and midstream travels.

The integrated multimodal setup presents the most economical and practically viable option. By opting for the lowest cost option for every route, the integrated model realizes complete demand fulfillment in all three phases and simultaneously lowers fixed transportation expenses by Tk. 1,545 thousand in comparison to the scenario with only road access (Tk. 6,846 comparado con Tk. 8,391 in total). This indicates a reduction in costs by 18.4%, directly validating the success of combining low-cost rail corridors with areas reliant on road transport. The ideal patterns show that rail is regularly selected for long-distance routes with excellent terminal access (e.g., Rangamati, Bandarban, Agrabad, City Gate), while road remains critical for regions without rail connections (e.g., Khagrachhari, Tejgaon, Kadamtoli) and for last-mile deliveries when no other options are available.

The findings demonstrate that optimizing fixed costs in multimodal systems relies on modal expenses as well as on network accessibility. Despite rail's cost benefits, a lack of connectivity directly raises overall system expenses—underscoring infrastructure deficiencies as a key factor in determining the best routing. The established model thus offers a practical, data-driven decision-making resource for logistics managers, showing that in the context of Bangladesh's existing infrastructure, multimodal integration achieves the lowest possible total fixed cost while guaranteeing full supply–demand satisfaction.

6. Future Recommendations:

This study successfully developed and optimized a multistage, multimodal fixed-cost transport network for a paper mill supply chain in Bangladesh using a linear programming model in Excel Solver. The integrated road–rail system effectively reduced total transport costs while meeting all demand constraints.

Future research could enhance the model by incorporating stochastic or fuzzy methods to handle uncertainties like delays or cost fluctuations, making it more robust in dynamic conditions. Environmental **costs**, such as carbon emissions, should also be included to support sustainable logistics planning.

Finally, though this study focused on a single-product flow, the framework can be expanded for multi-product and multi-industry networks, improving scalability and wider applicability both nationally and internationally.

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Fahim Faisal Tamim: Fahim Faisal Tamim is an undergraduate student in the Department of Industrial and Production Engineering (IPE) at Jessore University of Science and Technology (JUST), Bangladesh. His academic interests include supply chain management, logistics, data analytics, and sustainable industrial systems. He has worked on several research projects focusing on AI-driven agriculture supply chains, political disruptions in the RMG sector, green supply chains, and risk analysis in light engineering industries. Fahim has authored multiple research publications, including journal articles and conference papers on supply chain resilience, safety monitoring systems, and machine-learning-based industrial analysis. He is proficient in Python, Excel-based analytics, data visualization, and modeling tools such as K-means clustering, ISM, and system dynamics. He is also enrolled in the Future Nation Scholarship Program by UNDP and Coursera, pursuing the Product Analyst track. Fahim aims to build a career in data-driven supply chain and industrial optimization while contributing to sustainable engineering solutions.

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