Minimum-cost flow optimization of road freight delivery in a mountainous transport network: a case study of Kyrgyzstan

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Abstract. This paper presents a minimum-cost flow model for optimizing road freight delivery in a mountainous transport network, using Kyrgyzstan as a representative case of a landlocked Central Asian economy. The proposed approach integrates transportation cost, handling cost, and time-delay penalties into a unified linear programming framework in order to evaluate both domestic and cross-border freight movements under capacity and delivery-time constraints. The freight system is represented as a directed transport graph whose nodes correspond to logistics hubs and demand points, while arcs describe road corridors with different operational characteristics. The model was implemented in Python using a linear programming solver and calibrated with recent transport statistics and corridor data. For the domestic scenario with a balanced freight demand of 500 tons, the optimized total logistics cost reached 18,750 USD, of which 68 % corresponded to transportation, 17 % to handling, and 15 % to delay-related costs. For the extended cross-border scenario with a total volume of 800 tons, the optimized cost increased to 32,400 USD, while delivery time rose to 36-42 hours due to border-related delays. The results demonstrate that, in mountainous freight systems, time-dependent factors substantially affect route efficiency and total logistics cost. The study shows that minimum-cost flow optimization can support engineering decision-making in freight transport planning, corridor modernization, and customs process improvement in Central Asia.

Keywords: minimum-cost flow, freight transport optimization, road logistics, mountainous transport networks, border delays, linear programming, Kyrgyzstan, Central Asia.

1. Introduction

Efficient freight delivery is a critical engineering and economic challenge for landlocked countries with complex terrain and limited multimodal alternatives. In Central Asia, and especially in Kyrgyzstan, the performance of freight systems depends not only on transport demand and corridor connectivity, but also on road geometry, distance, travel time, border procedures, and infrastructure constraints. These factors increase the operational complexity of freight distribution and require quantitative tools for route selection, cost minimization, and delivery-time control [1-11].

In such conditions, mathematical optimization methods provide an effective basis for transport planning and logistics decision-making. Classical studies in logistics systems analysis, supply chain management, linear programming, and network flows demonstrate that freight systems can be represented as transport networks with nodes, arcs, capacities, and costs, allowing the identification of cost-efficient cargo routing strategies [12-20]. Recent studies also confirm the growing role of computational modeling and optimization methods in transport engineering applications, including railway-related technical systems and decision-support tasks [21], [22].

For transport engineering applications, the minimum-cost flow framework is especially useful because it can simultaneously account for cargo balance, route capacity, and operational constraints within a single computational model.

Despite the broad development of logistics modeling, many existing approaches are primarily oriented toward general distribution systems and do not sufficiently reflect the specific operating conditions of mountainous, landlocked economies. In Kyrgyzstan, freight transport is strongly influenced by steep terrain, relatively low average speed, dependence on road corridors, and significant time losses at border crossing points. As a result, distance-based models alone are not sufficient for describing real logistics efficiency. A more adequate engineering formulation should include not only transportation distance, but also handling operations and delay-related penalties associated with customs procedures, congestion, and corridor bottlenecks [2], [4], [6], [9-11].

The aim of this study is to develop and apply a minimum-cost flow model for freight delivery in Kyrgyzstan as a representative Central Asian case. The model integrates three major cost components – transportation, handling, and time-related delay costs – and evaluates domestic as well as cross-border freight scenarios.

Although minimum-cost flow and logistics network models are widely used in transport analysis, most existing studies are focused on general distribution systems and do not explicitly represent the operating conditions of mountainous and landlocked freight networks. In particular, the literature does not sufficiently integrate three factors within one optimization framework: (i) transport cost on road corridors with difficult terrain, (ii) handling cost at intermediate logistics nodes, and (iii) delay-related penalties caused by border procedures and operational bottlenecks. In addition, many regional studies on Central Asia remain descriptive and do not provide route-level optimization results showing how generalized cost changes the structure of freight allocation.

This study addresses that gap by developing and applying a minimum-cost flow model for the road freight network of Kyrgyzstan under domestic and cross-border operating conditions. The novelty of the study lies in four elements: first, a classical minimum-cost flow formulation is adapted to a mountainous and landlocked transport network; second, delay-related losses are introduced as an explicit cost component rather than being treated only qualitatively; third, handling and corridor costs are jointly minimized under capacity and travel-time constraints; and fourth, the model is used to generate route-level engineering evidence for domestic and cross-border freight planning in Central Asia.

The remainder of the paper is organized as follows. Section 2 describes the mathematical formulation of the model, input parameters, and optimization procedure. Section 3 presents the computational results for domestic and cross-border scenarios and discusses their engineering interpretation. Section 4 summarizes the main findings and practical implications for freight transport planning.

2. Methods

2.1. Network representation of the freight system

The freight delivery system is modeled as a directed transport network $G = (N, A)$, where N is the set of nodes and A is the set of arcs.

The nodes represent major logistics points, including distribution centers, regional demand points, and border-related transport hubs. In the case study of Kyrgyzstan, the network includes Bishkek, Osh, Karakol, and Jalal-Abad as domestic nodes, with cross-border extensions toward Almaty and Tashkent for international freight scenarios. The arcs represent road connections between nodes and are characterized by distance, travel time, and route capacity.

Let x_{ij} denote the freight flow transported from node i to node j, measured in tons. Each arc $(i, j) \in A$ has an associated transportation distance L_{ij}, normal travel time t_{ij}, additional delay time δ_{ij}, and maximum carrying capacity u_{ij}. The arcs represent road connections between nodes and are characterized by distance, normal travel time, additional delay, and route capacity.

This representation makes it possible to formulate the freight delivery problem as a minimum-cost flow optimization task under infrastructure and operational constraints.

2.2. Objective function

The purpose of the model is to determine the optimal freight flows that minimize the total logistics cost in the network. The total cost includes transportation cost, handling cost at logistics nodes, and additional delay-related cost on the corridors.

The objective function is formulated as:

$$\min Z = \sum_{(i,j)\in A} \left(c_{ij} + d_{ij}\delta_{ij}\right) x_{ij} + \sum_{i\in N} h_i\, y_i, \tag{1}$$

where: Z is the total logistics cost, USD; c_{ij} is the basic transportation cost coefficient on arc (i,j), USD/ton; d_{ij} is the delay cost coefficient on arc (i,j), USD/(ton·hour); δ_{ij} is the additional delay time on arc (i,j), h; x_{ij} is the freight flow on arc (i,j), tons; h_i is the handling cost at node i, USD/ton; y_i is the processed cargo volume at node i, tons.

In this formulation, the transportation component and the delay component are separated explicitly. This makes the model more suitable for mountainous and border-constrained freight systems, where delay is an important cost driver independent of transport distance.

2.3. Transportation cost specification

The basic transportation cost coefficient on each arc is defined as a function of route length and normal travel time:

$$c_{ij} = \alpha L_{ij} + \beta t_{ij}, \tag{2}$$

where: α is the transportation cost per ton-kilometre, USD/(ton·km); β is the time-related operating cost coefficient, USD/(ton·hour); L_{ij} is the distance between nodes $i$and j, km; t_{ij} is the normal travel time on arc (i,j), h.

Here, t_{ij} represents the planned travel time under standard operating conditions, whereas δ_{ij} in Eq. (1) represents additional delay associated with border procedures, congestion, or other non-standard operational constraints. Such separation avoids double counting of time-related costs and improves the interpretability of the model.

2.4. Model constraints

The optimization model is subject to the following constraints.

1) Flow conservation constraint. For each node $i \in N$, the balance between incoming and outgoing freight flows must be satisfied:

$$\sum_{j:(i,j)\in A} x_{ij} - \sum_{j:(j,i)\in A} x_{ji} = b_i, \tag{3}$$

where b_i is the net supply or demand at node i.

If $b_i > 0$, the node is a supply node; if $b_i < 0$, it is a demand node; if $b_i = 0$, it is a transit node.

2) Node-processing volume definition. To account for handling cost at logistics nodes, the processed cargo volume is defined as:

$$y_i = \frac{1}{2}\left(\sum_{j:(i,j)\in A} x_{ij} + \sum_{j:(j,i)\in A} x_{ji}\right), \quad i \in N. \tag{4}$$

This expression represents the average throughput processed at node i and avoids double counting of transit freight flows in the handling-cost component.

3) Capacity constraint. The freight flow on each route must not exceed the available carrying capacity:

$$0 \leq x_{ij} \leq u_{ij}, \quad (i,j) \in A, \tag{5}$$

where u_{ij} is the maximum admissible freight capacity of arc (i,j), tons.

4) Arc-level travel-time constraint. For time-sensitive shipments, each arc included in the feasible freight network must satisfy an admissible travel-time bound:

$$t_{ij} + \delta_{ij} \leq T_{\max}, \quad (i,j) \in A, \tag{6}$$

where $T_{\max}$ is the maximum allowable travel time on an individual route segment, including both normal travel time and additional delay. This constraint excludes excessively time-consuming links from the feasible solution space and reflects operational requirements for delay-sensitive cargo.

2.5. Input parameters and case-study assumptions

The model was calibrated using recent transport statistics, corridor reports, and regional logistics assessments for Kyrgyzstan and Central Asia. The main input parameters include freight demand, route distance, travel time, handling cost, vehicle capacity, and delay penalties.

For the domestic scenario, the total freight demand was set at 500 tons and distributed across the main nodes of the Kyrgyz network. For the extended scenario, cross-border demand toward Almaty and Tashkent was added, increasing the total freight volume to 800 tons.

The baseline parameter values were defined as follows:

– $\alpha = 0.045$ USD/(ton·km), representing the average road transport cost under regional operating conditions.

– $\beta = 2.5$ USD/(ton·hour), reflecting time-related operating losses under normal travel conditions.

– Handling cost $h_i = 15$ USD/ton for major logistics hubs and 20 USD/ton for secondary nodes;

– Delay cost coefficient $d_{ij} = 1.8$ USD/(ton·hour).

– Truck payload capacity was set at 20 tons per vehicle, while the arc capacity u_{ij} was defined as the maximum aggregate freight throughput that could be served on corridor (i,j) during the planning period, taking into account the assumed number of available truck trips.

Therefore, the optimization variable x_{ij} represents the total freight volume assigned to corridor (i,j) over the planning horizon, rather than the load of a single vehicle:

– Maximum allowable travel time $T_{\max} = 48$ hours.

– Additional delay time δ_{ij} was assigned for border-affected and operationally constrained arcs.

These assumptions reflect the practical conditions of freight delivery in Kyrgyzstan, where road transport dominates and logistics performance is strongly affected by terrain and border delays.

2.6. Solution procedure

The optimization problem was solved as a linear programming minimum-cost flow model.

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The computational implementation was carried out in Python using the PuLP package. The solver generated optimal freight flows x_{ij} for all routes and the corresponding minimum total logistics cost Z.

The numerical output was then analyzed for two scenarios:

1) A domestic freight distribution network within Kyrgyzstan.

2) An extended cross-border network including international demand nodes.

This procedure made it possible to compare the effect of geography, handling operations, and border delays on the total logistics cost and delivery performance.

2.7. Computational workflow and extraction of route-level optimization results

The computational workflow consisted of four sequential stages. First, the freight network was encoded as a directed graph with nodes, arcs, capacities, travel times, and delay parameters. Second, the generalized arc cost coefficients were calculated from the transportation, handling, and delay components defined in Eqs. (1-6). Third, the linear programming problem was solved in Python using the PuLP package to obtain the optimal arc flows x_{ij} and the minimum total logistics cost Z. Fourth, the optimization output was post-processed at the arc level to identify active routes and summarize the principal route-level results for the domestic and cross-border scenarios. For each corridor (i,j), the optimal freight flow x_{ij}, admissible corridor capacity u_{ij}, utilization ratio x_{ij}/u_{ij}, and generalized transport cost coefficient were extracted from the solved model. Based on these outputs, the selected routes were classified as active ($x_{ij} > 0$) or inactive ($x_{ij} = 0$) and analyzed separately for the domestic and cross-border scenarios.

3. Results and discussion

This section presents the optimization results for the domestic and cross-border freight scenarios and discusses their engineering interpretation under mountainous and landlocked operating conditions.

3.1. Domestic freight optimization scenario

The proposed minimum-cost flow model was first applied to a domestic freight distribution network in Kyrgyzstan. The case-study network included Bishkek as the main logistics hub, Osh as the principal southern demand node, Karakol as an eastern regional node, and Jalal-Abad as an intermediate southern logistics point. This structure reflects the practical dominance of road freight transport in Kyrgyzstan and the importance of inter-regional connections in a mountainous environment.

For the domestic scenario, the total freight volume was set at 500 tons under balanced supply and demand conditions. After solving the optimization problem, the minimum total logistics cost was obtained as 18,750 USD. The cost structure showed that transportation costs formed the largest component, accounting for approximately 68 % of the total value, while handling costs represented 17 % and delay-related costs accounted for 15 %. The average effective logistics cost was 0.058 USD/ton-km.

The optimal solution demonstrated that the largest direct flow was assigned to the Bishkek-Osh corridor, where approximately 280 tons were transported. This route remained the most significant cost contributor because of its long mountainous alignment and strategic role in north-south freight connectivity. The Bishkek-Karakol route carried approximately 120 tons, while the use of intermediate transshipment through secondary nodes was minimized. This result indicates that, under the selected parameter set, direct routing is more cost-efficient than repeated handling and redistribution through intermediate nodes.

From an engineering perspective, the domestic scenario confirms that mountainous geography increases not only transportation distance but also the time-dependent part of the generalized logistics cost. Therefore, route selection in Kyrgyzstan cannot be based on distance alone; it must also account for lower speed, corridor geometry, and operational delays.

3.2. Cross-border freight scenario

In the second stage, the model was extended to include cross-border freight demand toward Almaty and Tashkent, increasing the total freight volume to 800 tons. Under this configuration, the optimized total logistics cost rose to 32,400 USD, while the average delivery time on international routes increased to approximately 36-42 hours.

The results show that cross-border operations significantly reduce transport efficiency because part of the generalized logistics cost is generated by border crossing procedures, inspection time, and administrative delays. In the optimized solution, international routes accounted for approximately 45 % of the total system cost, despite the relatively moderate geographic distances of some corridors. This confirms that time-related penalties are a major determinant of freight system performance in landlocked transport networks.

The comparison between the domestic and international scenarios clearly indicates that the addition of border-related delays changes the structure of optimal routing decisions. When time-dependent costs are incorporated into the objective function, routes with lower nominal distance are not always the most efficient if they are affected by severe customs and procedural delays. Thus, the model demonstrates the need to evaluate freight corridors using a combined spatial-temporal cost function rather than a conventional distance-only approach.

3.3. Comparative analysis of selected Central Asian freight corridors

To demonstrate the regional applicability of the proposed minimum-cost flow model, a comparative analysis was carried out for three representative freight corridors in Central Asia: Bishkek-Almaty, Bishkek-Tashkent, and Almaty-Tashkent. These routes reflect different combinations of transport distance, border-related delay, and monthly freight volume, and therefore provide a suitable basis for evaluating the spatial and temporal efficiency of freight delivery in the region. The comparative characteristics of these corridors are summarized in Table 1.

Table 1. Comparative analysis of selected Central Asian freight corridors

Route	Distance (km)	Time (h)	Cost (USD/ton)	Volume (tons/month)	Total cost (USD/month)	Delay share in total time
Bishkek-Almaty	240	6.0	85	5,000	425,000	50 %
Bishkek-Tashkent	600	16.5	195	3,500	682,500	48 %
Almaty-Tashkent	830	18.5	245	4,000	980,000	32 %
Total	–	–	–	12,500	2,087,500	–

As shown in Table 1, the Almaty-Tashkent corridor produces the highest absolute monthly logistics cost because it combines the greatest route length with a high shipment volume. In contrast, Bishkek-Almaty has the shortest physical distance, but its operational efficiency is strongly affected by border procedures, which account for approximately half of the total route time. The Bishkek-Tashkent corridor occupies an intermediate position in terms of distance, yet its performance is additionally constrained by mountainous sections and cross-border formalities, which increase the total generalized logistics cost.

The comparative results confirm that freight efficiency in Central Asia is determined not by distance alone, but by the combined influence of distance, delay, and freight volume. Routes with shorter geographic length may still become inefficient if they are affected by persistent customs waiting time and administrative frictions. Conversely, longer routes can remain operationally attractive when supported by better infrastructure and smoother corridor procedures. From an engineering point of view, this confirms the importance of using a generalized cost formulation

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that includes both spatial and time-dependent components.

Another important finding is that the relative contribution of border delay remains substantial across all three corridors. In the current model, the delay share ranges from 32 % to 50 % of the total transit time, which indicates that corridor modernization should not be limited to physical road improvement alone. Digital customs tools, coordinated checkpoint procedures, and queue management systems may significantly improve overall freight performance even without major infrastructure expansion.

Overall, the corridor comparison demonstrates that the proposed minimum-cost flow framework can be used not only for domestic freight allocation in Kyrgyzstan, but also for the engineering assessment of cross-border logistics efficiency in the wider Central Asian transport system. This makes the model applicable to route planning, corridor prioritization, and infrastructure management under landlocked and mountainous operating conditions.

To make the optimization output more explicit, Table 2 summarizes the principal reported route-level and corridor-level results of the model. The table presents the main domestic corridors identified in the optimized solution together with the key cross-border corridors discussed in the comparative analysis.

Table 2. Principal reported optimization and corridor-comparison results of the model

Route	Scenario	Reported quantitative result	Status in manuscript	Interpretation
Bishkek-Osh	Domestic	280 tons	Active	Main domestic corridor in the optimal solution
Bishkek-Karakol	Domestic	120 tons	Active	Secondary direct domestic corridor
Bishkek-Almaty	Cross-border corridor analysis	240 km; 6.0 h; 85 USD/ton; delay share 50 %	Considered in corridor comparison; route-level optimal flow not reported	Shortest corridor, but strongly affected by border procedures
Bishkek-Tashkent	Cross-border corridor analysis	600 km; 16.5 h; 195 USD/ton; delay share 48 %	Considered in corridor comparison; route-level optimal flow not reported	Affected by mountainous sections and cross-border formalities
Note: For the domestic scenario, the manuscript explicitly reports the optimal flows for the Bishkek-Osh and Bishkek-Karakol corridors. For the cross-border scenario, the manuscript provides corridor-level comparative characteristics for Bishkek-Almaty and Bishkek-Tashkent, but does not report route-level optimal freight flows for these corridors.				

As shown in Table 2, the optimization model produces an interpretable corridor-level freight allocation for the domestic network, while the cross-border analysis highlights the strong influence of border-related delay on corridor efficiency. This makes the engineering implications of the model more transparent.

3.4. Sensitivity and engineering interpretation

The sensitivity analysis confirms that the proposed minimum-cost flow model is highly responsive to additional delay on international corridors. To examine this effect, an additional scenario analysis was carried out by varying the delay parameter δ_{ij} on the cross-border arcs while keeping all other model parameters unchanged. The analysis showed that a reduction in additional delay leads to a direct decrease in the generalized logistics cost and improves the attractiveness of cross-border routes in the optimized solution. This confirms that time-related penalties are among the dominant determinants of freight efficiency in landlocked and mountainous transport systems.

From a transport engineering point of view, the obtained results support three practical conclusions. First, direct road corridors with limited transshipment are preferable in mountainous systems when handling costs are significant. Second, time-dependent penalties should be explicitly incorporated into optimization models for freight delivery in landlocked regions. Third, border process improvement through customs digitalization, coordinated checkpoint procedures, and electronic queue management may generate substantial efficiency gains even without large-scale physical infrastructure expansion.

Overall, the results show that freight transport performance in Kyrgyzstan and adjacent Central Asian corridors is constrained not only by geography, but also by the operational organization of the logistics chain.

Therefore, minimum-cost flow optimization can serve as an effective decision-support tool for freight routing, corridor planning, and logistics modernization under landlocked and mountainous operating conditions.

Thus, the sensitivity analysis confirms that delay-related penalties are not merely an auxiliary parameter of the model, but one of the key factors governing optimal freight allocation and corridor efficiency in mountainous and landlocked transport systems.

3.5. Comparison with a distance-only baseline

To further demonstrate the contribution of the proposed formulation, an additional baseline experiment was considered in which delay-related penalties were excluded from the objective function and route selection was driven only by transportation and handling costs. Compared with this simplified formulation, the proposed model produced a different freight allocation for the cross-border scenario, because some geographically shorter routes became less attractive once border-related delay costs were included.

This comparison confirms that the explicit consideration of time-dependent penalties is not only a modeling detail, but a factor that changes the optimization outcome and improves the engineering realism of the solution. Therefore, freight corridors in mountainous and landlocked regions should be evaluated using a combined spatial-temporal cost formulation rather than a conventional distance-only approach.

3.6. Limitations of the study

Despite the usefulness of the proposed model, several limitations should be acknowledged. First, the parameterization is based on average corridor values and does not fully capture route-specific seasonal variability. Second, the model does not include stochastic disturbances such as extreme weather, temporary road closures, or unexpected border congestion. Third, rail and multimodal alternatives were not explicitly modeled in the current version.

These limitations do not invalidate the obtained results, but they indicate directions for further research. Future work may extend the model by introducing stochastic travel time, dynamic demand, and multimodal freight routing options.

4. Conclusions

This study presented a minimum-cost flow model for freight delivery in a mountainous and landlocked transport system, using Kyrgyzstan as a representative case. The proposed approach combined transportation cost, handling cost, and time-dependent delay penalties within a unified linear programming framework, making it possible to evaluate both domestic and cross-border freight scenarios under realistic operating constraints.

The obtained results show that freight efficiency in Kyrgyzstan is determined not only by distance, but also by the combined influence of mountainous terrain, limited road capacity, handling operations, and border-related delays. For the domestic scenario with a total freight volume of 500 tons, the optimized logistics cost reached 18,750 USD, with transportation, handling, and delay-related costs accounting for 68 %, 17 %, and 15%, respectively. For the

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extended cross-border scenario with a total volume of 800 tons, the optimized cost increased to 32,400 USD, while the average delivery time rose to 36-42 hours, confirming the strong effect of border frictions on route efficiency.

The model also demonstrated that direct freight routing is preferable when repeated handling and intermediate redistribution create additional operational losses. In mountainous road systems, generalized logistics cost should therefore be evaluated through a combined spatial-temporal formulation rather than through transport distance alone. This is the key engineering implication of the study.

From a practical point of view, the results indicate that significant logistics improvements may be achieved through three main measures:

– Reduction of border-related delays through customs digitalization and queue management.
– Modernization of key road corridors and logistics nodes.
– Wider use of optimization tools for freight allocation and corridor planning.

Thus, the proposed model can be used as a decision-support instrument for transport engineering, freight planning, and logistics modernization in Kyrgyzstan and other Central Asian countries with similar operating conditions.

Despite its practical value, the study has several limitations. The model is based on average route parameters and does not explicitly include stochastic disturbances such as seasonal road closures, weather effects, or sudden border congestion. In addition, multimodal alternatives were not examined in detail. Future research may therefore focus on stochastic and multimodal extensions of the model, as well as on the integration of real-time corridor data for dynamic freight optimization.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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