Cost optimization of intermodal freight transportation in the transport network

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Abstract. Intermodal freight transport is an alternative to trucking to distribute large volumes of goods. The article presents the solution of the problem of tactical planning and choice of transportation options. When using railway freight consignors take into account the traffic capacity. Trucking is used for short distances for transportation to intermodal terminals or direct supplies to customers. The study provides an analysis of trucking and intermodal transport in relation to cargo consolidation and cost of services on a model basis. The approach is applied to the industrial distribution system of the region.

1. Introduction

Intermodal freight transport is giving increasing consideration in the transport economy as it is seen as a way to improve traffic safety, reduce congestion on the road network and the level of air pollution. The growing interest in logistics has led to the rapid development of a scientific base in transportation [1-5]. Intermodal freight service allows combination of two or more modes of transport (road, rail, water) within the same transport distribution chain. As standard, the goods are supposed to be packed in containers, which eliminates the complexity of loading and unloading operations among any modes of transport. To increase the profitability of intermodal transportation, certain conditions need to be considered [6]:

The tariff per transport unit and kilometer should be significantly less for rail transport than for trucking, otherwise the cost of intermodal transport will exceed the cost of trucking, since the distance between intermodal chains is always greater than the direct shortest distance for trucking.

The distance between the consignor and the consignee must be above break-even. This is due to the fact that intermodal transport includes additional fees, which are charged by terminals for cargo from one mode of transport to another. The economic advantage of rail transport can only be offset by additional charges in excess of a certain distance.

Transportation is not time-critical, as it is known that intermodal transport usually takes much more time than direct trucking.

An efficient intermodal system requires a short-haul model. It is aimed at choosing: vehicles taking into account the capacity of the road network for each type of transport; transport services; and consolidation of freight flows. Scalable cost functions for road and rail transport are included in the model, which will allow for the real costs of reloading and transporting goods [7,8].

During the operation of the cargo terminal, several participants are involved:

- carriers that transport goods between intermodal terminals and consignors and consignees by trucking;
- employees of terminal complexes that reload goods from trucking to rail mode;
- train station dispatchers who coordinate the transportation of goods within the network;
operators who coordinate the work of the intermodal system. Intermodal operators may be shippers, consignees, freight consignors. Depending on the length of the time interval, the task is assigned a strategic, tactical or operational level. Long-term solutions in the field of intermodal transport include the location and layout of intermodal terminals, as well as the design of a railway network. Medium-term or tactical tasks are related to the planning of equipment capacities and the development of consolidation and pricing strategies. Short-term tasks are connected with routing and timetables, planning train loading and redistributing containers and wagons. The objective of the study is to determine the location of the intermodal terminal.

2. Theoretical basis

For an efficient intermodal transportation planning process, a model is needed to select vehicles for long-haul with a certain capacity of the road network to create a cost-effective cargo flow. Tactical planning of intermodal transportation includes the choice of modes of transport, related services and the consolidation of cargo flows. Scalable freight charges for trucking and rail traffic are included in the model to find the costs of transshipment and transportation.

For an optimal solution in a transport network with competing railway and trucking services consider an enterprise producing a certain product in one region. The demand region in which the consignees are located is far from the shipper region. Three options are available for transporting goods. In the first, a transport unit moves directly from the place of production to the place of consumption by means of motor transport. In other options, the movement is initially carried out to the intermodal terminal located in the supply region, then – by railway vehicles to the intermodal terminal of the demand region and at the final stage – by trucking from the terminal to the consignee. Rail transport carries out long-haul service and can be used either in the loading mode with fewer cars, when a consignee pays a freight charge for each unit of cargo, or in the full train mode when the car/train is purchased in general.

**Figure 1.** Multimodal transport network [9].

Figure 1 shows a simple multimodal network consisting of two terminals in the supply region and two terminals in the demand region [9]. For intermodal rail/trucking, pre-transportation of goods from production sites to terminals \( o \in O \) and subsequent transportation of goods for delivery from terminals \( d \in D \) to buyers is carried out by road. Transportation from \( o \) to \( d \) by rail is carried out long distances. In this logistics network, a set of nodes is defined as \( N = S \cup O \cup D \cup C \). A set of street options is defined as \( A = S \times C \cup S \times O \cup D \times C \), and the set of railway connections is presented as \( B = O \times D \).

Where \( C \) – customer recruitment; \( S \) – many production sites; \( O \) – set of terminals in the demand zone; \( D \) – set of terminals in the supply area, many nodes, \( N = S \cup O \cup D \cup C \); set of transport arcs, \( A = S \times C \cup S \times O \cup D \times C \); set of arcs of railway transport, \( B = O \times D \).
The solution of the planning problem includes testing a mathematical optimization model, determining cost functions, and evaluating the effect of cargo consolidation. To simulate flow on the arcs of the railway network \((x_{od})\) and cargo consolidation for services \((y_{od}, z_{ad}, x_{od}^L)\), define variables \(x_{ij}\) for flow arcs of a road network \((i, j) \in A\). With these variables, the solution is formulated as a mixed objective function (1) minimizes the total cost of transportation:

\[
\min Z = \sum_{s \in S} \sum_{c \in C} x_{sc} \cdot d_{sc} \cdot c^D + \sum_{s \in S} \sum_{o \in O} x_{so} \cdot d_{so} \cdot c^{pr} + \sum_{d \in D} \sum_{c \in C} x_{dc} \cdot d_{dc} \cdot c^{po} + \\
\sum_{o \in O} \sum_{d \in D} (y_{od} + z_{od}) \cdot d_{od} \cdot c^{f} + \sum_{o \in O} \sum_{d \in D} x_{od}^L \cdot d_{od} \cdot c^L
\]

where \(S\) – many customers; \(C\) – many production sites; \(O\) – many terminals in the departure area; \(D\) – many terminals in destination; \(x_{od}^L\) – flow on an arc of a railway network \((o, d) \in B\); \(B\) – set of arcs of railway transport, \(B = O \times D\); \(y_{od}\) – the number of trains on the railway arc \((o, d) \in B\); \(Z_{od} = l\) if the train is loaded for a volume above its carrying capacity and below the breakeven point on the arc of the railway \((o, d) \in B\); \(c^D\) – tariff rate; \(c^{pr}\) – prepayment; \(c^{po}\) – shipping costs; \(c^{f}\) – railway cost per kilometer in the railway network; \(c^L\) – cost in case \(c^L \geq c^{f}\); \(d_{ij}\) – distance between nodes \(i \in N\) and \(j \in N\); \(N\) – many nodes; \(x_{ij}\) – arc flow \((i, j) \in A \cup B\).

The intermodal transport process may include rail transport from terminals in the departure area to terminals in the destination area. If the network contains several terminals in one or both of these areas, and if rail transport is possible between terminals located in the same area, multi-stage consolidation is required.

For the model to work properly, it is necessary to introduce a number of restrictions on the volume of cargo delivery; sending goods from production sites to the terminal in the destination zone; on satisfying consumer demand; consolidation of goods on railways; the required number of trains \([10–16]\). Variables take integer values provided that production volumes, customer requirements, and train throughput parameters are integers. From model (1), we can conclude that its solution is a generalization of the classical transport problem.

Constraints (2) guarantee that the total volume of production will be delivered to consumers:

\[
\sum_{j \in OUC} x_{sj} = q_s \forall s \in S
\] (2)

Restrictions (3) and (4) represent the conditions of receipt / departure of goods at the terminals. Condition (3) ensures that all goods shipped from production sites to the terminal in the supply zone reach the terminal in the demand zone:

\[
\sum_{s \in S} x_{so} = \sum_{d \in D} x_{od} \forall o \in O
\] (3)

Restriction (4) indicates that all goods arriving at the terminal in the destination zone are sent to customers:

\[
\sum_{o \in O} x_{od} = \sum_{c \in C} x_{dc} \forall d \in D
\] (4)

Constraints (5) ensure the satisfaction of consumer demand:

\[
\sum_{i \in SUD} x_{ic} = n_c \forall c \in C
\] (5)

Restrictions (6) – (8) affect cargo consolidation on railways \((o, d) \in B\), setting variables \(y_{od}\). Restriction (6) determines the number of fully loaded train cars:

\[
y_{od} \geq \frac{x_{od}}{c^f} - 1 \forall (o; d)e\beta
\] (6)

Restriction (7) decides whether the train is selected for the remaining transport units \((z_{od} = 1)\). Here \(M\) – is positive number equals to or greater than load capacity:

\[
M \times Z_{od} \geq x_{od} - y_{od} \times c^f - z_{od} \forall (o; d)e\beta
\] (7)

Finally, restrictions (8) determine the number of transport units for which the railway service with a lesser load on the train is ordered.
\[ x_{ij}, x_{od}^L \geq 0 \quad \forall (i;j) \in U_{\beta}, (o,d) \in \beta \]  

(8)

Areas for solving variables are defined in (9) - (10).

\[ y_{od} \in N \quad \forall (o,d) \in \beta \]  

(9)

\[ Z_{od} \in \{0,1\} \quad \forall (o,d) \in \beta \]  

(10)

From conditions (2) - (10), we can conclude that the intermodal transport problem is a generalization of the classical one if rail transportation is omitted by applying \( x_{od}^L = y_{od} = z_{od} = 0 \).

Consider the solution to the problem of intermodal transport. The choice of transportation options, the restoration of traffic flows by applying the optimization model for a simple network with various cost parameters are made. The network is characterized by two production sites, three customers, one intermodal terminal \( O \) in the supply zone and one intermodal terminal \( D \) in demand zone. The location of the network nodes is selected so that the distance between the intermodal terminals \( d_{od} = 1000 \) km. Door-to-door road distances between production sites \( s \in S \) and consumers \( c \in C \), distances to transportation between production sites and the terminal \( O \), as well as the distance from the terminal \( D \).

Intermodal transport distances \( (d_{so} + d_{od} + d_{dc}) \) are much longer than the corresponding direct distance from door to door \( d_{sc} \). This is due to detour to intermodal terminals.

To limit the number of possible changes in the parameters, consider a fixed ratio between the transportation costs for a railway with a partial wagonload and the transportation costs for a railway with complete wagonload. It is assumed that freight charges by rail transport with a partial wagon loading is 25\% higher than the cost of a complete wagonload, that is, we set \( e = 1.25 \) and get \( c_{LTL} = 1.25 \cdot c_{FTL} \). The cost rates before and after transportation are equal and are collectively referred to as transportation cost coefficient. These ratios vary systematically. From this complete factorial design of the experiment, we get more than 300,000 combinations of parameters. An analysis of these results shows that differently structured decisions are optimal in relation to specific groups of cost ratios.

A gradual decrease in the share of intermodal transport and changes in demand for rail services are caused by limited production volumes at production sites and the effects of the consolidation of intermodal transport. For these reasons, optimal solutions may show that customers are serviced by a combination of two or more services. The analysis reveals a mechanism that determines whether a rail service with less load on the train has been chosen or door-to-door trucking. Therefore, considering a client \( c \), who will be served by nodes \( s \), a shipper faces with a question whether the cost of intermodal transport remains lower than the savings resulting from the use of rail transport. The results of the study of changes in tariff rates depending on distance are shown in Figure 2.

![Figure 2. Dependence freight charges on distance and mode of transport.](image-url)
Figure 2 shows the changes in rates depending on the distances in rail and road transport. The analysis showed that the use trucking is economically sound only at distances of less than 60 km. As for long haul, the use of rail is beneficial. In other words, when choosing transportation it is necessary to determine the maximum distance at which the use of intermodal transport is effective.

3. Conclusion
The article considers the classical problem of intermodal transportation by choosing modes of transport, transportation services and intermodal terminals. This task relates to tactical planning and provides many solutions that are optimal under specific conditions. To determine the optimal system, an estimate of costs in real time conditions is necessary. The study proved that intermodal transport is a cost–effective alternative to long-haul trucking. A mathematical optimization model can be used by shippers to make decisions about servicing customers by road, rail or a combination of both, and includes a cost function and effect of cargo consolidation. If the transportation involves the operation of several terminals in the study area, multi-stage consolidation of transportation in the developed scheme is possible. Using this approach will create sustainable transport chains with low costs.

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