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# Solving a dynamic routing problem using an optimization algorithm

O A Lebedeva<sup>1\*</sup>, J O Poltavskaya<sup>1</sup>, V Gozbenko<sup>1,2</sup> and A Mikhailov<sup>3</sup>

<sup>1</sup>Angarsk State Technical University, Str. Tchaikovsky, 60, Angarsk, Russian Federation

<sup>2</sup>Irkutsk State Transport University, Str. Chernyshevskogo, 15 Irkutsk, Russian Federation

<sup>3</sup>Irkutsk National Research Technical University, Str. Lermontova, 83, Irkutsk, Russian Federation

E-mail: kravhome@mail.ru

**Abstract.** Optimizing the configuration of the freight transport network is a challenge. The search for the optimal route solution in a dynamic urban multimodal transport network is aimed at minimizing the cost based on accurate forecasting of traffic flows and cost estimation. The purpose of the study is to review a methodology that can be applied centrally, by an organization that develops solutions for routing shippers, minimizing the total cost, assuming that all shippers involved in transportation send their requirements to a single coordinating center. Evaluation of a multimodal cargo routing system with restrictions on the number of vehicles is based on a hierarchical approach. It consists of several stages: prognostic modeling of the state of the traffic load of the road network and cost estimation for optimization, which includes a methodology for finding the optimal load to accelerate the convergence of the algorithm.

## 1. Introduction

In the Russian Federation, as in other developed countries, transport is one of the largest basic sectors of the economy, the most important component of the production and social infrastructure. Transport communications unite all regions of the country, which is a necessary condition for its territorial integrity, the unity of its economic space. They connect the country with the world community, being the material basis for ensuring Russia's foreign economic relations and its integration with the global economic system. The growth of world trade has significantly increased the load on urban transport infrastructure, especially in megacities, where there are high volumes of cargo shipments. One of the most important tasks for the efficient operation of the freight transportation system in a multimodal environment is to use the same infrastructure for both freight and passenger transportation, which leads to heterogeneous flow. This heterogeneity reduces the efficiency of urban transport due to the different overall dimensions and dynamics of movement between passenger and trucks. Trucks are forced to stop at long distances and accelerate from the stopping point, spending more fuel and polluting the air. The situation becomes even more difficult during a decrease in network capacity due to traffic accidents or the closure of railway crossings, when operational regulation and redistribution of freight traffic in a multimodal network is required [1-7]. In the absence of freight transportation control, it is possible to face the dissatisfaction of demand with the available capacity, load imbalance.



An effective cargo routing system will reduce time and cost costs, help increase mobility, and sustainability of urban transport systems [8, 9].

In connection with the important role of freight transportation, many studies are devoted to the problems of modeling, routing and traffic planning. The fundamental task in algorithms is the search for the shortest routes (1 – 4). The main difficulty lies in using a mathematical model that has no solution when applied to complex networks. Software development opens up the possibility of applying approaches that go beyond network modeling. Traffic flows and their states can be predicted using simulation models, which are more complex and can cover phenomena that cannot be formulated using mathematical models.

In the article, we consider the hierarchical modeling methodology for setting the task of centralized multimodal cargo routing, in which there are restrictions on the entry of vehicles into certain parts of the transport network. The problem of multimodal cargo routing is formulated in two tasks: scheduling the service and transport network, which can take into account complex constraints and optimize the solution procedure. In the proposed approach, the methodology is based on load balancing, which coordinates individual route decisions for several shippers.

## 2. Materials and Methods

Centralized routing of cargo flow between departure and destination points assumes that all shippers send their requirements to the central dispatcher, who develops individual routing solutions for each shipper, minimizing the total cost of delivery based on the state of the multimodal transport network. A multimodal freight transport network can be represented as a directed graph consisting of a set of nodes (N) with a set of directional arcs (A) connecting the nodes. A node in a transport network can be a crossroads, a railway station, a port terminal or a warehouse. An arc in a transport network may be one segment of a roadway or railway track. Let I and J be the sets of source and destination nodes that are a subset of N. The number of rolling stock of railway and motor vehicles is limited by the capacity of the transport infrastructure. The article presents a model of a directed graph G consisting of a set of nodes (NS), modal segments (L) connecting nodes. The NS set is a subset of N consisting of departure and destination nodes that take into account the limitations of transport infrastructure (port terminals, freight depots and railway stations). A modal segment is a segment served by one mode of transport. A route consists of a set of modal graph segments that can be used to satisfy freight demand between departure and destination points.

The general task of cargo routing has two levels of solutions: routing the distribution of goods on the service schedule and scheduling vehicles in the network. Decisions on routing a graph that minimize the total cost depend on the dynamics of the transport network (traffic congestion, travel time along the arc, and vehicle costs). The dynamics of the transport network is affected by the service schedule, since the travel time and congestion of a segment of the road network or railway section are determined by the distribution of freight traffic. Restrictions on the distribution of the volume of transported goods on the service schedule include available modal segments and intermodal routes. Restrictions on entering the segment and sending a freight vehicle include arc capacity and vehicle characteristics, operational restrictions.

The article proposes the option of routing the demand for freight transportation between the departure and destination nodes, which minimizes the total cost of delivery. Temporal analysis is sampled at intervals  $|K|$  and is used to pose the problem.

The task of cargo routing can be expressed as follows [10]:

$$\min TC(X) = \sum_{k \in K} \sum_{i \in I} \sum_{j \in J} \sum_{r \in R_{i,j}} S_{i,j}^r(k) X_{i,j}^r(k) = \sum_{k \in K} \sum_{i \in I} \sum_{j \in J} \sum_{r \in R_{i,j}} C_{i,j}^r(k) + k_r T_{i,j}^r(k) X_{i,j}^r(k) \quad (1)$$

where  $i$  – departure node index,  $i \in I$ ;  $j$  – destination node index,  $j \in J$ ;  $k$  – time interval index,  $k \in K$ , where  $K = \{0, 1, \dots, |K|\}$ ;  $l$  – modal segment index in graph G,  $l \in L$ ;  $R_{i,j}$  – the set of all possible intermodal routes from departure destination points.  $i, j, r$  – intermodal route index from departure point  $i$  to destination  $j$ ;  $S_{i,j}^r$  – the average cost of servicing one container on the intermodal route  $r$  from

node  $i$  to node  $j$  at time  $k$ , consisting of the cost of the vehicle, excluding time  $C_{i,j}^f(k)$ , the cost of the intermodal route, travel time  $T_{i,j}^f(k)$ .

Equation (1) minimizes the total cost of meeting demand (TC), where  $X$  is the routing decision consisting of the distribution of demand for freight transportation along all possible intermodal routes on the service schedule.  $K_r$  – is the travel time of the intermodal route  $r$ .

$$\sum_k \sum_{r \in R_{i,j}} X_{i,j}^f(k) = d_{i,j}, \quad \forall i \in I, \quad \forall j \in J \quad (2)$$

Equation (2) represents the constraints of the conservation of demand.

$$\sum_{l \in L} \sum_{j \in J} \sum_{r \in R_{i,j}} \sum_{r \leq k} X_{i,j}^f(r) \delta_{l,r,r,k} = x_l(k), \quad \forall l \in L, \quad \forall i \in I, \quad \forall k \in K \quad (3)$$

Equation (3) is a demand model of the modal segment when  $\delta_{l,r,r,k} = 1$  – intermodal route need  $r$  with departure time  $r$  uses the modal segment  $l$  at time  $k$ . Otherwise,  $\delta_{l,r,r,k} = 0$ .

$$0 \leq x_l(k) \leq u_l(k) v_l(k) \quad \text{for } \forall l \in L, \quad \forall k \in K \quad (4)$$

Equation (4) represents the restrictions on entry into a particular segment and the vehicle capacity, where  $L^R$  – a set of modal segments in which vehicle restrictions exist. The proposed approach can be expanded to a common task:

$$X_{i,j}^f(k) \geq 0 \quad (5)$$

$$\text{considering, } d_{i,j}, u_l(k), v_l(k) \text{ for } \forall i \in I, j \in J, l \in L, k \in K \quad (6)$$

$d_{ij}$  – total need for the number of containers from departure node  $i$  to destination node  $j$ ;  $X_{i,j}^f(k)$  – the need for containers (units) from source node  $i$  to terminal node  $j$  using intermodal route  $r$  with departure time  $k$ ;  $x_l(k)$  – the number of containers using the modal segment  $l$  at time  $k$ ;  $u_l(k)$  – the availability of vehicles for the modal segment  $l$  at time  $k$ ;  $v_l(k)$  – vehicle capacity for modal segment  $l$  at time  $k$ .

The cost functions are not used in the problem due to non-linearities and complex variables of the transport network simulation model, but are used to assess the state of the graph and cost variables in the problem (1-6) for more accurate route solutions.

Let be  $Z(k) = [Z_1(k), Z_2(k), \dots, Z_{|A|}(k)]^T$  vector of traffic flows on the arcs of the network from 1 to  $|A|$  at time  $k$ .

The relationship of the volume of the traffic flow along the arc  $a$  with the volume of traffic and other parameters in the network can be expressed as a nonlinear dynamic equation:

$$z_a(k+1) = f_a(z_a(k), q_a(k), Y(k), k) \quad \text{для } \forall a \in A, \quad \forall k \in K \quad (7)$$

where  $z_a(k)$  – the volume of traffic flows on the arc  $a$  at time  $k$ .

$$Y(k) = [Y_t^p(k): \forall l \in L, \quad \forall p \in P_l] \quad (8)$$

$P_l$  – a set of all possible routes in the transport network that satisfy the needs for freight transportation of the modal segment  $l$  the same mode of transport;  $p$  – network path index of the vehicle for the modal segment  $l$ ,  $p \in P_l$ ;

In (7)  $f_a$  is a nonlinear and time-dependent function of the volume of the traffic flow on the arc  $a$ . The effect of traffic volumes on adjacent arcs at time  $k$  is denoted by  $q_a(k)$ , and  $Y(k)$  – this is the departure vector of the cargo flow from all the source nodes at time  $k$ , as in (8). Since the parameters  $z_a(k)$  and  $q_a(k)$  affects previous container shipments up to a point in time  $k$  (то есть  $Y(r)$  для  $\forall r < k$ ), only  $Y(k)$  included in the equation (7). The volume of arcs in the transport network depends on various factors, such as cargo and passenger traffic, changes in the network, traffic accidents.

Let be  $W(k) = [w_1(k), w_2(k), \dots, w_{|A|}(k)]'$  arc travel vector ( $\Delta t$ ) from 1 before  $|A|$  at time  $k$ . Arc transit time is a function of the arc volume at time moment  $k$ , which depends on the flows of other arcs, therefore:

$$W(k) = g(Z(k), k), \text{ for } \forall k \in K \quad (9)$$

Let be  $t_l^p(k)$  travel time  $p$  if the freight vehicle leaves the source node in the modal segment  $l$  at time  $k$ . Suppose path  $p$  contains arcs,  $a_{p,1} \rightarrow \dots \rightarrow a_{p,N_p}$ , where  $N_p$  – total number of arcs on the way  $p$ . Define  $e_{a_p, n_p}(k)$ , as the time of entry into the arc  $a_{p, n_p}$  for a freight vehicle, using path  $p$  with departure time  $k$  from the origin. Then the travel time can be calculated as follows:

$$t_l^p(k) = \sum_{n_p=1}^{N_p} W_{a_p, n_p} \left( e_{a_p, n_p}(k) \right) \quad (10)$$

$$e_{a_p, 1}(k) = k \quad (11)$$

$$e_{a_p, n_p+1}(k) = e_{a_p, n_p}(k) + w_{a_p, n_p} \left( e_{a_p, n_p}(k) \right), \text{ для } n_p = 1, \dots, N_p - 1 \quad (12)$$

The task of sending the vehicle, taking into account the decision of the graph, can be expressed as:

$$\min \sum_{k \in K} \sum_{l \in L} \sum_{p \in P_l} \left( c_l^p(k) + \eta_l^p(k) t_l^p(k) \right) y_l^p(k) \quad (13)$$

where  $\eta_l^p(k)$  – vehicle travel time  $p$  for the modal segment  $l$ ;  $c_l^p(k)$  – cost of vehicle costs excluding travel time  $p$  for the modal segment  $l$  at time  $k$ ;  $t_l^p(k)$  – vehicle travel time  $p$  for modal segment  $l$  at time  $k$ ;  $y_l^p(k)$  – the number of containers using path  $p$  to satisfy the demand of the modal segment  $l$  at time  $k$ .

The objective function (13) is the total cost of transportation in the freight transport network, which is equal to TC if  $X$  is a possible solution to problem (1-6).

$$\sum_{p \in P_l} Y_l^p(k) = x_l(k), \text{ for } \forall l \in L, \forall k \in K \quad (14)$$

$$y_l^p(k) \geq 0 \text{ for } \forall l \in L, \forall p \in P_l, \forall k \in K \quad (15)$$

Constraints (14) and (15) are introduced to adjust demand in each modal segment.

$$\text{Given } X \in \Omega \quad (16)$$

Allowable set  $\Omega$  (16) is defined by constraints (2-6). Dynamic functions (7-9) are difficult to express directly mathematically because of non-linearities and complex interactions of traffic flows.

The optimization problem (1-6) may include penalty functions

$$\min J(X) = TC + \sum_{k \in K} \sum_{l \in L} \sigma_l \phi_l(x_l(k), u_l(k), v_l(k)) \quad (17)$$

where  $\sigma_l$  – modal segment penalty ratio;  $\phi_l$  – the penalty function of the modal segment depending on the type of cargo, as well as the possibility of entering the vehicle and the level of throughput in the modal segment.

In (17), all necessary conditions for minimizing the problem are taken into account - routes for one demand group are used that have the same marginal cost, which is less than the marginal cost of unused routes. The marginal cost of an intermodal route is defined as the partial derivative of the revised total cost  $J(X)$  with respect to the load on the route.

### 3. Results

The proposed approach to solving the problem of cargo routing consists of the following steps:

1) Data collection – the physical network of traffic flows and the upper levels of route optimization are combined, it includes the accumulation of statistics on the transport network by various methods, using a global positioning system installed in vehicles equipment, traffic sensors [11]. All collected data are entered into a simulation model, which is reconfigured to fit measurements for accurate prediction.

2) Simulation models are – developed to assess the main characteristics and dynamics of the multimodal transport network, taking into account decisions on the routing of the graph, freight and passenger traffic and changes in the network (traffic accidents, closure of sections of the road network) [12,13].

3) Cost estimation – determination of the cost of the intermodal route using the solution according to the graph and the search for optimal routes for the movement of trucks in the subnet. Then, travel time and cost are used to update segment maintenance costs. The scheduling algorithm is used to find the best schedule that minimizes the total cost.

4) Graph optimization – control of the entire decision-making process, while the algorithm searches for new routing decisions that can reduce the total cost until certain conditions are met, including reaching the maximum number of iterations or reducing the total cost (relative to a predetermined value) between two consecutive iterations. As soon as one of the conditions is satisfied, the final transport network is formed to implement the decision on the routing of freight traffic.

#### 4. Discussion

The replacement of mathematical functions by simulation models is carried out to generate more accurate volumes of traffic flows on the arc and its transit time. The resulting transit time of the modal segment is used to update the route time variables (1) in a manner similar to (10-12), which restores the indicator as the sum of the travel times of the path arcs.

The article considers a freight traffic routing system based on a hierarchical management methodology for solving a problem with restricting the entry of vehicles of a certain carrying capacity into specific network segments. It consists of several stages: prognostic modeling of the traffic load of the road network and cost estimation for optimization, which includes a methodology for finding the optimal load to accelerate the convergence of the algorithm.

#### 5. Conclusion

The methodology can be applied centrally by an organization that develops solutions for routing shippers, minimizing the total cost, assuming that all shippers involved in transportation send their requirements to a single coordinating center. The search for the solution to the optimal route in a dynamic urban multimodal transport network is aimed at minimizing the cost based on accurate forecasting of traffic flows and cost estimation.

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