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## METHODS AND ALGORITHMS TO SOLVE THE VEHICLE ROUTING PROBLEM WITH TIME WINDOWS AND FURTHER CONDITIONS

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**Abstract:** In this paper methods and algorithms are examined for solving one important problem of transport logistics, namely formation of roadmap. The proposed mathematical model is based on the well-known multi-depot heterogeneous vehicle routing problem with time windows algorithm. Modifications of the model provide additional conditions and restrictions. Algorithmic support of information transport system in an enterprise is connected with features of the vehicle routing problem. The suggested solution is based on modified Clarke and Wright Algorithm and Variable Neighborhood Search. The risk on the roads and the cost of toll roads are calculated, too.

**Keywords:** Formation of roadmap, Transport logistics, Clarke and Wright algorithm, Technologies of Yandex.Maps, Variable neighborhood search, Risk on roads

### 1. Introduction

Transportation is one of the most important parts of logistics systems. Improving transportation efficiency is one of the ways to reduce overall costs.

The concept of ‘transportation’ may cover the following spectrum of real-world enterprise problems:

- Organization of transport processes from supplier to the enterprise;
- Organization of transport processes between enterprise objects, for example movement of raw materials from receipt to the production of goods;
- Organization of the transport processes of goods to customers;
- etc. (several more less crucial transportation subtasks could be listed).

The problem of increasing efficiency of transport process should be divided into three areas: manufacturing, operational, program-target management [1].

The following sub-tasks are parts of the task 'Organization of transport process of goods to customers':

- choice of transport mode, formation of the vehicle fleet;
- determination of the degree of consolidation, formation of roadmap;
- packing problem, choice of logistics carrier.

All the above subtasks are also difficult, since both general and specific characteristics of the enterprise should be taken into account in the solution. Research in this area is still rather active, in spite of the large number of relevant publications [2]-[15].

The problem statement of formation of the roadmap is considered as substantiation of the mathematical model of Multi-Depot Heterogeneous Vehicle Routing Problem with Time Windows (MDHVRPTW) [13], [14] and its modifications. Methods, algorithms and information technologies for the solution of the problem are described. Data of a petrochemical enterprise are used for calculations and demonstration.

To help the reader in *Table I* the most often used abbreviations of the paper are listed.

*Table I*

Abbreviations and understanding

VRP	Vehicle Routing Problem
VRPTW	VRP with Time Window
HVRPTW	Heterogeneous VRP with Time Windows
MDVRPTW	Multi Depot VRP with Time Window
MDHVRPTW	Multi Depot HVRPTW
MDVRPPDTW	Multi Depot VRP with Pick-up and Delivery, and TW
FSMVRPTW	Fleet Size and Mixed VRP with Time Window
SDVRPTW	Split – Delivery VRP with Time Window
PVRPTW	Periodic VRP with Time Window
VRPTWSTST	VRPTW with Stochastic Travel and Service Time
c.u.	conventional units
DM	Decision-Making
OPT	Optimal

## 2. The problem and solution of the roadmap

The problem of rational routes formation may be described as a vehicle routing problem.

The modification of the mathematical model of the MDHVRPTW [16], [17] with additional restrictions and conditions is proposed in order to form rational routes for the transportation of finished products at a minimum of the planned (acceptable) costs.

The modifications are the following:

- Each customer can be serviced by several vehicles;
- Vehicles are not shared with more than one depot (each vehicle belongs to the base depot), i.e. a route should begin and end at one depot;
- The demands of each customer must be completely satisfied;
- The capacity of the vehicles must not exceed their load capacity;
- The boundaries of the 'time windows' for each customer must be observed, or else the planned costs increase by the amounts of the fixed penalties;
- Similarly, the time period of the route of each vehicle must not exceed the specified time period of each vehicle's return to the depot, otherwise the planned costs increase by the amount of the fixed penalty;
- The order summary for each vehicle must not exceed the capacity of the depot.

Selected routes must adhere to

- type M roads (the federal highway that connects Moscow with the capitals of other countries; the administrative centers of subjects of the Russian Federation refer to these types of roads as «M» roads);
- type P roads (highways of federal or regional significance that link the administrative centers of the Russian Federation);
- type A roads (highways of federal or regional significance that are entrances to major transportation hubs, e.g. airports, and entrances to special objects or exits from the administrative centers of subjects of the Russian Federation, which have no roads linking them to Moscow);
- sea or river ports, airports, railway stations, the borders of other countries, or roads linking federal highways to one another. Payment for the use of these roads at selected set of routes must not be higher than the fee that an enterprise is ready to pay for the use of toll roads, and the crash risk for the selected route must not exceed what the enterprise considers an acceptable value. The traffic situation on roads (traffic jams) must also be taken into consideration.

Rational routes that minimize the total costs must be found. These costs include the fixed cost of using vehicles (depreciation costs, cost of wear, restoration, all repairs, cost of maintenance, etc.), the cost of traveled distance and spent time (driver's wages), the cost of waiting time and service (additional driver's salary), the penalty for violating the time windows and the penalty for violating the time of return to the depot after servicing all customers on that specific route, and the cost of damages of the vehicles and of the goods from accidents.

### **3. Overview of some important methods and algorithms for solving the problem of roadmap formation**

Three basic extensions of the basic model VRP, namely, time windows VRPTW, the set of vehicle with different capacity (HVRPTW) and multi-depot (MDVRPTW) are discussed in the presented mathematical model.

Then achievements of the vehicle routing problem were studied in several papers by several authors, [13]-[15], [17]-[19] (*Table II*). In the right hand column the main

authors are listed as additional information. Details on results would need too much space.

Table II

Short summary - Methods and algorithms for VRP

References	METHODS	
	<i>Method of solutions</i>	<i>Authors involved</i>
VRPTW [19]-[21]	Branch-and-bound algorithm Hybrid evolution strategy Modified <i>Clarke_Wright parallel savings algorithm</i> Tabu search heuristic	P. Toth, D. Vigo P.P. Repoussis, C.D. Tarantilis, G. Ioannou D. Aksen, Z. Ozyurt, N. Aras D. Aksen, Z. Ozyurt, N. Aras
MDVRPTW [20], [21]	Hybrid heuristics Stochastic hybrid heuristics	I.D. Giosa, I.L. Tansini, I.O. Viera M. Mirabi, S.M.T. Fatemi Ghomi, F. Jolai c
MDHVRPTW [18], [6], [20], [21] [16]-[18]	Branch-and-cut-and-price algorithm Heuristic clustering algorithm Variable Neighborhood Search	A. Bettinelli, A. Ceselli, G. Righini R. Dondo, J. Cerdá
MDVRPPDTW [17], [18]	Particle swarm optimization algorithm	P. Sombuntham, V. Kachitvichayanukul
FSMVRPTW [20], [21]	Scatter search approach Multirestart deterministic annealing metaheuristic Three-phase metaheuristic	P. Belfiore, L. Faver, O. Braysy, W. Dullaert, G. Hasle, D.Mester, M. Gendreau O. Braysy O. Braysy, P.P. Porkka, W. Dullaert, P.P. Repoussis, C.D. Tarantilis
SDVRPTW [17]	Tabu search	S.C. Ho, D. Haugland, R. Seguin, M. Gendreau, G. Laporte
PVRPTW [20], [21]	Nonlinear integer multi-commodity network flow formulation New branch-and- bound strategies in branch and price <i>Variable neighborhood search</i> Column- generation method Integer linear programming solver with variable neighborhood search	N. Belanger, G. Desaulniers, F. Soumis, J. Desrosiers S. Pirkwieser, G.R. Raidl S. Pirkwieser, G.R. Raidl S. Pirkwieser, R. Gunther
VRPTWSTST [20], [21]	Tabu Search Tabu Search	X. Li, P. Tian, S.C.H. Leung D.Tasn, N. Dellaert, T. Woensel, T. Kok

The classification of VRPTW was described based on the material from [20], [21]. The main issue in these papers is the model MDHVRPTW. In [16] the mathematical model of MDHVRPTW and novel three-phase heuristic algorithmic approach are discussed, while paper [17] is about a local search improvement algorithm that explores

a large neighborhood of the current solution to discover a cheaper set of feasible routes: a modified variable neighborhood search algorithm is proposed. In [6] a modified variable neighborhood search algorithm is suggested using hybrid operator of insert and exchange.

The *Variable Neighborhood Search* is selected for solving the problem, as the algorithm has shown rather good results in solving combinatorial optimization problems are similar to the problems and tasks to be solved here.

#### 4. Algorithmic support of the problem of formation of roadmap

The *OPT\_Route* method ([8], [10]) was selected and used. This method is based on *Variable Neighborhood Search*, and it works as successfully as any other heuristics. A useful feature of the method is the ability to use different neighborhoods (Demand Move, Swap Move, Shift Move, Swap, 2 - opt). The method relates to the improvement heuristics.

The main idea of *OPT\_Route* is as follows: all customers, taking into account the distance between depots and clients, are appointed a defined cluster in the clustering process; within each cluster a set of rational routes are found using local search procedures with neighborhoods varying and take into account the conditions and limitations described above (Section 2). The last step of this method is to find indicators (consumption of gasoline, mileage of vehicles) for the found routes.

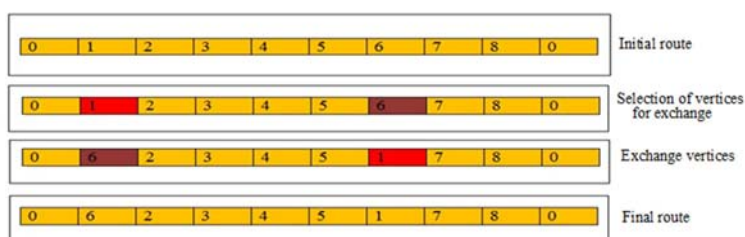
The formation of rational routes in planning a transport process system for the delivery of finished products is based on the following classical algorithms: the Clarke and Wright Algorithm and the Variable Neighborhood Search.

These algorithms have been modified to work for the subtask of the formation of a rational route in connection with the content of the roadmap problem statement.

The 6 steps presenting the algorithm *OPT\_Route*: are given below:

- Step 1. *Visualization procedure* - visualization of depots and customers on an interactive map of highways;
- Step 2. *Clustering procedure* - separation of all vertices, depots and customers into different clusters. The set consisting of one depot and some customers that are within the allowed distance from the depot refers to the cluster;
  - Input data: customer location and location of depot (address, geographical coordinates), distance between points;
  - Output data: clusters. Each cluster includes the following information: concrete depot, customers assigned to this depot, geographical coordinates, and distances between points;
- Step 3. *Rat\_Route procedure* - finding the set of rational routes for delivery of goods in each cluster. Here is scheme of *Rat\_Route procedure*;
  - Input data: information on depots and vehicles; information on risks and road sections; information on damages; information on toll roads; information on traffic jams; information on clusters; information on demands; time windows.
  - Output data: the set of routes.

- Step 3.1. Formation of limits from the list of possible restrictions specified in section 1 for validation of found routes, e.g. split delivery, limit of total time spent, limit of total traveled distance, possible types of roads, maximum coefficient of road accidents on the roads, damage accidents, toll roads, traffic situation;
- Step 3.2. Formation of the initial set of acceptable routes for each cluster by using the modified Clarke and Wright algorithm. Modification of this algorithm consists of an additional check for feasibility of routes for the selected conditions in step 3.1. At this step calculation of the objective function is performed. The objective function is cost, which includes the fixed cost of using vehicles (depreciation costs, cost of wear, restoration, tire repair, cost of maintenance and the repair of rolling stock), the cost of traveled distance and spent time (driver's wages), the cost of waiting time and service (additional driver's salary), the penalty for violating the time windows and the penalty for violating the time of return to the depot after servicing all customers on that specific route, and the cost of damages from accidents;
- Step 3.3. Finding rational routes by using procedures of local search with variable neighborhoods. At first, the solution on the previous step (the set of routes) is taken, secondly the selection random structure type of neighborhoods and procedure of local search for finding acceptable routes is applied (see *Fig. 1*), thirdly, verification of 'new' routes on violation of the selected constraints in step 3.1 and choice of the best solution by using the criterion - Best Improvement;



*Fig. 1.* Determination of rational route using neighborhood structure - *Swap Move*

- Step 4. *Activities\_Route procedure* - calculation of the required indicators of rational routes with using economic indicators;
  - Input date: information about route;
  - Output date: fuel cost, amortization costs, wheels costs, and costs for materials, spare parts and maintenance, additional driver fee, overheads, vehicle mileage, departure and arrival time;
- Step 5. *DM\_Carrier procedure* - the process of making a decision regarding the use of logistics carriers for delivery;
  - Input date: information about route, economic indicators, criteria for selection of logistics carriers, information about logistics carriers;

- Output date: recommendations on outsourcing;
- In this procedure, criteria for decision-making of the need for cooperation based on the expert opinion are formed; reference values of the criteria and the maximum difference between the values and reference values are determined; decision rules on outsourcing for transportation are formed. The decision-maker receives recommendations on outsourcing based on the developed methods;
- Step 6. *Final\_Route procedure* - formation of the final decision;
  - The decision maker analyzes the recommendations and roadmaps, and makes transportation plan.

## 5. Comparison of the results

The model presented in this paper contains 3 main limitations of the VRP, namely: time windows, vehicle fleet of various capacities and a lot of depots.

For increased effectiveness of the proposed *OPT\_Route* algorithm it is suggested to use test sets with the best known solutions for the VRPTW mathematical model, taking into account time windows and load capacity of vehicles. The total distance traveled and the numbers of used vehicles are considered as criteria for assessing the quality of the solution.

The test dataset is the classical 56 examples of Solomon ([22] and [23]). These examples are divided into six different classes of problems C1 and C2, R1 and R2, RC1 and RC2. The tasks of each class include 100 vertices and the central depot with vehicles of the same load capacity, but time windows are different. Test datasets with 25 and 50 clients were also examined, which were formed by cutting off the first 25 and 50 clients in each of 56 examples.

Experiments were done for 6 different groups considering the Solomon benchmark [23]. The main factors in the formation of test sets are the number of customers, coordinates of points (depots and customers), determining the position on the plane, the load capacity of the vehicle; time of customer service; duration and positioning of temporary windows.

In classes R1 and R2, points (depots and clients) have a random position on the plane, points (depots and clients) on the coordinate system are clustered in C1 and C2 tasks; points are arranged on the plane in the form of a random cluster structure in tasks RC1 and RC2. The tasks of R1, C1 and RC1 classes have a short customer service period that makes it possible to serve a small number of customers in one route (approximately 5 to 10). The tasks R2, C2 and RC2 have a long customer service period, which allows you to serve a larger number of customers in one route (over 30).

The client coordinates are the same for all tasks in one test class (i.e. R, C and RC). Classes are classified into two types, '1' and '2' (C1 and C2, R1 and R2, RC1 and RC2). Tasks of the 1<sup>st</sup> type have the capacity of the vehicle is 200 c.u. while the tasks of the second type have the capacity of the vehicle in the range from 700 to 1000 c.u.

Tasks also have different width of temporary windows. Tasks of the 1<sup>st</sup> type (C1, R1, and RC1) have narrow time windows, and tasks of the second type (C1, R1, RC1)

have wide time windows. The travel time equals the corresponding distance in all tasks of the test data set.

Temporary windows are suggested to be considered as non-rigid constraints to the *OPT\_Route* algorithm check, that is, the customer service time depends on the customer's requirements, but may be violated with the addition of a penalty value to the objective function. The duration of the route should not exceed the threshold value, which is determined by the value of the return of the vehicle in the depot. The objective function is minimization of the total distance traveled.

In the well-known problem classes, the *OPT\_Route* algorithm showed that it is able to find solutions no worse than the known algorithms (series 1 - 6). The algorithm does not find a solution, or finds more than an hour of computer time on a task with 100 clients.

The experiment showed that the proposed algorithm works better on problems where the coordinates of points (customers) are randomly scattered and not grouped by distance, that is, on the classes of problems R1 and R2, new record solutions for tasks R201.25 and R205.25 were found in these classes.

Finally a remark to this section: [24] and [25] give good summaries of solutions of the routing problem using search methods for complicated, multi-depot situations.

## 6. Application of the method for a petrochemical enterprise

The selected petrochemical enterprise must deliver the finished products to 36 customers with the demands given in *Table III*.

*Table III*

The demand of customers - various types of finished products

Point	Type of goods	$q_{il}$	Point	Type of goods	$q_{il}$	Point	Type of goods	$q_{il}$
1	A	450	6	A/B	200/250	11	A	475
2	A	400	7	A	250	12	A	550
3	A	400	8	A	200	...	...	...
4	A	200	9	A	450	35	A	270
5	A	150	10	A	300	36	B	240

Each depot has a number of finished products of the first and second type (*Table IV*).

Preferable time windows of service and service times are known (Fragment is shown in *Table V*).

Open service Yandex.Maps are used to obtain information about the distances and travel times, taking into account travels with and without traffic jams between points (cities). The risk on the roads and the cost of toll roads are calculated according to the formulas of the algorithm.



Table IV

Quantity of goods in the depot

Type of goods	Quantity		
	<i>Depot № 1</i>	<i>Depot № 2</i>	<i>Depot № 3</i>
$l_1$	4200	4500	1700
$l_2$	250	2000	2500

Table V

Preferable time windows of service and service times

Point	Time		
	<i>Start of time window</i>	<i>Start of time window</i>	<i>Service time</i>
1	8:00	9:00	120
2	13:00	15:00	60
3	12:00	14:30	60
4	16:30	18:00	70
5	16:00	19:00	80
6	9:00	10:00	60

Special conditions and solution algorithm, which should be considered when constructing of rational route, are configured in the selection window in the software solution. The software solution allows using the following algorithms: local search with variable neighborhoods; local search with different neighborhoods (Demand move, Swap Move, Shift Move, Swap, 2 - opt), tabu search; and allows taking into account conditions described in second section.

The clustering procedure is used to solve this problem. Three clusters have been obtained:

$$K1 = \{e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8, e_9, e_{10}, e_{11}, e_{12}\};$$

$$K2 = \{e_{13}, e_{14}, e_{15}, e_{18}, e_{19}, e_{21}, e_{22}, e_{24}, e_{26}, e_{28}, e_{30}, e_{31}, e_{33}, e_{35}\};$$

$$K3 = \{e_{16}, e_{17}, e_{20}, e_{23}, e_{25}, e_{27}, e_{29}, e_{32}, e_{34}, e_{36}\}.$$

For example, the first cluster is considered first. Three rational routes are formed to serve 12 customers by using *Rat\_Route* Procedure with Swap Move neighborhood (see section 4). The routes have the characteristics given in *Table VI*. These characteristics were valid for the whole enterprise.

The design procedure is supported by interactive maps of different kinds. *Fig. 2* and *Fig. 3* are typical screenshots of maps used during the design. These figures provide the reader only qualitative information, the details are important only for the designer.

Table VI

Characteristics of the routes

No	Sequence of points	Value of objective function	Coefficient of accidents	Violation of time windows (minutes)
1	0 – 1 – 11 – 9 – 4 – 0	13153.19	$0.000066185 \leq 0.6$	40
2	0 – 6 – 10 – 7 – 2 – 4 – 0	13870.19	$0.000086185 \leq 0.6$	155
3	0 – 6 – 12 – 3 – 8 – 5 – 0	14609.49	$0.000088490 \leq 0.6$	116

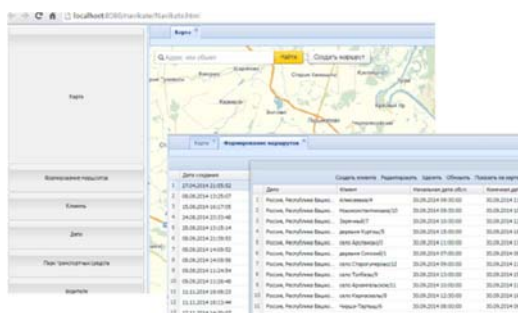


Fig. 2. Interface of the transport routing system

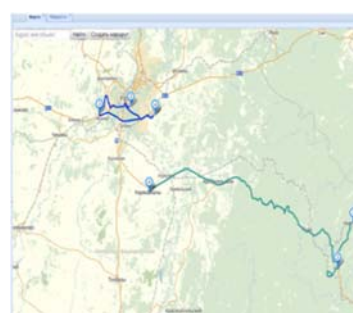


Fig. 3. Displaying the routes map

## 7. Conclusions

The main contribution of this study is that the modified MDHVRPTW model takes into account some additional conditions and limitations, in particular, the risk on the roads, the possibility of using of toll roads, and gives acceptable, useful results.

The use of this mathematical model is characteristic for the transportation goods pertaining to the class of 'dangerous'. The combination of well-known algorithms was not an easy task.

Modified Clarke and Wright Algorithm, Variable Neighborhood Search, calculation risk on roads and cost of toll roads, calculation of the required indicators, Yandex resources are used for algorithmic support of information-analytical transportation routing system in the enterprise.

The algorithm is realized with the use of modern high-level programming language and Java platform. Web-based client is implemented by using GWT. Eclipse was used as a development environment. Further test applications should be done to justify the solution and to assist in future improvements.

The industrial application proved the usefulness and applicability of the methods and algorithms described in this paper. However the work should be continued with

providing better quality interfaces, higher quality user manuals and other improvements, which are requested to make the system really useful and user friendly.

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