INTERNATIONAL BLACK SEA UNIVERSITY

FACULTY OF COMPUTER TECHNOLOGIES AND ENGINEERING
PhD. PROGRAM

INCREASE OF PERFORMANCE AND EFFECTIVENESS OF THE MULTI DEPOT VEHICLE ROUTING PROBLEM'S SOLUTION (ON THE EXAMPLE OF SOUTH CAUCASIAN LOGISTICS NETWORK

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Introduction

The thesis examines the value of real-time traffic information for optimal vehicle routing in a non-stationary stochastic network. Our goal is to develop a systematic approach to aid in the implementation of transportation systems integrated with real-time information technology. Based on many researches done in the fields of VRP and TSP we can implement them for our heuristics. Finding ways to develop decision making procedures for determining optimal driver attendance times optimal departure times, and optimal routing policies under stochastic time-changing traffic is firsthand goal of our research. With studies based on a road network in Georgia, we demonstrate significant advantages when using this information in terms of total costs savings and vehicle usage reduction while satisfying or improving service levels for just-in-time delivery. With such systems routing and controlling traffic and vehicles should be done more in more precise and easy manner. That means that many sectors of logistics industry can improve their work and make their services cheaper, that will also influence end-user. Our algorithm is adaptive and can react to number of stochastic effects and constrains that can be observed in real logistics networks.

Importance (significance)

Logistic networks and their tasks are nowadays most important area, from the stand point of vitally importance of Georgian logistic network in the context of increasing demand of international shipments (Silk road). Existing logistics network is not yet developed to satisfy these increasing requirements. Moreover, known to us algorithmic methods and techniques do not cover practical and realistic needs of (Silk road) international shipments. Therefore, there is an urgent need to develop relevant approaches and methods which can fully satisfy above mentioned problems and tasks. Those approaches and methods have to increase throughput of logistic network and generate significant economic effect. Modern society needs a constant increase in the volume of transport, increasing its reliability, safety and quality. This requires increasing the cost of improving the infrastructure of the transport network, turning it into a flexible, highly regulated logistics system. At the same time, the risk of investment increases significantly if the patterns of the transport network development are not taken into account, providing that the distribution of the loading of its sections is taken into account. Ignoring these patterns leads to the frequent formation of traffic jams, overload / underload of certain lines and nodes of the network, increasing the level of accidents, environmental damage. The theory of transport flows was developed by researchers of various fields of knowledge - physicists, mathematicians, operations research specialists, transport workers, economists. A wide experience of studying the processes of motion has been accumulated. However, the general level of research and its practical use is not sufficient.

Theoretical Value

As it is known, large variety of theoretical methods exists in this area. However, they can't satisfy practical requirement of Georgian logistics network, in particular with increasing impact of new developed intentional Silk Road logistic network. Most of existing nowadays heuristics cannot provide full specter of solutions for real life logistics networks. This theoretical framework will be used as a base for the practical and concrete algorithms. For example, in the existing paradigm, uncertainty and stochastic nature of the VRP is not fully reflected. With this in mind new theoretical approaches (accounting for practical needs of real environment) have been developed in the thesis. The solution of such problems is impossible without mathematical modeling of transport networks.

The main task of mathematical models is the definition and forecast of all parameters of the transport network functioning, such as traffic intensity on all network elements, traffic volumes in the public transport network, average traffic speeds, delays and time losses. All the said above was implemented in the approach of the thesis and has great importance for the future researches.

Practical Value

Main goal of the following research is to investigate existing approaches in the area of multi depot vehicle routing problem, to reveal its suitability to the practical needs of the Georgian logistic network and to develop new techniques and methods which will satisfy above mentioned needs. In particular, the following issues have to be developed in the thesis:

- A theoretical approach that can manage the uncertainty and stochastic nature of VRP in real life environment.
- Mathematical models which can accurately predict transportation stochastic parameters such as traffic volumes, congestion induced delays etc.
- Combination of models, algorithms and applied technical tools which will ensure the search of practically acceptable optimal routes and usage of advanced technologies. Also the framework to be developed must provide users ability to modify routes in simultaneous and parallel manner.
- Modification of widely used ALNS algorithm (which cannot be directly used for practical needs of logistics networks being under investigation); this modification must be directly applicable to the conditions of Georgian transportation network.

- A suitable programming framework which can effectively implement developed heuristics and algorithms must be accurately selected or developed from scratch.
- Detailed research of all statistical data, which may have important impact on the main traffic characteristics (like types of road congestions, delays, etc.,) on areas of interest. In case of absence of such data, reliable methods of determination and obtaining such information must be developed in the thesis.
- Convenient programming tools which help developed methods to be effectively implemented in practice must be selected.
- Technical implementation of proposed approaches and algorithms must be maximally cost effective.

Novelty

In the thesis a new set of algorithms and applied tools which combine the application of known algorithms for searching optimal routes (taking into account the actual conditions on the sections of planned routes) and usage of new technology of autonomous components ensembles, has been developed. In particular, the developed program complex allows users to modify promptly current routes based on local information and choose the most accessible routes which reflect local real situation. The originality of the developed complex also lies in the fact that all the necessary calculations are made by the autonomous components, associated with specific cars, in virtual machines of datacenters. This allows users to modify routes in simultaneous and parallel manner without the need to install expensive equipment and software in vehicles. The later significantly reduces the duration and cost of the necessary calculations. The technology developed in the thesis will also help to improve the efficiency and safety of traffic planning for unmanned vehicles.

Research Methods

In the thesis the following methods have been used:

- Collection and classification and estimation of necessary data.
- Modeling and simulation for obtaining required important parameters and characteristics of processes involved in the research.
- Intensive usage of global optimization methods.
- Developing and usage of wide specter of programming solutions.

- Deployment of modern advanced technical solutions to provide maximum effectiveness of proposed models and algorithms, which may result in significant reduction of costs.

Thesis Limitations

Due to the non-availability of data for Armenia and Azerbaijan logistic networks this dissertation is based on realistic information for Georgian logistics network. However, all of the developed methods and algorithms can be applicable to Armenian and Azerbaijan logistics network without significant changes.

Chapter I – Literature Review

Problem review

This dissertation discusses the problem of routing vehicles with time windows and in real-time conditions. To improve the efficiency of operational management, it is expected to use information and communication systems based on mobile technologies. This includes, first of all, mobile communication in real time between the control center and the drivers. Our goal is to maximally automate scheduling and planning routes and further control of vehicles and granting drivers with up-to-date information about possible difficulties in their route. Algorithms and framework have to work stable and fast, while taking in account stochastic nature of traffic flow and possible unplanned delays. Maximal automation means that each vehicle should be equipped with GPS and every driver has to have Smartphone to receive information about routes, plans and possible difficulties ahead on the road and routes to avoid them. So that datacenter can control process flow. As mentioned above each vehicle should be equipped with nowadays gadget and ACE has to have each AC assigned to each individual vehicle and depot. Also such kind of algorithm has to be flexible enough for concerning backhauls vehicle accident and many other unpredicted factors. It is obvious that such a huge framework won't be able to always complete every task that is given due to a stochastic nature of traffic itself. So we consider that it should get closest to optimal solution, to minimize total expenditure of the company and serving highest possible number of customers daily. If still many casualties occur daily algorithm has too find solution for solving this issue for example advising to add vehicles to fleet or maybe to add new depots in different locations.

VRP

Vehicle Routing problem (VRP) has been delineated along with outlined, quite thirty years past. VRP is the hardest optimization combinatorial problem. VRP is represented as "For every specific list of POIs (points of interest) with specific range of vehicles, cargo should be delivered to every customer". Main challenge is to make minimum (the optimum) list of (routes) for specific range of vehicles. The difficulty in applying this problem to the real life circumstances, is in stochastic behavior of traffic and plenty of additional constrains. For this extremely complicated combinatorial optimization problem, both exact and approximate algorithms have been proposed

Interest in such problems is due not only to their great applied value, but also to the complexity of the solution. A number of reviews and monographs on this topic have been published. Of the most significant are the works of P. D. Christofides, G. Laporte,

Using nowadays technologies and completely different approaches, lots of latest studies were created during this field. individual still manage to imply novelties in on 1st sight recent drawback like VRP. The vehicle routing problem refers to any or all issues wherever best closed-loop system methods that touch completely different points of interest, like during this case cities and countries. In the thesis a lot of different approaches of solving VRP are outlined, reviewed and proposed.

TSP

VRP itself is based on The traveling salesman problem (TSP) which is one of the most intensively studied problems in computational mathematics. TSP main problem to be solved as follows : "*Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?* "The traveling salesman problem (TSP) is one among the simplest to understand however anyway NP-hard routing problem. The TSP aims to decrease total distances traveled by salesman.

Different heuristics of solving this problem are also reviewed, such heuristics as Insertion heuristics, Greedy heuristic, The closest neighbor heuristics, Christofide heuristic, Lin-Kernighan heuristics, Tabu search, Simulated annealing and Ant colony optimization heuristics.

Algorithms

Genetic algorithm (GA) works in an exceedingly method the same as our environment. A basic GA starts with a randomly generated population of candidate solutions. Some (or all) candidates are then mated to provide offspring and a few undergo a mutating method. every candidate features a fitness worth telling researcher however featable they're. By choosing the foremost match candidates for coupling and mutation the general fitness of the population can increase. Applying GA to the TSP involves implementing a crossover routine, a measure of fitness, and additionally a mutation routine. a decent measure of fitness is that the actual length of the result. completely different approaches to the crossover and mutation routines are mentioned in (Johnson &; McGeoch, 1995).

CE (cross entropy) method can be referred as a model based search algorithm and it is quite a simple, efficient and decent way for solving and studying difficult kinds of COPs. Boer et al. (2005) CE method has two phases of application. Firstly it is generating some random data (needed for research such as routes, nodes & etc.) Than changes the specification of stochastic mechanism according to information and resulting more optimal pattern in following iterations.

Created on simulation theory the CE technique is showing good results defining exact mathematical frameworks that derive fast and optimum rules. It is also easy to implement for researcher such an approach already was applied for numerous optimization problems.

Branch and bound (B&B) methodology is today one amongst most generally used approach for determination large scale NP hard issues in combinatorial optimisation. Implementation of bounds for the perform to be optimized combined with the worth of the present best result allows the algorithm to look elements of the answer area solely implicitly.

Evolutionary algorithms are a class of nonlinear random optimization principle. Main Evolutionary algorithm principle is based on our nature itself. These types of algorithms tend to imitate main idea of evolution, survival of the fittest. EA is a consequence of computational approaches to adopt nature laws and evolution to solve difficult optimization problems. Such kind of approach is used in many spheres mainly for the optimization problem and the learning problem. For optimization, finding the optimal solution within the problem area. Optimization problems and learning problems are interconnected with each other. In evolutionary algorithms every individual from the whole population is a potential solution for the problem given. For the problems that are too difficult to be calculated and optimized, for that purpose the learning algorithm could be used to do fitness approximation

For our paper, we decided to implement new approach for detecting bottlenecks in our city (or country) where biggest probability of collisions and congestions may occur. Due to the lack of statistical data from traffic ministry or Google or other systems that can provide any exact statistics for most congested routes, we decided to run simulations in Tbilisi.

Which later will be added to knowledge base of ACE’s and datacenters. Randomizing plans and making more and more simulations we will receive data and logs that should be analyzed and most problematic zones (routes) will be detected.

Of course stochastic real life situation on road can't be predicted by simulations, but this statistical data received from MATSim computations will be taken into account for Datacenters.

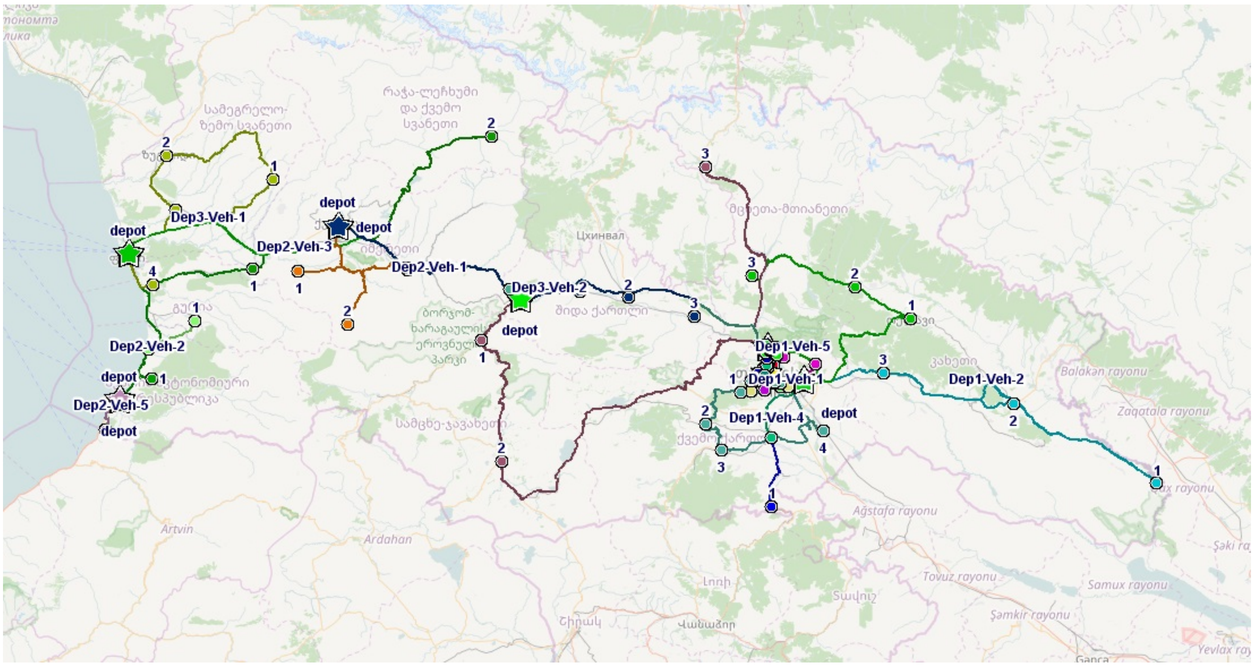
For planning departure time speed limitations of each node (route).

In the work the idea of Autonomic Components Ensembles (ACE), that are applied to the real-world Multi-Depots Vehicle Routing Planning with Time Windows (MDVRPTW), is proposed. Every vehicle is applied to each corresponding autonomic component AC (a virtual machine in datacenter) and share on-line data with every other vehicle. Moreover, ACs can reschedule routes in order to find the acceptable alternative routes that enable vehicles to meet time windows requirements and, at the same time, avoid the congested roads. Implementation of DEECo (Distributed Emergent Ensembles of Components) model to create dynamic ensembles of vehicles and non-congested route segments is also proposed in the paper.

Detailed description of components, components' knowledge, processes and interfaces is given.

Chapter II Methodology

Planning initial routes



The dissertation uses modern methods of operations research, including the construction of mathematical models, the theory of local search and computational complexity, as well as the methodology of experimental research using computer technology and commercial software packages for solving integer linear programming problems.

The formation of a route network is an important stage in the development of an efficient transport system of the city. The degree to which the route network is rationally developed, how well and harmoniously it is integrated into the transport network of the city, the satisfaction of the population with transportation and the efficiency of the transport companies depend. Under the route network is meant the aggregate of all routes of movement of transport on the territory of the city, district, etc. The route of traffic, in turn, is the path of the vehicle between the starting and ending stopping points in accordance with the schedule.

Simultaneously with the increase in the level of motorization of the population, the load on roads has increased, one of the essential parts of which is the distribution and logistics companies' vehicles fleet

In general, the scheme of work on the routing of cargo transportation consists of a number of stages. First, it is necessary to determine the shortest distances between all the points of departure and receipt of goods and between the road transport enterprises and the specified points, ie, to create a network of shortest distances. Then, taking into account these distances, determine the optimal fastening of consumers of the same cargo to suppliers.

At the last stage, the routes for the transport of different goods in the same rolling stock, the attachment of these routes to motor transport enterprises and the development of tasks for drivers to carry out the transportation of goods along the routes are determined. To do this, it is necessary to select those applications for the carriage of goods that can be carried out on the same rolling stock and which coincide in the time of the transportation. In this case, of course, you need to know the addresses of senders and recipients, the number and name of the cargo to be transported, as well as the distances between all senders and recipients.

Chapter III Adaptive real-world algorithm of solving MDVRPTW

Travel time delays are principally because of the thus known as 'recurrent' congestion that, for instance, develops because of high volume of traffic seen throughout peak commutation hours. Incidents, like accidents, vehicle breakdowns, weather condition, work zones, lane closures, special events, etc. are alternative necessary sources of traffic jam. this sort of congestion is labeled 'non-recurrent' congestion therein its location and severity is unpredictable. it's reported, that over five hundredth of all travel time delays are because of the non-recurrent congestion (Guner et al.

2012). because it was said, presence of congestions and their time characteristics don't seem to be known beforehand, however are discovered only the conclusion of an initial routing arrange is started. Once a vehicle chooses a link (road segment) to traverse, there's fixed likelihood that it'll truly traverse an adjacent link as critical the one chosen. A path from the supply to the destination is chosen a priori. Then there's a fixed likelihood upon inward to at least one of the nodes within the network that consequent link is full and an alternate route ought to be chosen.

For the initial construction of traffic routes or their adaptation, after the vehicles left the central warehouse, a series of routing tasks for vehicles with fixed routes is formulated. Each task characterizes a specific problem of static routing of vehicles with a non-uniform fleet of vehicles at a given time. A temporary scheduling method using sliding indicators is used and a re-optimization procedure is started to determine new traffic routes for vehicles each time the voyage time between the two points is updated. For vehicles that are in the process of adjusting the routes on their way to their destination, artificial intermediate vertices are created.

The repeated optimization algorithm is carried out further on the graph, which also includes these artificial vertices. Of course, artificial tops do not have their own demand, and vehicles must immediately leave them.

The theoretical approach (finding the answer of the primary stage: an initial (comprehensive) routing for all depot &; all of the vehicles) mentioned above, is implemented with the open-source toolkit Jsprit. Jsprit - a Java based, open source toolkit for determination rich traveling salesman (TSP) and vehicle routing problems (VRP))

Every vehicle must be controlled with agent. We count that an agent-based approach performs competitively with an on-line optimization approach. Modeling and solving a VRP by coordinating a set of agents can bring a number of advantages over more established approaches in the field of operations.

Agent advantages include the possibility for distributed computation, the ability to deal with complex sets of data from multiple customers, the possibility to react quickly on local knowledge and the capacity for real time (on-line) planning and routing.

Methodologies

The adaptive algorithm to solve MDVRPTW problem is projected within the paper. Realistic real-world situations, like presence of varied congestion types on roads, are rigorously thought of and accounted for within the algorithm. To overcome the shortage of realistic and reliable ways of congestion period estimation we have a tendency to use the MatSim large-scale agent-based simulation tool. This tool permits users to compose and run complex simulation models that are very close to the real-world situations. Our approach implements additionally involuntary elements ensembles conception. every vehicle is related to the corresponding autonomic component AC (a virtual machine in datacenter) and exchange on-line data with different vehicles. Besides, ACs will schedule routes so as to search out the suitable alternative routes that alter vehicles to satisfy time windows requirements and, at the same time, avoid the congested roads. The adaptive algorithm is able to reschedule and find alternative routed for several vehicles in parallel, that will increase the performance of proposed approach.

In the introductory in example review solution of the MDVRPTW (Multi Depots Vehicle Routing Planning with Time Windows) was described. The initial daily plan was received by using the Adaptive Large Neighborhood Search (ALNS) and Branch and Bound heuristics. But, this initial plan is only the first step of complex solution. In fact, as already mentioned above, it is just a solution for ideal road traffic, not considering a lots of realistic circumstances as congestions traffic accidents and so on. It cannot be counted as acceptable solution for real life traffic model. Since a fast growing number of vehicles and a limited capacity of the road network, traffic congestion has become a daily problem to overcome.

Due to traffic congestion are a reason for big delays, it is very expensive for companies such as logistic service providers and distribution companies that have to deal with the traffic daily. In specific, such delays cause massive expenses for hiring extra vehicle operators and also the use of additional vehicles, and if they're not accounted for within the vehicle route plans they'll cause late arrivals at customers or perhaps violations of driving hour’s regulations. Therefore, accounting for traffic jam includes a massive potential for value savings. We have developed a modification of the ALNS algorithm (written in the Jsprit framework).

One of the key functions of decision support systems in the field of transport logistics is the ability to calculate and construct efficient from the point of view of the cost of detour routes for various purposes on the transport network.

Our algorithm considers a probability of links’ congestion, estimation of probability of their release of busy route sections. Our modification of the algorithm can plan routes for any starting and finishing nodes. To provide the real-time adaptability the proposed heuristics uses the concept of autonomic components (AC) and autonomic component ensembles (ACE). ACs are entities with dedicated knowledge units and resources that can cooperate while making different computations. ACs are dynamically organized into ACEs. AC members of an ACE are connected by the interdependency relations defined through predicates.

Pseudo-code of proposed adaptive algorithm:

input: nsp: number of service points; RTW[nsp]: required time windows array;
PH[29]: planning horizon (starting and ending times);
nv: amount of available vehicles; np: amount of given characteristics of vehicles;
VP[nv,np]: vehicles characteristics array;
TCMD: travel and congestion management database ;
SRD: MatSim simulation results database;

Output: nr: amount of generated routes; RI[r]: set of generated routes;
NSSP: amount of successfully served service points;
OSSP: amount of overdue (delayed) serviced service points

1. **while** CurrentTime < PH[29] **do**:
2. spatial-temporal event occurs (a vehicle arrives to a service point at a certain time)
3. t← current time
4. i← number of a vehicle arrived to some service point at time t

5. j← number of service point SP at which the vehicle V_i arrived at time t
6. r← number of route along which the vehicle V_i travels at time t
7. k← number of SP, connected to SP_j in route r
8. MCong[j,k] ← congestion status of arc $A_{\mathbf{jk}}$
9. TW[r,j] ← required time window for the service point **j** in the route **r**
10. $CT_{\mathbf{jr}}$ ← type of congestion;
11. $tcong_{jr}^{0}$ ← starting time of congestion occurrence
12. $tcong_{jr}^{clear}$ ← expected time of congestion clearance
13. φ ← congestion duration; c← road non- congested capacity; ρ← road capacity during the congestion; q ← arrival rate of vehicles to the congested arc
14. Autonomic component AC_i receives a message from vehicle V_i
15. CDW_{jr}← cost to pay the driver that waits at the service point SP_j and executes the route ***r*** (see formula 1)
16. CTW_{kr}← cost (penalty) of violation the time windows assigned to the SP_k when executing the route ***r*** (see formula 1)
17. **if** $CDW_{jr} \leq CTW_{kr}$ **then**
18. decision: wait at SP_j

```
19.          else
          decision: reschedule and generate new route r*
          (by using the modified ALNS algorithm)
21.          end if
22.          if r* is null then
23.               decision: wait at SPj
24.          end if
25.          NSSP++ or OSSP++
23.          store obtained results to TCMD
24. end while
25. display obtained results
```

Chapter IV Application Of DEECo

In the work the idea of Autonomic Components Ensembles (ACE), that are applied to the real-world Multi-Depots Vehicle Routing Planning with Time Windows (MDVRPTW), is proposed. Every vehicle is applied to each corresponding autonomic component AC (a virtual machine in datacenter) and share on-line data with every other vehicle. Moreover, ACs can reschedule routes in order to find the acceptable alternative routes that enable vehicles to meet time windows requirements and, at the same time, avoid the congested roads. Implementation of DEECo (Distributed Emergent Ensembles of Components) model to create dynamic ensembles of vehicles and non-congested route segments is also proposed in the paper. Detailed description of components, components' knowledge, processes and interfaces is given.

In previous part we described the adaptive algorithm to solve Multi Depots Vehicle Routing Planning with Time Windows (MDVRPTW) problem. The heuristics is aimed to account for realistic real-world scenario, like presence of varied congestion varieties. The congestions are the foremost vital essential factors for the productive and practically acceptable solution of the MDVRPTW problem. Traffic jams cause serious delays.

A component's knowledge is exposed to the other components and environment via a set of interfaces (lines 5, 60). An interface (e.g., lines 1-2) thus represents a partial view on the component's knowledge. Specifically, interfaces of a single component can overlap and multiple components can provide the same interface, thus allowing for polymorphism of components.

Component processes are essentially soft real-time tasks that manipulate the knowledge of the component. A process is characterized as a function (lines 23-27) associated with a list of input and output knowledge fields (line 21,22). Operation of the process is managed by the runtime framework and consists of atomically retrieving all input knowledge fields, computing the process function, and atomically writing all output knowledge fields.

Being active entities of computation implementing feedback loops, component processes are subject to cyclic scheduling, which is again managed by the runtime framework [22]. A process can be scheduled either periodically (line 74), i.e., repeatedly executed once within a given period, or as triggered (line 28), i.e., executed when a trigger condition is met.

```
1. interface RouteSegmentsCongestionAware:
2.      initialSP, routeSegment, congestionStatus,  expectedCongestionInducedDelay

3. interface RouteSegmentAvailabilityAggregator:
4.          position, timetable, routeSegmentsAvailability

5. component  Vehicle  features RouteSegmentAvailabilityAggregator:
6.      knowledge:
7.          position = GPS(…),
8.          currentSP=(position, …),
9.          routeSegmentsAvailability=List<segmentsStatus>
10.         timetable = List<TimeWindowsForSPs>,
11.             route = {
12.                         List<SPs>,
13.                         onSchedule=TR
14.                          isFeasible=TRUE
15.                     },
16.          expectedCongestionInducedDelay=(…),
17.          vehicleParameters=List<Parameters>,
18.           costDriverWaitPayment=(….),
19.           costViolationTimeWindows=(….)

20.      process computeNewRoute:
21.              in routeSegmentsAvailability, in timetable,
22.              inout   route
23.          function:
24.                  if (!route.isFeasible ∧ (costDriverWaitPayment
25.                         >costViolationTimeWindows))
26.                      route ← ME.ALNS.computeRoute (position, timetable,
27.                                               routeSegmentsAvailability)
28.           scheduling: periodic(2000)


29.      process checkRouteFeasibility:
30.              in route,  in position, in  timetable, in routeSegmentsAvailabilities,
31.              out   route.isFeasible
32.          function:
33.              route.isFeasible ← ME.checkRouteFeasibility (route, position, timetable,
34.                                                   routeSegmentsAvailabilities)
35.          scheduling: triggered(changed(routeSegmentsAvailabilities) ∨
36.                                               changed(onSchedule))

37.      process  computeCostDriverWaitPayment:
38.             in routeSegment,
39.             in  CongestionInducedDelay,
40.             in  vehicleParameters,
41.             out CostDriverWaitPayment
42.         function:
```

```
            CostDriverWaitPayment← ME.computeCostDriverWaitPayment(routeSegment,
                                   vehicleParemeters,  CongestionInducedDelay)
        scheduling: triggered(changed(changed(routeGenerated.isFeasible)  ∨
                                   changed(onSchedule) ∨
                                  changed(routeSegmentsAvailabilities) )

    process  computeCostViolationTimeWindows:
           in routeSegment,
           in  CongestionInducedDelay,
           in  vehicleParameters,
           out costViolationTimeWindows
       function:
           costViolationTimeWindows ←
                 ME.computeCostViolationTimeWindows(routeSegment,
                       CongestionInducedDelay, vehicleParameters)
       scheduling: triggered(changed(changed(routeGenerated.isFeasible)  ∨
                                   changed(onSchedule) ∨
                                  changed(routeSegmentsAvailabilities) )

component  RouteSegmentsCongestion features RouteSegmentsCongestionAware:
   knowledge:
       initialSP=(…),
       endSPs =List<adjacentSPs>,
       routeSegment =(initialSP, endSP ∈ endSPs),
       segmentAvailability=(…),
       congestionStatus=[congestionStatus, type,  startingTime,
                      expectedCongestionClearanceTime,
                      congestionClearanceProbability],
        expectedCongestionInducedDelay=(….)

    process observeSegmentAvailability:
            out  segmentAvailability
        function:
            segmentAvailability ← MessageFromVehicle.getSegmentCurrentAvailability
        scheduling: periodic(1000)

    process computeCongestionInducedDelay:
            in routeSegment,
            in congestionDuration, in segmentNonCongestedCapacity,
            in segmentCongestedCapacity, in arrivalRate,
            out CongestionInducedDelay
        function:
            CongestionInducedDelay ←
                   ME.computeCongestionInducedDelay(routeSegment,
                   congestionDuration, segmentNonCongestedCapacity,
                   segmentCongestedCapacity)
          scheduling: triggered(changed(congestionStatus) )
```

An *ensemble* implements a dynamic binding among a set of components and thus determines their composition and interaction . In DEECo, composition is flat, expressed implicitly via a dynamic involvement in an ensemble. Among the components involved in an ensemble, one always plays the role of the ensemble's coordinator while others play the role of the members. This is determined dynamically (the task of the runtime framework) according to the membership condition of the ensemble.

```
ensemble UpdateRouteSegmentAvailabilityInformation
    coordinator: RouteSegmentAvailabilityAggregator
    member: RouteSegmentsCongestionAware
    membership:
        ∃ vehicle ∈ coordinator. routeSegmentsAvailability:
                    isAvailable(member.routeSegmentsAvailability)==TRUE
    knowledge exchange:
        coordinator: routeSegmentsAvailability ← member. routeSegmentsAvailability
        coordinator: expectedCongestionInducedDelay ← member.
                    expectedCongestionInducedDelay
    scheduling: periodic(2000)
```

An examples of a *component* definition has the form of a Java class:

```
@DEECoComponent
public class Vehicle extends ComponentKnowledge {
    public Position position;
    public ServicePoint currentSP
    public List< TimeWindowsForSPs > timetable;
    public Map<ID, segmentsStatus > routeSegmentsAvailability
    public Route route;
    public Delay expectedCongestionInducedDelay;
    public List <vehicleParameters> vehicleParameters
    public Cost costDriverWaitPayment,
    public Cost costViolationTimeWindows

  public Vehicle() {
      // initialize the initial knowledge structure reflected by the class fields
    }

@DEECoProcess
public static void computeNewRoute(
      @DEECoIn("routeSegmentsAvailability ") @DEECoTriggered Map<…>
                                              routeSegmentsAvailability
      @DEECoIn("timetable") List< TimeWindowsForSPs > timetable,
      @DEECoInOut("route") Route route
    ) {
        // re---compute the vehicle's route if it's infeasible
    }

@DEECoProcess
@DEECoPeriodScheduling(2000))
public static void checkRouteFeasibility (
          @DEECoIn("route") Route route,
          @DEECoIn("timetablel") List< TimeWindowsForSPs > timetable,
```

```
29.         @DEECoIn("position") Position position,
30.         @DEECoOut("route.isFeasible") OutWrapper<Boolean> isRouteFeasible
31          ){
32.             // determine feasibility of the route
33.          }
34            . ...
35.     }
```

A component definition has the form of a Java class (see the above code). Such a class is marked by the @DEECoComponent annotation and extends the ComponentKnowledge class. The initial knowledge structure of the component is captured by means of the public, non-static fields of the class (lines 3-11). At runtime, this initial knowledge structure is initialized either via static initializers or via the constructor of the class (lines 12-14). The component processes are defined as public static methods of the class, annotated with @DEECoProcess (e.g., lines 15-23).
The input and output knowledge of the process is represented by the methods' parameters.

The parameters are marked with one of the annotations @DEECoIn, @DEECoOut or @DEECoInOut, in order to distinguish between input and output knowledge fields of the process (e.g., lines 17-20). Each annotation also includes an identifier of the knowledge field that the associated method parameter represents.

When a non-structured knowledge field constitutes an inout/out knowledge of a process, the associated method parameter is for technical reasons (related to Java immutable types) passed inside an OutWrapper object (e.g., line 30). Periodic scheduling of a process is defined via the @DEECoPeriodicScheduling annotation of the process's method, which takes the period expressed in milliseconds in its parameter (line 25). Triggered scheduling is defined via @DEECoTriggered annotation of the method's parameter, change of which should trigger the execution of the process (lines 17-19).

Conclusion and Future Works

As the main goal of MDVRP is reducing the distances and on the basis of reducing distances also shortening total costs of whole travel, some effective heuristics should be applied to this given problem. There exist multiple techniques of solving VRP and TSP in exact methods which are described in this thesis. But with such methods optimal solutions cannot be obtained due too many constrains and complexity of real life environment. Such constrains as human factor and traffic congestions are not considered in most heuristics. Earlier in this thesis LNS and ALNS and their extensions were briefly explained. Both methods have great potential, but anyway there not enough for implementing of real world transportation problems. However, in general, this given heuristics work well with partitioning decisions. A number of powerful metaheuristics as Tabu search and genetic algorithm have also been proposed. But only by adopting and incorporating many approaches and heuristics we can get desired results. In our dissertation we proposed heuristics that can get close to optimal solutions. We believe that our approach can help in fields of logistic applied to our country's situation in this field.

In our thesis the following items have been studied and developed:

- Theoretical approach that considers uncertainty and stochastic nature of VRP real life environment in transportation fields
- Mathematical models which define and forecast all of the parameters of the transport network functioning, such as traffic intensity on all network elements, traffic volumes in the public transport network, average traffic speeds congestion conditions (congestion induced delays), have been proposed and developed.
- A set of algorithms and applied tools which combine the application of known algorithms for searching optimal routes and usage of new technology of autonomous components ensembles, has been developed. The developed program complex allows users to modify promptly current routes based on local information and choose the most accessible routes which reflect local real situation. The complex also allows users to modify routes in simultaneous and parallel manner without the need to install expensive equipment and software in vehicles.
- The modification of well-known algorithm ALNS which allows planning of partial routes by autonomic components (on virtual machines) has been proposed and implemented.
- The JSprit framework for modification of the proposed algorithms was used. Based on Java language this framework allows to conveniently describe and generate required solutions.
- To overcome the shortage of realistic and reliable ways of congestion period estimation we have a tendency to use the MatSim large-scale agent-based simulation tool. This tool has permitted us to compose and run complex simulation models that are very close to the real-world situations.
- Implementation of DEECo model to create dynamic ensembles of vehicles and non-congested route segments has been proposed and developed in the thesis.

The work is of a theoretical and experimental nature. New properties of various routing problems are obtained, known mathematical models are modified and new mathematical models are constructed, numerical methods of solution are developed. The developed methods are implemented as a set of programs. They have shown their effectiveness and can be used in solving practical problems of large dimension

List of Publications

1) Prangishvili A, Shonia O, Rodonaia I, Merabiani A,. (2017) Adaptive Real-World Algorithm of Solving MDVRPTW (Multi Depots Vehicle Routing Planning with Time Windows) Problem. *International Journal of Transportation Systems*, is.(2), p.1-6
2) Rodonaia I., Merabian A. (2016) Real-world applications of the vehicle routing problem in Georgia., *Journal Technical Science & Technologies (JTST*) IBSU vol*. 5,* is. (2) p.40 - 44
3) Merabiani A. (2017) Application of DEECO Framework to MDVRPTW Problem. "*Automated Control Systems*" (Online-Journal) is. N1(23)
4) Rodonaia I., Rodonaia M., Merabiani A. (2017) Application of Autonomic Component Ensembles Methods and Cloud Computing to MDVRPWTM Problem *Journal Technical Science & Technologies (JTST*) IBSU vol*. 6,* is. (1) p.30 -36