Variable Neighborhood Search for the Electric Bus Charging Stations Location Design Problem

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Abstract: In the paper we describe a mathematical model and propose a solution method for solving the electric bus charging station's location design problem. We formulate a location-scheduling mathematical model, where the set of possible charging stations can be in terminals and depots and tours of all vehicles are known and will be unchanged. To solve the problem, we propose solving method based on the Variable Neighbourhood Search metaheuristic. Using the proposed method, we realised extensive numerical experiments on the test datasets created from real operational data provided by the municipal transport operator in the city of Zilina.

1 INTRODUCTION

One of the main trends in transport sector nowadays is using of alternative energy sources as a power for vehicles due to the environmental aspects. Many manufacturers are developing vehicles with technologies like CNG, hybrid-fuel systems or full battery vehicles. This trend also affects bus manufacturers.

Many public transport providers are trying to include these types of vehicles into their fleet. The reasons for that can be environmental sustainability, government grants that support renewable resources, operating cost savings, or simply prestige in front of public and customers. Using these types of vehicles in service can be difficult due to the limitations that these technologies have. Especially electric buses have significant disadvantage compared to buses with combustion systems and that is maximum range. Most of the electric buses today has lower range than traditional diesel buses, and thus they cannot fully replace them. Therefore, providers must solve either battery charging or battery swapping in daily operating when using electric buses.

In battery charging technology, there are multiple possibilities. Electric bus can be recharged at stops by inductive road charging or with a plug-in technology at terminal stops. In these types of charging, charging speeds of chargers are rather fast. On the other hand, overnight charging is mostly in depots and charging speeds are lower because of durability of battery capacitors. If providers of public transport want to include electric buses into daily operations, they must think of building charging infrastructure.

In this paper we are dealing with a problem of electric bus charging stations location. We formulate location-scheduling mathematical model, where the set of possible charging stations can be in terminals and depots and tours of all vehicles are known and will be unchanged. To solve the problem, we propose solving method based on the Variable Neighbourhood Search metaheuristic. Using proposed method, we realised extensive numerical experiments on the test datasets created from real operational data provided by the municipal transport operator in the city of Zilina.

2 LITERATURE REVIEW

The topic of the charging infrastructure emerges in the literature during last few years. Authors are dealing mostly with the design of charging infrastructure for electric cars or a fleet of cargo vehicles. Some of the authors are also addressing the problem of charging infrastructure for electric buses considering the limitations related to this area. Authors in paper (Xylia, 2017) are proposing

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complex design of the charging infrastructure. Authors proposed linear model for the location of charging stations in the urban area and tested it on the data of Stockholm's bus lines network. The calculation was performed using a commercial CPLEX IP solver. To solve the problem of charging station location for electric buses, the modifications of the mathematical models for designing of the charging infrastructure for passenger electric vehicles can be used. In the paper (Dickerman, 2010) authors used a model that verifies the location of charging stations generated by the genetic algorithm. Several authors have been inspired by location problems leading to solve the mixed integer programming problem. In (Bauche, 2014) the demand for electric vehicles charging in the city of Lyon was estimated based on a traffic survey and a proper placement of charging stations was found by the cost minimization. The optimization problem was resolved by a universal IP solver. A similar methodology was used in works in (Cavadas, 2014), (Lam, 2014) and (Ghamami, 2015). Solutions of proposed optimization problems are usually verified using simulation methods such as in (Sweda, 2011). When designing a network of charging stations for electric buses, we will also take advantage of solving similar problems. In (Czimmermann, 2017) and (Kohani, 2017), authors have proposed the methodology and a mathematical model for location of charging stations for the fleet of electric vehicles using the location-scheduling model which is solved using the IP solver. We will also take advantage of solving different types of location problems. In the paper (Janacek, 2008) authors have designed an efficient algorithm for solving an uncapacitated facility location problem. The basic methodology for solving the problem of designing public service systems using location problems was described in (Janacek, 2012). Verification of all proposed methods and solutions will require extensive computational and simulation experiments, utilizing experience in designing of emergency medical stations network and simulation verification of these suggestions described in (Janosikova, 2017).

3 MATHEMATICAL FORMULATIONS OF THE PROBLEM

Our goal is to find optimal locations for charging stations for electric buses. In our approach we have focused on plug-in technology for charging vehicles. Number of charging points at each located charging station is part of the solution as well. The model was described in (Vasilovsky, 2019).

3.1 Problem Definition

The model respects current configuration of schedules and trips of buses. Possible locations of charging stations can be terminal stops and depots. At terminal stops, buses wait for a next trip, in depots they stay overnight. Daily tour of bus is to serve multiple trips of given schedule. Each trip is the set of stops that vehicle must serve at specified time. After the tour the bus returns to depot. Bus can have different schedules for each day in week thus the model simulates operating and charging of vehicles for multiple days (usually one week).

Let I be the set of terminal stops and depots, where charging station can be placed. Let D be the set of days. Let V be the set of all vehicles (electric buses). Daily schedule of vehicle $v \in V$ consists of ordered set of trips J_{vd} that vehicle serves during the day $d \in D$. Order of the trips is defined by the time sequence. Set J_{vd} contains deadhead trips (transfers without passengers between terminal stops) as well. Each trip starts and ends at terminal stop or depot. Each trip (except deadhead) has information about time of arriving at the stop and the time of leaving the stop. Arrival time at the terminal stop i_1 is the end time of the trip $j-1$ and departure time from the terminal stop i_2 is the start time of the trip j if $i_1 = i_2$. Otherwise, vehicle must serve deadhead trip between stop i_1 and i_2. Let's say that vehicle's $j-1$ trip has end time at 7:00 a.m. at the terminal stop i_1 and the next trip j starts at 7:20 a.m. at the terminal stop i_2 and i_1 6= i_2. Also let suppose that time needed for travelling between i_1 and i_2 is 10 minutes. Vehicle can leave terminal stop i_1 at any time between 7:00 a.m. and 7:10 a.m. to be at the terminal stop i_2 on time. For simplicity we allow that vehicle can only leave the stop at the following cases and that is immediately leaving the stop after arriving or staying at the stop as long as possible before needed transfer to the next trip's, i.e., at 7:00 a.m. or 7:10 a.m. in above example. From the point of charging, vehicle can be charged between 7:00 - 7:10 a.m. at the terminal stop i_1 or in the time 7:10 - 7:20 a.m. at the terminal stop i_2 (if there are charging stations placed at the stops i_1 and i_2). These cases are considered as the trips and set J_{vd} contains both. Because of that, additional set J_{pvd}, $J_{pvd} \subset J_{vd}$ contains trips $j \in J_{vd}$ with first case i.e." leaving the stop after arriving" case. This set is used for building constraints which choose from one of these cases. The value of energy consumption of vehicle v

$\in V$ on the trip $j \in J_{vd}$ during the day $d \in D$ is represented by b_{jvd}. Let T_{ijvd} is the set that represents time interval that vehicle $v \in V$ spends at the terminal stop/depot $i \in I$ before trip $j \in J_{vd}$ on the day $d \in D$. In this model, we use discretization of time intervals.

Set T_d is union of all T_{ijvd} for a day d. Charging speed of the charging station placed at stop/depot $i \in I$ is E_i in the kilowatt hour units (kWh).

Binary variable y_i represents decision about (not) locating of charging station at stop $i \in I$. It is set to 1 if charging station will be placed at the stop/depot i. Otherwise it is set to 0.

Integer decision variable q_i represents number of charging points at the station i. Binary variable x_{ijvtd} represents decision about charging vehicle. Variable is set to 1 if vehicle v is charged before the trip j at the stop i at the time t on the day d.

The continuous decision variable d_{jvd} represents amount of energy (kWh) stored in battery of the vehicle v before trip j on the day d. Value of the variable depends on amount of energy before trip $j-1$, consumption of energy on the trip $j-1$ and amount of the charged energy before trip $j-1$.

Binary decision variable z_{jv} represents decision which deadhead case will be applied for vehicle v and trips j and $j+1$. If z_{jv} is set to 1, vehicle v can be charged at the final stop of the trip $j-1$ (final stop of the trip $j-1$ is same as start stop of the deadhead trip j). If z_{jv} is set to 0, vehicle v can be charged at the final stop of the the deadhead trip j (start stop of the trip $j+1$).

3.2 Mathematical Model of the Problem

$$min \sum_{i \in I} q_i \tag{1}$$

$$q_i \leq S y_i \,, \forall i \in I \tag{2}$$

$$d_{1v1} = M \,, \forall v \in V \tag{3}$$

$$\sum_{v \in V} \sum_{j \in J_{vd}} x_{ijvtd} \leq q_i \,, \forall d \in D, t \in T, i \in I \tag{4}$$

$$d_{jvd} + \sum_{i \in I} e_i \sum_{t \in T_{ijvd}} x_{ijvtd} \leq M \,, \forall d \in D, v \in V, j \in J_{vd} \tag{6}$$

$$d_{jvd} \leq d_{j-1vd} - b_{j-1vd} + \sum_{i \in I} e_i \sum_{t \in T_{ij-1vd}} x_{ij-1vtd} \,, \forall d \in D, v \in V, j \in J_{vd} - \{1\} \tag{6}$$

$$d_{1vd} \leq d_{\tilde{j}vd-1} + \sum_{i \in I} e_i \sum_{t \in T_{i\tilde{j}vd-1}} x_{i\tilde{j}vtd-1} \,, \forall d \in D - \{1\}, v \in V, \tilde{j} \in J_{vd-1} \tag{7}$$

$$\sum_{i \in I} \sum_{t \in T_{ijvtd}} x_{ijvtd} \leq S z_{jvd} \,, \forall d \in D, v \in V, j \in Jp_{vd} \tag{8}$$

$$\sum_{i \in I} \sum_{t \in T_{ij+1vtd}} x_{ij+1vtd} \leq S(1 - z_{jvd}) \,, \forall d \in D, v \in V, j \in Jp_{vd} \tag{9}$$

$$y_i \in \{0,1\} \,, \forall i \in I \tag{10}$$

$$q_i \in Z^+ \,, \forall i \in I \tag{11}$$

$$x_{ijvtd} \in \{0,1\} \,, \forall d \in D, v \in V, j \in J_{vd}, i \in I, t \in T_{ijvtd} \tag{12}$$

$$d_{jvd} \in R^+ \,, \forall d \in D, v \in V, j \in J_{vd} \tag{13}$$

$$z_{jvd} \in \{0,1\}, \forall d \in D, \forall v \in V, j \in Jp_{vd} \tag{14}$$

The objective (1), is to minimize the total sum of charging points of the electric infrastructure. Constraint (2) ensure that charging points can be sited at the location i only if charging station is placed at the location i. Constraint (3) initializes battery state of the vehicles to full battery capacity on the first day before first trip j. Constraint (4) ensure that number of vehicles charged at the station i at the same time t must be lower or equal to number of charging points q_i at i. Constraint (5) prohibit to exceed battery capacity. Constraint (6) ensure that battery is charging and discharging according to trips and charging at charging stations. Constraint (7) is similar to constraint (6), except that constraint is applied for last trip e_j of the previous day $d \in 1$ and first trip 1 of the next day d. Constrains (8) and (9) ensure that vehicle v is charged before or after deadhead trip j. Constraints (10 - 14) are obligatory constraints.

4 VARIABLE NEIGHBORHOOD SEARCH

Variable Neighborhood Search (VNS) is a metaheuristic used to solve combinatorial and nonlinear optimization tasks. Its principle consists in systematically changing the structure of the neighborhood while searching for a solution. VNS can be implemented in a variety of ways, where slightly different steps and strategies can be used compared to basic VNS, but the principle of changing the neighborhood remains. In this work, we will deal with basic VNS (Mladenovic, 1997)

4.1 VNS

Changes to the structure of the neighborhood in VNS are based on the following principless:

- A local optimality criterion in one neighborhood may not be a local optimality criterion for another neighborhood.
- The global optimality criterion is a local optimality criterion for all neighborhoods.
- Empirical evidence shows that for most tasks the local optimality criteria are relatively close to each other.

VNS is described by three basic steps:

- Finding an initial solution (Shaking procedure) where the algorithm try to avoid a local minimum in the given area.
- Local search, where the current solution could be improved by using simple heuristics (replacement heuristics, insertion heuristics...).
- Changing of neighborhoods, where the algorithm can continue searching in the next neighborhood or start searching the neighborhoods from the first one.

4.2 Solution Approach

4.2.1 Creating a Starting Solution

The finding of initial solution for the VNS algorithm in our paper was implemented in two ways:

In the first method, a so-called "simulation test run" was launched, where charging stations and charging points were created in the event that an electric bus arrived at a stop and its battery capacity dropped below 70% and no charging point was available for charging, at that stop there was a new charging station built (if there was no charging station at the stop) or another charging point was added to the stop (if a charging station was already built at the stop).

In the second method, the number of charging stations to be built was determined At each stop it was decided whether a charging station would be built on it or not based on probability. If a charging station was built at a given stop, the number of charging points in the range of one to five was generated for it. Subsequently, the solution created in this way was subjected to verification of the admissibility of the solution using simulation. If the solution was admissible then this solution was used as the starting solution. Otherwise, the random solution generation process had to be repeated.

The advantage of the first method of generating the initial solution was the speed of the solution generation, because only one simulation run was always enough to generate an acceptable solution. In the second method, a situation could arise that the generated solution might not be admissible and the whole process could be repeated several times, which significantly increased the time for creating the initial solution.

The disadvantage of the first method was the same starting point for VNS algorithm, and thus the process of searching for admissible solutions was limited only to the set of admissible solutions that can be reached from this single solution. In the second method, it is assumed that due to the different starting points for the VNS algorithm, we were able to search a larger set of admissible solutions than in the first case.

4.2.2 Local Search

The local search process in the current neighborhood of the solution was implemented by randomly selecting a solution from the current neighborhood of the solution to avoid getting stuck in the local optimum and to examine a larger number of admissible solutions. Acceptance of the searched solution as the new best solution of the solved problem was realized in the case that the searched solution was admissible, where the verification of the admissibility of this solution was tested using simulation. When searching each neighborhood, the neighborhood was defined in a way where all solutions in the current neighborhood were better in terms of the objective function than the best solution found so far.

4.2.3 Change of Neighborhood

After completing the search of the current neighborhood for the best solution found so far, it was necessary to decide on the next neighborhood to be searched. If admissible solution was found in the current neighborhood, this solution was accepted as the best solution found so far and the search of the neighborhood continued in the first neighborhood of the defined neighborhood structure. Otherwise, the search continued in the next neighborhood of the neighborhood structure. If a situation arose in which the algorithm did not find an acceptable solution even in the last neighborhood of the defined neighborhood structure, the VNS algorithm ended its operation.

4.2.4 Structure of the Neighborhoods

The neighborhood structure for the VNS algorithm in our approach consists of five neighborhoods. The basic structure of the neighborhood is organized in such a way that when moving to the next neighborhood, this neighborhood is more extensive in terms of the number of solutions in the given neighborhood and more computationally demanding when choosing the solution from the current neighborhood.

The Neighborhood Induced by the Charging Point Withdrawal Operation
This neighborhood contains solutions that can be reached by removing any charging point from the best-found solution. When removing charging point, the charging station must not be cancelled, which means that this point could only be removed from stations where there is more than one charging point.

Neighborhood Induced by Canceling of the Charging Station
This neighborhood contains solutions defined by canceling the station from the set of built charging stations of the best-found solution, which means that the number of charging points at the cancelled charging station was set to zero.

Neighborhood Induced by Operations of Building a Charging Point and Cancelling the Station
In this neighborhood, there are solutions that can be reached by cancelling the charging station and at the same time adding a new charging point to an already built charging station from the set of built stations of the best solution found so far.

Neighborhood Induced by the Operation of Building a new Charging Station and Cancelling Another Charging Station
This neighborhood contains solutions that were defined by building a new charging station at a stop where a charging station has not yet been built and at the same time cancelling a charging station from the set of built stations. In the case of cancelled station, the condition that the given station had two or more charging points had to be met. The value of the objective function of the solution where the station with only one charging point would be cancelled is the same as the value of the objective function of the best-found solution.

Neighborhood Induced by the Operation of Exchanging Two Charging Stations
In this neighborhood, there are solutions that were created by exchanging the number of charging points between the two built charging stations of the best-found solution. To make such a solution more advantageous than the best solution found so far, one charging point was removed from one of these stations after the process of changing the charging points, which caused a decrease in the value of the objective function compared to the value of the objective function of the best solution found so far. Removing a point could also lead to the cancellation of the charging station itself.

4.2.5 Verification of Feasibility of the Solution

When generating a starting solution or examining the solution in the currently searched neighborhood, it was necessary to verify whether these solutions are feasible. A feasible solution for the problem of charging station placement is one where the charging station placement covers the requirements of all shifts performed during the week.

To verify the admissibility of the solution, a heuristic simulation approach based on the discrete event simulation of the operation of electric buses during the week was created. Individual events were inserted into the event calendar, which was implemented using a priority queue, where the priority for each event was the time at which the given event should occur. When selecting currently processed events, the event with the lowest occurrence time was selected. During the simulation, four types of events occurred:

Arrival of the Electric Bus at the Stop
In this event, the battery capacity of the electric bus was reduced due to the length of the route it travelled before reaching the relevant stop associated with the event. After each simulation spet, there was a check of the current battery capacity, where if the current capacity dropped to negative values, it meant that the electric bus would not be able to reach next stop. In this case, the simulation ended its operation, and the currently tested solution was marked as infeasible solution. If the battery capacity did not drop below zero value, further events were planned. If the charging station was built at the current stop and free charging point was available for charging, the start and end of electric bus charging events were added to the event calendar. The times of occurrence of these events were planned considering the currently missing battery capacity and the next connection that has electric bus to perform. If the stop of the next trip was different from the current stop, events for the start and end of the execution of the manipulation move to the starting stop of the next trip were added to the event calendar. If the electric bus had no other trip scheduled after the current trip, the electric bus ended its operation at the depot for the given day.

Departure of the Electric Bus From the Stop
The processing of this event meant the departure of the electric bus from the stop associated with this event.

Start of Electric Bus Charging
The processing of this event caused one charging point to be occupied at the charging station at the stop associated with the event.

End of Electric Bus Charging
When processing these events, the current battery capacity of the electric bus was increased in relation to the time during which it was connected to the charging point. After increasing the current battery capacity of the electric bus, one charging point was released at the charging station of the stop connected to the event.

5 NUMERICAL EXPERIMENTS

The implementation was carried out in the IntelliJ IDEA Community Edition 2020.3.2 development environment. The language used for the implementation was Java using JDK version number 15. The experiments were performed on our personal computer. Computer parameters:

- Processor: Intel(R) Core(TM) i5-7300HQ CPU @ 2.50GHz 2.50 GHz
- Installed RAM: 8.00 GB (Usable memory: 7.87 GB)
- Operating system: Windows 10 Home

To test the implementation of the VNS metaheuristic, it was necessary to choose the type of electric bus that will be used during the experiments. The Urbino 8.9 electric model from the Solaris brand was used as the type of electric bus. The parameters specified by the manufacturer for this electric bus are:

- Battery capacity: 140 kWh
- Energy consumption: 0.8 kWh/km
- Charging speed (plug-in): 1.33 kWh/min
- Charging speed - depot: 0.4 kWh/min

5.1 Test Scenarios

Three scenarios were proposed for testing, which represent the operation of the electric bus in different climatic conditions. All scenarios are created from real operation data provided by the DPMZ – transportation company.

The first scenario represents the operation of the electric bus during the spring months. During these months, significant effects of heat or winter are not frequent, therefore the parameters of the electric bus were kept as specified by the manufacturer.

Another scenario represents the operation of the electric bus during the winter months. Because of low temperatures on the battery, the capacity of the electric bus was reduced by 25%. Also in the winter months, it is necessary to heat the interior of the bus, which represents additional battery consumption, therefore the energy consumption per kilometre was increased by 35%.

The last scenario represents the operation of the electric bus during the summer months. During these months, the battery consumption is burdened by the operation of the interior air conditioning, therefore we also increased the energy consumption per kilometre by 35%.

For each of these scenarios, three variants of the type of electric bus used were used. In the first variant, the parameters of the electric bus were set to their default values, in the second, the battery capacity of the electric bus was increased by one third, and in the third variant, the battery capacity was reduced by one third.

5.2 Numerical Experiments

Experiments were carried out testing different configurations of the VNS metaheuristic in terms of the number of neighborhoods it searches and in terms of the order of neighborhoods in which the search is performed. During the execution of the experiments, metaheuristics was run several times due to the stochastic nature of the selection of elements in individual neighborhoods.

5.2.1 Testing the VNS Configuration

In this subsection, the individual experiments performed with different configurations of the VNS algorithm are explained. For each experiment, the value of the objective function, the number of charging stations and charging poits and the time required to perform the experiment with the given configuration are given. The effectiveness of individual experiments was evaluated according to the averages of the objective function values and the time required for the calculation.
In all tables the column denoted as “stat” is the number of locations where the charging station will be built, column denoted as “Pts.” Represents the number of charging points at all stations, “Obj.” is the value of the objective function and “comp. time” is the computation time in second.

5.2.2 Basic Configuration

For the basic configuration, all neighborhoods were used in the order in which they were listed in section 4.

Table 1: Results for Basic configuration.

	Scenario	Stat.	Pts.	Obj.	Comp. time [s]
Standard battery capacity	Spring	8	8	240 000	492
	Winter	10	16	318 000	720
	Summer	9	11	276 000	392
Increased battery capacity	Spring	8	8	240 000	593
	Winter	10	11	303 000	425
	Summer	8	8	240 000	275
Decreased battery capacity	Spring	10	13	309 000	284
	Winter	11	19	354 000	500
	Summer	10	14	312 000	493

Table 2: Results for three operations.

	Scenario	Stat.	Pts.	Obj.	Comp. time [s]
Standard battery capacity	Spring	8	9	243 000	148
	Winter	10	15	315 000	254
	Summer	10	12	306 000	198
Increased battery capacity	Spring	8	9	243 000	186
	Winter	9	13	282 000	201
	Summer	8	8	240 000	175
Decreased battery capacity	Spring	11	12	333 000	184
	Winter	12	19	381 000	234
	Summer	11	15	342 000	253

Table 3: Results for four operations.

	Scenario	Stat.	Pts.	Obj.	Comp. time [s]
Standard battery capacity	Spring	8	9	243 000	144
	Winter	10	16	318 000	239
	Summer	10	12	306 000	163
Increased battery capacity	Spring	7	10	219 000	135
	Winter	11	12	333 000	155
	Summer	8	8	240 000	155
Decreased battery capacity	Spring	10	12	306 000	168
	Winter	12	18	378 000	265
	Summer	11	17	348 000	281

5.2.3 Changing the Number of Operations Inducing Searched Neighborhoods

In the following experiment, algorithm configurations with a lower number of operations inducing individual neighborhoods were tested. In the first experiment, a configuration with the first three operations inducing neighborhood was used, in the second with the first four operations.

5.2.4 Changing the Order of Searched Neighborhoods

In this experiment, configurations were designed that contain all the neighborhoods of the basic configuration, but the order of searching these neighborhoods was changed. In this experiment, the order of searched neighborhoods was opposite to that of the basic configuration.

Table 4: Results for opposite order of operations.

	Scenario	Stat.	Pts.	Obj.	Comp. time [s]
Standard battery capacity	Spring	9	13	282 000	452
	Winter	11	20	357 000	516
	Summer	10	17	321 000	461
Increased battery capacity	Spring	7	13	228 000	391
	Winter	9	20	303 000	517
	Summer	9	18	297 000	453
Decreased battery capacity	Spring	11	18	351 000	521
	Winter	12	27	405 000	689
	Summer	10	19	327 000	537

5.3 Discussion

Configurations with three and four operations inducing individual neighborhoods gave the worst results in only two cases, even though they worked with a smaller number of admissible solutions searched. Since the neighborhood order of these configurations was taken from the order of the basic configuration, we can assume that the order of searched neighborhoods has a significant impact on the solutions that the algorithm can produce.

The configuration that searched neighborhoods in the reverse order of the base configuration did the worst, where the solution value it was able to deliver for individual scenarios represented the worst value delivered among all configurations in most scenarios.

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6 CONCLUSIONS

In the paper we described the mathematical model and propose solution method for solving of the electric bus charging station's location design problem. We formulated location-scheduling mathematical model, where the set of possible charging stations can be in terminals and depots and tours of all vehicles are known and will be unchanged. To solve the problem, we proposed solving method based on the VNS metaheuristic. Using proposed method, we realised extensive numerical experiments on the test datasets created from real operational data provided by the municipal transport operator in the city of Zilina. From the numerical experiments we can see that choosing to search the neighborhoods from simpler to more complex ones (basic configuration) is a better strategy than searching the neighborhood s from more complex to simpler ones.

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