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SOLVING THE GARBAGE TRUCK ROUTING PROBLEM FOR COLLECTING RECYCLABLES FROM BIG RECYCLING BINS USING THE VRP SPREADSHEET SOLVER

Abstract. *There are numerous ways of organizing the municipal solid waste collection system. For instance, separate collection of segregated recyclable solid waste can be based on a network of pickup points equipped with big recycling bins (BRB) to which citizens have unlimited access. The key to motivate citizens to use these bins is to provide a robust and efficient system of emptying them. The schedule of segregated solid waste collection from BRBs in Krakow municipality is prepared by decision-makers using manual tools, and there is a need for tools supporting decision-making, as solid waste management is getting more and more complicated due to laws and regulations. In this paper, the Vehicle Routing Problem (VRP) for segregated solid waste collection from BRBs is solved using Large Neighborhood Search algorithm implemented in the VRP Spreadsheet Solver and illustrated with a case study based on selective recyclables collection from BRBs in Krakow municipality. The real SWM system was adapted for requirements of the VRP Spreadsheet Solver, and obtained results were compared with the requirements of the garbage trucks routing problem in Krakow municipality.*

Key words: *Vehicle Routing Problem, Solid Waste Management, Large Neighborhood Search, municipality management, city logistics, segregated solid waste collection, reverse logistics.*

Introduction.

The public concern for environmental preservation makes reverse logistics one of the most relevant issues of sustainable city logistics. Municipal Solid Waste Management (SWM) is an increasingly complex task which objective is - among others - to provide robust and efficient solid waste collection. Nowadays, SWM should also effectively promote solid waste segregation, so that recyclables can be collected separately and recovered. Solid waste collection planning became more complicated and the amount of data included in decision-making in SWM increased rapidly absorbing a huge amount of resources. Computerized systems based on operations research tools and techniques can support the decision-makers of SWM in solid waste collection planning, so that solid waste collection service can be performed at desirable quality level, the total cost can be reduced, and waste recovery can be improved (Ghiani *et al.*, 2014; Edalatpour *et al.*, 2018; Erfani *et al.*, 2018; Le Son and Louati, 2016; Bing *et al.*, 2014; Chen *et al.*, 2019; Erdinç *et al.*, 2019; Lou *et al.*, 2020).

In Krakow municipality solid waste management is coordinated by the Municipal Cleaning Company (MPO Krakow). The SWM consists of collection of segregated solid waste of seven types: paper and cardboard, metals and plastics, glass, bio, other solid waste (mixed), green waste, and bulk solid waste. Paper and cardboard, metals and plastics, glass, bio, and other solid waste (mixed) are collected periodically with relatively high frequency (i.e. several times a month); the service of green waste collection is provided in summer; and bulk solid waste is collected several times a year. MPO Krakow introduced two types of pickup points of recyclable solid waste (i.e. paper and cardboard, metals and plastics, glass, and bio): (1) collection from solid waste source, i.e. from bins belonging to particular buildings or houses, and (2) collection from drop-off (or pickup) points, i.e. Big Recycling Bins (BRB, see Figure 1) to which citizens have an open access (MPO Krakow). MPO Krakow serves 639 locations of BRBs; each BRB point contains bins dedicated for paper and cardboard, metals and plastics, and glass. Every type of recyclables is collected separately once a week.

The schedule of segregated solid waste collection from BRBs in the municipality of Krakow is prepared by decision-makers using manual tools. No effective computer-aided decision-making tools are used for garbage trucks routing. In this paper, the VRP for segregated solid waste collection from BRBs is solved using Large Neighborhood Search algorithm (LNS) implemented in the VRP Spreadsheet Solver (Erdoğan, 2017b) and illustrated with a case study based on selective recyclables collection from BRBs in Krakow municipality. This is an attempt of using ready-made user-friendly tool for supporting decision-making process in SWM. The real SWM system was adapted for requirements of the VRP Spreadsheet Solver using K-Mean Clustering, but it has not influenced the usefulness of the results of the garbage trucks routing problem for the decision makers of MPO Krakow.

The main contribution of the paper is the conceptualization of the garbage truck routing problem for segregated solid waste collection from BRBs as an optimization problem. The LNS algorithm implemented in the VRP Spreadsheet Solver is dedicated to VRPs and finds feasible solutions which are acceptable for decision makers of the SWM of MPO Krakow. Presented garbage truck routing problem was solved for real primary instances of the SWM system of Krakow municipality. The real SWM system was adapted for requirements of the VRP Spreadsheet Solver, and obtained results were compared with the requirements of the garbage trucks routing problem in Krakow municipality.

The reminder of the paper is organized as follows. The next section provides a short literature review on Solid Waste Management and the VRP for SWM with BRBs. Then garbage truck routing problem is presented, together with necessary adjustments to the requirements of the VRP Spreadsheet Solver. In the subsequent section data instances are presented and the results of computational experiments are reported.

Solid waste collection routing problem.

Among numerous decision-making problems faced by SWM we can distinguish solid waste collection routing problem as the one which contributes significantly to the quality level of solid waste collection service, to the level of total costs, and the level of recyclables recovery. It belongs to the family of rich Vehicle Routing Problems (Cordeau *et al.*, 2007; Cordeau *et al.*, 2001; Crainic and Laporte, 1998). The relevance of garbage truck routing problem for the integrity of municipal solid waste management systems is significant (Asefi *et al.*, 2019; Ayvaz-Cavdaroglu *et al.*, 2019; Yousefloo and Babazadeh, 2020; Ramos *et al.*, 2018).

Garbage trucks are used for collecting segregated solid waste from pickup nodes and for transporting it to specialized sorting units. The objective of the solid waste collection routing problem is to find routes for all the garbage trucks, so that all the pickup nodes can be emptied within desired time windows, desired amount of segregated recyclables can be delivered to sorting units, and the total profit of performing the service can be maximized (Oliveira Simonetto and Borenstein, 2007; Markov *et al.*, 2016; Gdowska *et al.*, 2019; Korcyl *et al.*, 2015; Korcyl *et al.*, 2016, 2019). The fleet of garbage trucks consists of vehicles which can differ one from another with capacity, size, and exclusive assignment to certain types of solid waste. In real selective solid waste collection systems, an important issue is to route garbage truck subject to their size and the time windows of pickup nodes (Xue *et al.*, 2015). Some pickup nodes can be served only within predefined time windows and visiting them should be scheduled carefully, so that they can be served in the preferred period and garbage trucks' extra dwell time or extra kilometrage can be avoided (Buhrkal *et al.*, 2012). Solid waste collection is a periodic service which is repeated several times a month what also should be considered during designing the VRP for a given SWM (Teixeira *et al.*, 2004).

Solid waste collection routing problem with Big Recycling Bins in Krakow municipality.

Solid waste collection routing problem faced by MPO Krakow has already been investigated as a optimization problem (Hanczar, 2010; Korcyl *et al.*, 2015; Korcyl *et al.*, 2016, 2019; Gdowska *et al.*, 2019; Jakubiak, 2016). General conclusion was that the SWM system has huge potential for optimization, and hitherto no efficient optimization tool for decision-making support had been implemented in MPO Krakow. Nowadays, when SWM is getting more and more complicated due to regulations on selective collection of recyclables it is advisable to introduce ready-to-use decision-making tools for supporting problem solving in company. In this paper, possible utilization of open operations research tool for solving solid waste collection routing problem is presented.

As it was already mentioned, MPO Krakow performs the periodic service of selective collection of recyclables, both from solid waste sources as well as from big recycling bins; garbage truck routing for these two systems can be considered separately. This work is dedicated to the latter. In January 2020, 639 BRB points are in Krakow municipality. The SWM system uses two types of BRBs: (1) the smaller - capacity 1.5 m^3, and (2) the bigger - capacity 2.5 m^3 (Figure 1). Each garbage truck can collect every type of segregated solid waste, but during one route the garbage truck must collect only one type of recyclables. Selected collection of segregated solid waste from BRBs may be divided into separate problems dedicated to each type of recyclables, and in this paper, we focused on metals and plastics collection from BRB served by the MPO Krakow. Selective collection of other recyclables from BRB can be solved in the same way.

Figure 1 Big Recycling Bins used by MPO Krakow. Capacity: 1.5 m^3 and 2.5 m^3. Source: (MPO Krakow)

In the SWM under investigation the garbage truck routing problem for collecting recyclables from BRBs is not a typical VRP, since the objective is not to find routes which cover all the pickup nodes and minimize the total cost (or to maximize total net profit), but to find 20 balanced routes. Nowadays, MPO Krakow organizes segregated solid waste collection from BRBs according to the schedule prepared using manual tools and decision-makers' know-how. In result Krakow municipality is divided into 20 sectors and BRBs in each sector must be emptied once a week. BRBs for metals and plastics are served by 4 teams five days a week. Each team consists of two workers who have fixed assignment to a garbage truck. According to the schedule in use, each team serves one sector every weekday, and must collect solid waste from all the nodes belonging to the sector on one go. The same team performs also solid waste collection from solid waste sources and other jobs, so it is hard to estimate the fixed cost of serving BRBs. Anyway, the main objective of MPO Krakow is to find 20 routes (4 working teams times 5 days a week gives 20 routes per week) to balance the workload of 4 teams and to minimize the total driven kilometrage. In results, in this research we could neglect the fixed cost of using garbage trucks as well as the profit made of serving each BRB point, because all BRBs must be emptied and the pricelist is regulated by the municipal authority.

Computational experiments and obtained results.

Considering specific requirements of MPO Krakow as well as limitations of the VRP Spreadsheet Solver, the garbage truck routing problem for collecting recyclable from BRBs was formulated as follows.

(1) VRP Spreadsheet Solver serves for instances of maximum 200 pickup/delivery nodes, so the set of 639 BRB points (Figure 2) had to be reduced. We used adapted K-Mean Clustering algorithm ((Wilkin and Huang, 2007; Qi *et al.*, 2017; Likas *et al.*, 2003) to aggregate 639 points to 50, 100, 150, and 200 clusters (Figure 3).

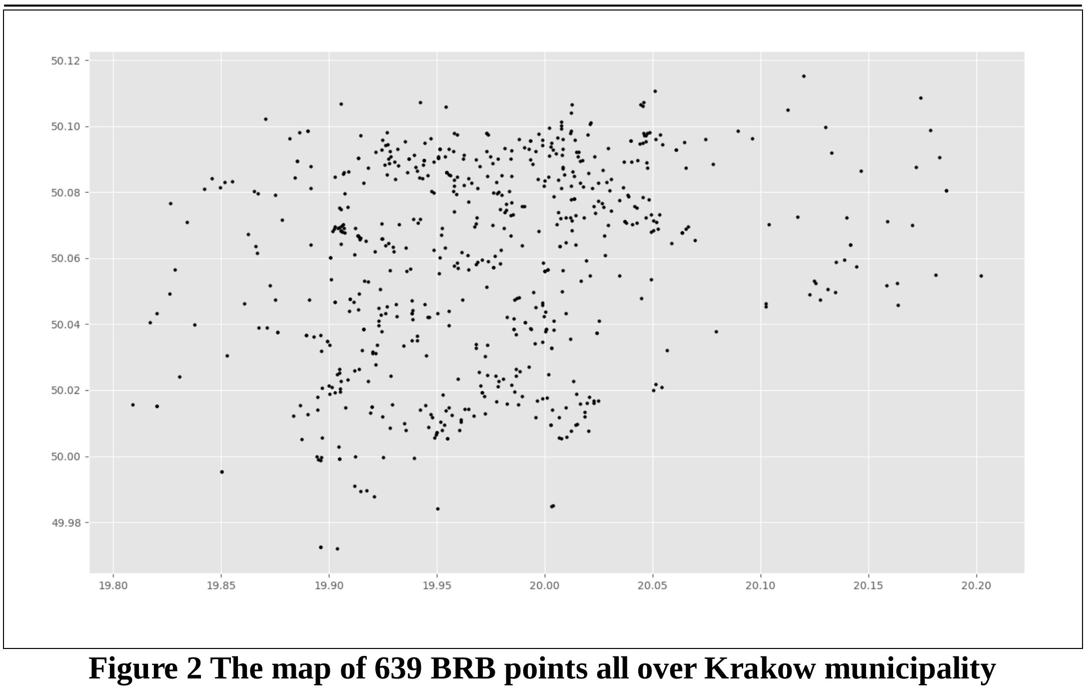

Figure 2 The map of 639 BRB points all over Krakow municipality

Adapted K-Mean Clustering algorithm works in the following way:

Step 1. Choose the number of clusters (50, 100, 150, and 200 clusters).

Step 2. Randomize the initial positions of clusters' centroids.

Step 3. Compute "distances" between centroids and BRB points as the sum of the average distance between the centroids and BRB points belonging to it, plus Euclidian distance between the given BRB point and the centroid. This approach guarantees that at least one BRB point belongs to each cluster, and the average number of kilometers in clusters is balanced.

Step 4. Assign each BRB point to the closest cluster.

Step 5. For each cluster find new centroid based on arithmetic mean of coordinates of BRB points belonging to the cluster.

Step 6. Repeat Steps 3-5 until the average distance between new and previous positions of all the centroids is not greater than in the previous iteration.

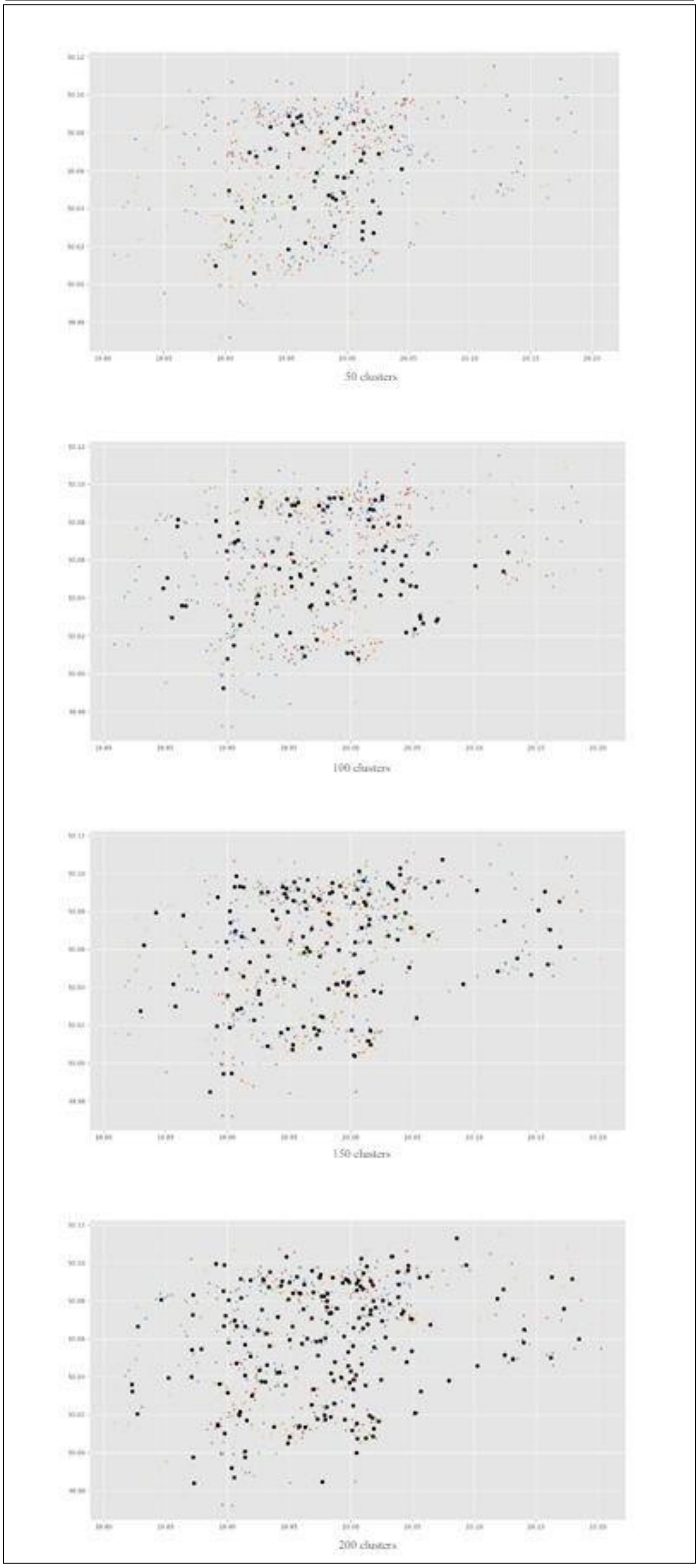

Figure 3 Clusters

(2) VRP Spreadsheet Solver solves VRP for 24-hour time horizon. MPO Krakow requires 20 routes per week, i.e. 4 routes per day. Each working team serves one route a day, and they have predefined time window of performing their service. We decided to clone each team 4 times and find 20 parallel routes using VRP Spreadsheet Solver. Therefore, the objective was to find 20 routes served by 20 garbage trucks of 4 types (*A*, *B*, *C* and *D*), i.e. 5 garbage trucks of each type are on decision-makers' disposal. The capacity of each type of garbage trucks: *A* - 24 m^3, *B* - 16.6 m^3, *C* - 30 m^3, and *D* 36.8 m^3.

(3) Although MPO Krakow uses 2 types of BRBs (capacity: 1.5 m^3 and 2.5 m^3), we assumed that all the BRBs are identical and their capacity is 2 m^3. Garbage trucks press solid waste in the rear of the vehicle, so the real capacity of each BRB was divided by 4.

(4) VRP Spreadsheet Solver aims at maximining the total net profit. According to the specific character of segregated solid waste collection from BRBs, MPO Krakow requires minimizing the total driving distance of total working time of 20 routes as well as balancing the workload assigned to routes. We decided to test the VRP Spreadsheet Solver just as a tool for garbage routing, so profit from serving each pickup point was 0, fixed cost of using garbage trucks was 0, and unit travel cost was 1. For such assumptions, the value of the objective function must have been negative, because the objective was to minimize the total travel cost.

(5) To obtain parallel routes we left time windows considerably wide: each depot and pickup node is available from 8 a.m. till 8 p.m.

(6) All the garbage trucks start their work at MPO Krakow headquarters (Depot A) which is the main depot and garage for garbage trucks. Garbage trucks end their routes at specialized sorting unit (Depot B). After serving BRBs garbage trucks may be assigned to other jobs, so from the perspective of this research it is not necessary to direct them back to their home depot.

Computational experiment for a solution were executed on a computer with the Intel Core i7 quad-core CPU, running at 2.5 GHz in a Win10 OS, with 16 GB of RAM. The problems were solved, using the VRP Spreadsheet Solver, version 3.4 (Erdoğan, 2017a). Note that computation time increased significantly with the number of clustered BRB points: for 50 clusters computation time was 156 sec., for 100 clusters - 780 sec., for 150 clusters - 2652 sec., for 200 clusters - 6240 sec. (Figure 1Figure ***4***).

Obtained results are presented in **Results obtained with the VRP Spreadsheet Solver** (Table 1). Unfortunately, in the VRP Spreadsheet Solver we cannot define the minimum number of routes we would like to get. Therefore, for each instance less than 20 routes were found. Such solutions do not meet requirements of MPO Krakow. However, we would like to emphasize that obtained results can be used for the evaluation of routes found using manual tools. The advantage of the VRP Spreadsheet Solver is visualization of results on maps delivered by Bing Maps. Visualizations of exemplary solutions of garbage truck routing problem for collecting recyclables from BRBs in Krakow municipality are presented in Figure 1.

Table 1

Results obtained with the VRP Spreadsheet Solver

Number of nodes (clusters)	Total net profit	Number of routes	Average distance	Average driving time	Average working time	Total distance	Total driving time	Total working time
50	-327.03	13	25.16	1:05	2:23	327.03	14:05	31:07
100	-381.42	14	27.24	1:14	2:27	381.42	17:26	34:28
150	-424.70	15	28.31	1:24	2:32	424.70	21:04	38:06
200	-508.25	15	33.88	1:41	2:49	508.25	25:23	42:25

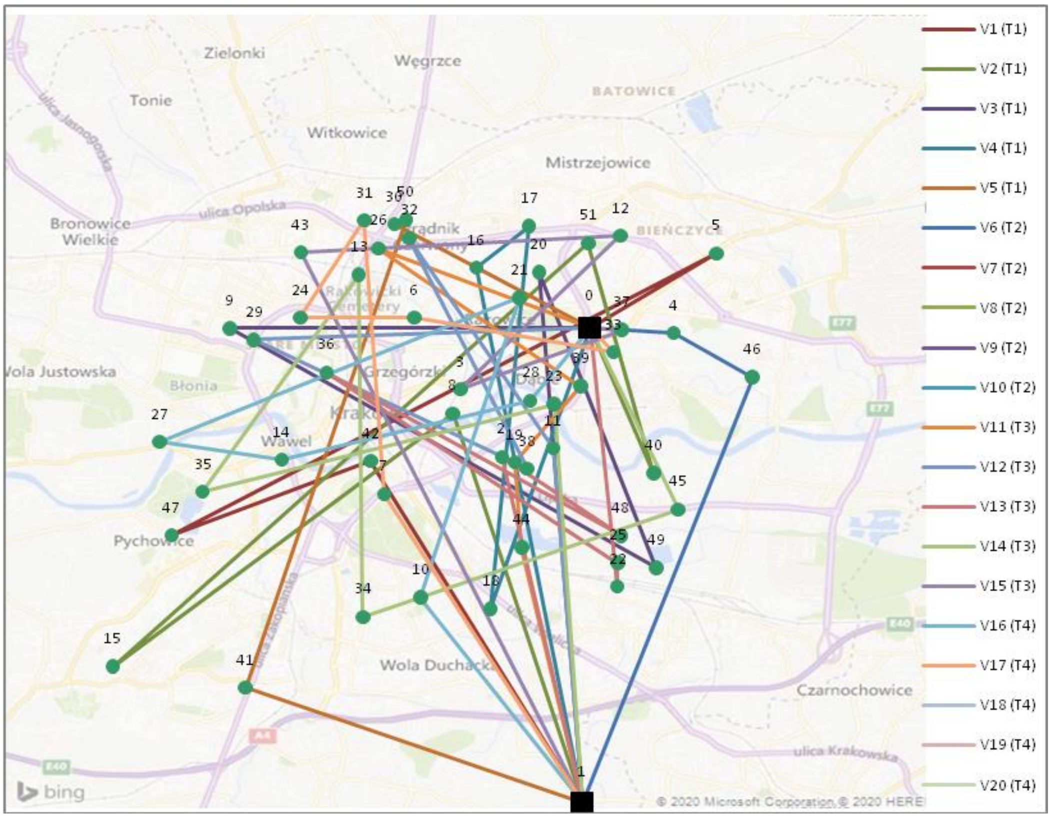

Figure 4 Routes for 50 nodes

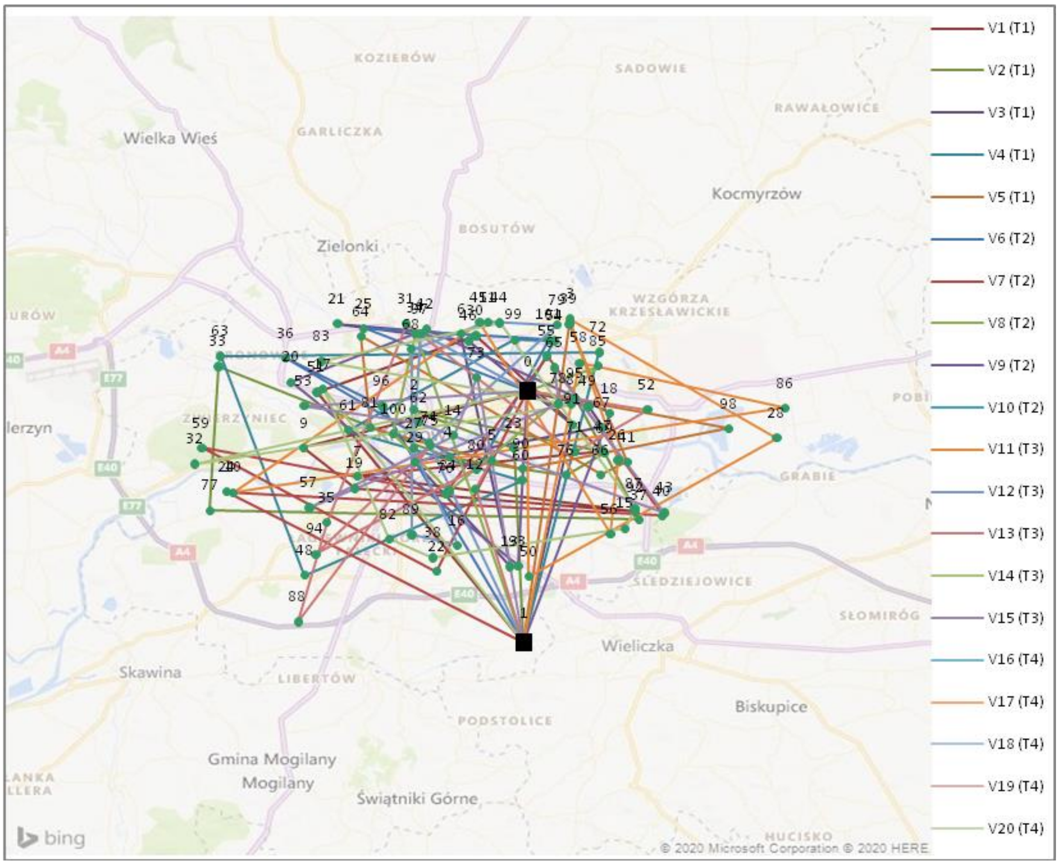

Figure 5 Routes for 100 nodes

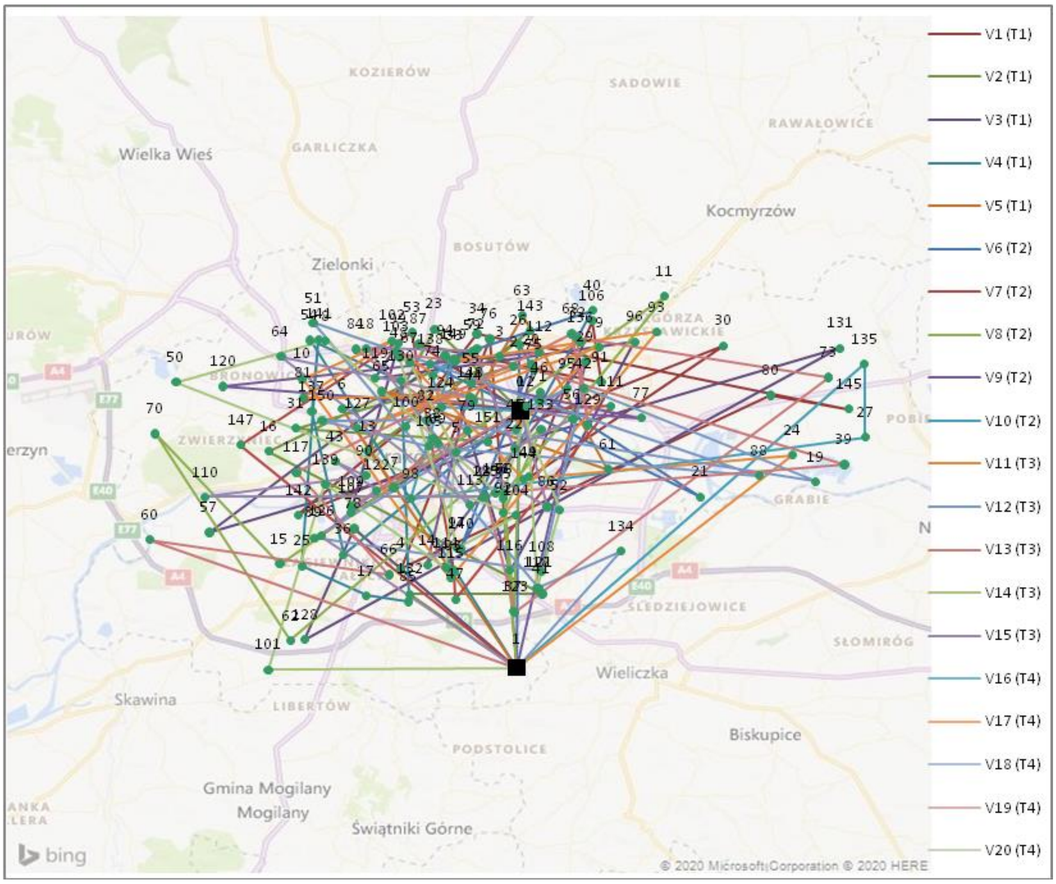

Figure 6 Routes for 150 nodes

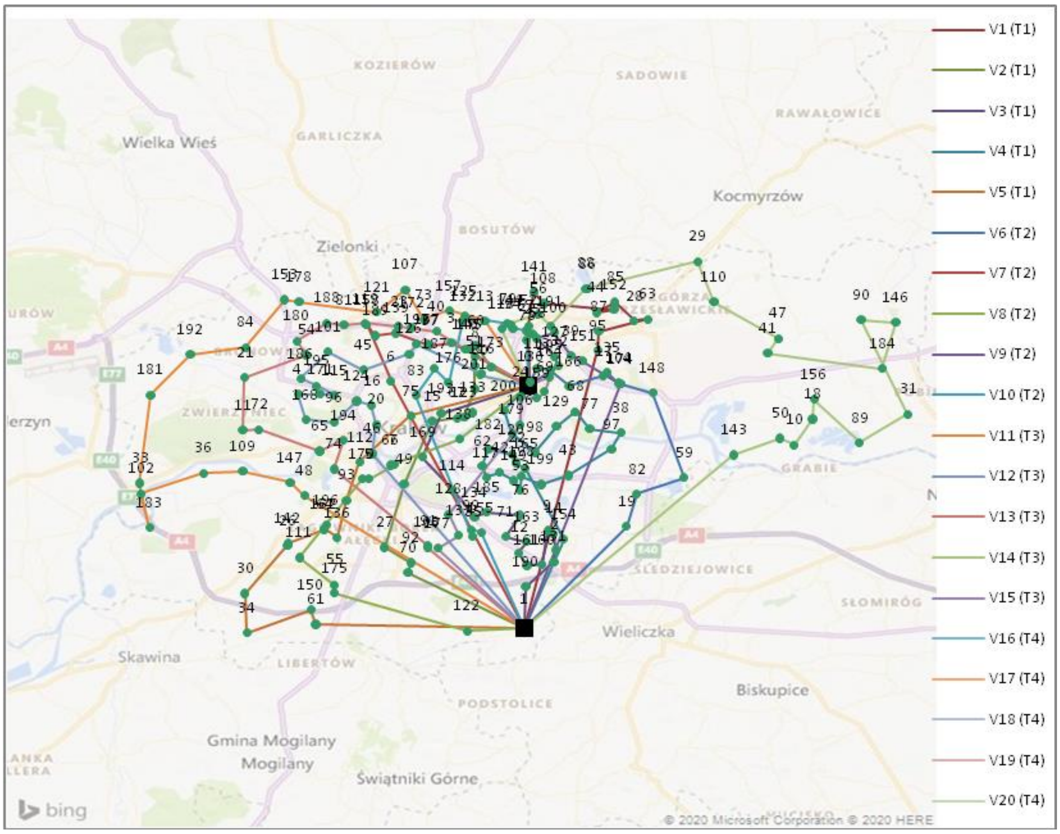

Figure 7 Routes for 200 nodes

Conclusions.

The VRP Spreadsheet Solver used for garbage truck routing problem for collecting recyclables from BRBs in Krakow municipality is a useful tool for solving typical VRPs. The tool is user-friendly and easy to use and does not need any additional software. The VRP for MPO Krakow shows that a significant shortage of the VRP Spreadsheet Solver is its focus on typical VRPs. Easy way of modifying this tool is hardly possible. Solutions obtained for the problem analyzed in this paper do not satisfy the requirements of MPO Krakow, however may serve as a starting point for the reflection upon the operational strategy of the company.

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