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How to improve WEEE management? Novel approach in mobile collection with application of artificial intelligence

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ABSTRACT

In global demand of improvement of electrical and electronic waste management systems, stakeholders look for effective collection systems that generate minimal costs. In this study we propose a novel model for application in mobile collection schemes - on demand that waste be taken back from household residents. This type of the waste equipment collection is comfortable for residents as they can indicate day and time windows for the take-back. Collecting companies are interested in lowering operational costs required for service. This lowering includes selection of a sufficient number of vehicles and employees, and then minimising the routes' length in order to achieve savings in fuel consumption, and lowering of emissions. In the proposed model we use a genetic algorithm for optimisation of the route length and number of vehicles and fuzzy logic for representation of the household residents' satisfaction on the take-back service provided by collection companies. Also, modern communication channels like websites or mobile phone applications can be used to send the waste equipment take-back request from the household, so it has the potential to be developed in future applications. The operation of the model has been presented in the case study of a city in southern Poland. The results can be useful for collecting companies and software producers for preparation of new applications to be used in waste collection.

1. Introduction

One of the most important types of household waste is electrical and electronic equipment (WEEE). Such items contain a variety of materials that are easily recycled like metals, plastics, or glass (Huisman and Magalini, 2007; Oguchi et al., 2012). There are also some hazardous substances, which cause major environmental and health problems (Bogaert et al., 2008). Regarding the disposal of hazardous components and substances, WEEE management systems have been introduced in developed and developing countries (Ongondo et al., 2010). In the European Union (EU) the new Directive on WEEE requires higher levels of collection 65% of the total mass of the equipment placed on the market (POM) as an average of the three preceding years (European Commission, 2012). This requirement is to be achieved by 2019. However in 2012 in the majority of the EU members, the collection rate was below 50% and average for the entire EU was 38% (Eurostat, 2014).

There are many factors that contribute to collection rates. They depend on reverse logistics and attitudes of end users towards disposing of unwanted electrical and electronic equipment. Waste collection companies should prepare schedules for WEEE take-back and for the location of containers or the drop off places. Also they should inform the residents about the container location or the collection schedule. However, it is up to end users when and where they dispose of the broken and unwanted equipment. The WEEE regulations are designed to minimise the negative impact on the natural environment. Therefore the collection should be provided by legal companies, and the waste should be transported to treatment facilities where disassembly operations of discarded WEEE items are in compliance with environmental standards. Improper disposal of the obsolete equipment by end users, e.g. together with municipal waste or at scrap points poses a threat for the contamination of the natural environment (Wang et al., 2011; Saphores et al., 2012). One more factor to consider is vehicle emissions. Inefficient collections' schedules and allocation of more vehicles than is required leads to an increase of emissions (Salhofer et al., 2007).

We would like to propose a variant of a mobile collection – on demand. This system could be widely used by collection companies. The advantage of this approach to the residents is twofold: ease and convenience, which plays a significant role in choosing a method of waste disposal. A collection vehicle makes a stop at a residence and the old equipment is carried out by the company's employees. In order to schedule a pick up, the resident has a choice

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of a wide variety of readily available communication channels via telephone, website, or mobile apps.

A concept of this type of collection builds in a punctuality factor of the take-back resulting in positive feedback.

To encourage household residents to dispose of WEEE properly and to prepare optimised collection schedules, we propose an innovative program based on a multi-criteria collection model. This approach will use fuzzy logic – to measure the satisfaction of the residents depending on an average delay and maximum delay of waste collection and vehicle routing problem with time windows (VRPTW). The genetic algorithm will be used as the heuristic approach to optimize the route length of WEEE collection vehicles.

In this approach, the optimal number of vehicles, route length, and satisfaction of the residents in the take-back of the waste equipment are calculated. These attributes are necessary to cut collection costs. On demand collection system will be an important step in efforts to increase WEEE collection levels.

2. Collection type characteristics

Collection methods of WEEE can vary depending on requirements of environmental law. In the EU, collection types are described in the WEEE Directive (European Commission, 2012), and similar methods are used in other countries (Dwivedy et al., 2015).

The main types of collection can be classified as either stationary or mobile. The stationary model requires containers placed close to residential neighbourhoods or at municipal collection centres. Once the containers are filled, they are hauled off to a treatment facility. The WEEE can also be returned to retailers for re-use or recycling. The mobile collection is provided by service vehicles travelling along a route. This process can be arranged for different municipality sizes on weekly, bimonthly, quarterly or any other appropriate time schedules. This type of collection is very convenient for citizens since the pick-up of WEEE takes place at the end user's residence. Fig. 1 summarizes the different collections types.

A variation of mobile collection type of unwanted equipment is by prior arrangement via telephone, website, or mobile applications. This type of collection has the possibility to be widely applied because it allows arranging collections by residents as needed (Song et al., 2012).

For the evaluation of waste collection strategies the multi-criteria analysis has been used (Arıkan et al., 2015; Dosal et al., 2013). It includes the assessment of the economic and environmental impacts. Fuzzy logic was applied to solve general solid waste problems in (Xu et al., 2014), for WEEE treatment strategies (Bereketli et al., 2011), and WEEE recycling activities (Yeh and Xu, 2013).

The waste collection can be supported by information technologies using Geographic Information System (Chang et al., 1997), Radio Frequency ID systems (Faccio et al., 2011) or advanced systems proposed for Smart Cities (Medvedev et al., 2015).

The collection companies are interested in lowering transportation costs. The main impact on operational costs is the personnel involved and fuel for vehicles (Zsigraiova et al., 2013). Fuel consumption is directly related to the number of vehicles in service and the route length. Although this type of waste collection method is used by some companies, system engineering methods with scientific models are rarely used (Pires et al., 2011).

The effectiveness of the take-back system depends on end user's attitudes to waste and recycling (Li et al., 2012; Milovantseva and Saphores, 2013). Some of the reasons for discarding WEEE are malfunctioning, breakage, costly repairs, or upgrading. If the collection is improperly organised, it discourages the residents from disposing of WEEE in a legal way. Instead the WEEE items will be stockpiled, sold at scrap points, or disposed together with municipal waste (Darby and Obara, 2005; Hicks et al., 2005). The household residents must be informed about collection options. There are new possibilities for information exchange via websites or apps for mobile phones. These new forms of communication are developing quickly.

For collecting companies, it is necessary to pick up WEEE effectively, minimising the number of vehicles and collection staff (Friege et al., 2015). Household residents are interested in the most convenient methods of disposal (Gatersleben et al., 2002). This can be measured as customer satisfaction. Determining factors in high customer satisfaction are punctual pick up by the collecting company and ease of requesting service. The latter would be available via phone or online scheduling.

3. Model description

Collections from households are scheduled by residents. The customer satisfaction level is described in Helgesen (2006). If the collection of unwanted equipment is punctual, it enhances a resident's satisfaction. In this model heavy equipment is removed by the collecting company's staff. If that service is satisfactory, residents promote it through the word of mouth (Zeithaml, 2000).

Therefore in this model we propose to measure the satisfaction of the residents based on an average delay and maximum delay of waste collection (Meuter et al., 2000). The customer satisfaction is paramount to the success of WEEE collections, because the opinion of an unsatisfied customer has a great impact on dissuading other residents from participating (Hill and Alexander, 2006).

The new approach of WEEE collection can be regarded as a variant of vehicle routing problem with time windows. The area of WEEE collection is represented by a graph in this model. Streets are the edges and intersections are the nodes. Constrained or unconstrained graphs can be used for better representation of

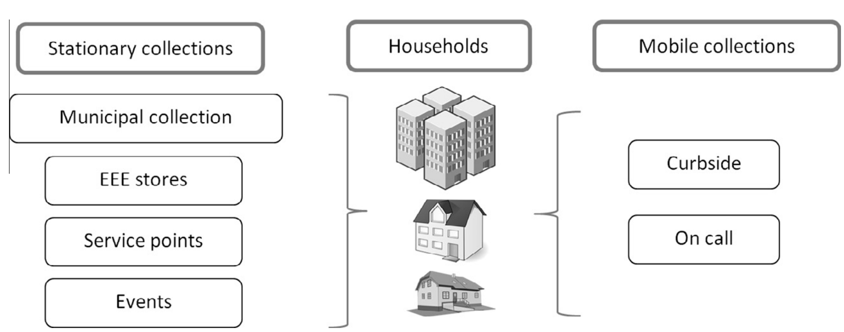

Fig. 1. Different collections types of WEEE.

one-way streets. Each edge is assigned: length, the number of households, and a type of residence. To simplify the model, the households are assumed to be adjacent to one another along the street.

The purpose of this study is to find the optimal route for collecting vehicles in accordance with a single-day schedule generated by households. An optimisation procedure requires the following parameters:

- number of vehicles for waste collection,
- effective volume of the vehicle cargo compartment,
- effective vehicle speed in a city,
- location of collecting company headquarters – base point, where the WEEE is unloaded, one of the graph nodes,
- duration of unloading in base point,
- large home appliances' loading time from household into a vehicle.

The optimisation process for each day consists of the following steps:

1. Modification of the graph representing the streets: for each take back point it is assigned new graph node. A street, where a household is situated is divided depending on location of the household.
2. The initial solution generation: the new added nodes are sorted according to declared available take back hours from a household. The first point of take back is assigned to the first collecting vehicle, the next to the second one, etc. Thus each vehicle is in service for 1/n of requests from the households. The initial solution is remembered as stored solution.
3. The initial population generation: the initial solution is copied to all the individuals. To ensure diversity of the population all except a determined number (the elite) individuals are subject to multiple mutations.
4. Iterative loop of the genetic algorithm: at each generation, for each individual the value of the fit function is calculated (as described in a section below). This value determines the chances of an individual pass to the next generation. The individual with the greatest value of the fit function is compared with the stored solution, and if it is better it takes on this role.
5. After presumed number of generation the stored solution is the optimisation procedure outcome.

3.1. Genetic algorithm

The described problem is computationally complex, so exact optimisation algorithms cannot be applied due to high calculation time required. In such cases, heuristic approaches should be used to obtain a solution near the optimal one within the acceptable computation time. An approach involving artificial intelligence has a fundamental advantage: it is not required to understand fully all inner dependencies of the model or even to know some of them. The only requirement is that the model allows a value of the objective function to be calculated. The objective function is the function defined in the solution domain and determines the solution quality. The objective function does not need to be differentiable and none of its gradients need to be known.

For these reasons the genetic algorithms are widely applied for varieties of vehicle routing problem (Ghannadpour et al., 2014). Genetic algorithms resemble evolution processes in the living nature (Darwin, 1869) and were introduced for the first time by Holland (1975). Their advantages have enabled wide applications in many fields of science and technology (Goldberg, 1989).

As in other papers (Liu et al., 2009; Ursani et al., 2011; Tasan and Gen, 2012) an individual is considered as a set of routes for each vehicle. They are nodes lists starting from the base point, including all assigned waste equipment take-back calls and ending at the base point. The structure of a single individual is shown in Fig. 2.

The individuals defined above create a population. In each generation it is a trial of mutation of each individual. The probability of such an event is a parameter of this algorithm. The structure of the individuals requires the definition of few variants of the mutation operator, which are randomly selected (Fig. 3):

- exchange of two randomly selected take-back calls for one, randomly selected vehicle,
- change of the sequence on the randomly selected subsequence of calls for randomly selected vehicle,
- exchange of randomly selected subsequence of calls for randomly selected pair of vehicles.

The operator of crossover operates on randomly selected pairs of the individuals. The OX crossover (Goldberg, 1989) is applied here, popular for permutation genotypes. It is based on a random selection of a subsequence with the same length and the same localisation in each of the two individuals taking part in crossing. Then the elements of the subsequence are sorted in accordance with the sequence where they occur in the partner. The probability of an individual participating in crossing is another parameter of the algorithm.

The initial population is created from individuals described before as initial solutions. To assure diversity, the individuals undergo multiple mutations (algorithm parameter).

The offspring generation is created with the roulette wheel rule – the probability of being accepted is proportional to the fitness function value. The fitness function is here identical to the objective function of the optimisation. A modification called elite selection is introduced – an established number of the best individuals (the elite) pass to the next generation unconditionally. The next modification involves storing the best-so-far solution. This solution does not take part in the optimisation process, but finally is the optimisation result. As mentioned before, the operation of the algorithm is controlled by a number of parameters, which are shown in Table 1.

The overall flowchart of the genetic algorithm is shown in Fig. 4. It should be noted that the stop condition is not explicitly expressed here. It can be the presumed number of steps (most common), the expected value of the objective function or the moment, when the progress of the optimisation slows down.

3.2. Determination of the fitness function

For evaluation of proposed vehicle routes, the travelled distance and values determining the accuracy of the collection time from households are required. The calculation of the three parameters is required for each individual:

- L – total routes length of the vehicles,
- D_{avg} – average delay of arrival time to a household,

1	0	1	5	9	20	19	21	22	
2	0	2	6	10	11	18	23	24	27
3	0	3	7	13	12	17			
4	0	4	8	14	15	16	25	26	

Fig. 2. The structure of a single individual (with 4 vehicles in service).

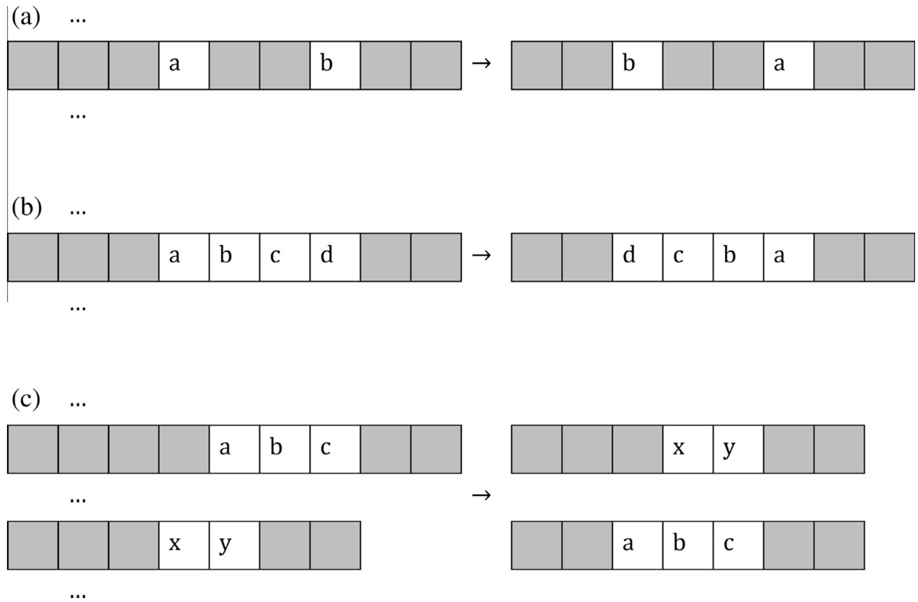

Fig. 3. Three variants of the mutation operator.

Table 1
Parameters of genetic algorithm.

Parameter	Value
Population size	500
Number of steps	100
Probability of mutation	0.3
Probability of crossover	0.3
Elite size	5

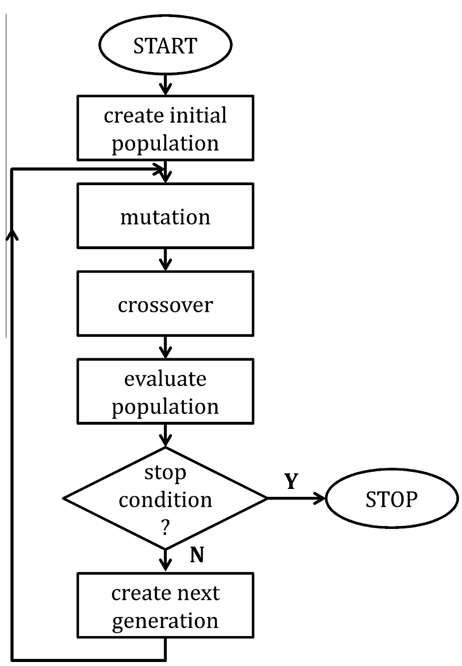

Fig. 4. The overall flowchart of the genetic algorithm.

- D_{max} – maximum delay of arrival time to a household.

To calculate this, a route of the vehicles is simulated, starting from departure from the base point. It is assumed that they arrive at first collection point exactly on time. Then each vehicle visits each household in compliance with the schedule. All vehicle routes between a couple of vertices are determined using Dijkstra's algorithm. The travel time depends on route length and vehicle speed. Each vehicle must meet the following requirements:

- if a large home appliance is to be collected, a vehicle can travel to another node after loading the equipment, the loading time is added to arrival time,
- if a vehicle arrives ahead of a household's scheduled time, it can travel to another node,
- if a vehicle arrives late, the delay is included,
- if the vehicle is fully loaded it has to come back to the base point and then continue on the route (like in the generation of the initial solution).

The procedure of the calculating of the distance travelled and the time consumed by a single vehicle is shown in Fig. 5, where t denotes total time of single vehicle service, $d_{i,j}$ – distance between i-th and j-th node, T_i – the collection time declared for i-th node, t_{lapp} – time for large appliance loading, p – points to the previously serviced node.

Additionally the length of the reference route is calculated:

- L_0 – route length precisely in accordance with the sequence of calls, optimal taking into account the quality of service of the collection (representing the route of the initial solution)
- L_1 – the shortest route not taking into account collecting times for all calls. It is optimal regarding collection cost.

A value of the objective function in the range $[0,1]$ is assumed, where 0 - represents solution unacceptable, and 1 - fully acceptable. The description rules of the objective function are as follows:

1. if D_{avg} is acceptable and relation L/L_0 is low, the objective function value is high,
2. if D_{max} is high, value of objective function is low,
3. if L/L_1 is high, value of objective function is low.

It might seem that the rules involving L_0 and L_1 act identically, but it concerns an individual task. In general, for various graph topologies representing transportation networks and various sets

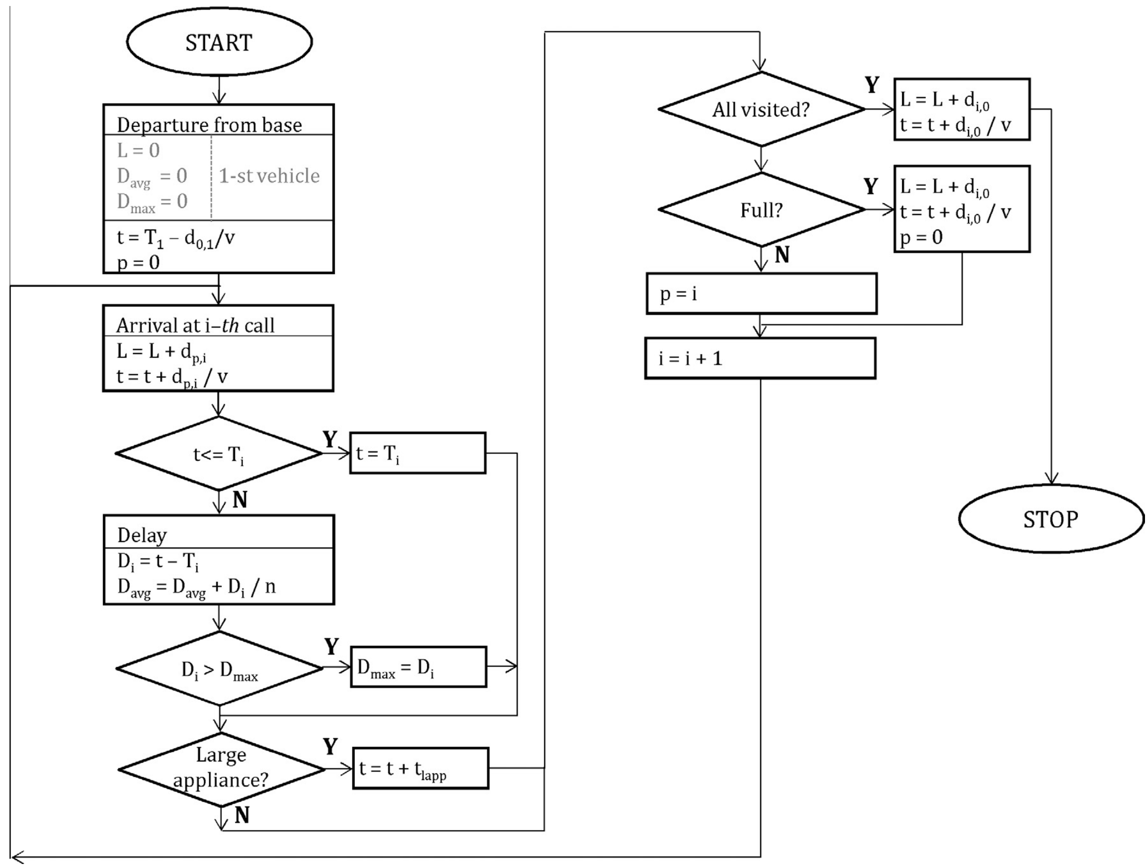

Fig. 5. Calculation of the distance travelled and the time spend by a single vehicle.

of collection calls, once the value of L_0 is important, and other time the value of L_1.

These statements contain some imprecise expressions of the relationship: acceptable, low, high, long. Indeed, in many real situations, crisp, clearly defined boundaries are often impractical. This is because classic Boolean logic uses only two values: true or false. The mathematical formalism allowing for handling such statements is provided by fuzzy logic (Mamdani, 1976, 1977). In this approach, a binary logical expression, determining whether an item belongs or not to a set is replaced by a continuous function that determines the degree of an element membership in a set. The membership function takes values from the range [0, 1], where 0 means that the element is certainly not in a set, and 1 means complete membership. Thus, in fuzzy logic, the truth of any statement becomes a matter of degree.

Based on these concepts, a system of decision making, using descriptive terms, similar to those listed above can be built. The knowledge of such a system is contained in the fuzzy rules (implications) acting on fuzzy (imprecise) quantities. A classical Mamdani fuzzy inference process was applied as used by Ross (2004), Běhounek (2008) and Shi et al. (2009).

For the relationships describing the value of the objective function, the appropriate membership functions are assigned. For simplicity, the trapezoidal function was chosen; it consists of simple line segments. Such trapezoidal functions are fully described by four real numbers ($d \geqslant c \geqslant b \geqslant a \geqslant 0$), as follows (1):

$$f_m(x) = \begin{cases} 0 & x \leqslant a \\ \frac{x-a}{b-a} & a < x \leqslant b \\ 1 & b < x \leqslant c \\ \frac{d-x}{d-c} & c < x \leqslant d \\ 0 & x > d \end{cases} \tag{1}$$

The course of each of these functions has been chosen empirically. They are shown in Fig. 6(a–d).

If a rule contains a logical operator, the fuzzy equivalent must be used. In the role of fuzzy operators of conjunction, alternative and negation the functions of minimum, maximum and complement to unity are used as typical. As a result of the operators' action, the values are calculated for each of the antecedents of the implications.

As the successors of implications the terms "the value of the objective function is high" and "the value of the objective function is low" are used. They correspond to the membership functions, which are shown in Fig. 7(a and b).

For the aggregation of the results of all three fuzzy implications, the function of maximum is used. Then sharpening is made using the method of centre of gravity – the x-coordinate of the centre of gravity of the figure obtained by the aggregation is the value of the objective function. It is calculated according to the following formula (2):

$$x_{gc} = \frac{\int_X y dx}{\int_X dx} \tag{2}$$

where x_{gc} denotes the requested value and the y function describes the shape of the resultant figure.

The process of the objective function calculation described above is illustrated in an example (Fig. 8). The properties of a sample individual are summarised in Table 2.

4. Case study – WEEE collection on demand in Tychy, Poland

The operation of this model is presented in a case study of WEEE take-back in a suburb of Tychy, a city in the Silesian region of Poland. The calculations are based on simulation of calls from

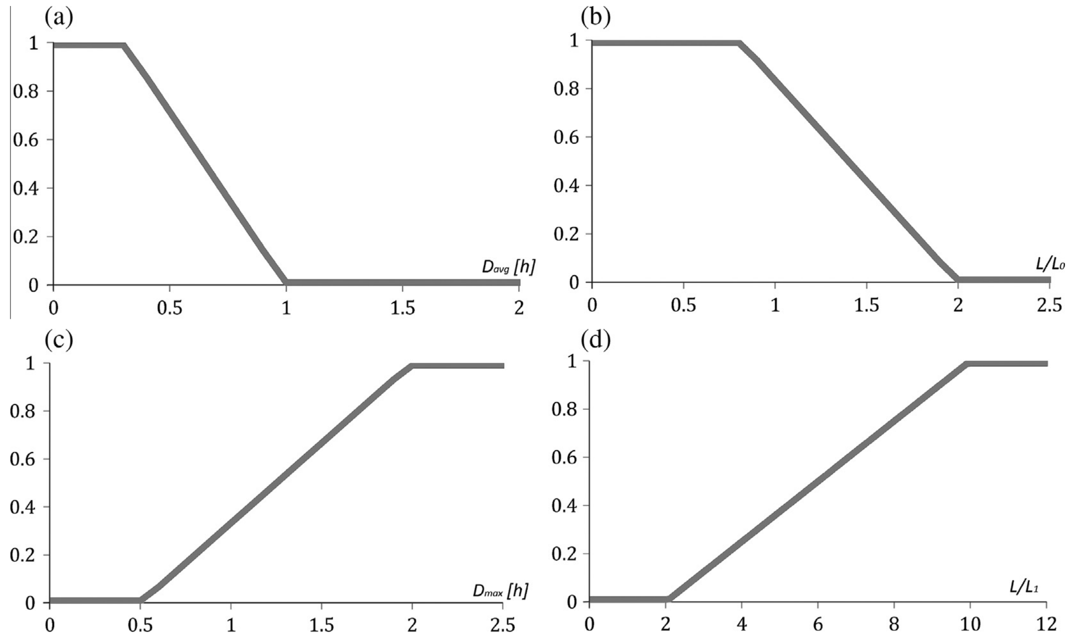

Fig. 6. (a) Average delay D_{avg} is acceptable [h], (b) relation L/L_0 is low, (c) maximum delay D_{max} is high [h], (d) relation L/L_1 is high.

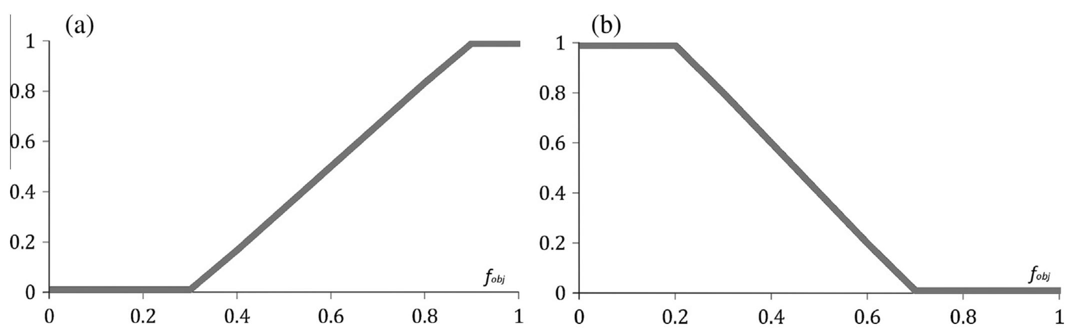

Fig. 7. (a) The value of the objective function is high, (b) the value of the objective function is low.

the residents that correspond to real conditions of the equipment possession in the households and life span of the equipment. The population of the entire city is 130,000. In the suburb used for calculations the majority of residents live in flats.

There are 10,811 of households and about 40,000 citizens. Fig. 9 is a map of the area; Fig. 10 represents the streets.

The procedure for generating the calls from household uses the data of the average lifespan of the equipment (Widmer et al., 2005; Robinson, 2009) and is protected against the unrealistic cases (for example two or more washing machines for a single household). These data are included in Table 3, with differences of number of EEE in households living in blocks or single family homes (GUS, 2012). Large home appliances are assigned a digit 0 and medium size appliances 1 for calculation purposes.

It is assumed that the waste equipment of large or medium size is included in calculation as these types require most of the volume of the collecting vehicle. In the calculation we take into account 65% of the equipment put on market to be collected in compliance with future WEEE Directive requirements. Each item of the waste equipment is represented by one collection call. The total number of calls per year can be calculated from formula (3):

$$N_{dem} = \eta \sum_{a \in App} \sum_{e \in Edg} n^e_{hh} c_{ae} r_a \tag{3}$$

where

η - efficiency = 0.65,
App - set of all waste appliances,
a - an appliance,
Edg - set of all graph edges,
e - an edge,
n^e_{hh} - the number of households at given edge,
c_{de} - the incidence of appliance an at edge e (multi-storey building or detached house),
r_a - the inverse of an average lifetime of appliance a.

For each day a list of calls is generated, including time windows - pick up hours and type of residence. The number of collection days is set at 200, and working hours are from 10 AM to 6 PM. General characteristics of collection calls from the households are shown in Table 4.

Optimisation was applied for several sets of waste equipment collection requests for five days with the highest number of calls or volume of the equipment to be collected. In Table 5, characteristics of calls for selected days are presented.

The optimisation was provided for various numbers of available vehicles. The effectiveness was calculated for 1, 2, 3 and 4 vehicles. Vehicles are the same type with an effective capacity of 6 m^3 to be loaded into one vehicle. The average travelling speed of vehicles is 30 km/h. For large home appliances loading time is 20 min. For

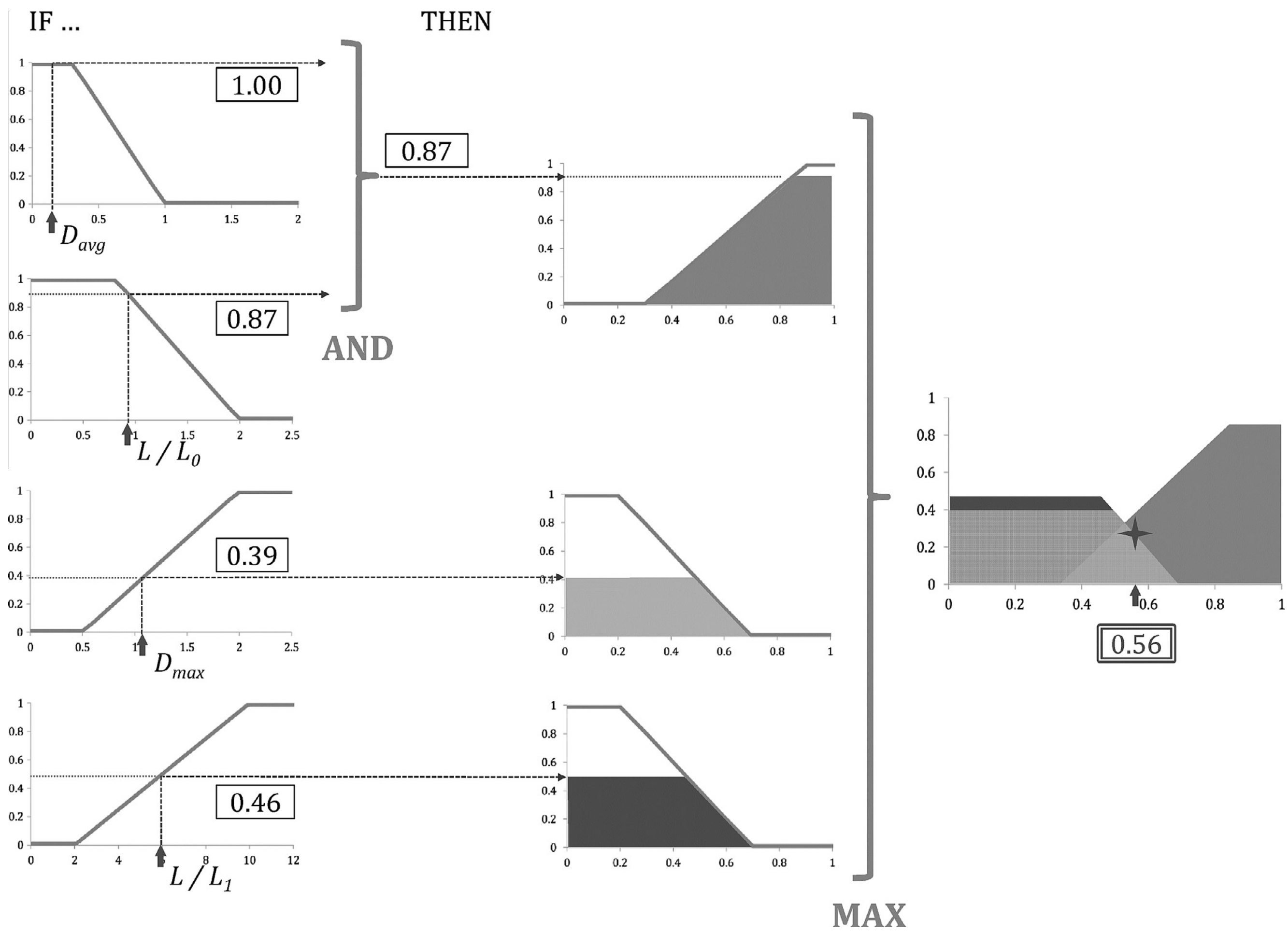

Fig. 8. An example of the objective function calculation.

Table 2
Sample data for calculation of the objective function value.

Property	Value
L [m]	71,558
D_{avg} [h]	0.1239
D_{max} [h]	1.1187
L_0 [m]	74,997
L_1 [m]	11,990

medium size appliances loading time does not have to be taken into account. Unloading the waste equipment at the base point and other operations require one hour. Results for optimisation series are shown in Table 6. The procedure was implemented in C++ language. The calculation time was less than one minute for standard PC computer with Intel Core i7 CPU 2.2 GHz and 8 GB RAM.

The genetic algorithm is a non-deterministic procedure, so the next set of routes for the same input data may be different. For investigation of the effect, the optimisation was run 10 times for each selected day and the number of the vehicles. The test results confirm the proposed algorithm is repeatable and generated data are reliable. It is illustrated in Fig. 11. It includes a set of 10 optimisation runs for the day number 98 with 3 vehicles in service. The values of the objective functions are in the range 0.69–0.70. To avoid complications of fluctuations, the best-obtained result has been excluded (Table 6 always includes the second-best value of the objective function).

The most important conclusion of the analysed data considers the number of utilised vehicles. One or two vehicle cannot assure the required accuracy of collection time from each household. It is especially significant for initial solution before optimisation. In the majority of cases, both average and maximum delays are unacceptable.

For accurate and effective collection, at least three vehicles are required. In Fig. 12, how the objective function value depends on the number of collecting vehicles is shown. Larger number of vehicles does not bring any significant improvement.

Similar results can be seen after analysis of average (D_{avg}) and maximum delays (D_{max}). These relations are shown in Figs. 13 and 14. For three vehicles, these values are not significantly poorer than for greater number.

After analysis of the data from Table 6, the total route length of the vehicles is shortened but the quality of service is lowered (calculated as delay). However, if three or more vehicles are used the delays are in the accepted range (Fig. 6a, c).

Change of the objective function value in optimisation is an increase of several percent, to 23%, for a day number 154 with one used vehicle. The average shortening of total route length is 28%. The maximum improvement of 37% is for day number 98 with two used vehicles.

In Fig. 15, the change of the objective function is shown together with the total length of the route for that day.

The routes of the collection vehicles after optimisation start from base point and run through all assigned nodes representing the households. If a vehicle is fully loaded it returns to the base.

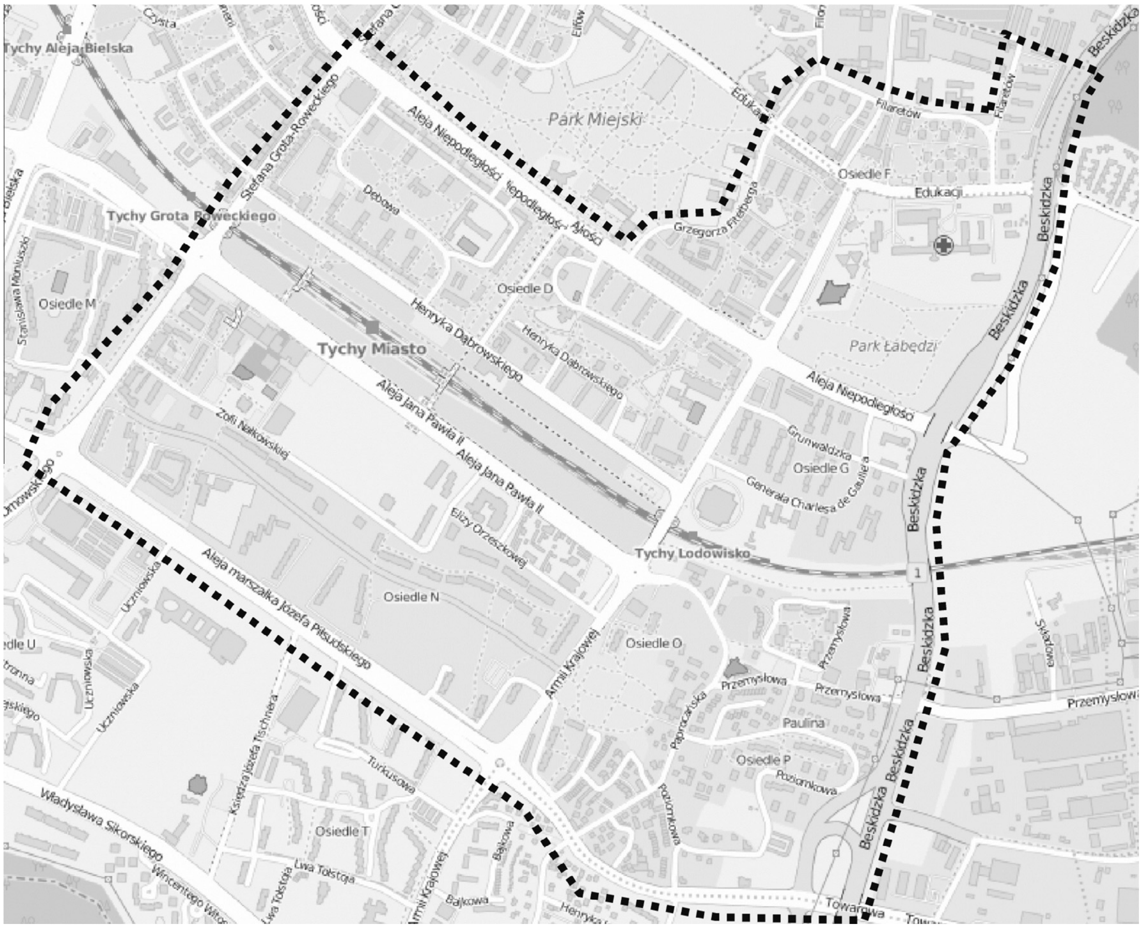

Fig. 9. Plan of the area under study.

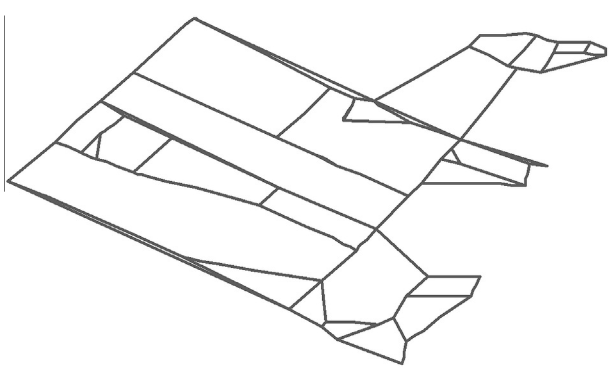

Fig. 10. Graph of the transportation network.

Examples of the routes for vehicles (day number 154, 4 vehicles, 86 calls) are shown in Fig. 16. As it can be seen, the routes overlap and there is visible zoning depending on the collection call. In general, the route set is not optimal according to its length (relation L/L_1 is within the range 4.0–5.0), but the accuracy of arrival time is acceptable (in this case D_{avg} = 10 min, D_{max} = 54 min).

5. Discussion and conclusions

WEEE treatment and processing after collection gives the possibility of recycling of almost all materials used in that kind of equipment, and of minimising the negative impacts on the natural environment and human health.

To achieve all these benefits efficient collection of WEEE is necessary. We have seen the development of communication channels, especially websites or mobile phone apps that enable finding the nearest waste collection sites (eSCHROT, 2015; Ewaste App, 2015). However most of these applications offer simple browsing capabilities to locate collection points.

Therefore, in our study we have proposed a novel approach focused on improvement of a mobile collection. The aim is to increase WEEE collection rate, taking into consideration a new EU collection target of 65% beginning with 2019 (European Commission, 2012).

On one hand, WEEE collecting companies are obliged to prepare the containers, vehicles and to employ staff to execute WEEE take back from households. All those factors contribute to operational costs for these companies. To solve the problems of minimising operational cost, numerous studies have been carried out (e.g. Nowak et al., 2008; Achillas et al., 2012; Mota et al., 2015). They include optimisation of collection networks and vehicle routes, while others are focused on preparation of adequate containers for transportation (Gamberini et al., 2009). The paper presented by Kuo et al. (2012) using genetic algorithms deals with the stationary model of containers located in the fixed sites.

On the other hand, we need to involve the EEE end users, who would like to discard unwanted equipment, by offering them improved service in WEEE take back. The residents can choose a disposal method. Sometimes they decide to store WEEE in households and in some cases the residents mix WEEE with municipal waste or sell at scrap points (Wang et al., 2011; Wath et al.,

Table 3
Characteristics of large and medium home appliances.

Equipment type	Width [cm]	Depth [cm]	Height [cm]	Mass [kg]	Possession in houses [%]	Possession in flats [%]	Waste equipment/year	Type
Washing machine	60	50	85	75	87	89	0.08	0
Mower	55	75	44	10	84	3	0.15	1
Refrigerator	60	60	175	55	98	98	0.08	0
Dishwasher	45	60	82	40	5	14	0.1	0
Tumble dryer	60	60	82	75	1	5	0.1	0
Washer-dryer	60	60	82	75	2	6	0.1	0
Desktop computer	20	50	45	8.5	50	40	0.5	1
Gas/electric oven	60	60	85	42	48	45	0.1	0
Microwave	44	34	25	10.9	51	45	0.1	1
Home cinema	44	32	15	7.4	16	16	0.12	1
Vacuum cleaner	48	28	32	5.8	96	96	0.1	1
Food processor	30	30	40	4.5	61	61	0.12	1
Printer	35	24	20	5.2	40	40	0.3	1
Laptop	38	27	8	2.3	25	30	0.3	1
DVD player	36	21	10	1.26	52	52	0.2	1
Radio/cassette	25	15	20	1.5	23	23	0.2	1
Television set	50	74	20	6.3	98	98	0.2	0

Table 4
General characteristics of collection calls.

Variable	Value
Annual total number of calls	12,691
Total volume of waste equipment [m^3]	707
Total mass of waste equipment [kg]	114,195
Daily average number of calls	63
Daily average volume of waste equipment [m^3]	3.53
Daily average mass of waste equipment [kg]	571
Minimal daily number of calls	37
Maximal daily number of calls	86

Table 5
Characteristics of calls for optimisation.

Variable	Day 52	Day 98	Day 126	Day 154	Day 155
Number of collection calls	82	62	85	86	77
Volume of waste equipment [m^3]	3.35	6.19	4.24	3.79	6.57
Mass of waste equipment [kg]	730	821	760	672	1023

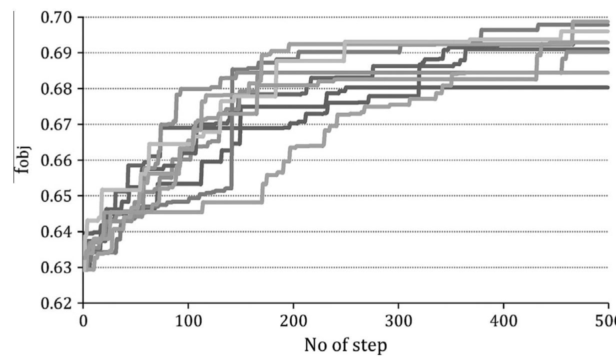

Fig. 11. The convergence of optimisation processes for the same date (day 98, 3 vehicles).

2011). Also it is necessary to inform the EEE end users about the best and most convenient methods of disposal.

To solve this problem we have proposed a novel model by joining two approaches in improved mobile WEEE collection.

Table 6
Results of optimisation for selected days.

Day	No. of vehicles	Initial solution				Optimal solution				Change of f_{obj}	Change of L
		f_{obj}	D_{avg} [min]	D_{max} [min]	L [m]	f_{obj}	D_{avg} [min]	D_{max} [min]	L [m]		
52	1	0.47	10	47	48,075	0.57	19	73	27,653	0.22	0.42
	2	0.47	3	26	50,738	0.56	20	73	32,916	0.18	0.35
	3	0.53	1	12	45,564	0.61	14	62	32,947	0.15	0.28
	4	0.55	0	12	51,514	0.61	13	62	40,106	0.11	0.22
98	1	0.53	15	85	30,645	0.56	18	78	24,243	0.06	0.21
	2	0.54	1	21	34,051	0.65	14	51	21,298	0.20	0.37
	3	0.63	0	3	32,028	0.70	7	42	24,322	0.10	0.24
	4	0.61	0	3	34,398	0.69	5	44	24,498	0.13	0.29
126	1	0.49	17	90	55,779	0.59	19	66	33,237	0.21	0.40
	2	0.52	4	44	49,159	0.60	16	64	35,397	0.15	0.28
	3	0.55	2	29	55,248	0.62	12	58	41,756	0.13	0.24
	4	0.56	1	21	60,394	0.62	6	53	47,721	0.11	0.21
154	1	0.49	4	27	59,075	0.60	16	64	34,174	0.23	0.42
	2	0.49	1	18	65,228	0.59	18	68	41,827	0.19	0.36
	3	0.56	0	14	66,160	0.62	12	60	52,201	0.10	0.21
	4	0.58	0	2	65,683	0.65	10	52	49,994	0.12	0.24
155	1	0.50	12	82	64,040	0.59	18	67	41,007	0.19	0.36
	2	0.50	2	24	63,522	0.59	18	69	41,765	0.18	0.34
	3	0.52	1	10	65,206	0.60	11	63	46,344	0.15	0.29
	4	0.58	0	22	64,102	0.65	10	53	48,780	0.12	0.24

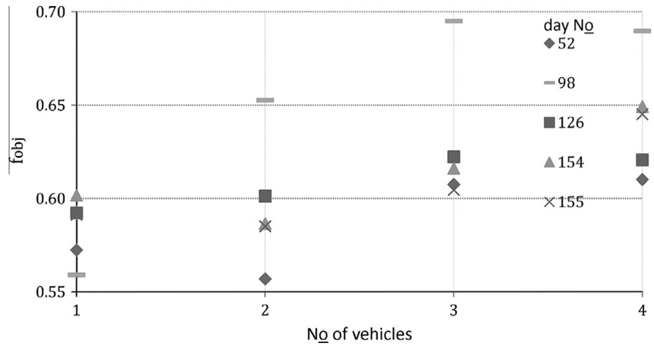

Fig. 12. The value of the objective function depending on the number of vehicles.

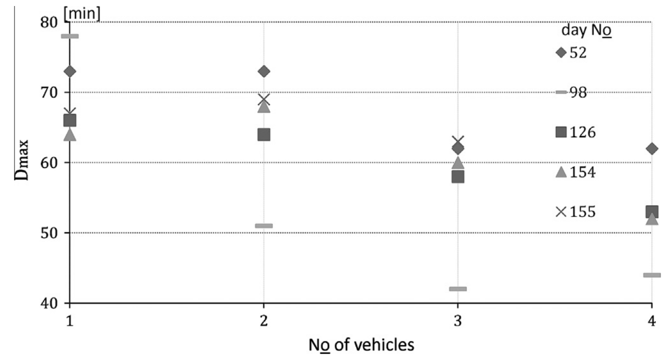

Fig. 14. The value of maximum delay depending on the number of vehicles.

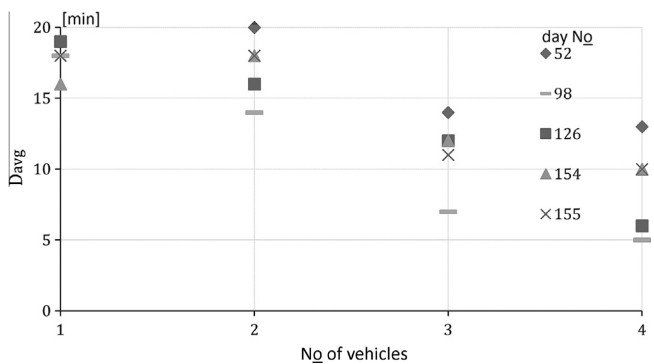

Fig. 13. The value of average delay depending on the number of vehicles.

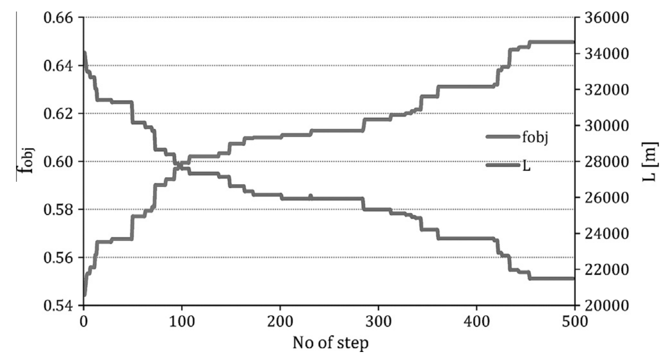

Fig. 15. The progress of the optimisation process (day number 98, 3 vehicles, f_{obj} – objective function, L – total route length).

There are few papers where the genetic algorithm and fuzzy logic have been used to solve vehicle routing problems (Chiang and Hsu, 2014; Lau et al., 2009). The end users satisfaction has been discussed together with VRP approach by Ghannadpour et al. (2013). However these studies have been focused in deliveries in supply chains.

In our study we propose a new concept of mobile collection of WEEE to increase the collection rate.

All modern communication channels can be applied in WEEE take back request from the household. They include convenient methods of phone calls, website submissions, or mobile apps. It also decreases inconvenience for the residents, who would like to

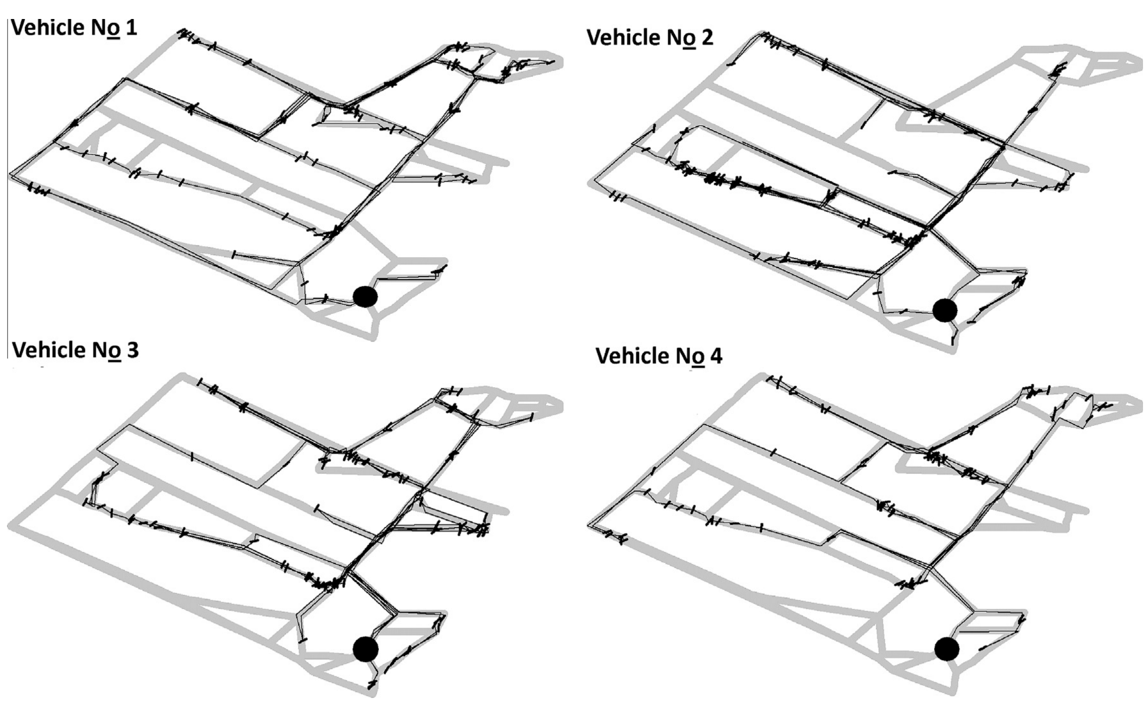

Fig. 16. Sketch of the vehicle routes for day 154 and 4 vehicles (the base is marked by a black circle; black perpendicular lines indicate pick up calls).

dispose of the equipment by minimising the delay in take-back of the obsolete equipment from the households. As the collecting companies are responsible for WEEE take-back, we have proposed the optimisation procedure that allows to reduce collection cost by minimising route length, the number of vehicles and the number of collection staff. Application of the genetic algorithm allows for fast preparation of a collection schedule in an individual work day for a set of waste collection calls from the households. The calculated route results are close to optimal, and the calculation time requires less than a minute on a PC with a standard configuration. The quality of service – i.e. the WEEE take-back delay after the requested time by residents is within acceptable limits.

Model operation has been presented in a case study in a city suburb with a number of over ten thousand households. Our results are useful for collecting companies. They can improve the standard service of take-back with the support of a genetic algorithm optimisation that generates a sequence of WEEE take-back from households and the number of vehicles.

The presented model is fully parametric; the boundaries of the quality of service can be altered depending on local surveys, and other parameters like average speed and capacity of collecting vehicles are configurable. This approach could be developed to meet growing demands in case of a larger city. However, there are many waste collecting companies in big cities, thus the whole amount of service needed is shared among them. Therefore, we expect the size of task should not be significantly bigger for a single company.

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