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Combining an artificial intelligence algorithm and a novel vehicle for sustainable e-waste collection

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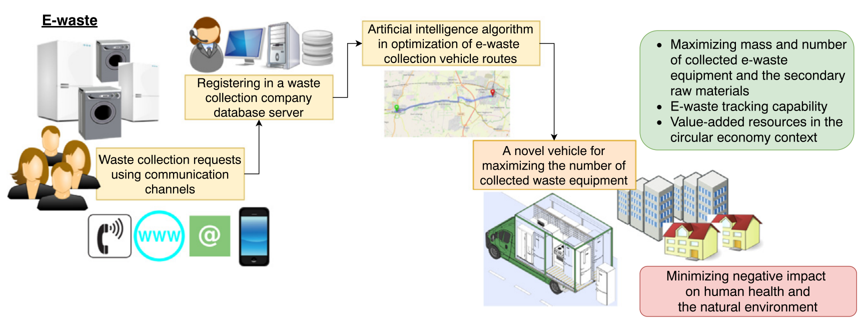
HIGHLIGHTS

- Combined artificial intelligence supported collection and a novel vehicle body.
- Harmony search algorithm for route optimization in on-demand e-waste collection
- A novel construction of waste collection vehicle body with convenient loading
- The efficiency of waste collection including routing and packing for the vehicles
- Benefits for the environment and human health by the collection of hazardous waste

GRAPHICAL ABSTRACT



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ABSTRACT

Mobile collection of waste electrical and electronic equipment is a collection method that is convenient for residents and companies. New opportunities to use mobile apps and internet applications facilitate the ordering of waste pickups from households and preparation of a collection plan for a waste collection company. It improves the secondary raw materials collection in a circular economy approach after recycling waste equipment. This study presents a combined methodology for improving the efficiency of e-waste collection. An online e-waste collection supporting system uses a Harmony Search algorithm for route optimization of waste collection vehicles. The results of the optimization are better compared to other artificial intelligence algorithms presented in the literature and the number of visited collection points is higher from 1.2%–6.6% depending on the compared algorithm. To increase the efficiency of waste loading and packing, a novel collection vehicle body construction is presented. The design includes the convenient loading of waste from both sides of the vehicle and the rear side being equipped with a hydraulic lift. The proposed vehicle model can be used for e-waste collection in places with limited parking spaces or where the parking time is limited, such as in densely populated city centers. The waste equipment packing efficiency increases and eliminates the necessity of including a container loading problem in the algorithm and allows increasing waste equipment number loaded in a collection vehicle.

1. Introduction

Waste electrical and electronic equipment (WEEE or e-waste) has become a priority in the policy of waste management in developed and developing countries (Ongondo et al., 2011; Widmer et al., 2005).

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This category of waste has a high recycling potential and also includes hazardous substances (Oguchi et al., 2011). A reverse supply chain of WEEE complies with the requirements of the principles of the circular economy. The concept of the circular economy assumes the maximum use of raw materials in the closed economy circuit and minimisation of the waste stream to the landfill (Korhonen et al., 2018; Parajuly and Wenzel, 2017). Therefore, the preferred methods of disposal of used products are the ones that enable their re-use, repair, and recycling (Laustsen, 2007). WEEE is a category for which a separate collection through various channels must be ensured. There are various entities responsible for reverse logistics chain operation. The implemented EU directives and legislation in other countries define the scope of duties and responsibilities of parties involved in the waste collection (European Commission, 2012). WEEE is generated both by inhabitants and companies. Waste collection companies must provide effective methods for collection of WEEE by ensuring the appropriate measures, i.e. vehicles, employees, as well as preliminary preparation of information campaign about the methods of waste collection, location of containers, etc. (Friege et al., 2015; Gamberini et al., 2009; Nuortio et al., 2006; Purkayastha et al., 2015). At the same time, the inhabitants are obliged to remove waste properly, in line with the information provided by the equipment manufacturers, whereas the companies responsible for waste collection and municipal companies should take care of transport and shipment of waste to a WEEE dismantling facility (Borthakur and Govind, 2017; Wang et al., 2016).

It is essential in the circular economy approach to fully support efficient e-waste management using all communication channels and the information system supporting waste collection. Properly collected waste through legal channels minimizes risk with contamination of hazardous substances from various components and parts of waste equipment including batteries, liquid crystal displays, printed circuit boards, electrolytic capacitors, etc. At the same time, the e-waste collection on demand contributes to social acceptance of novel and convenient for individuals' method of handling and pick up of waste items. Park et al. investigate the efficiency of door-to-door service WEEE collection in Korea including public perception, user satisfaction, public relation and promoting strategies of this collection service (Park et al., 2019). Another significant benefit of the on-demand collection method is the acquisition of the equipment of high recycling potential including ferrous metals, non-ferrous metals, precious and rare earth metals, and plastics. For waste collection companies, the important thing is to obtain the largest possible mass of waste with simultaneous reduction of waste collection costs (Costa-Salas et al., 2017; Kang and Schoenung, 2006; Nowakowski et al., 2017; Tsai and Hung, 2009). On the other hand, for the inhabitants, it is important that waste collection should be carried out in a manner which is convenient for them, that the schedules of equipment collection are clear and the location of containers is appropriate (Król et al., 2016; Saphores et al., 2006, 2012).

2. Literature review

There are many possible methods of e-waste collection. They include stationary waste collections carried out in municipal waste collection points, EEE stores and mobile waste collections run as curbside recycling as well as carried out in mobile points located in frequented areas (European Commission, 2012). The mobile collection can be executed as a curbside or alternatively on demand when a resident calls a collection company or uses a mobile app to request WEEE pickup (Gu et al., 2019; Nowakowski et al., 2017, 2018). This method gains increasing interest due to cost reduction, its convenience for residents and popularity in many countries, including the developing countries (Agrawal and Mittal, 2017; Cao et al., 2018) and also benefits for the collection of e-waste of stockpiled in households by individuals. The number of stockpiled e-waste in households (Nowakowski, 2019) has high recycling potential and therefore some novel and acceptable by individuals modern collection methods should be applied broadly. Sun et al. investigate using a platform "Internet and WEEE collection" as a business solution for improvement of e-waste collection in China (Sun et al., 2020).

However, the level of the collection in many countries is relatively low, while at the same time many companies complain about excessively high collection costs and lack of effectiveness - i.e. too low stream of waste collected despite high costs being incurred. It can be confirmed on the basis of Eurostat data, as well as various publications from other countries (Dwivedy et al., 2015; Eurostat, 2018; Li et al., 2017). In European Union in 2016 the ratio for all categories of WEEE placed on the marked and waste equipment collected was 38%. It includes large home appliances with ratio of 47%, small home appliances 40%, and ICT equipment – 48%. A frequent reason for that is the unwillingness of waste collection companies to incur additional costs. The criterion of costs incurred in relation to potential revenue from the collected equipment is one of the most important elements when estimating the effectiveness of reverse logistics chain. The costs incurred during waste collection include personnel costs, costs of containers and vehicles, as well as administrative costs. Due to this, waste collection companies would be most willing to collect large and heavy equipment, equipment with significant content of metals or the equipment of high market value, like ICT equipment or mobile phones (Dat et al., 2012; Kang and Schoenung, 2006).

Different forms of communication like telephone, Internet and mobile applications, for supporting the mobile equipment collection were proposed in order to improve its effectiveness. The main purpose is to request a collection of WEEE within a specified date and time windows convenient for a resident (Gao et al., 2015; Nowakowski et al., 2018). Chinese case study presented by Jian et al. provides insight into the promotion of WEEE recycling and analyzes the selection of collaborative strategies for various reverse supply chain players (Jian et al., 2019). A development of the collection model combining Internet and Recycling was proposed by Gu et al. with a support of dedicated mobile app Aibolv (Gu et al., 2019).

A collection company after receiving a request of WEEE collection calls has to prepare a waste collection plan for a specified date. A sufficient number of vehicles and the employees participating in the waste collection have to be organized to collect WEEE from requested locations. This task requires using artificial intelligence algorithms for optimization of vehicle routes and a number of the vehicles because it is a typical vehicle routing problem with time windows (VRPTW) (Buhrkal et al., 2012; Kim et al., 2009; Toth and Vigo, 2014). It is intended to reduce transport costs and use resources, i.e. vehicles and employees participating in waste collection. The new collection model supported by the assistance of Internet and Communication technologies proposes Xue et al. This study included survey for fifteen companies operating in China and a variety of waste categories (Xue et al., 2019).

This study is the development of the information system supported by artificial intelligence investigated in previous research (Nowakowski et al., 2017, 2018). The key improvement for this method focuses on maximizing the number of collection points – from residents who would like to dispose of waste or unwanted equipment from households. As a result, the exhaust emissions from the waste collection vehicles can be reduced by using a lower number of vehicles by the collection company and collecting a higher mass of the raw materials from waste equipment. To achieve this goal we propose the application of the Harmony Search (HS) algorithm indicating some advantages of the previously described algorithms (Simulated Annealing (SA), Improved Bee Colony Algorithm (BCOi), Tabu Search (TS) and Greedy Algorithm (GrA)). Another issue guiding this study was the efficiency of the mobile collection, especially taking into consideration the collection costs and the volume of the e-waste collected by vehicles. In many cases, the collection companies managers complain about the number of waste WEEE items is too low, or WEEE was not properly packed inside a collection vehicle. This was the reason to skip other WEEE collection points and return to a company base to unload the e-waste. This is one of the major problems increasing collection cost in the mobile collection on-demand method. The results of the personal communication with the managers of the collection companies was an idea to design a novel body construction for convenient loading of waste equipment with the easy adjustment of its position in a vehicle and completing a collection according to prepared plan. This proposal is an important step towards the improvement of the excellency of the reverse supply chain especially by enabling efficient use of a vehicle payload and using HS algorithm in optimization. It helps also with a simplification of the WEEE collection model without including three-dimensional packing problem in the algorithm (Dowsland and Dowsland, 1992).

Since requesting the waste collection in time windows and vehicle routing, the VRPTW problem occurs (Toth and Vigo, 2014). The additional restrictions occurring in business practice (e.g. maximum vehicle payload capacity, acceptance of different types of equipment by vehicles, heterogeneity of WEEE and fleet, potential need to unload waste and continue waste collection) enforce the extension of classical VRPTW model.

Container loading problems and vehicle routing and loading problems were discussed in another study (Nowakowski, 2017). Mar-Otis discusses vehicle routing problems with split loads and date windows for WEEE using Greedy Randomized Adaptive Searching Procedure (Mar-Ortiz et al., 2013). The problem of vehicle routing with time windows in a mobile collection and WEEE loading is a novel issue and it was discussed in a study by Nowakowski et al. (Nowakowski et al., 2017).

The construction of a fully functional information system supporting mobile collection of WEEE on demand was described in the article Nowakowski et al. (2018). The results obtained in this study indicated the efficiency of using in the application the following algorithms: SA, BCOi, TS and GrA. SA and TS are metaheuristics, which assume searching the neighborhood of a given solution and the possibility of moving to a worse solution after meeting a specific condition (SA uses a parameter called temperature, and TS uses a Tabu period). GrA assumes making the locally optimum decision at every step of constructing a route (by selecting the vehicle with the lowest cost and nearest e-waste collection point).

Despite the adaptation of many different metaheuristics to solve problems derived from VRP, we assumed that the WEEE mobile collection planning problem can be successfully solved by HS. As Yi et al. (2019) noted, HS is simple in concept and easy in implementation. In addition, it does not require initial values for the decision variables and compared to some popular metaheuristics it imposes fewer mathematical requirements and can be easily adapted for different problems (Lee and Geem, 2005). Other arguments that convinced us about the choice of HS are: its considerable popularity (Yi et al., 2019) and designation of better solutions for some optimization problems than solutions created by other popular methods.

3. Materials and methods

3.1. Application of Harmony Search algorithm in the e-waste collection on demand

The method of mobile waste collection on-demand was presented in Fig. 1. A resident who would like to dispose of waste equipment request a collection from a WEEE collection company within specified time windows. After registering all requests for a certain day in a database it is necessary to perform optimization of routes. When the optimization is finished a driver of a collecting vehicle receives a sequence of the collection points.

HS was proposed by Geem (2000) and assumes the storage of *HMS* sorted solutions (called harmonies, which are described with pitches, representing decision variables) in *HM* (harmony memory) structure. The procedure is based on iterative development of subsequent solutions and comparison of their values of objective function with the value of objective function of the worst harmony located in *HM* - if the created result is better, then it will replace the stored solution.

The harmony process creation itself assumes determination of subsequent pitch values, based on two variables - *HMCR* and *PAR*. The first of them is responsible for the probability of the use of knowledge gathered in *HM* (the value of i pitch is selected with *HMCR* probability on the basis of pitch values in position i in the harmonies placed in *HM*; the random selection of permissible value with $1 - HMCR$ probability is carried out), whereas the second one is responsible for the possibility to modify the value originating from *HM* (the operation is performed with probability equal to $HMCR \cdot PAR$).

This paper is based on the modified algorithm structure, proposed by Boryczka and Szwarc (2018). It assumes better adaptation of the method to combinatorial optimisation and allows to achieve relatively good solutions for Asymmetric Traveling Salesman Problem by describing pitch values with integers, corresponding to the numbers of nodes visited by the salesman (the sequence of pitches corresponds to the sequence of travel). The selection of pitch value in i position - occurring with *HMCR* probability - is not made directly from the pitch values in i position, located in harmonies from *HM*, but uses the list of nodes that are successors of the node represented by the pitch in $i - 1$ position in the created harmony. If none of the available nodes is present in the harmonies located in *HM* (directly after the analysed vertex), the permitted city is selected randomly. Additionally, the selection of pitch value i, consistent with the described probability, takes place using the roulette wheel method (harmonies described with a more favourable value of objective function are promoted), whereas the selection of the nearest node from the $i - 1$ vertex was determined instead of the value modification occurring with $HMCR \cdot PAR$ probability. Moreover, the avoiding premature convergence mechanism was introduced,

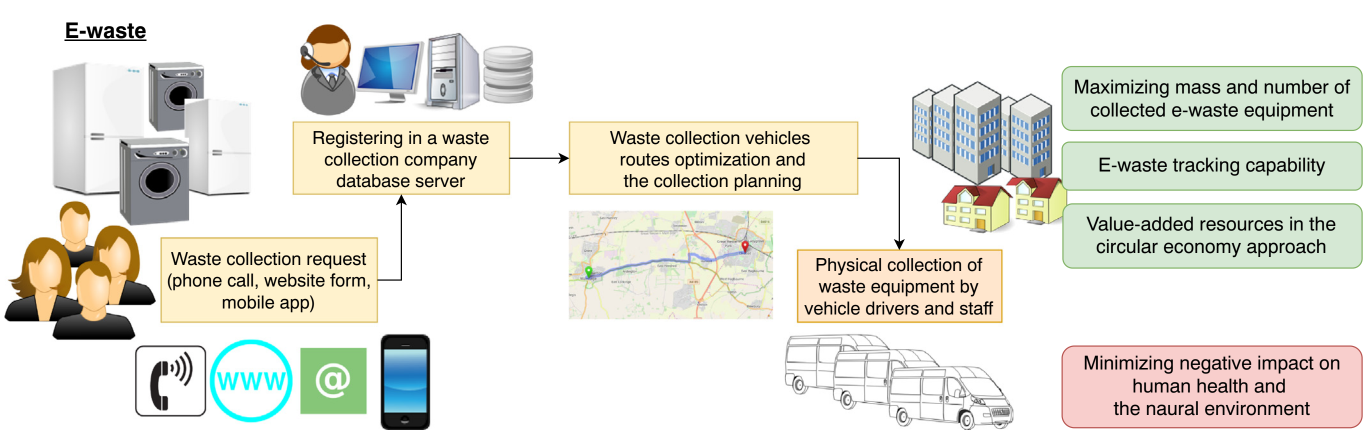

Fig. 1. Framework of the collection system waste on-demand.

assuming the repeated drawing of *HM* elements after performing *R* iterations from the last approval of a created solution (as a result of the operation, the best harmony remains unchanged).

In order to enable the feasible solutions to be constructed by HS, it was necessary to introduce additional modifications. In our implementation of the algorithm, we assumed harmony representation through travel plans of subsequent vehicles. The procedure for developing a new solution consists of iterative performance of two steps - selection of the next available vehicle and assignment of the possible collection points to it. The steps are repeated until all available vehicles have been analysed or all points have been served. The procedures related to *R*, *HMCR* and *PAR* parameters are similar to the ones proposed by Boryczka and Szwarc (2018), however:

- When analysing the selection of the vehicle for which the route is constructed iteratively, for the operation performed with *HMCR* probability, the value of objective function of the harmonies that assume the use of this means of transport is taken into consideration. The vehicle with the lowest cost of usage is selected with $HMCR \cdot PAR$ probability.
- For the selection of the point based on *HMCR* probability, the random selection of available node was replaced, in case it is impossible to determine the relevant successors, with the selection of the point based on the roulette wheel, assuming the promotion of nodes for which the highest result of the quotient of values of the collected secondary raw materials is achieved, to the unit of distance from the last visited node.

The algorithm is performed for *IT* iterations.

3.2. Novel body construction of a collecting vehicle

A novel vehicle body can be assembled in any commercial vehicle. It is most suited to a typical van or small lorry (Fig. 2). Cargo compartment of the vehicle is supported on a frame for assembling additional components of the body. From both sides, aluminum shutters enable access to all equipment and also make possible rotations or other adjustments for each loaded waste appliance if necessary. Additional equipment can also be loaded from the right or left side (Fig. 2c). The rear side of the vehicle is equipped with a hydraulic lift for loading heavy equipment. In the floor, the idlers enable free movement of the waste equipment towards the front, and the rearrangement of position is also easier for equipment placed on the idlers. A special grate placed in the middle of the vehicle is designed for fastening waste items for secure transportation, such as equipment posing a hazard to the environment like monitors or cooling equipment. It prevents the equipment in this category from possible breakage while in transit (ACRR, 2009).

Real-world mobile collection of e-waste shows there are numerous difficulties with the arrangement of the waste equipment inside a vehicle. Fig. 3 shows an example of a vehicle where the loading was conducted from the rear side of the vehicle. It is common practice resulting in loading a lower number of the waste equipment items and lowering the efficiency of the collection.

The novel construction has distinct advantages when we compare it with the existing vehicles for mobile collection of WEEE (Fig. 2c). For a great majority of vehicles used in waste collection, loading is from the rear side. Some larger vehicles like lorries can also be equipped with a hydraulic lift but there is no or limited access from the side of a vehicle. The flat floor makes rearrangement of waste equipment more time consuming and difficult. Any rearrangement of waste equipment by unloading requires additional time and therefore is not suitable for the collection where parking time can disturb traffic or parking is limited. It is especially useful in districts with multi-storey buildings, old towns, places with limited parking space or narrow pavements.

The possibility of using information systems supporting WEEE mobile collection on demand to solve the combined problem of loading and packing can help in the preparation of shipments in a reverse supply chain. Transportation of WEEE in a mobile collection unit must take into consideration uncertainty of unknown dimensions of waste equipment (variation of size of equipment described by a resident when calling collection company or placing an online order) as well as rejection of the WEEE collection by a resident, or the offer of additional equipment by a resident. In such case, a collection plan for a vehicle even including routing and packing in the optimization model becomes invalid. Therefore, the presented design of a novel vehicle body construction brings more flexibility in the collection of waste items.

A new approach of the mobile collection combines using the HS algorithm and collection vehicle body. An optimized routing plan of vehicles will be assigned using the HS algorithm and compared with selected artificial intelligence algorithms. The proposed algorithm will be compared with selected other artificial intelligence algorithms. The novel collection vehicle will help to load waste equipment from the left, right and rear side of the vehicle and enable easier rearrangement of e-waste inside the vehicle's body. This proposal is an important step towards the improvement of the e-waste collection in the circular economy approach by maximizing the use of a vehicle payload and using the HS algorithm in the vehicles routing optimization.

4. Results

4.1. Evaluation of the algorithm effectiveness

On the basis of Boryczka and Szwarc (2018) and conducted empirical research, we determined the following parameter values: $HMS = 5$, $HMCR = 0.98$, $PAR = 0.25$, $R = 1000$ and $IT = 10000$.

In order to determine the effectiveness of the proposed approach to designing Harmony Search, the obtained results were compared with the results determined by GrA, TS and SA, which were implemented on the basis of the description presented by Nowakowski et al. (2018)

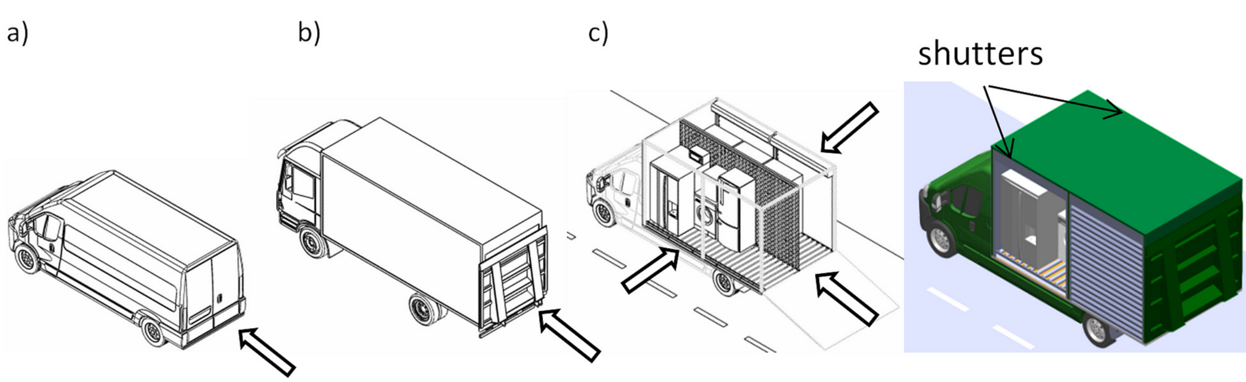

Fig. 2. The main types of the vehicles for mobile e-waste collection and the loading principle of waste equipment - van (a), lorry (b), a novel vehicle (c) - the vehicle body is shown as transparent for viewing the interior with loaded e-waste.

Fig. 3. Real-world case study of interior of e-waste collection vehicle.

(with Tabu period amounting to 2, probability of accepting a worse solution in the first iteration equal to 0.3, epoch length amounting to 50, α equal to 0.98, the same stop condition for both metaheuristics, i.e. 50 iterations from the moment of the last acceptance of the better solution, and $\zeta = 5\%$; TS and SA were based on the solution determined by GrA).

The research was performed using Lenovo Y50–70 laptop with the following configuration: Intel Core i7-4720HQ (4 cores, from 2.6 to 3.6 GHz, 6 MB cache), 16GB RAM (SODIMM DDR3, 1600 MHz), HDD 1000GB SATA 5400 RPM Express Cache 8GB, Windows 7 Professional N Service Pack 1 64-bit. We selected 25 pseudorandomly generated waste equipment collection requests as the 'test bed' (their characteristics was presented in Tables 1 and 2) and one case study assuming the occurrence of problem instance in the city of Łódź (Poland), where 2 vehicles of a company collecting WEEE are intended to serve 25 requests (the visualization of the issue was presented in Fig. 4, where collection points were marked with cross, whereas the base was marked with

Table 1
Values of parameters of test assignments.

No.	Parameter	Value
1	Minimum number of collection points	50
2	Maximum number of collection points	120
3	Minimal distance between WEEE collection point [km]	0.2
4	Maximum distance between WEEE collection point [km]	5
5	Minimal number of vehicles	2
6	Maximal number of vehicles	5
7	Minimum weight of waste equipment at a collection point [kg]	0.5
8	Maximum weight of waste equipment at a collection point [kg]	100
9	Minimum secondary raw material value at a collection point [EUR]	10
10	Maximal secondary raw material value at a collection point [EUR]	150
11	Maximum number of categories of waste equipment	3
12	Working hours	7
13	Probability of a time window occurrence [%]	20
14	Minimum volume of equipment at collection point [m^3]	0.01
15	Maximum volume of equipment at collection point [m^3]	2
16	Minimum vehicle loading time [s]	300
17	Maximum vehicle loading time [s]	1200

Table 2
Values of parameters of used fleet.

No.	Parameter	Value
1	Probability of accepting the type of equipment [%]	95
2	Minimum travel cost per km [EUR]	0.5
3	Maximum travel cost per km [EUR]	2
4	Minimum usage cost of a vehicle [EUR]	400
5	Maximum usage cost of a vehicle [EUR]	600
6	Minimum payload of a vehicle [kg]	500
7	Maximum payload of a vehicle [kg]	2500
8	Minimum cargo capacity of a vehicle [m^3]	10
9	Maximum cargo capacity of a vehicle [m^3]	32
10	Minimum vehicle unloading time [s]	600
11	Maximum vehicle unloading time [s]	2400

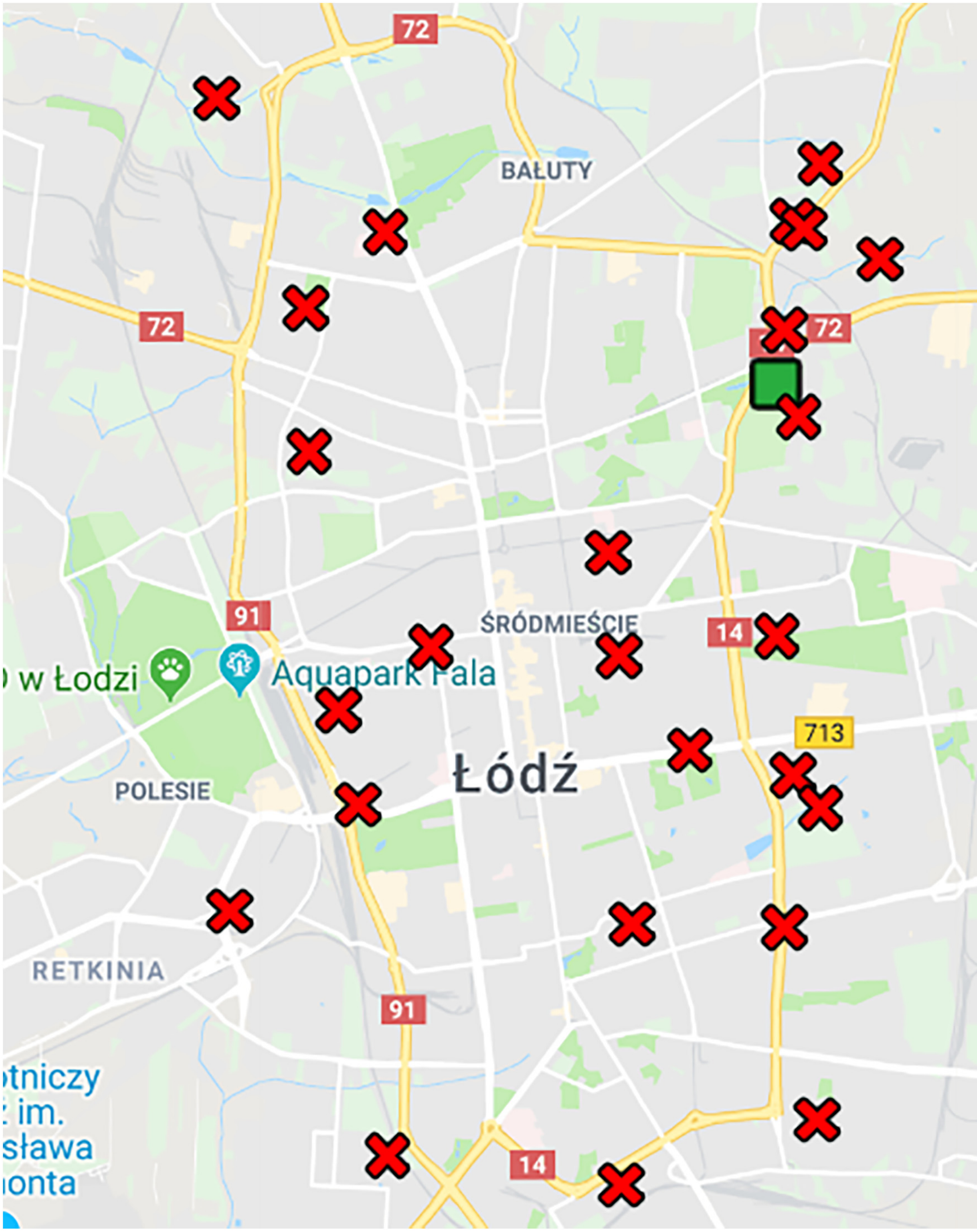

Fig. 4. Visualization of the e-waste collection points in a city in Poland on copypastemap.com.

square), characterised by the attribute value consistent with the pseudorandom instances. In order to ensure the reliability of results, every task was solved by each nondeterministic algorithm (TS, SA and HS) 30 times (due to the smaller size of the case study, we have increased the number of repetitions for it to 35, thus providing more reliable results), each time using a different seed.

Table 3
Summary of results for pseudorandom set of tasks.

Algorithm	$\overline{f}$	σ_f	$\overline{t}$ [s]	σ_t [s]	$\overline{it}$	σ_{it}	$\overline{m}$ [kg]
GrA	1	0	<1	0	1	0	3387.5
SA	0.962	0.026	14.85	17.53	59.31	56.91	3568.09
TS	0.967	0.024	3.49	4.14	58.73	51.3	3546.06
HS	0.948	0.023	14.2	12.59	5835.53	2788.17	3611.88

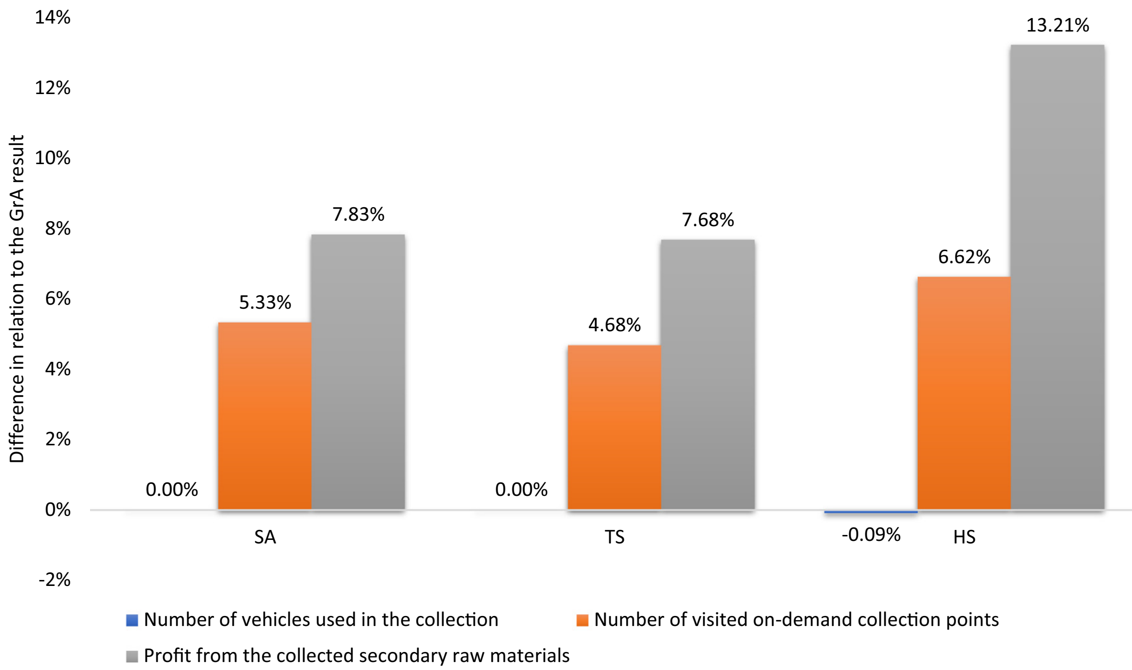

Fig. 5. Summary of results for pseudorandom set of tasks.

The evaluation of effectiveness of the proposed HS was carried out on the basis of the f proposed by Nowakowski et al. (2018) and described with a formula (its average value was marked as $\overline{f}$, whereas the standard deviation from the sample was marked as σ_f):

$$f = v_f + c_f + t_f + p_f, \tag{1}$$

where v_f is the indicator of the value of the collected equipment, c_f is the cost indicator, t_f is the time indicator, and p_f is the served collection points indicator. It is assumed that the smaller the value of f, the better travel plans are.

The indicator of the value of the collected equipment v_f was described as:

$$v_f = \frac{1}{2} \cdot p_p \cdot \frac{\sum_{i=1}^{v} \sum_{j=1}^{pb_i} bp_{ij}}{\sum_{i=1}^{v} \sum_{j=1}^{pn_i} np_{ij}}, \tag{2}$$

where p_p is the parameter of profit (the difference between the cost of conducting the collection and the value of raw materials obtained from the collected equipment) significance, v is the number of vehicles that can be used in the collection, pb_i/pn_i is the number of collection points on the vehicle route i in the base/new solution, bp_{ij}/np_{ij} is the value of equipment in point j of the vehicle route i in the base/new solution.

The cost indicator c_f was described as:

$$c_f = \frac{1}{2} \cdot p_p \cdot \frac{\sum_{i=1}^{v} \left(un_i \cdot \left(c_i + \sum_{j=2}^{rn_i} \left(d_{i(j-1),ij} \cdot ct_i \right) \right) \right)}{\sum_{i=1}^{v} \left(ub_i \cdot \left(c_i + \sum_{j=2}^{rb_i} \left(d_{i(j-1),ij} \cdot ct_i \right) \right) \right)}, \tag{3}$$

where ub_i/un_i is a variable defining the usage of the vehicle i in the base/new solution, rb_i/rn_i is the number of vertices in the i vehicle schedule in the base/new solution, c_i is the initial vehicle i usage cost, ct_i is the cost of driving 1 km by vehicle i, and $d_{i(j-1),\ ij}$ is the distance between point $(j-1)$, and j of the i vehicle route [km].

Variables ub_i and un_i were defined as:

$$\begin{aligned} ub_i &= \begin{cases} 1 & \text{if vehicle } i \text{ has been used in the base solution,} \\ 0 & \text{otherwise,} \end{cases} \\ un_i &= \begin{cases} 1 & \text{if vehicle } i \text{ has been used in the new solution,} \\ 0 & \text{otherwise.} \end{cases} \end{aligned} \tag{4}$$

Time indicator t_f was described as:

$$t_f = p_t \cdot \frac{\sum_{i=1}^{v} t_{i,ns}}{\sum_{i=1}^{v} t_{i,bs}}, \tag{5}$$

where p_t is the parameter of time significance, and $t_{i,\ ns}/t_{i,\ bs}$ is the time difference between returning to the base and starting the travel by vehicle i in the new/base solution.

The served collection points indicator p_f was described as:

$$p_f = p_g \cdot \frac{\sum_{i=1}^{v} pb_i}{\sum_{i=1}^{v} pn_i}, \tag{6}$$

where p_g is the parameter of the significance of the number of served points.

Table 4
The results of Wilcoxon Signed-Rank Test for pseudorandomly generated problem instances.

M1\M2	GrA	SA	TS	HS
GrA	N/A	1	1	1
SA	1.5E-109	N/A	1.29E-23	1
TS	2.4E-111	1	N/A	1
HS	1E-124	3.07E-97	2.6E-108	N/A

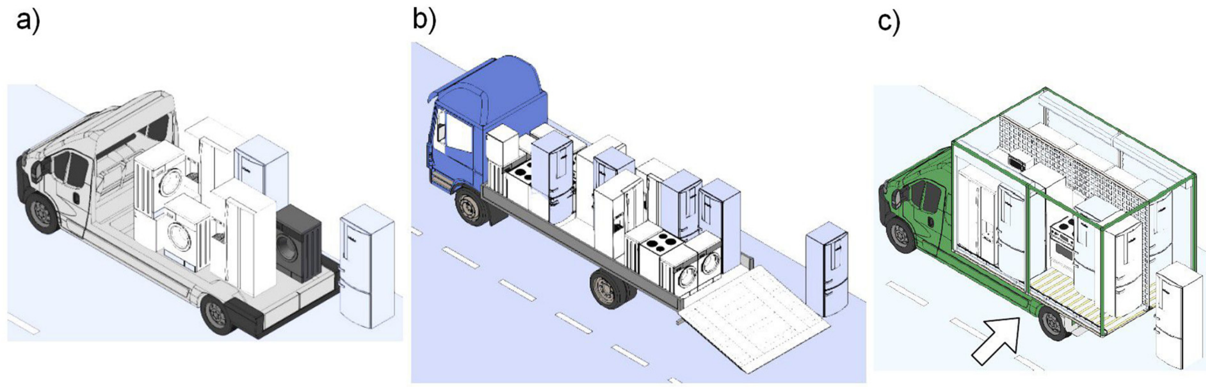

Fig. 6. Instances of loading van (a), lorry (b) and the novel vehicle (c). The novel vehicle has easy access from the left side, the right side, and rear.

Additional conditions were introduced to ensure the existence of a summary value of weights equals to 1:

$$p_p + p_t + p_g = 1, \quad 0 \leq p_p, p_t, p_g \leq 1, \quad p_p, p_t, p_g \in \mathbb{R}. \tag{7}$$

We assumed that $p_p = 0.2$, $p_t = 0.1$ and $p_g = 0.7$.

Additionally, the analysis covered the number of iterations after which convergence was achieved it (the iteration number in which the best result was determined; its average value was expressed by $\overline{it}$, whereas the standard deviation from the sample was expressed as σ_{it}) and the time to reach convergence t, expressed in seconds (the average value was marked as $\bar{t}$, whereas the standard deviation from the sample was marked as σ_t). In addition, for the pseudorandom task set, we analysed the average mass of collected e-waste equipments $\overline{m}$, expressed in kilograms.

To ensure that the differences across analysed algorithms are important in the statistical sense, the Wilcoxon Signed-Rank Test was used for the f value. The value of 0.05 was adapted as a significance level (a lower result indicates to accept alternative hypothesis according to which M1 yielded lower results than M2).

4.2. Results analysis

The results obtained by particular algorithms for pseudorandomly generated problem instances were presented in Table 3 and Fig. 5. The problem instances are representing real-life conditions of requesting WEEE pick up from a household. On their basis, the occurrence of significant effectiveness of the proposed HS was discovered, which over a very short period of time (amounting to 14.2 s on the average) determined the best solutions among the plans constructed by the tested methods. The developed plans were characterised not only by a higher number of the points served, but also by the limitation of vehicle use and increase of profit. Compared to the plan constructed by GrA, HS reduced by 0.09% the average number of vehicles used in the collection of e-waste, increased by 6.62% the number of serviced collection points, and increased by 13.21% the profit from the collected resources. Its results were also described by the lowest σ_f value (among metaheuristics), demonstrating the highest predictability of solutions, and thus enabling its application in business practice. The achieved values of $\overline{it}$ and σ_{it} also prove that IT value is not too low for the analysed tasks.

Each of the tested metaheuristics improved the solution determined by GrA. The conclusions presented by Nowakowski et al. (2018) were also confirmed, indicating significant effectiveness of the examined SA (in comparison with GrA and TS), which was simultaneously characterised by the longest period of achieving convergence.

The results of Wilcoxon Signed-Rank Test for pseudorandomly generated problem instances were presented in Table 4. Based on their analysis, it is recommended to use HS. In addition, alternative hypotheses were also accepted, according to which SA obtained better results than GrA and TS, and TS created better plans than GrA.

The results presented in Fig. 5 show the HS algorithm gained better results than SA, TS and the base solution algorithm GrA. Some of the instances of the waste equipment collections are visualized in Fig. 6.

For the two types of the collection vehicles (Fig. 6a and b) it was not possible to load another piece of waste (refrigerator) because of the actual arrangement of waste appliances already placed in the cargo compartment of the vehicle. A refrigerator can be placed easily in a novel collection vehicle from the left side. Although it is possible to unload some equipment and rearrange it for other types of vehicles (Fig. 6a, b), making space for the additional piece of waste it could be difficult for two reasons. In urban areas, it can bring traffic disruptions both for other traffic participants and for pedestrians. The second reason is that any rearrangement of waste appliances is time-consuming and therefore the collection of waste in another point would excess expected time window. For the calculated instances the number of visited points by HS could be higher from 1.2% to 6.6% depending on the algorithm. At the same time a potential profit from the waste collection for HS could be higher 5.1% to 13.2% depending on the compared algorithm. This value does not directly come from reduced number of collection points (and at the same time lower number of collected waste appliances) but also from the necessity to unload the waste at a collection company base and returning for the collection. Therefore, a novel collection vehicle can be loaded faster from three sides with an option to place another piece of waste in spare place inside and free rotation of the equipment in the vehicle.

The summary of results for the analysed case study was presented in Table 5. This confirmed the observations for pseudorandom set - the best results were determined by HS, whereas the worst results were achieved by GrA. All algorithms constructed travel routes in a very short time, demonstrating the possibility to use them for solving actual problem instances.

The travel plans generated by specific algorithms were presented for the analysed case study in Figs. 7, 8, 9, and 10. Due to the inability to collect every type of equipment by one of two available vehicles, GrA, based on greedy decisions taken, served only 19 waste collection points, whereas TS served 22 waste collection points, SA - 23, and HS - 24.

Table 5
Summary of results for the case study.

Algorithm	$\bar{f}$	σ_f	$\bar{t}$ [s]	σ_t [s]	$\overline{it}$	σ_{it}
GrA	1	0	<1	0	1	0
SA	0.86	0.01	1.55	0.89	56.69	41.62
TS	0.88	0.015	<1	0.1	63.63	40.41
HS	0.84	0.006	1	0.51	4440.8	2798.17

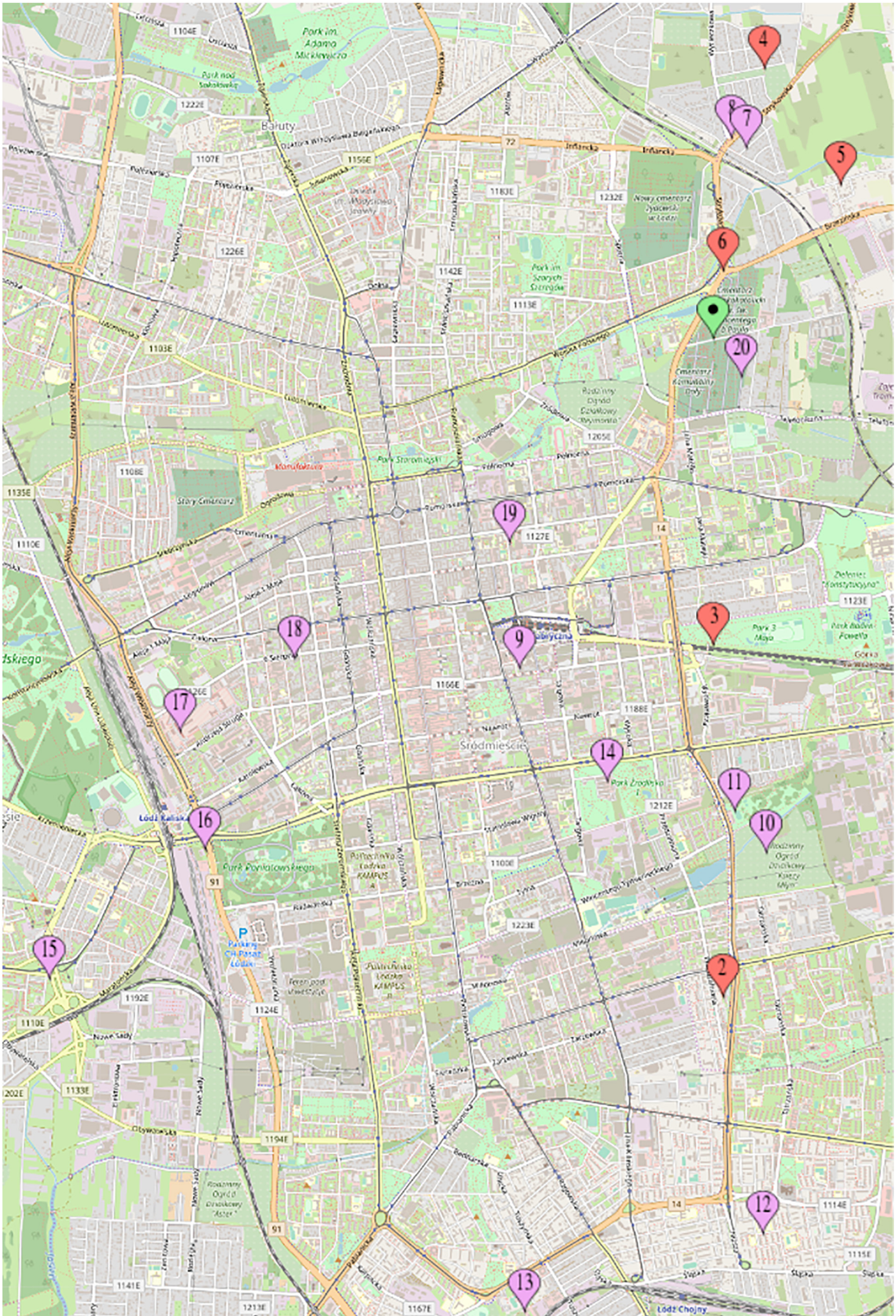

Fig. 7. Waste equipment collection sequence for Greedy Algorithm (visualization on mapcustomizer.com).

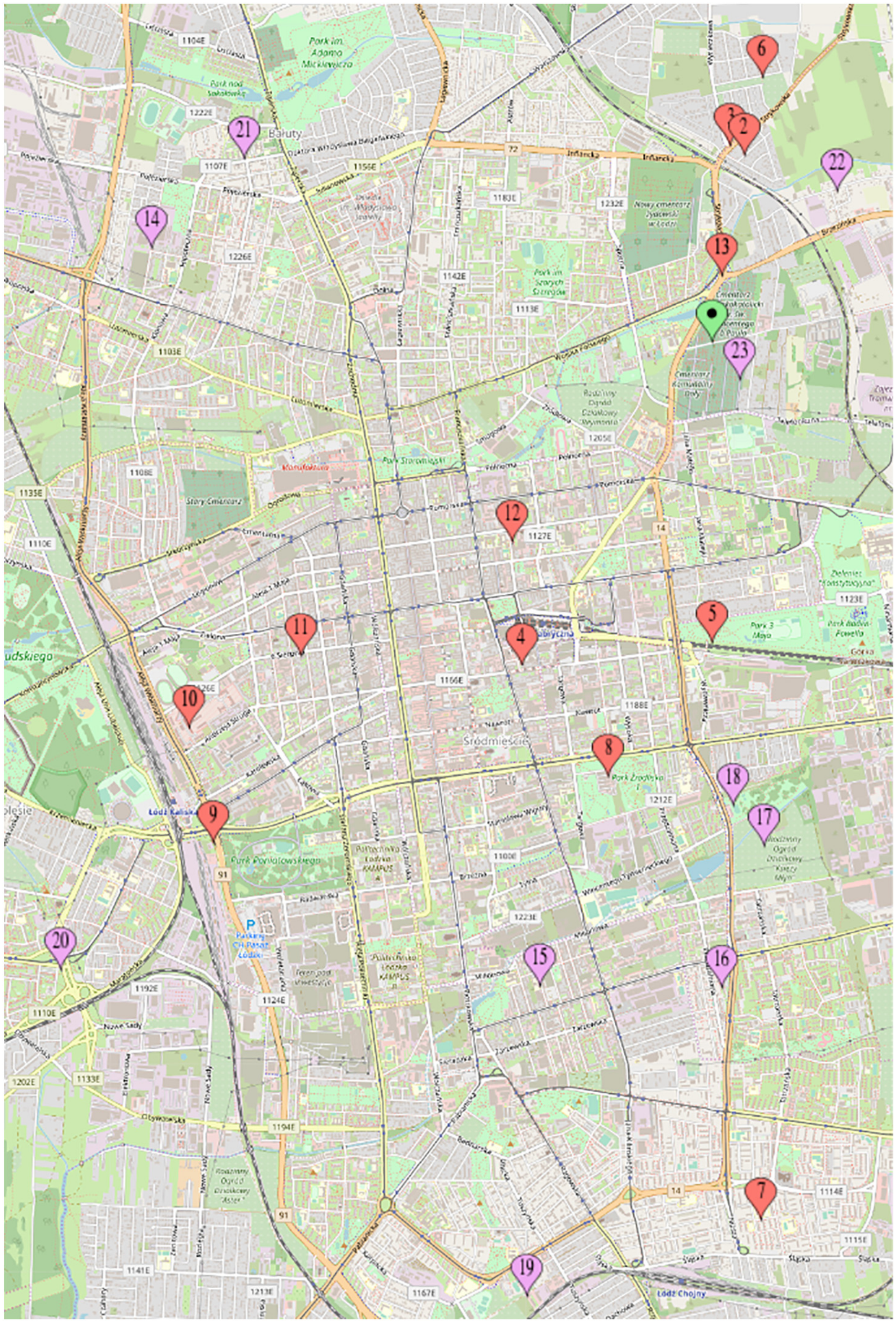

Fig. 8. Waste equipment collection sequence for Tabu Search algorithm (visualization on mapcustomizer.com).

The results of Wilcoxon Signed-Rank Test for the analysed case study were presented in Table 6. They confirmed the conclusions based on the average values, according to which it is recommended to use HS.

5. Discussion

Mobile collection on demand is an alternative solution for e-waste collection compared to stationary collection in local or municipal collection centres, supermarkets and shops with electrical and electronic equipment where old equipment can be delivered by customers. This mobile method is more flexible and convenient for residents because the collection vehicles can collect waste equipment directly from a house or an apartment when waste collection is requested by a resident (Jafari et al., 2017; Saphores et al., 2006; Schultz, 1999). The collection staff can also help in removing heavy appliances like refrigerators, dishwashers or washing machines. Taking into consideration the potentially large number of collection requests from an area of a city or agglomeration, the collection plan must be supported by an information system using a vehicle routing problem with time windows algorithms (Ghannadpour et al., 2014; Kim et al., 2009; Ombuki et al., 2006; Zachariadis et al., 2013). For this purpose, we applied HS, that supports optimization of collection vehicles' routing plan for WEEE pickup from residents. Some novel applications have been described in recent works (Cao et al., 2018; Gu et al., 2019). Mobile e-waste collection on demand has the potential to be developed in highly populated countries like China or India where the waste collection rate is low (Agrawal and

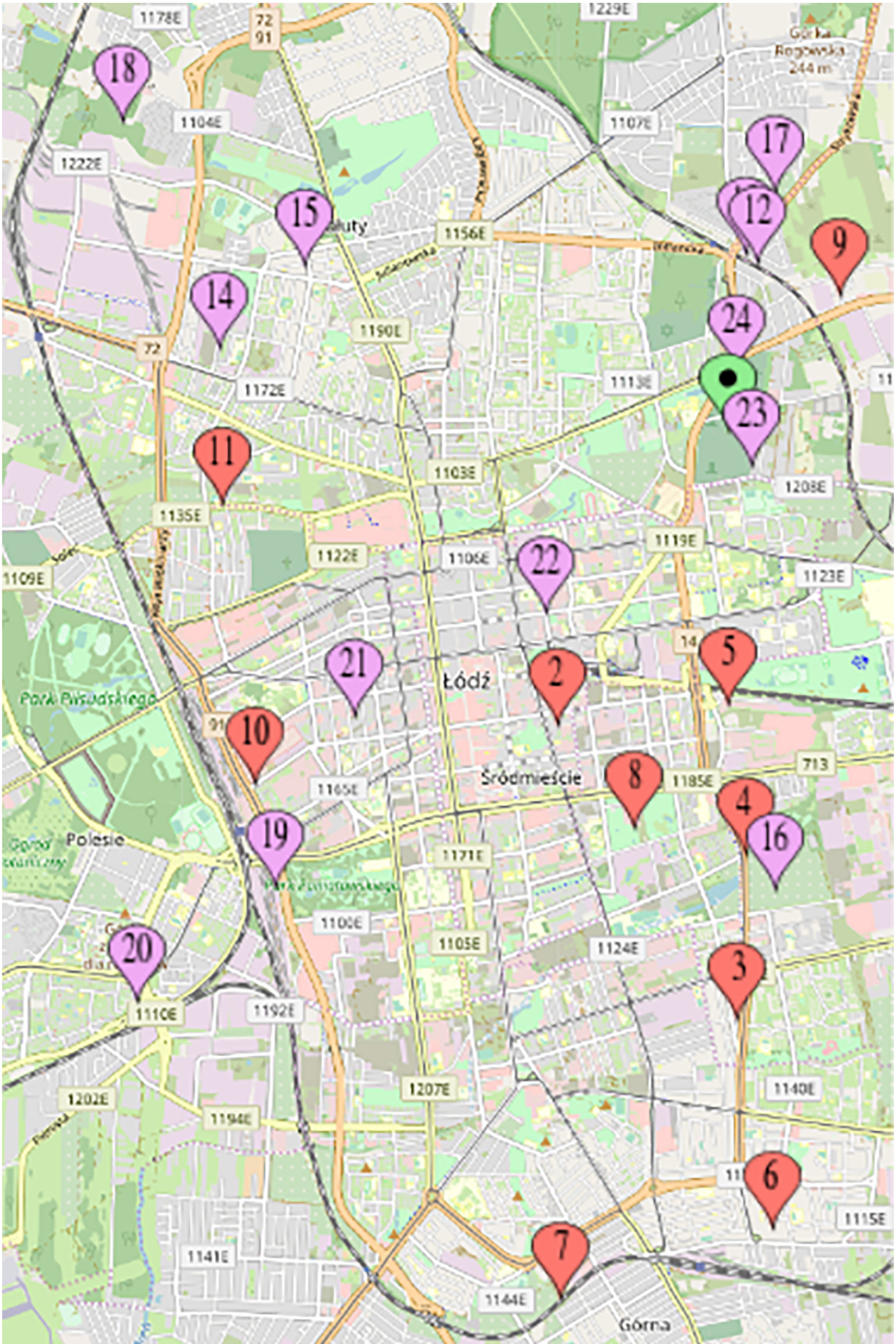

Fig. 9. Waste equipment collection sequence for Simulated Annealing algorithm (visualization on mapcustomizer.com).

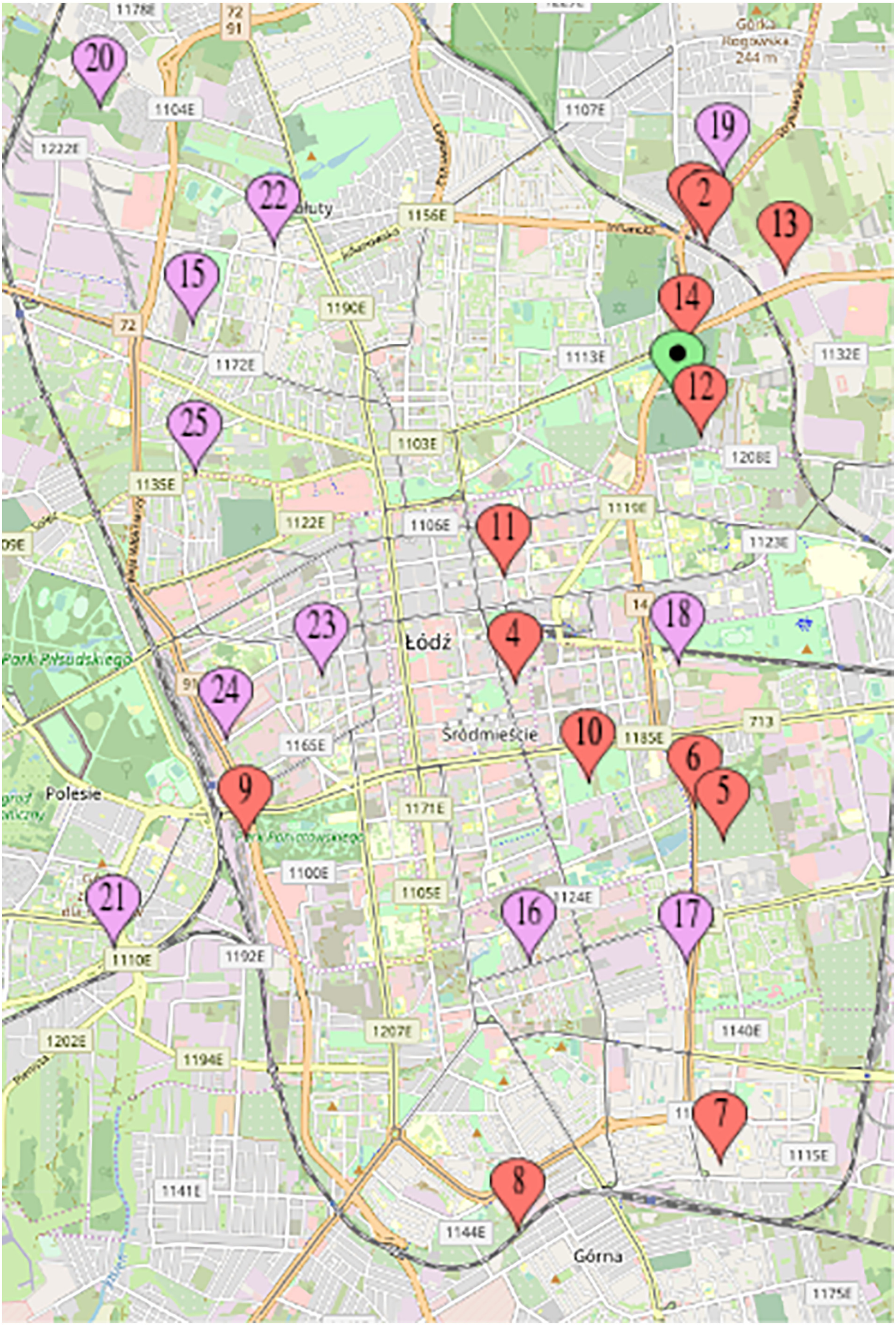

Fig. 10. Waste equipment collection sequence for Harmony Search algorithm (visualization on mapcustomizer.com).

Table 6
The results of Wilcoxon Signed-Rank Test for the analysed case study.

M1\M2	GrA	SA	TS	HS
GrA	N/A	1	1	1
SA	1.23E-07	N/A	2.09E-06	1
TS	1.24E-07	0.999998	N/A	1
HS	1.21E-07	4.11E-07	1.24E-07	N/A

Mittal, 2017; Wang et al., 2018). This study proposes further development of mobile collection and collection on-demand of e-waste including improved the HS algorithm and a novel collection vehicle to increase collection of secondary raw materials in the circual economy approach.

In this paper, we have presented HS supporting the information system designed for route planning with time windows for collection vehicles. The results indicate the potential usability of HS with possible output being shorter routes and increased number of visited locations. The HS algorithm allowed to improve vehicle routing, and the number of visited points can be increased by 1.2%–6.6% depending on the compared algorithms: GrA, TS, and SA. The total efficiency of the collection depends on the amount of collected waste equipment, loading the payload capacity of a vehicle, and the costs of vehicle use and labor (Dat et al., 2012; Kang and Schoenung, 2006; Moussiopoulos et al., 2012). Therefore, in vehicle route planning it is important to include the container loading problem. A proposal of a such model was presented in the study including both approaches (Nowakowski, 2017). The research results of the vehicle routing problem with time windows and container loading problems indicate the higher importance of loading as a priority in a cost efficient supply chain (Bortfeldt and Homberger, 2013; Bortfeldt and Wäscher, 2012). To solve the container loading problem, it is necessary to include the precise dimensions of each piece of waste for loading into a vehicle - the mobile collection plan may change due to uncertainty. This may occur when a resident provides the wrong data about the equipment category or dimensions, or a resident has additional equipment for the collection, or an accepted location is unavailable for waste pickup (rejection of the waste collection or absence of a resident). This causes significant problems in the accuracy of model calculation and can increase collection costs significantly. This was confirmed after personal communication with representatives of the collection companies in Poland as one of the most important obstacles to efficient vehicle use in mobile collection on demand. Therefore, it allows much easier loading than in any conventional lorry or van (mostly from the rear). It brings the flexibility of parking the vehicle during handling and loading the waste equipment. Therefore, the payload volume of the vehicle can be maximized. In the described pseudorandom tasks total mass of waste equipments was increased by 6.62% comparing to the GrA solution.

Another factor contributing to the inefficiency of this method is the difficulty in loading equipment in densely populated areas with high traffic volumes and parking limitations. In such case, a vehicle has limited time for parking and limited space for handling and loading the waste equipment. We proposed a novel vehicle body construction with flexible loading capability. The WEEE can be loaded from the left and right side of the vehicle. At the rear, the vehicle is equipped with a hydraulic lift for loading large and heavy equipment. The rollers assembled in the floor of the vehicle enable easy moving or rotating the equipment, so it can be rearranged in a short time.

A combination of HS supporting the mobile collection information system together with a novel construction of the collection vehicle can contribute to improving the efficiency of total mass of collected secondary raw materials from e-waste. The results of our study indicate benefits for the waste collection companies. It is possible to shorten loading time and unloading the vehicle in a collection company base.

The novel vehicle's capability of maximizing the number of e-waste items improves the economic efficiency of the waste collection. It also allows for securing the load. The supporting construction of vehicle's body is equipped with a special grate for easy securing and fastening of the loaded equipment. It applies for each item as the access is allowed from each side of the vehicle. The requirements of the European Standardization Organization included in the relevant standards for WEEE includes guidelines for transportation and logistics companies (CENELEC, 2013). The European Committee for Electrotechnical Standardization (CENELEC) 50625 series standards focus on proper recycling and secure handling and transportation of the waste equipment to prevent contamination of the natural environment against hazardous substances. It can occur if e-waste is improperly loaded or broken in transit. It applies for the categories of waste equipment such as temperature exchange equipment, monitors and television sets both cathode ray tubes and flat panel displays. When considering loading and transportation of the waste items from any category of WEEE by the novel vehicle it is possible to secure all items by with the aid of tensioning straps. Additionally, minor items can be placed in special small containers attached to the grate inside the novel collection vehicle.

6. Conclusions

Improving the efficiency of the circular economy approach in e-waste collection is crucial for securing a high recycling rate of valuable resources and secondary raw materials. Properly conducted e-waste collection contributes to lowering the impact of hazardous substances on the natural environment and human health. This paper presented an integrated approach with an improved information system designed to support the mobile collection of e-waste on demand. The HS algorithm used for solving the VRPTW problem gives better results than other algorithms presented in previous studies. Applying artificial intelligence algorithms can improve waste collection and the total mass of the secondary raw materials. The number of collection points calculated by the HS algorithm could be higher from 1.2% to 6.6% depending on the compared algorithm. At the same time, a potential profit from the secondary raw materials from the waste collection for the HS algorithm could be higher 5.1% to 13.2% and the total mass of collected waste appliances up to 7%.

However, in the real world, it is difficult to predict all events and details concerning the dimensions and number of pieces of equipment to be collected. Therefore, as an additional contribution, we presented a novel design for a vehicle body that enables easy loading of the waste equipment and simplified rearrangement inside a vehicle. It facilitates loading and reduces the parking time of a collection vehicle, especially in densely populated areas with high traffic volumes.

Future work will focus on evaluating the information systems and novel body design of vehicles to compare loading and handling times for various categories of e-waste. For this purpose, it is necessary to include modeling of loading and unloading costs and its impact on the collection efficiency.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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