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Municipal Solid Waste Container Location Based on Walking Distance and Distribution of Population

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Cities around the world enlarge every single day and the production of various fractions of waste grows as well. The goal of waste separation and material recovery arising from novel directives of EU and legislation changes encourages the municipal administrators to support the suitable infrastructure of collection points. The decision regarding these points is an important task because their number is not the only indicator for higher separation rate. Inhabitants decide upon the walking distance to the closest collection point which was already presented in the public researches. However, collection points cannot be everywhere due to economic and aesthetic reasons. The aim of the paper is to propose an approach for locating collection points for municipal solid waste, taking into account the walking distance, the number of collection points and the utilization of installed capacities. The approach considers multiple criterions related to economic, social and environmental issues. This is achieved by proposing a mixed integer programming model. The calculation of walking distances is based on the air distance of the address points and the potential positions for the container location. The approach is presented in the case study for the municipality in the Czech Republic while locating mixed municipal waste containers. The model brings benefits in the form of increasing possibility of application since the number of separately collected waste fractions grows. It serves for stakeholders and municipal administrators for making decisions about purchasing a certain number of containers and its placement within the analysed area. Further development of the model can be focused on higher accuracy calculation of the walking distances or the distribution of inhabitants' regular pathways. Additionally, the research might be connected with the computation of changing ratio during time among waste fractions, which is caused by diverting from the mixed municipal waste.

1. Introduction

The production of waste increases with the growth of population while inhabitants are encouraged to increase the separation rate (Karak et al., 2012). In the case of the EU, the separation and material recovery goals come from the directives and local legislation (Directive (EU) 2018/851). To fulfil the separation rates, a suitable infrastructure of waste containers has to be implemented with regards to the economic possibilities. The population welfare point of view should be also reflected as it is closely related to the willingness to separate. The development of current direction also tends to the smart concepts, which can identify the gap for improvements in efficiency related to costs. (Tan et al., 2015) assessed the waste management strategies by pinch analysis. The smart trend in waste management was also stated by (Bong et al., 2018) where the agriculture field was analysed. Implementation of the wireless sensor network in the collection was analysed in (Ramson and Moni, 2017). A monitoring application was introduced to determine the current state of fill-height while assessing the applicability in the waste management sector (Yusof et al., 2018). An environmental point of view is to be mentioned as well, see the emission analysis of transportation modes in (Van Fan et al., 2018). It has been revealed that the production of greenhouse gasses and other air pollutants do not decrease

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concurrently, which has to be analysed with regards to the overall emission evaluation. The role of stakeholder is very important when assessing the risks related to future cleaner production (Ngan et al., 2018).
The enhanced monitoring and data processing enable the optimisation of collection system. Extensive research on location routing problems can be found in (Prodhon and Prins, 2014), where the various tasks of locating and routing variants were classified, and the most suitable algorithms were assigned. This category of tasks can be used for sustainable development. The industrial aspects of the fleet sizing with respect to the infrastructure were clearly presented in (Hoff et al., 2010), with challenges for future development in these tasks being defined for both maritime and road issues. The grid of collection points also plays an important role in waste management. An optimal location of collection points was analysed in (Ghiani et al., 2012). It was formulated as mixed integer linear programming (MILP) model, while also capacities of the individual collectors were selected. In the context of daily waste production, clustering aggregation has been compiled to define areas. The solution was found using two-phase heuristics. The results revealed savings compared to the real situation in tens of percent. This study was followed by the paper (Ghiani et al., 2014), where zoning decisions for collection vehicles were added. Constructive heuristics were introduced to the whole process. The algorithms thus ensure the compatibility of vehicles and collection vessels within the same collection points. This has helped to save the required number of vehicles and shorten the distance travelled. It has been found from the real practice that the location of the collection points and the routing is closely related. The study (Huang and Lin, 2015) introduced a two-phase procedure to cover the residential blocks of the collecting tank networks and subsequent collection. The aim of the approach was to minimize the distance and to determine the minimum number of operating vehicles. Routing was solved using Ant Colony Optimization. Another combination of two related tasks was presented in (Hemmelmayr et al., 2014), where the location of the collection sites, their size and number and subsequent collection were solved. It was solved heuristically using variable neighbourhood search while using MILP formulation for locating solved with exact algorithms. The introduced approach has shown positive results due to the integration of tasks. The reviewed tasks were solely concentrated on the operational points of view, however, the targeted future limits, possibility of separation or combination of criterions has not been adequately analysed.
For proper implementation of routing and collection system, it is needed to appropriately locate and allocate the collection points (using criterions). It is also important not to go for half-empty containers – i.e. the demand for the minimum fill-level for the individual points as well as the total system. Cities are constantly growing and producing more and more different waste. It is appropriate to separate this waste as much as possible for its subsequent use. The increasing number of separately collected fractions is being pushed also by the legislation both EU and local. In the situation, where people have a collection point too far from their housing, they do not use them. It is, therefore, appropriate to deal with the distribution of waste collection points (plastics, glass, paper, or bio-waste). The optimal distribution of collection points, including their capacities, should be effectively balanced to obtain the general solution where people can reach them easily. The novelty of this paper lies in the definition of compromise between spatial distribution (availability), quantity (price) and capacity (fullness) of collections points, where the trade-off is proposed.

2. Problem Description

The problem is defined as the distribution of waste collection points in the specific area with the different conditions to be met taking into account the walking distance, the number of collection points and the utilization of installed capacities. Conditions are formulated according to the requirements from the real operation.

2.1 Mathematical Model

There were formulated three different objective functions:

- Walking distance based,
- Number of collection points,
- Multi-objective with the combination of previous.

The notation that is used to develop the mathematical model is described in Table 1.
The objective function given by Eq(1) minimizes the total walking distance between all waste producers and identified collection points. Eq(2) summarises the number of intended collection points. Multi-formulation is used in Eq(3) where the objectives f_1 and f_2 are combined and weighted by lambdas.
Eq(4) defines the balance for each node, which states the amount of accumulated waste at collection points. This amount has to be less than assigned capacity as in Eq(5). The total utilisation rate of all containers is restricted by constraint Eq(6). The individual utilisation rate is given in Eq(7) for all intended collection points. The amount of waste is restricted by the production at the initial node. It forms the condition that the flow will not continue over other nodes, see Eq(8). The SOS1 property is guaranteed by Eq(9), where only one capacity can

be selected for each collection point (starting with capacity 0 for the first $k = 1$). Eq(10), Eq(11) and Eq(12) state the type of variable (binary and positive continuous).

Table 1: The notation

Type	Symbol	Description
Sets	$i \in I$	Nodes – collection points
	$j \in J$	Edges
	$k \in K$	Set of possible collection point capacities
Parameters	p_i	Waste demand (production) in the node i
	$A_{i,j}$	Incidence matrix
Type	Symbol	Description
Parameters	$B_{i,j}$	Submatrix of $A_{i,j}$, where the values -1 are omitted
	d_j	Edge length
	$c_{i,k}$	Matrix defining possible capacity values for each node i
	U^T	Minimum required total utilisation rate
	U_i^I	Minimum required individual utilisation rate for each node i
	q_k	The auxiliary parameter, values equal to 1 except the first which is 0
	λ_1	The optimum value of the objective function f_1
	λ_2	The optimum value of the objective function f_2
Variables	x_j	Waste flow on the edge j
	t_i	Waste accumulated at node i
	$h_{i,k}$	SOS1 variables (special order set of type 1, see (Williams, 2009)) indicating the installation of specific capacity of containers at node i
	f_1	The objective function for total walking distance
	f_2	The objective function for the number of collection points
	f_3	Combination of f_1 and f_2

$$f_1 = \sum_{j \in I} d_j x_j \quad (1)$$

$$f_2 = \sum_{i \in I} \sum_{k \in K} h_{i,k} q_k \quad (2)$$

$$f_3 = \lambda_2 f_1 + \lambda_1 f_2 \quad (3)$$

The constraints then take the following form:

$$-\sum_{j \in J} A_{i,j} x_j + p_i - t_i = 0 \qquad \forall i \in I \quad (4)$$

$$t_i \leq \sum_{k \in K} c_{i,k} h_{i,k} \qquad \forall i \in I \quad (5)$$

$$\sum_{i \in I} \sum_{k \in K} c_{i,k} h_{i,k} U^T \leq \sum_{i \in I} t_i \quad (6)$$

$$t_i \geq \sum_{k \in K} c_{i,k} h_{i,k} U_i^I \qquad \forall i \in I \quad (7)$$

$$p_i \geq \sum_{j \in J} B_{i,j} x_j \qquad \forall i \in I \quad (8)$$

$$\sum_{k \in K} h_{i,k} = 1 \qquad \forall i \in I \quad (9)$$

$$h_{i,k} \in \{0,1\} \qquad \forall i \in I, \forall k \in K \quad (10)$$

$$x_j \geq 0 \qquad \forall j \in I \quad (11)$$

$$t_i \geq 0 \qquad \forall i \in I \quad (12)$$

The task is to calculate the stated model individually with Eq(1), Eq(2) and Eq(3) to be minimised. Values of λ correspond to the optimum values of objectives when solving the first and second model. These calculations will be compared and analysed in the following section.

3. Case study and results

The proposed model was tested through a case study for the municipality Tábor from the Czech Republic. The population is approximately 35,000 people, while the housing development varies across the area. The constructed network consists of ca. 118,000 edges and 6,000 nodes. The problem was implemented in GAMS (General Algebraic Modeling System) and solved using CPLEX solver 12.6.2.0. The optimality gap was set to 10 % due to its time-consuming computation. The starting values were generated with the help of a simpler model, where the objective function was different. The network was generated using the developed algorithm with data containing GPS coordinates of the address points and its number of inhabitants. It matches the selected number of address points with the potential collection points according to the distance criterion, while the extreme values were omitted. As the analysed waste stream was selected the mixed municipal waste.
Population distribution represents an important role in this task. The graphical illustration of population density across the analysed area is in the Figure 1. The grid of potential collection points corresponds with the address points depicted on the map.

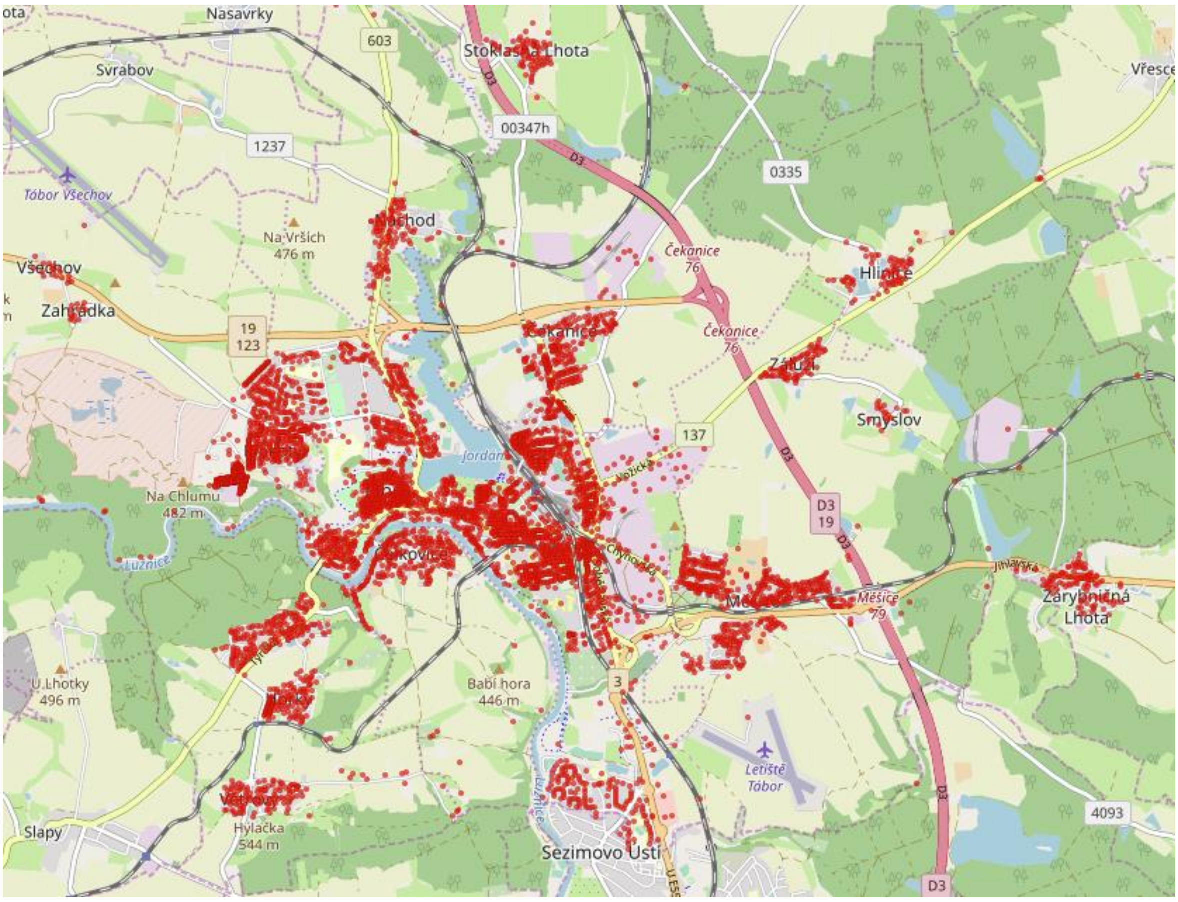
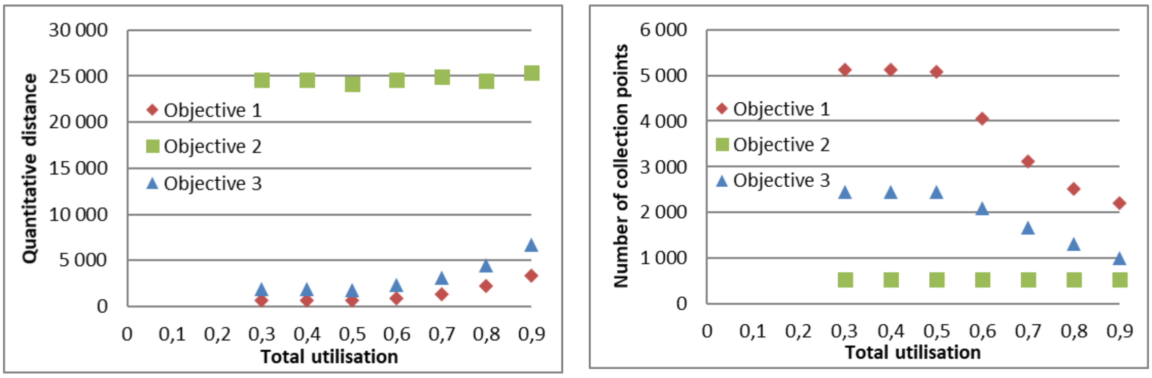


Figure 1: Population distribution corresponding with the potential collection points

3.1 Utilisation rate analysis

There were two different constraints considering utilisation rate – total and individual. The results of the calculation are highly sensitive to specific values. The number of collection points or quantitative distance also differs with regards to the objective function. These connections can be seen in the Figure 2, where the individual utilisation rate was 0.3. The results were also calculated for the utilisation rate of 0.1, while they presented almost similar character.



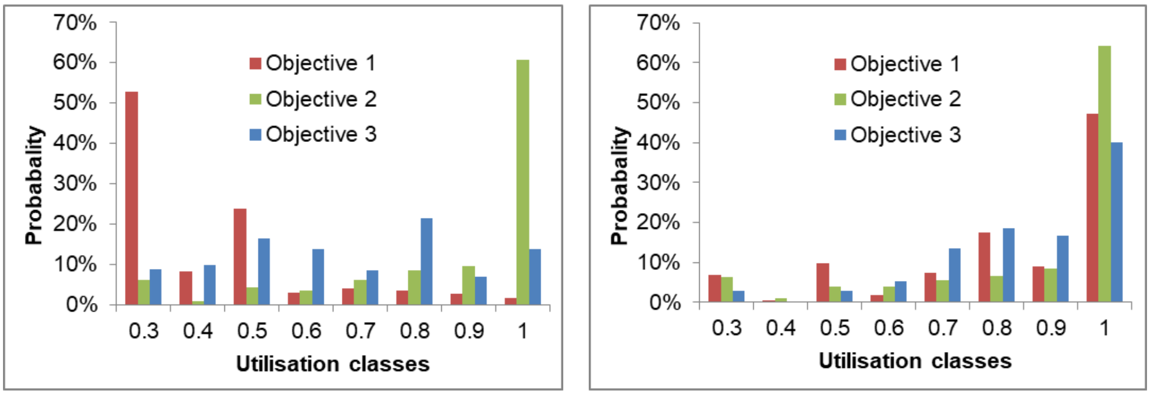
a) Values for quantitative distance *b) Values for the number of collection points*

Figure 2: The relations of objective values for the individual utilisation rate 0.3

Objective 1 represents a very good solution in terms of walking distance compared with objective 2. Objective 2 sets the boundaries for the minimum number of collection points. It can be seen that with increasing value of individual utilisation rate, the total number of collection points decreases where it is possible, to fulfil the condition. Higher values of individual utilisation rate (more than 0.4) were not possible to consider due to technical limitations at some collection points (low population density at some point or too distinct closest collection point). The combined objective 3 bring benefits of both objectives. It represents a balanced compromise between average walking distance and minimising the number of installed collection points (lower cost of purchasing and consequent routing).

3.2 Further assessment

The Figure 3 presents the comparison of utilisation distribution for the selected total utilisation rates. The histograms show the percentage representation of collection points with the utilisation rate belonging to each class between 0.3 and 1. The target is to utilise the capacity of collection points as much as possible.



a) Histogram for total utilisation 0.5 *b) Histogram for total utilisation 0.8*

Figure 3: The comparison of utilisation distribution for $U_i^I = 0.3$

For lower U^T, objective do not show a desired distribution since a lot of collection points are utilised less than half. Objective 2 performs well for both lower and higher total utilisation rate. However, considering the walking distance it is absolutely not suitable for real implementation. The multi-objective approach again proved its strong power because for lower total utilisation, it is quite evenly distributed. For higher utilisation, the most frequent is the full capacity.

3.3 Time complexity

The reduction of time needed for the calculation is possible. Based on the previous analysis, the individual utilization rate is not important when defining boundary conditions, since the total utilization rate will fulfil the requirement themselves. The objective value 1 was highly sensitive on total utilisation rate with an exponential dependency while individual rate multiplied this effect. Objective 2 was much more demanding on time (around

8,000 s), however, its computation times were almost constant with regards to utilisation rates. Objective 3 calculated well until it reached the total utilisation rate 0.7, where it started copying objective 1 shape with higher times. This confirms the use of objective 3, however, there should be set proper constraints regarding utilisation.

4. Conclusions

An approach for locating of collection points was proposed while considering walking distance and number of collection points. It was formulated as a MILP problem. Different objectives were used to analyse results (social, economic and their combination). The goal was to watch the dependencies of utilisation rates of container capacities. Constraints were formulated for individual spots and also for the total utilisation rate. The model was tested on the dataset for the municipality of the Czech Republic for location mixed municipal waste containers. Best performance was observed for the combined objective function – minimised walking distance and number of collection points. It represents an acceptable compromise from all points of view including the computational times (with some limitations). Future research can consider the link between the number of collections, the capacity, and the cost with regards to routing problems. The approach can serve municipalities for the spatial distribution of containers for newly collected waste fractions. However, the approach itself is computationally complex and with increasing size of the task and new constraints, the heuristic approaches have to be implemented (Davendra et al., 2014). The emission point of view can be considered as travelled distance while analysing the growing separation rate and consequent material recovery and saving of primary fossil fuels.

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