

Waste collection route optimisation for the second waste-to-energy plant in Budapest

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ABSTRACT

The city of Budapest produces approximately 680–700 000 tonnes of municipal solid waste every year, of which $<2/3$ is being recycled or used for energetic purposes, the rest ends up in a landfill. To combat this environmental and logistical problem the installation of a second waste incineration plant has been proposed in the south of the city. The only cost associated with fuel consumption in the case of waste to energy powerplants (WtE plants) is the transport cost, as the city council provides economic support for waste disposal. Since the transportation has a huge influence on the cost of operation, logistical optimisation of the transport routes promises a direct impact on cost savings. In this study the logistical optimisation of the Southern Budapest area was carried out using image processing and logic based algorithm programming. As a result the optimal transport of 230 000 tonnes of municipal solid waste (MSW) was solved resulting in a 4 835.2 km monthly travel distance reduction. This value can be translated to 7 823 €/month cost, 9 459.6 kg/month CO₂ and 45.3 kg/month NO_x emissions reduction in the urban areas.

1. Introduction

Municipal solid waste (MSW) generally includes all types of solid waste generated from residential, institutional, and commercial establishments. In order to decrease the environmental burden caused by the waste production of the growing population and economies, a linear economy of the non-recyclable MSW management is to be transformed into a circular model. A circular economy in terms of waste management minimises the consumption of finite resources, as well as waste generation, decoupling economic growth from resource depletion and environmental load (Hoang et al., 2022). It is estimated that the worldwide waste generation exceeds 2 billion tons annually, most of which ends up in various landfill sites or is disposed into the oceans and the rural landscapes. Calorific utilisation of municipal solid waste is one of the solutions of the problem, and has been target of research to overcome technological, socio-economic and legal challenges of its development (Khan et al., 2022). Waste incineration is a method of utilising the calorific value of the MSW in waste-to-energy (WtE) power plants for which various technologies have been developed to increase efficiency to the highest (Sani et al., 2023; Tan et al., 2015; Kovács et al., 2023). Besides heat and electricity, several valuable raw materials come to be

during the process, while the residual volume of the MSW is reduced significantly to filter cake. MSW collection and transportation is one of the main concerns in MSW system designs, since it has a significant transport and collection cost, not to mention the traffic load on the city's infrastructure. Several studies have already targeted the minimisation of environmental load due to MSW transportation. Taşkın and Demir (2020) investigated the environmental and energy impacts of urban MSW collection and transportation management systems from the life cycle assessment perspective. It was applied to eleven municipalities of the Turkish Kayseri province by modelling three alternative MSW collection and transportation scenarios. The study reflected on the necessity of building transfer stations before transporting the MSW to the landfill. The calorific value of MSW ranging from 7.5 – 10.5 MJ/kg largely depends on its composition, but with the involvement of pre-selection in the facility itself significantly can increase this amount. A study conducted by (Thanos) Bourtsalas et al. (2019) in South Korea revealed that the average calorific value was 9.7 MJ/kg, and the average amount of energy recovered was 1.5 MWh/ton waste processed. It has been estimated that 8 % of the district heating demand was provided by WtE in South Korea in 2019. WtE plants can contribute to about 0.6 % of the total electricity demand of South Korea. In South Korea with combined recycling/composting and WtE rates of about 80 %, as compared

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Nomenclature		F_{degree}	kilometre-degree equivalent [km/1°]
Abbreviation		f_{pop}	population density [person/km ²]
HUHA	name of the Budapest waste incineration plant	f_{MSW}	linear MSW density [kg/km]
MSW	municipal solid waste	k	current transport capacity of the vehicle [kg]
NIMBY	not in my backyard	l	road length in a zone [km]
WtE	waste to energy	m_{MSW}	MSW content [kg]
VRP	vehicle routing problem	$\dot{m}_{\text{MSW, specific}}$	specific MSW production [kg(MSW)/person/year]
Latin letters		r_{equator}	radius of the Earth at the equator [km]
a	specific road length [km/km ²]	$\dot{v}$	specific fuel consumption [l/100 km]
A_{Bp}	area of Budapest [km ²]	V_{vehicle}	fuel consumed [l]
$A_{\text{Bp, pixel}}$	number of pixels located in the area of Budapest [1]	Greek letters	
A_{zone}	area of the zone [km ²]	α	polar angle of Budapest's location [°]
$A_{\text{zone, pixel}}$	number of pixels located in the area of the zone [1]		

to the average EU28 with 65 % and the US 36.5 % even if the EU and the US had higher GDP per capita than South Korea ((Thanos) Bourtsalas et al., 2019). Several studies target the topic of WtE system optimisation for developing countries too, such as the comparison of anaerobic digestion and cogeneration of heat and power conducted by Alizadeh et al. (2023) and the multi-criteria decision analysis for MSW incineration plant in Iran by Feyzi et al. (2019) MSW based heat production helps increase the import independency of energy supply for district heating systems, a technology which has proven to have a potential to transfer cities towards nearly zero energy communities (Rey-Hernández et al., 2023).

In this study, a systematic model has been developed for the optimization of MSW processing routes, which make the energetic utilization plausible. If a natural gas fuelled combined heat and power plant is compared to a MSW fuel based one, it can be seen that although the MSW requires highly complex flue gas treatment, the economic advantages of the fuel make the investment quick to return. While gas makes the production dependent on foreign import, MSW comes to be locally in a renewable manner. According to Hungarian law, MSW is considered to be 50 % renewable. The district heating system of Budapest relies primarily on gas, but one WtE plant operates in the north of the city. However, the production of MSW in the city of 2 million inhabitants is 680,000–700,000 tons per year, and the existing plant can treat 410 000 ton annually. The rest is transported to a nearby landfill, which is the least favourable solution according to the current MSW treatment strategy of the EU. Therefore, the development of a second WtE plant conception is a subject of research at Budapest University of Technology and Economics. The currently operating HUHA 1 and the HUHA 2 discussed in this study are designed with the consideration to incinerate the entire waste production of the Capital in mind.

The location of the second plant has been considered to be fix in southern Budapest and it is not to be investigated in this study. The plant had initially three possible locations in Budapest of which the southernmost option has been chosen by the southern section of the Budapest ring road. The location provides good coverage for the previously landfill-transport dominated Southern-Budapest area with a safe distance from the densely populated area, whilst being close to the already existing district heating pipe systems. Yet it is important to mention that plant siting is a complex process, significantly influencing the overall waste treatment efficiency, environmental pollution and societal reactions. The optimal siting process must be a subject of thorough investigation, such as GIS-based spatial analysis, and analytic hierarchy process for the multi-criteria evaluation of relative preferences of different environmental and social factors, as e.g. Khan et al. (2018) performed in their research for Alberta, Canada. While the environmental effect can mostly be negated with proficient flue gas filter system, the social resistance is a harder problem to be tackled. The

phenomenon is best described by the “not in my backyard” (NIMBY) effect. Xu and Lin (2020) conducted study in four metropolises in China show that people are willing to pay various amounts of money to prevent a waste incineration facility from being built in their neighbourhood.

The transportation of MSW from the locations of production to the WtE plant can be optimised to increase the overall efficiency of the plant. MSW collection and transportation costs are accountable for a vast amount of the MSW management expenditures. According to Yadav and Karmakar (2020) 70–85 % of total management cost is spent on developing countries, whereas this proportion is around 50–75 % in developed countries. Several MSW collection and transportation models and case studies are available in the literature, reflecting on the importance of the optimised MSW logistics. Son and Louati (2016) proposed a generalised vehicle routing model including multiple transfer stations, gather sites and inhomogeneous vehicles on time windows for MSW collection. Travelling in one-way routes, the number of vehicles per m² and waiting time at traffic stops have been taken into account. The proposed model has been tested in Danang, Vietnam and reported in a case study. Akhtar et al. (2017) developed a modified Backtracking Search Algorithm in capacitated vehicle routing problem models with the smart bin concept to find optimal waste collection route solutions by minimising the sum of waste collection route distances. A threshold waste level was introduced to minimise the number of bins to be emptied, finding an optimal range and minimising the collection distance. A scheduling model compared the results of the developed model with conventional methods in terms of travel distance, collected waste, fuel consumption, fuel cost, efficiency, and CO₂ emission. The experiment resulted in a 36.8 % distance reduction, 36.78 % waste collection efficiency increasement, fuel consumption and CO₂ emission reduction of 50 % and 47.77 %, respectively. Hannan et al. (2018) proposed a modified particle swarm optimisation algorithm in a capacitated vehicle routing problem model to determine the best MSW collection and transport route optimisation alternatives. Results showed that 70 % of threshold waste level performs better than all node consideration regarding collected waste, distance, tightness, efficiency, fuel consumption and cost. Hong et al. (2023) investigated the strategic planning of transfer stations and vehicle fleet dispatch in a city-level classified waste collection system for Chengdu, China. Vu et al. (2018) elaborated a GIS-based dual phase model integrating the handcart pre-collection phase and truck collection phase for a study area located in Hai Phong, Vietnam. Two vehicle routing problems were independently modelled for 30 scenarios of handcart and truck routes. Compared to the status quo condition, a 13.76 % reduction in truck travel distances was shown to be attainable using the proposed model of the authors. Blazquez and Paredes-Belmar (2020) developed a design of a household waste collection system based on a two-stage procedure. First, a bin-location allocation problem was solved by selecting

collection sites from a set of potential sites and determining the type and number of bins at each selected collection site. Second, bin-to-bin waste collection routes are obtained for a fleet of homogenous vehicles. The results for the routing phase suggest a larger number of routes in the morning works shift since these routes have shorter distances. Das and Bhattacharyya (2015) proposed an optimal MSW collection and transportation scheme for minimising the length of each waste transportation and collection route by formulating a mixed integer program. A heuristic solution for the waste collection and transportation was proposed to provide an optimal way of transportation. Results showed that >30 % of the total waste collection path length could be reduced by using the proposed scheme. Hina et al. (2020) developed a vehicle routing problem based on a wide set of rules such as zone constraints, vehicle capacities, time windows, road infrastructure and commodity type. A pilot study was conducted for different areas of two Pakistani cities resulting in a reduced distance by up to 18 % in Islamabad and 9 % in Rawalpindi. The collection time was reduced from 7.5 h to 5.8 h and 8.3 h to 7.2 h in Islamabad and Rawalpindi, respectively. Nguyen-Trong et al. (2017) proposed a model for optimising municipal solid waste collection and tested it by a case study to Hagiang, Vietnam. The methodology consisted of two steps. First, a classical vehicle routing problem using mixed integer linear programming was applied to identify the optimised plan for each vehicle. Second, the GIS was integrated with an agent-based model and an experiment was carried out in order to examine the plan in a dynamic context. As a result of the optimisation the cost of the MSW collection was reduced by 11.3 %. Alsobky et al. (2023) provided an optimised MSW collection system for the greater Cairo area in Egypt to accommodate various housing levels and considering the available resources. A case study was conducted for Al-Mostakbal, Egypt by optimising the collection routes. The pick-up time was optimised too using the appropriate vehicle type, fleet size and rounds. Authors applied a dynamic routing using developed production models and developed a simulation model using developed production models. The result was a highly efficient framework with a potential to cover urban areas. Luís Padilha and Luiz Amarante Mesquita (2022) proposed an innovative approach to analyse the financial viability of the combination of consolidated destinations for the management of MSW that use waste to energy, considering the complementation of revenues for small cities. Gafti et al. (2023) developed a mixed integer linear programming model to minimize the cost of waste collection and transportation from various MSW production areas. Also the use of cross-dock centres have been taken into consideration. The results were applied in Korasan Rezavi province in Iran. Vecchi et al. (2016) presented a sequential approach involving three phases for solving the optimisation problem for MSW collection truck routes. According to the authors, various methods can be utilized in reducing truck travel distance, carbon dioxide emission and the cost of MSW logistics. In the developed approach Binary Integer Linear Programming (BILP), Capacitated Arc Routing Problem (CARP) and Mixed Integer Linear Programming (MILP), were utilised and evaluated by using real data. Rizwan et al. (2018) developed model is based on a case study of Abu Dhabi Emirate to find the optimal routing for collecting and processing the generated MSW into energy and value-added products. Zilka et al. (2021) carried out a comprehensive study about the use of trams for the transport of waste from urban areas to waste incineration facilities in Prague and neighbouring municipalities. Originally mixed municipal waste was transported to an incineration plant directly by garbage trucks. Authors proposed a case in which municipal solid waste was first taken to transfer stations and from there transported over a longer distance in a large volume by means of tram or truck. The use of trams results in an overall cost level of €16.41 per ton of waste transported, which represents a slight saving against the existing system at a cost of €17.19 per ton.

Based on the review of the available literature it can be stated that the optimisation of urban MSW transportation has been a target of research recently. However, no publication has been found for Budapest, Hungary, a city of two million, where a second waste-to-energy plant is

planned to increase urban sustainability. In this research the waste collection procedure has been optimised using a novel procedure of transport route path finding optimisation in order to minimise fuel consumption, emission and transportation cost and to maximise plant efficiency. Further highlights of novelty of the study include a completely self-developed logic-gate based transport route optimisation method using graph structures and the development of the geographical coordinate-based search radius method for finding the optimal new zones to supply.

2. Methodology

2.1. MSW production rate definition

To optimise the transport routes, the simplified approach of dividing Budapest into zones and then defining a centre point for each zone has been used from which the waste will be collected. In order to increase the accuracy of the model the specified collection zones were made to be much smaller in size compared to the city districts, resulting in a total of 182 zones. According to the model, waste collection vehicles will be departing from the proposed plant, taking the shortest possible route to the designated centre point of the target zone. Once the centre point has been reached the amount of waste corresponding to their capacity will be collected and returned to the WtE plant. This chain of events continues until the MSW capacity of the WtE plant has been reached.

In order to specify the collection routes a location based MSW generation database is needed. Contact has been made with the MSW handling organization of Budapest in order to obtain the data necessary for the study, unfortunately to no avail, since such database did not exist at the time of this study. Combatting this informational gap, an alternate method was chosen: picture based information extraction from population density maps using image processing has been carried out.

Fig. 1(a) shows the map used in the analysis method. The image processing was necessary since the map did not have any information detailing the size of each zone. The colour and spatial data in these figures were used to determine the area, population density and thus the population of the indicated zones. In Hungary, 381 kg of waste per capita is produced annually, according to data published by the European Parliament (Annual, 2024). Based on the population density and the calculated zone area data, the population number in a given zone can be determined, which allows the determination of the amount of MSW generated in the zones.

The algorithm responsible for the analysis was written in Python. This programming language was used throughout the study in case of every algorithm. The basic task of the program was to detect and isolate the zone outlines in the image, measure their area, isolate these areas into individual graphical files, and then determine the geometric centre points of each area.

The first step is to feed the image to be analysed into the program. However, this image still contains a lot of information that is considered as noise or disturbance, which prevents the algorithm from accurately defining the contours of the zones. To avoid this, the following method has been used: first, the colouring scheme of the image is converted from RGB to HSV colour model. With this method, instead of R (Red), G (Green) and B (Blue), the colour channels will take H (Hue), S (Saturation) and V (Value). HSV (hue, saturation, value; also known as HSB, hue, saturation, brightness) is an alternative representation of the RGB colour model, designed in the 1970s by computer graphic artists to better match the colour perception properties of human vision. It allows us to better distinguish the intensity of pixels in an image, the results can be seen in Fig. 1(b). The conversion greatly simplifies the filtering process since in HSV colour composition the colour data is contained in only one channel, V, instead of three channels as in the case of RGB.

By choosing the right boundary values based on the differences in intensity the sections of the Danube can be separated from the rest of the image so that the river may not appear in the map's zonal recognition. In

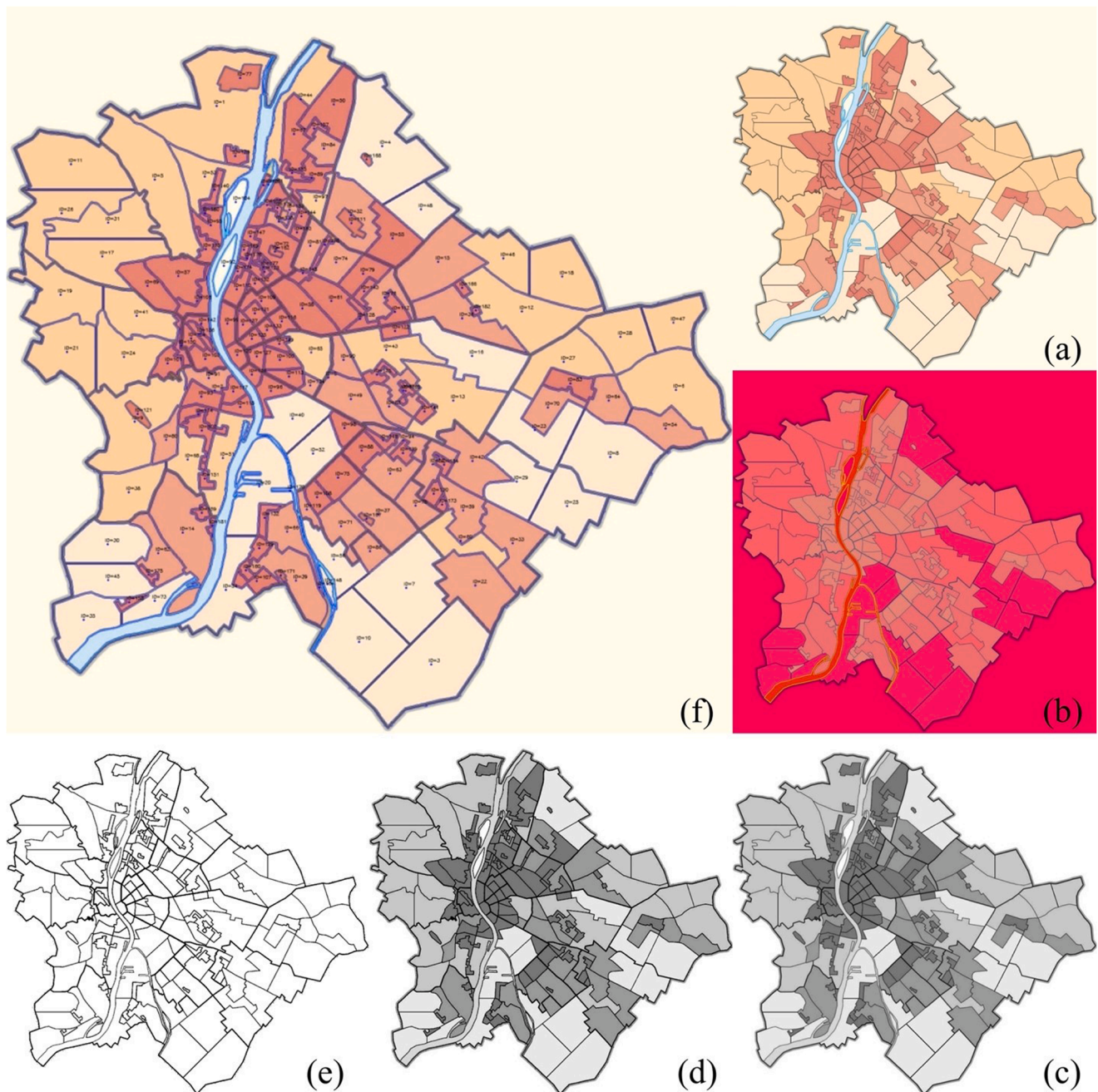


Fig. 1. Steps of the image processing seen in order: (a) Population density map used for the processing, (b) the map converted into HSV colour mode, (c) the grey scaled map before and (d) after the histogram modification, (e) image following the thresholding and finally (f) the image processing result: Budapest with all identified zones and geometric centre points (Magyarország, 2024).

the enlarged image on the right, the sharp contours between the Danube and the surrounding areas can be observed. The selected Danube image is separated by creating a mask. This mask will later be used to isolate the river area.

The input image is converted into a grey-scale image, i.e. from a colour image to a black and white image, so that the algorithm is not disturbed by colours. The previously created mask of the Danube area, also in black and white, is superimposed on this image preventing the zone classification of the river. In order to further differentiate the contour lines the histogram of the picture has been stretched, altered in such a way that results in dark tones to further darken and light ones to further lighten. The resulting images are shown in Fig. 1(c) and (d).

Following this procedure, the picture was subjected to thresholding resulting in the disappearance of every shade of grey except for the

darkest colour, which represented the contour lines of the zones. The result can be seen in Fig. 1(e).

Then, by defining the contours, one can isolate the zones they encircle. Each zone was identified with the exact area, geometric centre point data and was assigned an ID number based on the area size of the zone. The area was determined based on the relation between the total number of pixels located in the image and the number of pixels located inside the zones with the help of the pixel/km² proportionality factor calculated specifically for Budapest.

$$A_{zone} = \frac{A_{zone, pixel} \cdot A_{Bp}}{A_{Bp, pixel}} \quad (1)$$

The identified zones were masked onto the original map resulting in picture seen in Fig. 1(f) above. 182 zones were identified within the city.

For each zone the amount of waste generated can be calculated based on the population density, the calculated zone areas and the specific waste generation index of Hungary, which is 381 kg(MSW)/person/year. The calculation method can be seen below:

$$m_{MSW} = f_{pop} \cdot A_{zone} \cdot \dot{m}_{MSW, specific} \quad (2)$$

2.2. MSW collection route definition

The centre points were associated with geographical coordinates to enable the routing simulations later on. These centre points were associated with the zone in which they are located in as hypothetical collection points. Following this point only 100 out of the 182 available centre points were used in the simulations since the other 82 zones were supplied by the already existing WtE plant located in northern Budapest. Out of the 100 centre points associated with coordinates a complete graph was constructed to enable free path choosing for the path optimising algorithm. The graph had 100 vertices and thus 9900 edges, since in real life cases the route A → B does not equal to B → A most of the time due to road blockages, one-way roads and potential traffic jams resulting in a better alternative pathing.

An algorithm was developed in order to simulate the 9900 paths between the centre points with the help of an open - source graph template library developed by the Eötvös Loránd University (LEMON, 2024). Based on these results the graph was weighed in two ways. First, the graph vertices were each assigned with a variable value depicting the amount of waste located in the zones at any time. Second, the edges connecting the vertices were assigned with the actual distance values between the centre points simulated earlier.

This way the total road length covered between zones could be determined throughout the collection process, but there is no information regarding the travel distance covered inside of the zones during the actual collection process, since each zone is represented solely by a vertex point. To combat this issue a ratio-based method was developed to quantify the distance travelled within the zone as a function of the remaining empty capacity of the garbage truck and the waste density of the zone.

Firstly, the concept of specific road length was created indicating the road length per unit of square area. This value has been averaged to $a = 24.9 \text{ km/km}^2$ for Budapest. Utilising this information, the road length located in each zone can be determined.

$$l = A_{zone} \cdot a \quad (3)$$

This method was chosen with the hypothesis in mind that waste collection requires moving along each street located in the zone to be emptied. Following this logic, densely populated areas require much shorter distance to be covered to collect the same amount of waste than suburban areas. To visualise this, the linear MSW density variable was created, which gives the distance a transport vehicle must travel to pick up one unit of municipal solid waste.

$$f_{MSW} = \frac{m_{MSW}}{l} \quad (4)$$

By identifying the travelled inner distance, the fuel usage necessary to empty a zone can be calculated, taking into account that the average consumption of a garbage truck is 73 l/100 km. It is important to note that all MSW transport vehicles currently in use at the time of the study have a capacity of 8 tonnes (Fuel, 2024).

$$v_{vehicle} = \frac{k}{f_{MSW} \cdot l} \cdot \dot{v} \cdot \frac{l}{100} \quad (5)$$

Also important to note that the city's topography was not taken into consideration during the calculations due to information constraints and limitations of the software used.

3. Optimisation logics

3.1. Definition of supplied zones

The maximum capacity of the analysed WtE power plant is 230 000 tonnes of MSW per year determined earlier in a study conducted by the official district heating supplying authority of Budapest. This value is largely exceeded by the amount of waste located in the 100 defined zones currently used in the graph system. The power plant cannot supply the entire defined area, since it has limited capacity that cannot be exceeded. For this reason another algorithm was developed aimed at aiding the definition of the most advantageous, actually supplyable zones. This algorithm was based on three simple principles:

1. it must give preference to zones located closer to the WtE plant,
2. if a zone was "opened" – waste collection has been initiated – the zone must be fully emptied, no trace of MSW can be left,
3. the maximum capacity of the WtE plant cannot be exceeded.

With these considerations in mind the algorithm defined the optimal zones to be supplied. The results are going to be shown later in the Results and Discussion section.

3.2. Route optimising algorithm

Since all the possible routing combinations and the supplyable zones were defined as shown above, all the information necessary to design an optimising algorithm was secured. The method of optimisation was founded on a self-developed algorithm due to the immense amount of vertex points used in the calculations. To calculate the optimal pathing between these points with heuristic algorithms or linear integer programming would take immense computational resources, making the optimisation highly inefficient, thus the self-developed algorithm was created to combat this issue. The logic behind the algorithm is illustrated in Fig. 2.

First the algorithm analyses whether all the waste has been collected in the supplied zones or not. If there is waste remaining in any of the zones, an MSW transport vehicle will be departed from the WtE plant. The first point of interest will be the vertex point farthest away from the power plant. The reason behind this decision is the following:

1. All the previously identified zones must be emptied without exception, so the farthest vertex will be visited anyway.
2. If the vehicle's first destination is the farthest point, the most cost-effective way of transportation is covering the distance leading to the zone with empty MSW storage capacity, minimising the weight of the vehicle.
3. If the farthest zone is emptied and the vehicle still has some storage capacity, it can supply other zones on the way back from the zone to the WtE plant. Since the return route must be covered in any case the minor detour caused by the second zone's supply only increases the total travel distance by a marginal amount. This method can be called "Trickle back supply".
4. The trickle back supply method is only viable, if the outer rim of the visited zones is emptied first compared to the inner ones for logical reasons: one can simply not collect any waste on the way back if the zones closer to the power plant have been supplied first hand.

Once the waste has been collected in the farthest zone the algorithm analyses whether there is any storage capacity left in the vehicle. If the answer is yes, then it searches for another zone to supply on the way back. In order to find the optimal zone to supply secondly a search radius method was developed. The illustration of the radius mechanics is shown in Fig. 3.

Firstly, an aerial straight line is defined between the current location of the vehicle and the location of the power plant marked with green

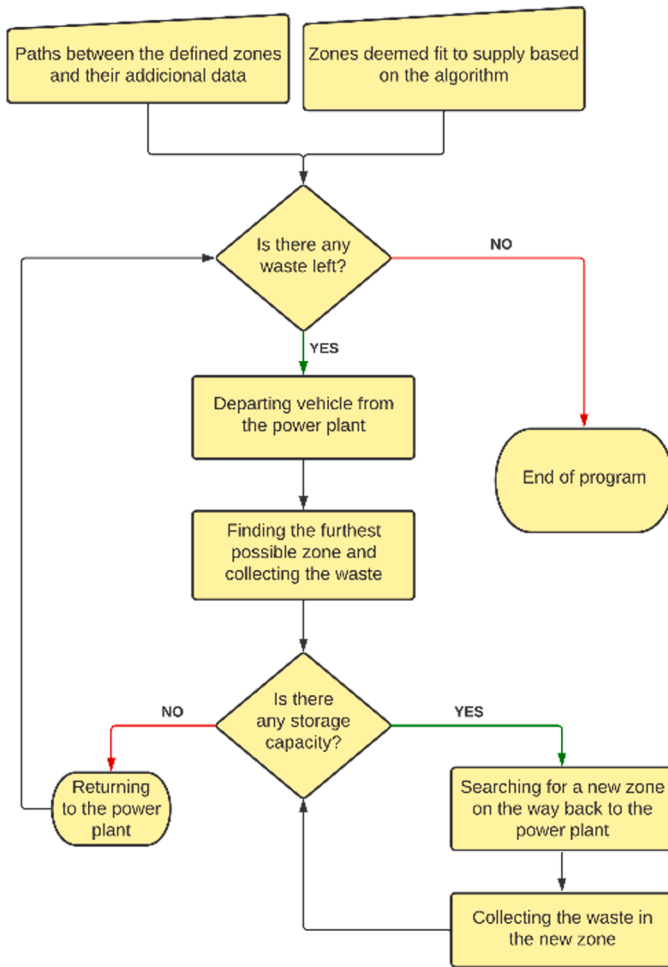


Fig. 2. Flowchart of the optimising algorithm's logic.

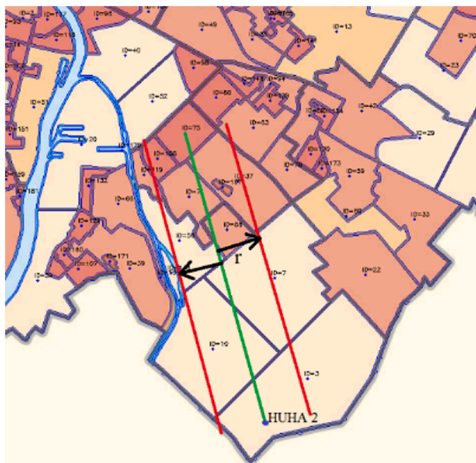


Fig. 3. Visualisation of the search radius method.

colour in Fig. 3. Secondly, a pair of vectors perpendicular to the aerial line are defined. The length of these vectors indicates the end of the search radius at any given moment. The search radius itself is a rectangle defined by the length of the aerial line and the vectors. The length of the vectors is cyclically increased by 0.01° measured on the latitudinal degree of Budapest, which equates to $75.124 \text{ km}/1^\circ$. The calculation method for this value is expressed by Eq. (6).

$$F_{\text{degree}} = \frac{2 \cdot r_{\text{Earth, equator}} \cdot \cos \alpha \cdot \pi}{360^\circ} \quad (6)$$

$$F_{\text{degree}} = 75,124 \frac{\text{km}}{1^\circ}$$

The maximum length of the search vectors was set to the third of the travel distance between the current vehicle location and the power plant. This was just an initial value that was optimised later on, the results are shown in the Results and Discussion section. With each cycle the length of the vectors was increased up to the maximum limit, and during these cycles the algorithm analysed the vertex points based on these considerations:

1. which zone vertex point is located inside the radius (r),
2. the MSW content of the zone,
3. the surplus distance required to cover due to the detour to a second supplied zone.

Based on these considerations the algorithm determined the optimal vertex point as the secondary destination. After this step the waste collection is initiated at the second destination, and the algorithm analyses again whether the vehicle has free storage capacity or not. If the answer is yes, then a new search radius is defined based on the methods shown above and a new zone is supplied. This continues either until the storage capacity of the vehicle is full or all of the MSW has been collected in the zones within the search radius.

If the storage capacity is full, the vehicle is returned to the power plant and the algorithm analyses the amount of MSW left in the zones. If there is uncollected waste, a new vehicle departs. Otherwise the program terminates.

To encapsulate this methodology the pseudo code of the optimisation algorithm was created visible in Fig. 4.

The results of the self-developed algorithm were compared to an already existing linear integer programming vehicle routing problem (VRP) algorithm to justify its development. During the comparison it became evident that the self-developed algorithm was superior compared to the existing VRP algorithm. Due to the sheer number of possibilities presented by the large-scale graph system used during the study the VRP algorithm was unable to provide a solution even at 20 vertex points, not mentioning the 100 originally used vertex points. This can be attributed to the immense computational requirements of the VRP algorithm due to its inefficient pathfinding methods, as it scaled factorially.

4. Results and discussion

4.1. Definition of supplied zones

As it was previously mentioned, the WtE plant could not intake the total amount of waste generated in the 100 identified zones, thus creating the need of identifying the best possible zones to supply. For this reason, an algorithm was created detailed in the Definition of Supplied Zones section. The results of the algorithm are presented in Fig. 5(a).

Fig. 5 shows the zone centre point locations (vertex points) based on geographical coordinates. The zones which were deemed fit to be supplied by the algorithm were marked with green dots, while the unsupplied zones are marked with red crosses. Altogether 85 zones were supplied out of the 100. It can be observed that certain zones which remained unsupplied lay physically closer to the WtE plant (marked with a blue star) than other supplied zones. This can be explained by the three conditions detailed previously in the Definition of Supplied Zones section, mainly by the following criteria:

1. if a zone was “opened” – waste collection was initiated – the zone must be fully emptied, no trace of MSW can be left,

Algorithm 1: Route optimisation

```

while capacity_used < WtE_capacity do
    area = max(distance(WtE, areas))
    collected_waste += min(area.waste, transport_capacity)
    capacity_used += collected_waste
    transport_capacity -= collected_waste
    travel_distance += distance(WtE, area) + in_area_distance
    while transport_capacity != 0 do
        areas_in_ROI = distance(area, line) < r
        if length(areas_in_ROI) > 0 then
            area = min(distance(area, areas_in_ROI))
            collected_waste += min(area.waste, transport_capacity)
            capacity_used += collected_waste
            transport_capacity -= collected_waste
            travel_distance += distance(WtE, area) + in_area_distance
        else
            break
        end
    end
    end
    travel_distance += distance(area, WtE)
end
end

```

Fig. 4. Pseudo code of the route optimising algorithm.

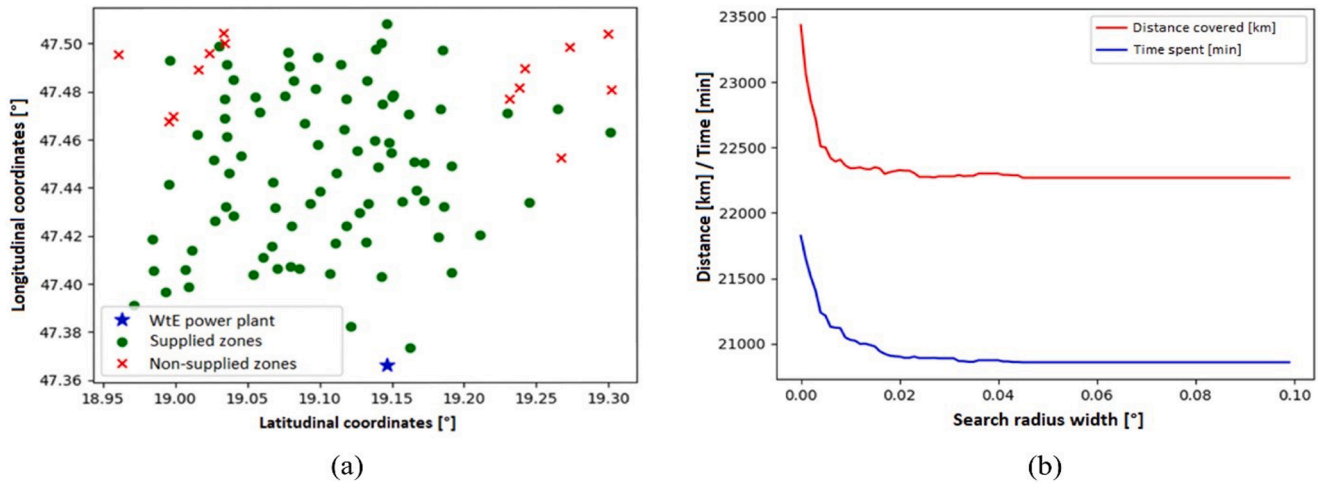


Fig. 5. Results of the suppliable zone algorithm (a), total covered distance and time based on the maximum search radius width (b).

2. the maximum capacity of the WtE plant cannot be exceeded.

The zones left untouched were not supplied as their MSW content was too high for the power plant to take in at the given state of the calculation. As a result the algorithm resorted to supplying zones further away with less MSW content.

4.2. Search radius optimisation

It was also mentioned earlier that the search radius used to determine the potential next suppliable zone was set with an initial value as a max search radius width. This value had to be optimised in order to find the best possible distance and fuel consumption reduction value. To achieve this goal the optimisation algorithm was run 150 times, meanwhile the total amount of distance covered by all of the vehicles and the time it takes to cover it was registered continuously. The algorithm was modified in the following way:

1. the maximum search radius was set to $r = 0$ at the first run,

2. and was gradually increased by 0.001° with every run cycle.

The results of this simulation can be seen on Fig. 5(b).

The red graph depicts the distance while the blue graph signifies the time. The sharp drop at the beginning of the graph can be explained by the significance of the search radius, since the width being zero is equivalent to not having any way to search for a potential second suppliable zone, thus not having a search radius. It can be concluded that even a small search radius width can have massive impact on the covered distance length and the time associated with it. At higher search radius values inverse proportionality can be experienced between the radius width and the measured metrics. The higher width provides zone options farther away from the original pathing, thus reducing the likelihood of the algorithm choosing them as secondary collection points. After a certain amount of runs stagnation can be observed in both measured metrics.

The optimal maximum search radius value came to be $r = 0,045^\circ$. Theoretically it could be higher, but it would not change the outcome of the savings due to the stagnating metrics. On the other hand, the

computational resource requirements would rapidly increase, making the optimisation method highly inefficient.

4.3. Results of the transport route optimisation

With access to the optimal maximum search radius width the program was modified to accommodate these values. In this chapter the results are going to be detailed starting with Fig. 6, which provides a small insight into the inner workings of the algorithm. The structure of the diagram is equivalent to Fig. 5(a), while the red dots represent the 100 defined zones. On the first run a simple travel – collection – return type MSW transport can be observed. The second run presents a slightly more complicated collection route where the vehicle upon emptying one zone searches for and collects MSW from two additional zones before returning to the power plant. The third run was hand picked as the most complex route made by the algorithm: upon emptying the first zone it was sent to it emptied two additional zones completely and collected waste in one additional zone on its way back to the WtE plant. This extraordinary case resulted in a total of 4 supplied zones within a single run, all with minimal detours.

The ID numbers in order of visit of the three runs illustrated above are the following:

1. run: 1.0 → 16.0 → 1.0
2. run: 1.0 → 159.0 → 181.0 → 14.0 → 1.0
3. run: 1.0 → 34.0 → 56.0 → 145.0 → 10.0 → 1.0

A portion of the dataset generated by the algorithm can be observed in Table 1. Since the total number of runs necessary to transport the MSW generated in the course of one week is 553, presentation of the entire dataset would be outside of the possible boundaries of this article. For this reason, only a part of it is going to be shown to illustrate its structure seen in the table mentioned above.

The algorithm was constructed to collect data regarding the distance covered during travelling between zones, the time necessary to do so, the distance covered within the zones themselves, the total distance travelled based on these data, the fuel consumption of the runs and finally the costs associated with the transport. This dataset is available for every vehicle present in the simulation. In addition to this information the algorithm also collected data in regards to the free capacity of each vehicle returning from its journey to monitor the quality of the program code.

To achieve a final result the savings were calculated compared to the current system in place. The following results can be seen in Table 2 below.

It can be seen from the results visible above, that the overall efficiency is rather low with a value of 5,2 % in the economic aspect. This can be explained by the fact, that the official MSW handling administration of Budapest unfortunately does not track the routing data of their vehicles. Thus, we had to implement a fictional transport routing method as a method of comparison, which were also based on our pre-optimised routing data, the only difference being that the fictional routes did not use the search radius mechanism to find other supplyable zones once their zone was emptied. This means that due to the lack of available data the impact of optimisation would exceed the calculated value by multiple folds.

5. Conclusion

In this study a novel method of waste collection definition and transport route optimisation was carried out with self-developed algorithms using the python programming language. A method of image processing was developed to combat the lack of reliable waste generation data. Using this approach the area-based waste generation data were defined with great accuracy. Furthermore, the zone areas and the geometric zone-centre points were defined, providing the foundation to the graph-based optimisation method. The 9900 possible routes between the graph vertex points were simulated, providing the necessary travel distance and travel time datasets. In addition, a method was developed to measure the in-zone distances covered during the collection process by each vehicle using linear waste generation metric.

Using the simulated data and the waste generation calculated earlier the graph system was weighed accordingly to perfectly model the real-world scenarios. A transport route optimising algorithm was developed onto the graph system to find the optimal pathing of each vehicle. The algorithm was aimed at maximising the used transport capacity of the vehicles while also minimising the detours necessary to the alternative supply zones.

The results of the self-developed algorithm were compared to a linear integer programming VRP algorithm where it was deemed superior both in terms of computational requirements and computational speed. The VRP algorithm was simply unable to calculate the system using the full 100 nodes due to having factorial proportionality to the number of nodes.

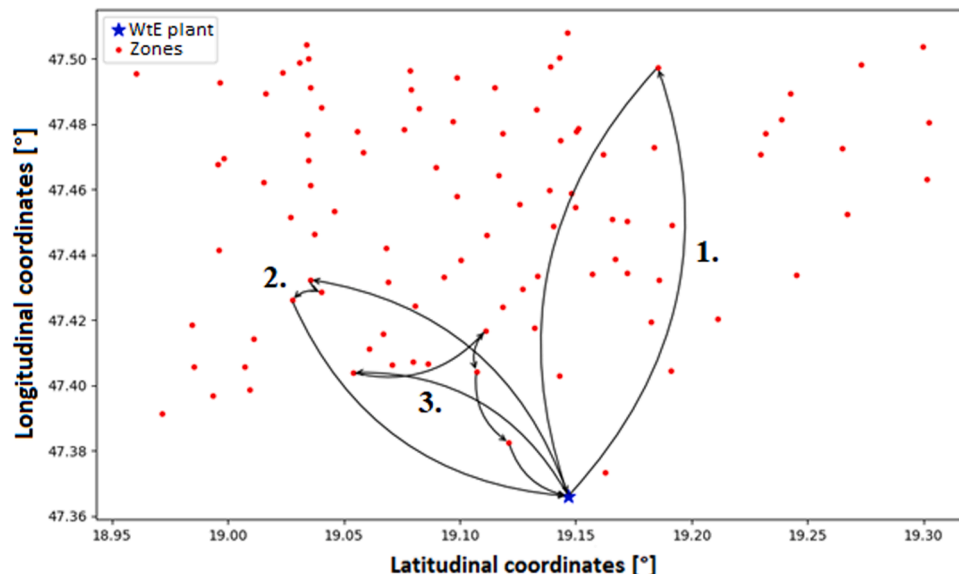


Fig. 6. Visualisation of three waste collection route determined by the algorithm.

Table 1
Visualisation of the dataset produced by the optimising algorithm.

Visited IDs [-]	Distance [km]	Time [min]	In-zone distance [km]	Total distance [km]	Fuel usage [l]	Costs [€]
1.0 -> 16.0 -> 1.0	83.30	66.00	25.27	108.57	79.26	175.65
1.0 -> 16.0 -> 1.0	83.30	66.00	25.27	108.57	79.26	175.65
1.0 -> 16.0 -> 112.0 -> 1.0	70.40	71.00	14.82	85.22	62.21	137.87
1.0 -> 64.0 -> 1.0	62.00	48.00	4.71	66.71	48.70	107.93
1.0 -> 64.0 -> 1.0	62.00	48.00	4.71	66.71	48.70	107.93
1.0 -> 64.0 -> 1.0	62.00	48.00	4.71	66.71	48.70	107.93
1.0 -> 64.0 -> 1.0	62.00	48.00	4.71	66.71	48.70	107.93
1.0 -> 64.0 -> 1.0	62.00	48.00	4.71	66.71	48.70	107.93
1.0 -> 64.0 -> 1.0	62.00	48.00	4.71	66.71	48.70	107.93
1.0 -> 64.0 -> 54.0 -> 1.0	62.70	51.00	4.71	67.41	49.21	109.06
1.0 -> 54.0 -> 1.0	55.60	39.00	4.71	60.31	44.03	97.57
1.0 -> 54.0 -> 1.0	55.60	39.00	4.71	60.31	44.03	97.57
1.0 -> 54.0 -> 1.0	55.60	39.00	4.71	60.31	44.03	97.57
1.0 -> 54.0 -> 1.0	55.60	39.00	4.71	60.31	44.03	97.57
1.0 -> 54.0 -> 1.0	55.60	39.00	4.71	60.31	44.03	97.57
1.0 -> 54.0 -> 23.0 -> 1.0	58.00	61.00	19.56	77.56	56.62	125.47
1.0 -> 24.0 -> 1.0	67.30	63.00	7.18	74.48	54.37	120.49
1.0 -> 24.0 -> 1.0	67.30	63.00	7.18	74.48	54.37	120.49
1.0 -> 24.0 -> 1.0	67.30	63.00	7.18	74.48	54.37	120.49
1.0 -> 24.0 -> 1.0	67.30	63.00	7.18	74.48	54.37	120.49
1.0 -> 24.0 -> 1.0	67.30	63.00	7.18	74.48	54.37	120.49
1.0 -> 24.0 -> 1.0	67.30	63.00	7.18	74.48	54.37	120.49

Table 1 (continued)

Visited IDs [-]	Distance [km]	Time [min]	In-zone distance [km]	Total distance [km]	Fuel usage [l]	Costs [€]
1.0 -> 24.0 -> 124.0 -> 1.0	51.30	70.00	6.72	58.02	42.35	93.86
1.0 -> 124.0 -> 1.0	44.90	58.00	0.60	45.50	33.21	73.61
1.0 -> 124.0 -> 1.0	44.90	58.00	0.60	45.50	33.21	73.61
1.0 -> 124.0 -> 1.0	44.90	58.00	0.60	45.50	33.21	73.61
1.0 -> 124.0 -> 1.0	44.90	58.00	0.60	45.50	33.21	73.61
1.0 -> 124.0 -> 1.0	44.90	58.00	0.60	45.50	33.21	73.61
1.0 -> 124.0 -> 1.0	44.90	58.00	0.60	45.50	33.21	73.61

Table 2
Impact of optimisation on costs and emissions.

Impact of optimisation on costs		
	Original routing	Optimised routing
Distance [km]	23 477.11	22 268.31
Time lenght [min]	21 824.00	20 857.00
Fuel usage [l]	17 138.29	16 255.87
Costs [€]	37 982.16	36 026.52
Monthly savings [€]		7 823
Impact of optimisation on emissions		
	Original routing	Optimised routing
Distance [km]	23 477.11	22 268.31
Specific CO ₂ emissions [kg CO ₂ /l]	2.68	
Fuel usage [l]	17 138.29	16 255.87
CO ₂ emissions [kg]	45 930.62	43 565.72
NO _x emissions [kg]	219.95	208.62
Monthly CO ₂ savings [kg]	9 459.59	
Monthly NO _x savings [kg]	45.30	

The results indicate a 7 823 € monthly potential saving which equates to 93 871 € saving annually. The optimisation also impacts the environmental side of MSW transport by reducing the carbon-dioxide and nitrogen oxide emissions of the vehicles by 9 459.6 kg and 45.3 kg, respectively each month. This value can also be represented in an annual timeframe meaning the avoidance of 113.5 tonnes of CO₂ and 543.6 kgs of NO_x emissions annually in the Capital. This result not only provides a minimal investment, instant cost saving measure for the power plant, but it also reduces the pollutant emissions and the traffic load in the inner-city regions.

CRedit authorship contribution statement

Kende Kocsis: Writing – original draft, Methodology. **József Kövendi:** Software. **Balázs Bokor:** Writing – review & editing, Investigation, Conceptualization.

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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Data availability

Data will be made available on request.

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