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METHODOLOGY FOR ROUTE OPTIMIZATION FOR SOLID WASTE COLLECTION AND TRANSPORTATION IN URBAN AREAS

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Abstract. *This paper presents a routing optimization methodology for collection and transportation of municipal solid waste in large urban centers. The framework for the development of this methodology is an integrated system of sustainable waste management. The aim of the study is to identify and analyze the elements, criteria and data relevant to the development of optimization models of transport routes, assuming the main criterion to be the fuel consumption and the reduction of negative impacts on the environment and human health. The organization, collection and transportation of municipal waste are conditioned by the limitations related to geographic and environmental criteria. The project of transportation route optimization and improvement of municipal waste collection system comprises of three phases: the formation of a 3D road network, calculation of fuel consumption, and optimization of waste collection and transportation. GIS technology has significant advantages in modeling urban network, whereas the application of GIS tools is conditioned by the quantity and quality of information. Using GIS tools and techniques will save up to 60 - 80% of the costs incurred in the system of solid waste management.*

Key words: *Municipal solid waste, environmental protection, waste collection, waste transportation, optimization*

1. WASTE COLLECTION AND THE ENVIRONMENT

In highly developed countries, about 1.5 kg of municipal waste per capita is generated per day. The problem is particularly acute in large urban centers. The pronounced negative environmental and health impacts of waste have significantly increased the interest of researchers in finding the optimizing solutions to the issue of municipal and other kinds of waste management in urban areas in the last twenty years. As a result of these studies, a

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system of integrated sustainable management of municipal waste (ISWMS), which is of great importance for the sustainable development of urban areas, has been developed. ISWMS establishes principles and models of municipal solid waste management from its generation at the source to final disposal, including all operations (collection, transport, temporary disposal, etc.) and treatments in certain stages of the process.

Cost analysis of municipal solid waste management indicates the influence of a very large number of complex factors, the most important being the following: the amount and the composition of solid waste, terrain features, technologies and techniques used for waste collection, types and characteristics of vehicles and other transport equipment, distance from the landfill site, labour costs and others. The collection and transportation of municipal solid waste in urban areas is becoming an extremely troublesome and complex issue. It is estimated that, out of the total amount of funds needed for the management of municipal solid waste in urban areas, about 60-80% is allocated to waste collection, most often to fuel costs. For this reason, even a small improvement in collection activities may result in significant overall cost savings. For this reason, the optimization of roads for collection and transportation of municipal waste become a crucial issue. In this paper, we propose the use of geographic information systems (GIS), software for 3D modeling of waste collection and transportation routes, with the aim to minimize fuel consumption, while taking into account the traffic and geographic features (e.g. slopes, relief) of the area where the waste is being collected.

The vehicles intended for waste collection and transportation usually emit significant quantities of pollutants into the atmosphere, particularly carbon dioxide (SO_2) and nitrogen oxides (NOx), which contribute significantly to the greenhouse effect and the occurrence of acid rain. Reduction of pollutant emissions, through economic use of fuel, contributes to the improvement of environmental quality in urban areas.

Technological development and population growth have accelerated the process of urbanization. A significant increase in population has influenced a reduction of infrastructure utilities such as water supply, channeling waste water, sewage, waste water treatment and solid waste management. Waste management is becoming an extremely significant issue, despite the fact that most of the local budgets is often spent on solving the likewise. The collection and transportation of waste is a meeting point between the producers of waste-service users (residential, commercial and industrial buildings) and waste management systems. Efficient and effective waste management system is based on the relationship between service providers and users. In the past few years, due to the growing population in cities, increasing costs and environmental health impact, many municipalities have been forced to improve their waste management programmes and test their economic viability.

The proposed model can be used as a tool in making decisions about possible improvements in the efficiency and effectiveness of the waste management system, aimed to reduce the costs of waste collection and transportation to landfills or costs of treatment plants. The data used in this paper to calculate the fuel consumption of municipal solid waste collection and transportation are provided in the list of literature. The model uses geo-information technologies and tools to determine optimal transport routes that would minimize fuel consumption and pollutant emissions into the environment.

The aim of this study was to identify and analyze the elements, criteria and data relevant to the development of optimization models for solid waste collection and transportation routes, taking fuel consumption and reduction of negative impacts on the environment and human health as the main criteria. A framework for the design and the implementation of optimal solutions for the collection and transportation of solid waste, in order to reduce the cost of solid waste management and improve the environmental quality, has been proposed.

2. A Methodology for Model Development

The illustration of certain elements of the proposed model has been given in the case of the city of Nis. Waste is disposed in the city landfill, which is about 4 km away from the city center. The landfill, due to inadequate and uncontrolled disposal of municipal and industrial waste, has an extremely negative impact on the quality of the environment.

Fig. 1 Location of the landfill in Nis in relation to the city (left) and site layout (right)

The project of transport routes optimization and improvement of municipal waste collection system consists of three phases: the formation of a 3D road network, calculation of fuel consumption, and the optimization of transport routes waste collection and transportation routes with minimum fuel consumption.

The network consists of a system of interconnected elements and can be visualized as a series of lines by which data points are connected. Network characteristics can be used to model the benefits, limitations and hierarchy. In fact, network characteristics are the properties of network elements that influence the effectiveness and efficiency of transport routes, e.g. the time required to move, the fuel consumption for a given length of time, the restrictions of movements of special vehicles (garbage trucks) in the area of particular streets, limitations for speed limits and one-way streets, etc. Its elements are used for measuring, modeling and reducing the cost of collection and transportation of municipal solid waste. It is recommended, for each phase, to develop a special module, using the Visual Basic for Applications. It is necessary to ensure the exchange of data between the modules. The base of the development model consists of the data from spatial databases. The structure of the proposed model for optimization of transport routes and the flow of information are shown in Figure 2.

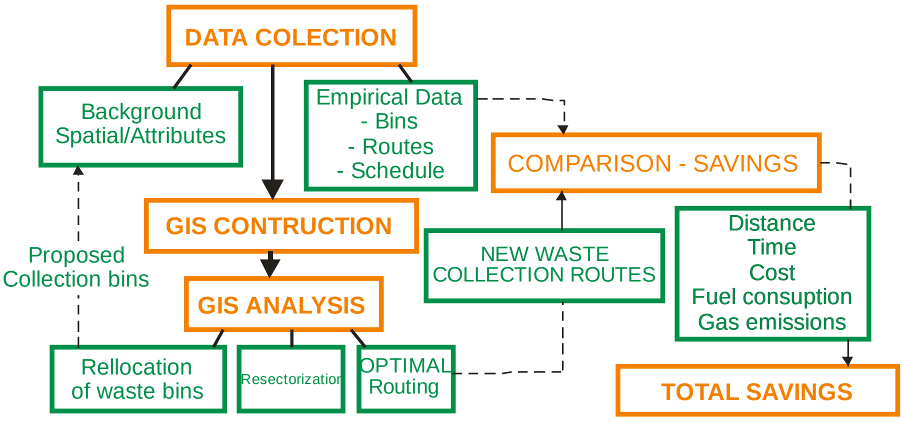

Fig. 2 Structure of the model for optimization of transport routes

GIS technology has significant advantages in modeling urban networks. The first phase of the optimization of transport routes requires the use of GIS tools for creating spatial database, which contains digitalized detailed information on the road network, in the form of appropriate geographic objects. A significant factor that affects fuel consumption is a slope; therefore, it is necessary to develop 3D models of transport routes, allowing each digital segment of the route reflect its actual physical characteristics in the space.

The factors that affect fuel consumption during collection and transportation of waste are distance travelled and operating conditions and characteristics of the vehicle. COPERT method is applied to monitor and calculate the impact of these factors. By using this method and the corresponding software, pollution emissions can be monitored and the basis for the assessment of fuel consumption can be provided. The method takes into account different driving conditions, such as vehicle load and ascent-slope of roads. It is recommended to use the data available in the COPERT base for heavy duty vehicles (7.5 to 16 tons) and EURO 3 fuel standard.

The basic fuel consumption, which is a function of speed only, FCS (g/km) for a given category of vehicles is given by the equation:

$$FCS = 1068{,}4 * V^{-0{,}4905} \quad (1)$$

Driving characteristics (in urban areas, rural areas or on a highway) may be represented by different mean values of the speed V (km/h), in order to explain the diversity of driving performance and corresponding fuel consumption.

When calculating fuel consumption for heavy vehicles, such as vehicles for waste collection and transport, it is necessary to take into account the effect of vehicle load and gradient-slope transport routes. To evaluate and calculate specific fuel consumption, f_c (g/km), it is necessary to make a correction of FCS as shown in the equation (2), where LCF (Load correction factor) is a dimensionless value which defines the correction conditioned by load, and G_rCF is a dimensionless factor for slope correction.

$$f_c = FCS * LCF * G_rCF \quad (2)$$

In case of any road in the city, fuel consumption should be calculated while loading and transporting waste. Fuel consumption depends on the vehicle weight; the lower total weight of the vehicle, the lesser the load on the engine is. According to the COPERT method, the reference value for correcting the load that is different from 50% is indirectly contained in the equation (1). The correction of fuel consumption for heavy commercial vehicles must be performed by using the equation (3).

$$LCF = 1 + 0,36 * (LP - 50)/100 \quad (3)$$

In equation (3), LP shows the actual operation of the vehicle for collection and transport (garbage vehicle), as a percentage of maximum. No matter how much the correction is conditioned by the load of the vehicles, LCF can vary but it remains constant for each collection cycle.

Ascent on the routes, i.e. the slope of the roads affects the tensile resistance of special vehicles. Therefore, the use of engine power is the key factor that determines the fuel consumption of vehicles for collection and transport. Due to the significant weight of the garbage vehicle, the effect of the slope and the ascent is much higher in case of heavy commercial vehicles, such as vehicles for waste collection and transport. For all vehicle weights, the slope correction factor can be calculated as a polynomial function of an average vehicle speed, as expressed by equation (4), where p is the degree of the polynomial functions, and A_0 and A_j are the slope coefficients of the route functions.

$$G_rCF = A_0 + \Sigma A_j * V^j \quad (4)$$

Using the equation (4), the results are obtained for road slopes between -6% and + 6%. If the obtained results can be represented by an exponential function, then the equation is valid for a wider range of road slopes (-15% to + 15%).This can be expressed by equation (5) where x is the slope percentage of the road.

$$G_rCF = 0,41e^{0,18* x} \quad (5)$$

In Figure 3, the slopes of the terrain in a part of the city of Nis have been illustrated.

Fig. 3 The slopes of the terrain in a part of the City of Nis – an illustration

3D network can be composed of a series of arcs connected by nodes. Each arc is a set of vertices and segments. Vertices are defined as the points at which the waste collection route changes its direction. The segments are lines that connect two adjacent vertices. The 3D model used for the research should adequately justify the fact that the length of each road segment depends on the slope of the road and has a specific f_c. Any change in the slope of the route requires a new segment of the route with a different f_c. It is very important that the 3D model of the road network for waste collection and transportation takes into account the slope of the road when calculating fuel consumption.

Fuel consumption is calculated for both directions (up and down). In each arc, fuel consumption FC_k is calculated based on the equation (6), where L_{seg} is the length of the *i*th segment (km), f_{ci} is adequate fuel consumption of the segment, and n is the number of segments included in the arc (part of the road where the waste is being collected in one segment).

$$FC_k = \Sigma (L_{seg} * f_{Ci}) \quad (6)$$

The data on fuel consumption for each arc (FC_K) are stored in a spatial database and then used in the process of establishing a transport route for waste collection with the lowest fuel consumption.

The next step is to optimize the transport routes of vehicles for collection and transportation of municipal waste, which represents the basic measure of the system efficiency. It is essential that each vehicle is allocated a number of collection points that can be reached with minimum fuel consumption. The optimal trajectory with minimum fuel consumption is the one that has the lowest fuel consumption among possible routes and which covers all the points for waste collection. The total fuel consumption for a given route (TFC) is calculated by the equation (7), as a function of fuel consumption at each arc FC_K, as previously defined by equation (6).

$$TFC = \min (\Sigma FC_k) \quad (7)$$

where m is the number of arcs in the analyzed route.

Fig. 4 The existing municipal waste collection route in a part of the city of Nis (one vehicle in a single pass)

In order to illustrate the inefficiency of waste management system, Figure 4 shows a waste collection route in the part of the city of Nis. In areas where waste is collected once a week, one vehicle in a single pass can collect municipal waste from about 180 four–membered households.

3. THE ELEMENTS OF TRANSPORTATION ROUTES OPTIMIZATION

Application of GIS tools is conditioned by the quantity and quality of information. The most important information necessary for the application of these tools are: the maps of the area for waste collection, service users GPS position, sizes and other characteristics of the vessels for waste collection, waste quantity, frequency of waste collection, the position of vehicles for waste collection, landfill position, payload for waste collection, transportation time of waste to the landfill, length of roads for waste collection in a single pass, speed limits for waste collection vehicles, the time required for emptying, cleaning and disinfection of vehicles at the landfill, the working time of employees, etc. All variables must be available in order to obtain the adequate roads for collection and transportation of municipal waste by using this software.

According to the methodology described, development of the systems for optimizing routes for municipal solid waste collection is comprised of the following key steps:

- Data on population density, quantity and composition of waste, topographic maps, maps of the existing road network, and the details on the containers and the vehicles for waste collection are used to digitize the road network and determine the position of waste collection containers.
- Geographic coordinates for road network have been determined.
- The map of the road network is integrated into a geographic information system.
- The location of containers for waste disposal in collective housing zones has also been determined.
- The optimization of routes for collection and transportation of municipal solid waste has also been carried out by using a network analytical tool.
- A detailed analysis of the cost of a new waste collection and transportation system has been performed.

It is necessary to use GPS to analyze the location of containers for solid waste collection in the whole city. From the created network data sets, roads for collection and transport of collected waste to the landfill can be successfully optimized. To achieve this, the first step is to city zoning, bearing in mind the areas of individual and collective housing, the quantity and composition of waste, traffic and other characteristics of individual urban areas. It is necessary to be aware of all issues of importance for the development of optimal transport routes. To optimize the stop points, traffic characteristics and limitations should also be taken into account.

The organization, collection and transportation of municipal waste is conditioned by the limitations related to geographic and environmental criteria, which should be separately analyzed in the early stages, i.e. at the stage of defining the requirements and criteria for improving the system which may be answered by developing technical means of optimization. These limits relate primarily to: climate and weather conditions, the characteristics of the territory in which the waste is collected, traffic density, the amount and the composition of waste, diversity of waste producers, waste types that should be collected more often, share of waste which requires specific techniques of collecting, etc. The most important technical aspects of the limitations are: technical characteristics of vehicles for collection and transport, the introduction of special containers for special waste types, high operating costs, specific working conditions of the employees engaged in collecting and transporting of waste, taking measures to reduce negative impacts on environment and complexity of logistics support system for collection and transportation of municipal waste. Limitations in the field of environmental protection define the framework in which adequate technical solutions should be chosen and implemented, the ones that provide the expected level of quality of utility services to customers, with an optimum level of acceptable costs of collection and transportation of municipal waste.

Fig. 5 Typical positions of waste collection vehicles in the city

The main limitations in defining the model and the optimization of transport routes are the vehicle capacity and the capacity of collection and transport. Vehicle capacity is the maximum amount of waste collected per vehicle. Capacity collection and transportation is daily capacity for each vehicle: the maximum number of stops, maximum load, maximum volume and weight, etc. We should bear in mind the capacity constrained routing and the time needed to collect waste in certain city areas. If the capacity of the vehicle is greater than the volumetric capacity of the route, the drivers will execute only one delay and this will be the last stop before returning to the landfill. If the volumetric capacity of the route is greater than the capacity of the vehicle, which is often the case, the vehicle will have to make several trips to the landfill. It is assumed that each vehicle route begins and ends at the landfill. It is necessary to ensure the proper balance of available vehicles for waste collection and transport. The objectives should be to reduce the number of vehicles and the time of collection in a single pass.

Recycling yards are vital in increasing the efficiency and the improvement of municipal waste system due to the fact they represent the indirect model of separate waste collection (assuming that waste producers have an economic interest to occasionally participate in the system of waste collection on a voluntary basis). Also, hazardous household waste can be landfilled in special containers in recycling yards and due to the necessary equipment and land area, recycling yards are places for significant investment. For these reasons, formation of mini centers for the disposal of useful components of municipal waste (glass, plastic, paper and cardboard, etc.) should be technically and economically more acceptable solution.

Recycling yards may be directed to provide services in industrial zones where industrial non-hazardous waste is generated, as well as small amounts of industrial hazardous waste and hazardous household waste, with the potential for recycling / reuse of waste materials that are often considered the ultimate waste (sawdust, paper, cardboard, etc.). Thus conceived recycling yards are likely to provide a return on investment.

Recycling yards and mini centers for disposal of useful materials from municipal waste should be designed on the basis of data on the quantities and types of waste to be temporarily disposed of. This allows proper sizing of bins and the best frequency of collecting waste components. On the other hand, the existence and the use of recycling yards can significantly contribute to optimizing and improving the efficiency and effectiveness of the collection and transportation of municipal waste.

The main advantage of GIS application is the integration of spatial information and data management. Based on the user’s address, GIS can provide spatial information about the user, including a specific location in the x, y, z coordinate system and the geometry of space for waste collection, usually as a point, but sometimes as a line or polygon. When this spatial information is merged with other data that have spatial components (such as streets) we can obtain very important aspects about the data. For example, one can display the user's location on a map, with the surrounding street network, other users or facilities for waste collection. GIS allows the designing of key components of the optimization matrix. This matrix includes distance and travel time on the street network, between any two points, taking into account constraints such as speed restrictions, one way streets and precise spacing between individual users. Application of GIS based tools, for management of the system for collection and transportation of municipal solid waste, reduces operating costs by organizing routes that minimize overlap and thus reduces the number of vehicles needed to provide service to customers and optimize the number of stopping places along the route.

The basic rule of optimization of roads for collection and transportation of municipal solid waste should be: a collection vehicle begins its journey completely empty and ends full on a lot of the landfill, for the least possible time and the shortest route.

Optimization involves selection of the shortest road route to bypass all the places for waste collection and scheduling for the most efficient tour of all points in the shortest time or the shortest routes. This means providing services for greater number of users, by using a small number of vehicles and minimizing the driving time and distance, while still complying with all the requirements of the efficient and effective service.

It is recommended to use the GIS application and the module optimization tool known as "Router Solver" which was developed in order to collect input and output data for optimization procedures. In the GIS environment, routing of vehicles involves finding the optimal distance to the disposal or collection center (if it is a separate collection of useful components of municipal waste). If necessary, it is possible to use an additional module "Network Analyst". The resulting route is kept as a part of the system for managing the collection and transportation of municipal waste.

4. CONCLUSION

The collection of municipal solid waste in urban areas is a service of utmost importance for the city infrastructure. The development of the municipal system, the introduction of public private partnerships model (PPP) in utilities and creating a space for competition can significantly improve the quality of this service.

The complexity of problems related to municipal waste collection and transportation network requires different solutions for each part of the city. The first option is to solve the problem and determine the location of collection on route junctions; another possibility is to place collection points on the arcs of the route. In both cases, roads for collection and transportation of waste are adjusted to cost function, that is, the minimum fuel consumption or the shortest distance. For each of these optimized parameters (e.g. 3D shortest distance), other parameters (2D distance, fuel consumption, etc.) are evaluated in order to be compared to the procedure of optimizing waste transport routes.

Using GIS tools and techniques will save up 60 - 80% of the costs incurred in the management of solid waste; however, the use of these tools requires trained personnel who will perform optimizing and allocating routes to individual vehicles. This technique can also be used as a support in decision-making process for effective management of collection and transportation of municipal solid waste, balancing of vehicles load, fuel consumption management, scheduling workers and vehicles, and the overall minimization of waste management costs, both at the local and regional level.

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METODOLOGIJA OPTIMIZACIJE PUTEVA SAKUPLJANJA I TRANSPORTA ČVRSTOG OTPADA U URBANIM PODRUČJIMA

U radu je prikazana metodologija optimizajije puteva sakupljanja i transporta komunalnog čvtstog otpada u velikim urbanism centrima. Okvir za razvoj metodologije predstavlja integralni system održivog upravljanja otpadom. Cilj rada je identifikacija i analiza elemenata, kriterijuma i podataka od značaja za razvoj modela optimizacije transportnih puteva, uzimajući, za osnovni kriterijum, potrošnju goriva i smanjenje negativnih uticaja na životnu sredinu i zdravlje ljudi. Organizacija sakupljanja i transporta komunalnog otpada uslovljena je ograničenjima vezanim za geografske i kriterijume zaštite životne sredine Projekat optimizacije transportnih puteva i unapredjenja sistema sakupljanja komunalnog otpada sastoji se iz tri faze: formiranje 3D mreže puteva, izračunavanje potrošnje goriva i optimizacija sakupljanja i transporta otpada. GIS tehnologija ima značajne prednosti u modeliranju urbanih mreža, a primena geoinformatičkih alata uslovljena je količinom i kvalitetom informacija. Korišćenjem geoinformatičkih alata i tehnika štedi se 60 – 80 % troškova koji nastaju u sistemu upravljanja čvrstim otpadom.

Ključne reči: *komunalni čvrsti otpad, zaštita životne sredine, sakupljanje otpada, transport otpada, optimizacija*