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DYNAMIC VEHICLE ROUTING PROBLEM FOR SMART WASTE COLLECTION

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Abstract. *This paper examines waste management problems in urban areas and analyzes systems employed in waste management. The first part of the paper focuses on waste collection and transport activities in urban systems, as well as on understanding the causes behind the ineffectiveness of traditional waste collection systems. A smart waste collection container prototype is presented with the aim of achieving more efficient waste collection, coupled with the application of modern information and communication technologies in waste collection and transport systems. The waste collection problem is defined as a dynamic CVRP. To solve this problem, a methodology is proposed based on heuristics for defining optimal dynamic routes so as to minimize total costs, that is, transport costs.*

Key words: *Dynamic vehicle routing problem, Smart waste collection, Information technologies, Communication technologies*

1. INTRODUCTION

Waste management is an extremely complex process that involves a series of steps, technologies, and public participation. The success of waste management depends on the cooperation of the public and the government, where both actors bear responsibility and should cooperate in order to achieve adequate management of this process. Waste management systems are very complex. They monitor the entire cycle from generation, collection, transportation, treatment and disposal of waste and solve problems related to

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the construction of landfills, design and construction of recycling centers, transfer stations and various other systems for processing waste and waste products. Today's waste management systems are based on the greatest possible utilization of waste, processing, recycling, reuse. Municipal waste management - MSW is defined through four basic functions: collection, transport, processing and final disposal [1]. However, it should be emphasized that the transport function occurs between each of the mentioned functions. Waste collection and transportation costs account for 60-80% of the total costs of an MSW system [2]. Thus, this article focuses on operational decisions at the first and second stage, collection and transportation. The function of municipal waste collection refers to the use of vehicles for collecting waste from collection points, and the function of waste transport refers to the activity of taking the collected waste to a disposal center.

As a rule, the traditional method of collecting and transporting municipal waste is carried out by specialized vehicles for emptying waste containers according to a predetermined schedule. However, this conventional collection of municipal waste is very inefficient because the level of filling of the waste container very often varies from partially filled to overflowing, which leads to unnecessary consumption of resources.

In relation to the traditional method of collection, there are numerous studies in which researchers treat the amount of waste at container locations as a stochastic quantity. In papers [3, 4] the authors discussed a model of waste management with stochastic demand at the locations of waste receptacles. In these papers, solving the defined problem leads to significant savings compared to the traditional way of collecting municipal waste. Also, in [5] the authors presented a stochastic model of waste management where they showed the advantage of applying stochasticity compared to a deterministic model. However, even with such models, there may be an unnecessary consumption of resources, because individual containers for municipal waste may be partially filled.

The amounts of municipal waste generated in containers are mostly stochastic in nature, and the accumulation of waste itself depends on several factors, the more important being seasons, holidays, sports and cultural events, etc. Certain studies indicate that only about 40% of municipal waste is collected from containers that are filled more than 75% [1]. All this shows that a waste collection system should be implemented much more efficiently. One of the ways to develop the most efficient waste collection model is the application of modern information and communication technologies. The application of such technologies in the system of waste collection in urban areas contributes to the reduction of transport costs of the UPC as well as a more rational use of resources [6, 7]. The goal of this paper is to present a hybrid system of municipal waste collection with the application of modern information and communication technologies. In addition to numerous studies that have been conducted with the aim of optimizing the municipal waste collection system, the development of smart cities shows that there is still a lot of room for improving waste management systems [4, 8, 9].

2. SMART WASTE MANAGEMENT

A smart city is a city or settlement that uses advanced information and communication technologies - ICT and innovation to make its infrastructure, services, and functions more efficient, sustainable, and livable. A smart city uses sensors, data and communication networks to better manage resources, respond to the needs of citizens, improve the quality of life, and reduce the negative impact on the environment [8]. Such cities aim to be smart and sustainable in all aspects, including transportation, energy management, healthcare, education.

Widespread and inexpensive availability of cloud computing services, rapid penetration of smart phones in urban populations, as well as the rise of the Internet of Things - IoT in the form of deployment of a variety of sensors, drive smart city technologies that offer new application domains in city planning and operations. The IoT refers to the use of network protocols to form a universal network of interconnected things that are not necessarily considered as computers. It was projected that there would be 34 billion connected things in the world in 2020 [10], and the IoT will dominate the smart city technologies.

Smart waste management systems are the answer to the challenges faced by traditional waste management practices. These systems consist of several key components that work together to optimize the waste management process, ensuring efficiency, sustainability and economic benefits.

Waste management as a part of a waste collection system has been a topic of interest in operations research and it has been demonstrated that optimized route planning and scheduling in waste collection can lead to significant cost reductions. Consequently, route optimization has been the main motivation for developing smart waste collection systems. There are some studies of monitoring smart bins, where the authors present monitoring solutions based on radio frequency identification - RFID [11]. This system utilizes load sensors to estimate the accumulated weight in the trash bins and relays the data to collectors' pocket PCs - PDA. Collected data is then uploaded to an online database for further processing and analysis. In [12], the authors present an IoT based smart garbage system that utilizes a pay-as-you-throw - PAYT model for food waste management. The system proposes custom-designed household garbage bins that are equipped with load sensors and cellular Internet modules. The system is tested through a pilot study in Seoul, Korea, and the authors underline that the power consumption (battery-based operation) is the main trade-off of the system. In [13], the authors emphasize that "an efficient, cost effective and environment friendly solution for real time bin status monitoring, collection and transportation of municipal solid waste is still a major challenge to the local municipal authorities" and propose a theoretical model using rule based decision algorithms. A further review of the literature reveals many studies where researchers try to use smart technologies in the waste collection system to achieve the most optimal system possible. In the continuation of the paper, a prototype of a smart container for waste and a hybrid methodology for optimizing municipal waste collection routes will be presented.

2.1 Smart Container for Collecting Municipal Waste

One of the key components of smart waste collection systems is smart containers. Smart containers represent a revolution in the way waste is collected and managed. The prototype of a smart container for municipal waste collection presented in this paper supports GPS/GPRS and includes sensors for data collection. The proposed system allows the status of a municipal waste container to be monitored in real time. The smart vessel consists of the following elements Fig. 1: standard underground container, solar panel, ultrasonic sensor, GPS and GPRS modem. The solar panel is used to charge the battery located under the cover, from which the system receives energy. The battery capacity needs to be defined in relation to the requirements of the case study. The ultrasonic sensor measures the filling level of the container using ultrasonic beams. These sensors can monitor any type of waste (mixed waste, paper, plastic, glass, clothing, bio-waste, liquids, electronics, metal...) in bins and containers of different types and sizes. Ultrasonic technology ensures high and reliable measurement accuracy.

Sensors can be connected to several IoT networks or GPRS to provide fast data transfer. An ultrasonic sensor is placed under the lid of the waste container and measures the filling level, regardless of what is deposited inside.

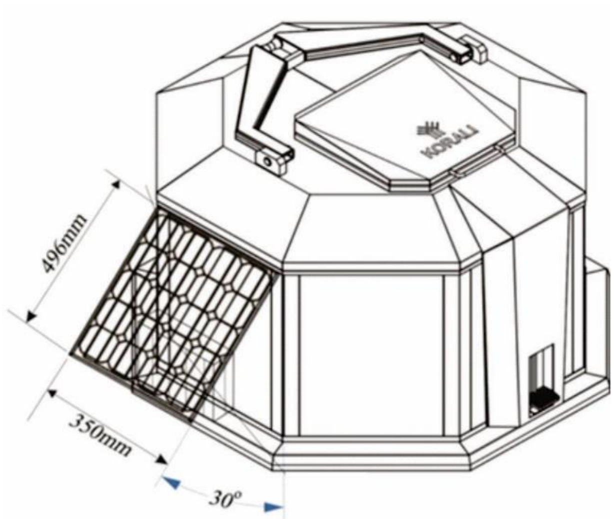

Fig. 1 Prototype of a smart container for municipal waste

To measure the level of filling in the prototype of the storage tank in this study, an ultrasonic sensor or a long-range transducer type JSN-SR04T V2.0 is used. This type is a waterproof ultrasonic sensor that contains a non-contact distance measurement module and provides high accuracy. This ultrasonic sensor detects objects from 20 cm to 600 cm with an accuracy of 3 mm and a measuring angle of 20◦. Also, another important feature of this sensor is its operation at temperatures from -20 to +70°C. This proposal of a smart container is designed in such a way that it gives an estimated filling of the container with waste as shown in Fig. 2. In many studies, you can find systems that, in addition to the fullness of the container, also provide information about the mass of waste as well as the current temperature in the container itself. Wireless sensor networks have become a key element in the sensor development process for smart waste systems.

Apart from the various transducers used to measure the data, one of the main purposes of the sensor is to establish a level of communication that is effective over the greatest possible distance. Data that has been collected from the sensors is transmitted via GPRS to the cloud where it is temporarily stored. The data is downloaded from the cloud and processed in order to obtain the real condition of the filling of containers at predefined locations.

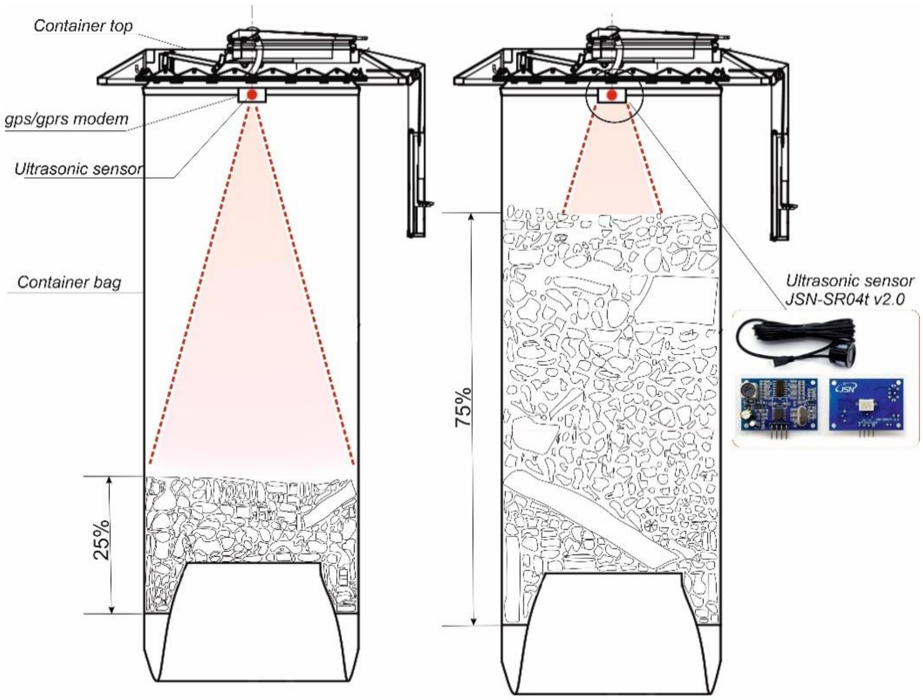

Fig. 2 Prototype of a smart container with an ultrasonic sensor

Figure 3 shows the communication of the smart container prototype with the master dispatcher via the cloud. After processing, the data is forwarded to the municipal waste collection vehicles.

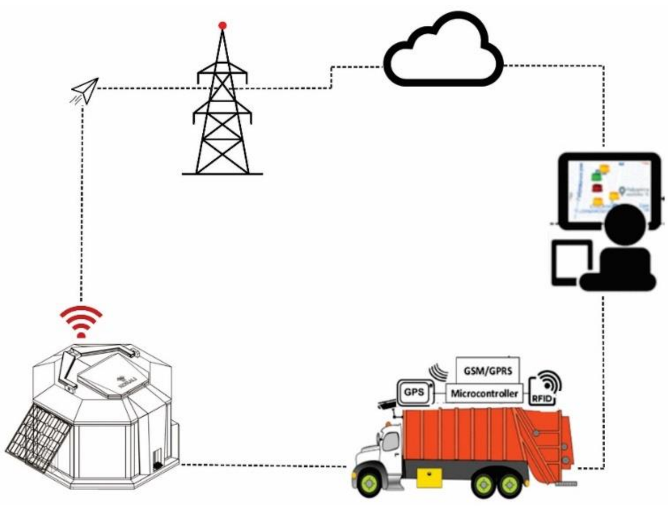

Fig. 3 Information flow diagram from a smart container to vehicles

3. PROBLEM DESCRIPTION

Regarding the choice of a waste collection route in a smart waste system, the search for optimal waste collection routes is considered an optimization problem that requires the reduction of collection costs and time. These costs relate to the distance traveled by each vehicle for waste and the number of vehicles required. This type of problem is known in the literature as the Vehicle Routing Problem - VRP. This name is used for a whole class of problems whose goal is to find a large number of routes for a group of vehicles located in a depot. The original VRP is also known as the capacity vehicle routing problem - CVRP and includes constraints, for example, each vehicle in a fleet has a permanent and uniform load and there is one depot. The original problem has several variants [14] that add constraints to a real-life problem. With CVRP, it is assumed that the vehicles are identical-homogeneous (equal capacity) and have a common starting point, and the only limitation that exists is the vehicle capacity. The objective function expresses the requirement to minimize the total cost (e.g. weight function of the number of routes and their total length or time) when serving all users [4]. CVRP can be expressed using basic notations from the theory of transport networks as follows. Let the transport network be defined as $G = (V, A)$, where $V = \{0,1, 2, ..., n\}$ is the set of containers for collecting municipal waste, while A is a set of branches, i.e. a set of connections between municipal waste containers. The determined pair (i, j) represents a connection, i.e. a branch that connects node $i \in V$ with node $j \in V$. Each container location from the pool $\{1, ... , n\}$ has a certain demand (in this paper, the amount of waste) that must be collected and transported to the depot.

The depot demand is always 0. A set (k) of vehicles of the same capacity (Q) (if the fleet has different capacities, the problem would be a different type of VRP problem) must be employed to collect waste from n container locations, m vehicles must start and finish their routes in the depot. A route is defined as a cycle of the lower cost of transport networks (G) that passes through the depot and the total demand of the vertex set must not exceed the total vehicle capacity. The purpose of the problem is to minimize the distance, time, or cost of k vehicles while meeting the following requirements: (1) the depot is the start and end point of each route; (2) each container location may be visited only once by one vehicle; and (3) the total demand of each route does not exceed the capacity (Q).

By introducing a smart container in the municipal waste collection route planning system, the classic CVRP becomes a dynamic CVRP. The difference between these two problems is that with classic CVRP, the vehicle receives a route plan at the beginning of the working hours and performs collection along defined routes. With dynamic CVRP, the route plan is formed in real time, that is, based on the limit of the filling of containers with waste. The transport network in which the dynamic CVRP was applied is shown in Fig. 4.

Numerous methods can be found in the literature for solving CVRP, which belongs to the group of NP-hard problems. The quality of the CVRP solution most often depends on the quality of the definition of the transport network, and considering the complexity of the problem, heuristic and metaheuristic methods are most often used to solve it. Heuristic methods perform a limited exploration of the search space and usually deliver good quality results in small computing times and meta heuristic methods are generic methods of exploration in the solution space for searching and optimization problems.

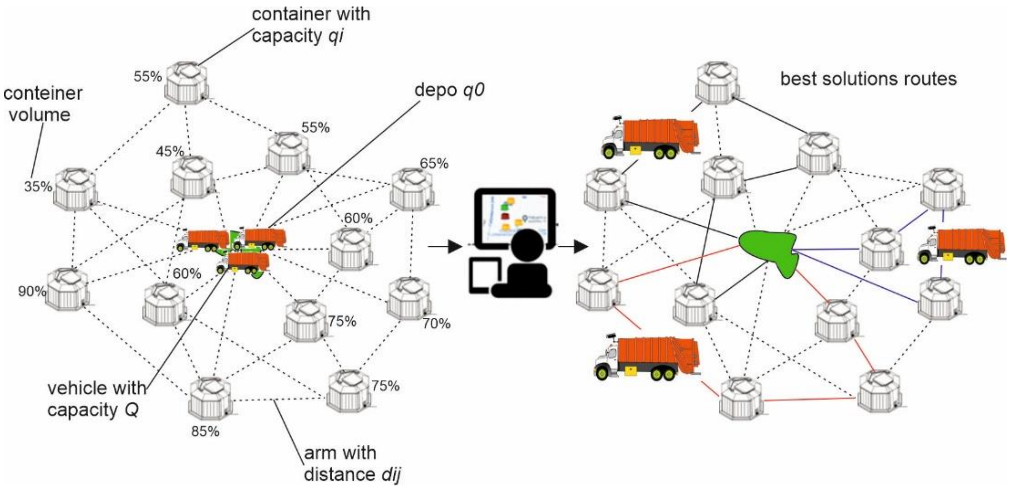

Fig. 4 Graphic representation of dynamic CVRP

These methods provide a design line adaptable to each context, and they can generate more efficient algorithms [15, 16]. In what follows, the focus will be on the presentation of the hybrid system for the optimization of municipal waste collection routes, that is, on the collection, storage, processing and sensor data. In relation to Fig. 3, which shows the information flow and communication subsystems, Fig. 5 indicates which of them are part of the optimization of the municipal waste collection route.

The optimization process consists of 4 steps:

- Container selection: the containers visited by the waste collection vehicle are selected from the defined transport network. The selection of containers is based on the fill-level criteria of each container from the transport network. A threshold will be established to select the nodes that must be collected. The criterion that is set in this case is the fill-level of 75%,
- CVRP data: once the container fill data is obtained from the transport network nodes and their locations, the geographic information of each node is loaded from the geographic information subsystem to obtain the distance matrix that will be used to apply CVRP,
- CVRP solver: based on the data obtained from the previous step and by defining a heuristic algorithm, problem solving is approached, that is, the design of routes for municipal waste collection,
- Best solution found: after the best or most favorable solution is found (during the specified time under the stopping criterion), it is forwarded to the vehicle operator. The data persistence subsystem receives information and stores the collection plan solution for that day.

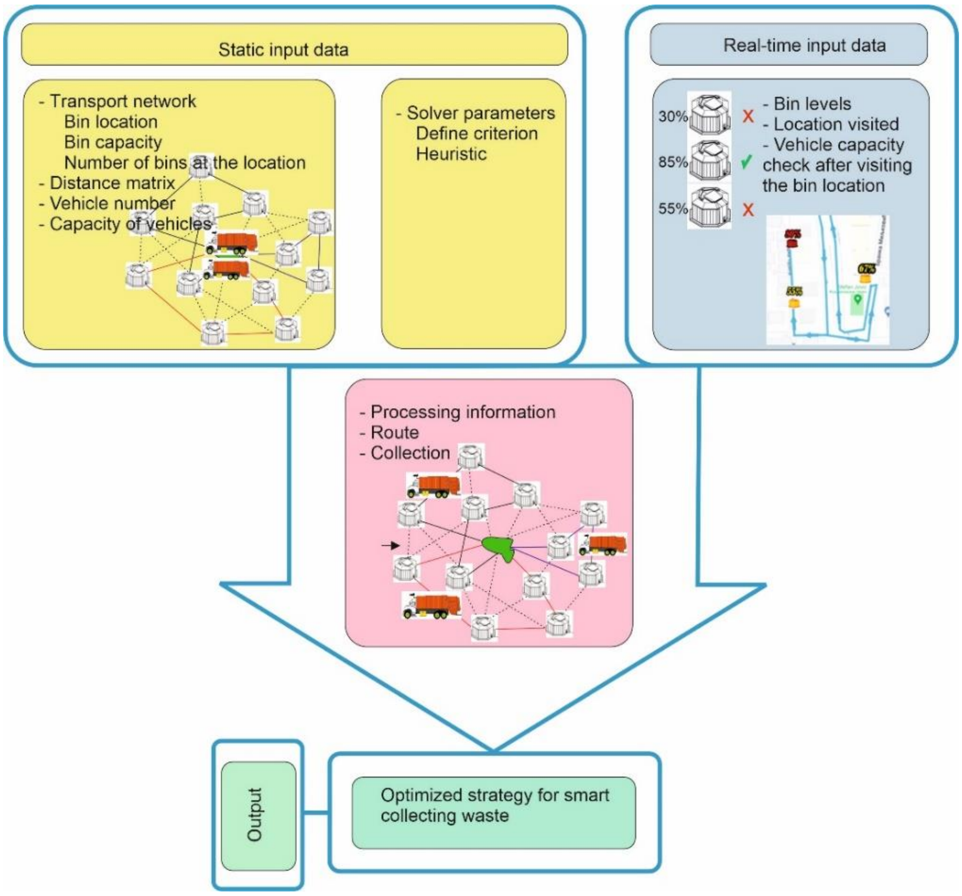

Fig. 5 Real time routing model

4. Mathematical Model and Method for Dynamical CVRP

Waste collection models are most often solved as capacity-constrained vehicle routing problems – CVRP. The CVRP model assumes that all vehicles are identical and have a common starting point (depot), and the only limitation that exists is the vehicle's capacity. The objective function expresses the requirement to minimize the total transport costs when collecting municipal waste from the transport network [17, 18].

The proposed formulation is based on the following assumptions:

- The fleet is homogeneous.
- Each route should start and end at a depot,
- The vehicle is always empty when it leaves the depot,
- Each container location participates in only one route,
- The total amount of waste collected in one route must not exceed the capacity of the vehicle on that route.

Before formulating the mathematical objective function F, certain assumptions need to be introduced. We assume that there are k vehicles at the depot, each with a known capacity Q_k. To ensure the feasibility of the solution, it is necessary that $q \leq Q_k$ for each node i (i = 1, …, n) and each vehicle k (k = 1, …, K).

This problem involves determining the minimum number of vehicles (with capacity Q_k) needed to serve all demands q_i. The minimum number of vehicles affects traffic safety in urban areas [19]. For each $i, j, k \in V$, the following decision variable can be defined:

The variable x_{ijk} is equal to 1 if vehicle k, after visiting bin location i, proceeds to visit bin location j; otherwise, it is 0.

The variable l_i is equal to 1 if bin level is over 75% at the bin location i; otherwise, it is 0.

The mathematical formulation of the CVRP can be presented in the following manner:

$$F = \min \sum_{k=1}^{K} \sum_{i=0}^{n} \sum_{j=0}^{n} c_{ijk} x_{ijk} l_{ik} \tag{1}$$

subject to:

$$\sum_{i=0}^{n} x_{i0k} = 1, \quad k = 1, 2, \ldots, K \tag{2}$$

$$\sum_{j=0}^{n} x_{0jk} = 1, \quad k = 1, 2, \ldots, K \tag{3}$$

$$\sum_{k=1}^{K} \sum_{i=0}^{n} x_{ijk} = 1, \quad j = 1, 2, \ldots, n \tag{4}$$

$$\sum_{i=1}^{n} q_i x_{ijk} \leq Q_k, \quad k = 1, 2, \ldots, K \tag{5}$$

$$\sum_{i=1}^{n} x_{ijk} = \sum_{i=1}^{n} x_{jik}, \quad i = 1, 2, \ldots, n; k = 1, 2, \ldots, K \tag{6}$$

$$\sum_{i, j \in S} x_{ijk} \leq |S| - 1, \quad \forall S \subseteq \{2, \ldots n\}, k = 1, 2, \ldots, K \tag{7}$$

$$x_{ijk} = \{0,1\}, \quad i, j = 1, 2, \ldots, n; k = 1, 2, \ldots, K \tag{8}$$

$$l_{ik} = \{0,1\}, \quad i = 1, 2, \ldots, n; k = 1, 2, \ldots, K \tag{9}$$

Constraints given in Eqs. (2) and (3) imply that every vehicle that leaves a depot returns to that same depot. The constraint shown by Eq. (4) stipulates that each bin location must be visited only once by exactly one vehicle. Constraint in Eq. (5) implies that the total capacity of bin location requests, served by one vehicle, must not exceed the capacity of that vehicle. Constraint in Eq. (6) enables the preservation of vehicle flow, i.e. the fulfilment of the condition that vehicle k must leave bin location j after serving bin location *j*. Constraint in Eq. (7) prevents the occurrence of cycles that do not represent a complete route. Constraint in Eq. (8) defines the passage through the branch between bin location *i* and *j* by the *k* vehicle and can have a value of 0 or 1. Constraint in Eq. (9) defines that the bin location is not visited if the bin level is less than 75% and can have a value of 0 or 1.

Heuristic or metaheuristic algorithms are most often used to solve dynamic CVRP. In what follows, the procedure for solving the dynamic CVRP for municipal waste collection will be presented. The procedure is based on the well-known Clark-Wright saving algorithm [20]. This algorithm is most often used in the literature for almost all vehicle routing problems. The pseudo code of C-W's cost-saving algorithm for solving dynamic CVRP is shown in Algorithm 1.

Algorithm 1: C-W saving algorithm for solving dynamic CVRP

```
start
    Defining the distance matrix for all locations of containers whose filling is greater than 75%;
    Defining Q_k;
    Define the demand matrix by nodes for containers whose filling is greater than 75%,
    ComputeI s`;
    Sort s` in a non-increasing sequence;
    Form a partial route;
    Vehicle filling = q_i;
      For For all savings from the range
        if Operational constraints met
          if Vehicle filling + q_i ≤ Q_k
            Vehicle filling = q_i + Vehicle filling
            Form a route
          end if
        end if
      end for
    Print routes;
    Print vehicle fill;
end
```

The of the aforementioned methodology is reflected in the fact that after servicing each container location, a new distance matrix and a demand matrix are formed based on the criterion that the container is more than 75% empty. This means that the planning of municipal waste collection routes is done in real time. Also, it is very important that a certain container that is filled less than 75% for more than 5 days is also included in the emptying system. This criterion is important for the reason that municipal waste must not remain in the container for more than five days due to the spread of unpleasant odours and negative impact on people's health in the environment.

5. Optimization Of The Dynamical CVRP Model And Results

The CVRP dynamic model considered in the paper is defined by the transport network shown in Figure 6. The nodes of the transport network represent the locations of containers for municipal waste disposal and are defined by coordinates, i.e. latitude and longitude. At locations where there are two or more containers, their position is defined by one node or one coordinate. The container for collecting municipal waste, which is explained in detail in Fig. 1, has a volume of 3 m^3 [21].

The municipal waste collection vehicle has a capacity of 60 m^3 and departs from the depot, i.e. from the node marked "1" with the assumption that it is empty, and goes around the nodes of the transport network according to the order generated based on the procedure presented in Fig. 5. When servicing orders, care must be taken that the vehicle may visit each node only once.

Fig. 5 The transport network of container nodes

In [1], this model is considered as a deterministic model where the amount of waste per node is taken as the number of containers multiplied by the volume of the container. This means that we work with the assumption that all containers are maximally filled with waste, which does not correspond to the real model. The aim of considering this model is to demonstrate the feasibility of applying the methodology presented in this paper and to obtain optimal routes for the movement of vehicles for the collection of municipal waste, that is, to keep transport costs to a minimum.

The shortest distance matrix represents the real distance between all pairs of nodes within the transport network. The matrix is symmetric, that is, the distance from node *i* to node *j* is equal to the distance from node *j* to node *i*. For the purposes of solving the dynamic CVRP model, the amount of waste per node is defined based on the analysis of the periodicity of emptying the container, thus simulating the operation of the smart container. The paper emphasizes that this is a prototype of a smart container which is in the validation phase. The optimization of the model based on algorithm 1 was performed for a period of one month. The municipal waste collection period is three times a week. The period when the largest amount of waste is generated was chosen. The criterion for visiting the node was defined in the previous part of the paper, that is, that the container is 75% full and that the container must be emptied after seven days, regardless of how full it is. Table 1 shows the simulation results of the dynamic CVRP model and the results of the optimization of the deterministic model considered in paper [1]. The results show that the application of the dynamic CVRP model achieves a significant reduction in the total distance traveled by about 27%. In addition to the great savings in the traveled distance, the collection time is also reduced because the total length of the route is 16 with the deterministic CVRP, and 9 with the dynamic CVRP model. The obtained results show that the so-called idling of the vehicle is reduced, which directly affects the reduction in environmental pollution with a lower emission of harmful gases. Also, Table 1 shows that by about 26% fewer vehicles visited container locations with the dynamic CVRP, noting that none of the containers were overfilled.

Table 1 Result for CVRP models

The period of collection	Deterministic CVRP model		Dynamic CVRP model	
	Distance [km]	Visited locations	Distance [km]	Visited locations
First week	32.78	80	27.96	60
Second week	45.36	80	30.91	68
Third week	38.44	80	26.54	56
Fourth week	32.78	80	23.87	53
In total	**149.36**	**320**	**109.28**	**237**

In order to see the advantage of applying the dynamic CVRP model, Fig. 6 shows the ratio of visits to locations by route, where it is clearly seen how many empty runs of municipal waste collection vehicles there are in the deterministic CVRP model. This ratio indicates that the implementation of the dynamic CVRP model in a real municipal waste collection system would significantly reduce operating costs and vehicle driving time.

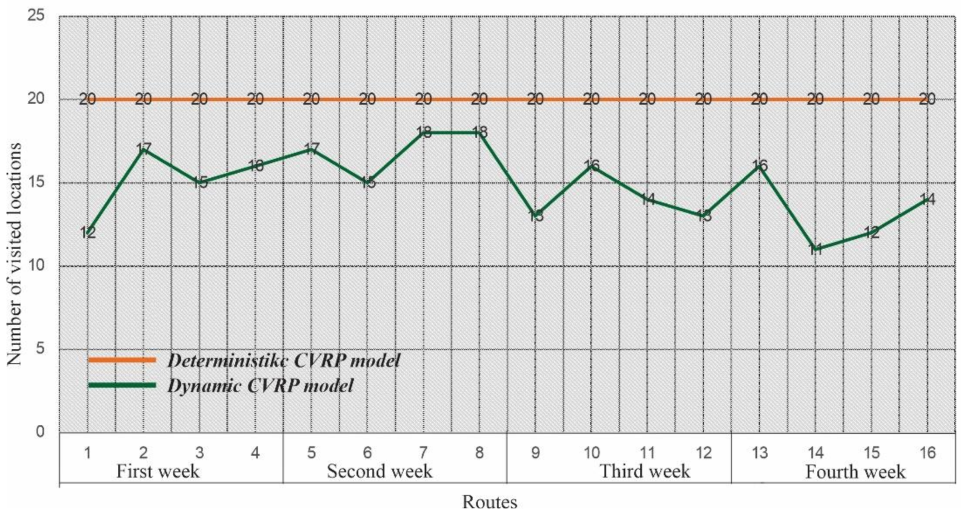

Fig.6 Graphic display of location visits by route

6. CONCLUSIONS

Smart waste management systems are transforming the way we manage waste, providing innovative and sustainable solutions to the challenges faced by traditional waste management practices. Utilizing state-of-the-art technology and innovative design, these systems optimize the collection, transport and treatment of waste, reducing the environmental impact of waste disposal and contributing to a cleaner and healthier urban environment. In addition, smart waste management systems offer significant economic and social benefits, promoting savings, income generation and overall well-being.

As cities around the world continue to expand and urbanize, the need for efficient and environmentally friendly waste management solutions will only grow. Smart waste management systems offer a promising path towards achieving sustainable urban living, city by city.

This paper provides an insight into the complexity of waste management problems and the need for more advanced approaches. It also indicates that the transition to smart waste management systems is justified and will contribute to more efficient collection and transport of waste. This will result in reduced costs and reduced negative environmental impacts, paving the way for a better future, which was demonstrated by the simulation of the dynamic CVRP model.

The optimization of routes contributes, in addition to reducing transport costs, to the reduction of exhaust gases and fuel consumption, which is of great importance for the protection of air and the environment. Optimal vehicle movement routes minimize transport costs, which significantly affects the economy and profitability of waste collection companies. This optimization also contributes to the aesthetics of the city environment itself, because the number of vehicle passes and the time spent passing through populated areas are reduced, which affects the general appearance of the city and the quality of life of citizens. By using sensors and automating the municipal waste collection process, a high degree of efficiency and precision is achieved in the planning and execution of operations. Such automation significantly improves the work of waste collection companies, thus facilitating and speeding up the entire process, while reducing the so-called empty moves. The development of such a system represents the future of the development of the city of Niš, which is already entering the process of implementing smart systems.

The future direction of the research is the simulation of the presented methodology of dynamic routing of vehicles during the collection of municipal waste in order to obtain accurate data on the saving of transport costs. Also, the future direction of research is the integration of artificial intelligence and machine learning into smart waste management systems, which have a great potential to transform the waste management industry and support sustainable living in urban environments. As these technologies become more advanced and available, their use is expected to become more widespread, leading to additional innovations and advances in waste management. However, it is important to note that the integration of these technologies also presents certain challenges, such as the need for large datasets and the potential for errors in the algorithms. It is therefore crucial that these technologies are implemented in a responsible and ethical manner, with appropriate safeguards to ensure their effectiveness and fairness.

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