

# Execution time as a key parameter in the waste collection problem

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**Abstract** —Proper waste management has been recognized as a tool for the green transition towards a more sustainable economy. For instance, most studies dealing with municipal solid wastes in the literature focus on environmental aspects, proposing new routes for recycling, composting and landfilling. However, there are other aspects to be improved in the systems that deal with municipal solid waste, especially in the transportation sector. Scholars have been exploring alternatives to improve the performance in waste collection tasks since the late 50s, for example, considering the waste collection problem as static. The transition from a static approach to a dynamic is necessary to increase the feasibility of the solution, requiring faster algorithms. Here we explore the improvement in the performance of the guided local search metaheuristic available in OR-Tools upon different execution times lower than 10 seconds to solve the capacitated waste collection problem. We show that increasing the execution time from 1 to 10 seconds can overcome savings of up to 1.5 km in the proposed system. Considering application in dynamic scenarios, the 9 s increase in execution time (from 1 to 10 s) would not hinder the algorithm's feasibility. Additionally, the assessment of the relation between performance in different execution times with the dataset's tightness revealed a correlation to be explored in more detail in future studies. The work done here is the first step towards a shift of paradigm from static scenarios in waste collection to dynamic route planning, with the execution time established according to the conclusions achieved in this study.

**Keywords** - municipal solid waste management system; route optimization; waste collection; dynamic approach; sustainability.

## I. INTRODUCTION

Worldwide waste production has increased due to rapid population growth and economic development [1]. Waste management is a global issue, particularly for developing nations that lack the infrastructure to treat waste efficiently [2]. New regulations require enhanced municipal solid waste management systems (MSWMS) due to the paradigm change in Europe toward a more sustainable economic development [3, 4]. For instance, the European Parliament acknowledges that higher

rates of trash recycling might create more commercial opportunities and help to resolve the environmental crisis [5]. The research community is currently studying novel methods to enhance MSWMS operations in several areas, including recycling tactics, biologic treatments, and job optimization, as a result of the authorities' recognition of the need for effective waste management [6, 7]. The cost-demanding nature of the solutions most scientists have investigated for recycling technologies underlines the demand for cost-effective MSWMS solutions. Information and communication technologies (ICT) can be an interesting tool for this purpose, exploring alternatives to save resources in some tasks.

There has been an increase in the demand for a wide variety of services in cities in the last decades, necessitating an improvement in logistics and operations [8]. ICT tool use is one technique that several nations have embraced to raise the caliber of public services. The term "Smart City" or "City 2.0" has been popular in the literature due to the use of technology and data sciences in cities, and several studies have been done on applying technological solutions to common problems in the urban environment [9]. According to the pioneer in the field, Giffinger, "a smart city is a city that performs well in a forward-looking style in six qualities, founded on the clever combination of endowments and activities of self-decisive, independent, and aware citizens" [10]. Academics and several initiative projects attempting to develop the infrastructure for smart cities have used each one of these components' distinct indicators and variables as a point of reference. For instance, the most technologically advanced industries include health, education, transportation, and customer services [11]. However, other entities, such as the MSWMS, could also profit from technological tools to enhance their offerings.

The MSWMS involves the collection, processing, control over the amount of waste generated, reuse, recovery, and final disposition. The collection alone is responsible for around 60% of the total operational cost from all the above mentioned aspects [12]. The huge amount of resources spent on this task is related

to the high cost of fossil fuels, the main energy source for trucks. In addition to the fuel cost, most entities in charge of the MSWMS adopt inefficient waste collection protocols based on scheduled routes or the driver's decision of routes to be followed. This approach can lead to trucks visiting empty dumpsters or taking too long to visit a dumpster that is already full. The poor decision-making regarding the routing assembly has serious consequences for citizens' health and well-being, reinforcing the need to seek better solutions [13]. Therefore, there is a need to scientifically determine the best route for trucks to perform the waste collection task, which could save resources to be used in other activities of MSWMS concern, such as recycling strategies.

The mathematical formulation of the route optimization problem in the waste collection is to reduce the traveled distance of the trucks to serve all clients, which is the well-known Vehicle Routing Problem (VRP) [14]. A new class of problems, the Waste Collection Problem (WCP), has emerged due to adjustments made to the classical formulation over time to satisfy waste collection criteria [15]. Despite the body of research on the subject, writers frequently view the WCP as a static problem where the locations and requests are known before the execution. Based on a comparison of the shortest distance discovered with a predetermined procedure, researchers have been working for years to improve the performance of their algorithm. However, dynamic techniques can be more effective than static ones when considering the volatility of waste generation [16]. In other words, route planning that is done dynamically may result in greater cost reductions for the collection operation. Concerns about the algorithms' execution time would arise with the paradigm shift from static to dynamic approaches. Faster algorithms would be needed to complete the operation without delay, given that routes will be dynamically planned during truck pauses to provide a service.

In this regard, more studies dealing with execution time assessments to increase the feasibility of route optimization algorithms for dynamic scenarios is required. Therefore, here we solved a capacitated waste collection problem within a constrained execution time using Guided Local Search (GLS), the finest metaheuristic accessible in OR-Tools. The execution time to determine the stop criteria was evaluated from 1 to 10 seconds. The major goal was to assess the algorithm's performance improvement when execution time was increased and determine which performed the best. The model area consists of 50 paper waste dumpsters in Bragança, Portugal. Resíduos do Nordeste (<https://www.residuosdonordeste.pt/>), the company in charge of MSWMS in the northeastern region of Portugal, provided locations for dumpsters, and a method described in earlier publications was used to calculate trash levels over time [17]. The paper is organized as follows: section II brings a literature overview, section III shows the methodology, section IV shows the results, and finally the conclusion is presented in section V.

## II. BACKGROUND

An advanced search protocol was performed to gather the literature dealing with the application of ICT in MSWMS. First, the keyword "municipal solid waste" was searched in the "all fields" option in Web of Science (WoS) and Scopus to identify

all works dealing with MSW in the last 5 years (2017-2022). The registers were completely downloaded from both databases and processed in biblioshiny, a tool from the bibliometrix R package. The list of the most frequent keywords in both databases has demonstrated that most works dealing with MSWMS in the literature approach environmental aspects, such as biological treatments, recycling alternatives, and chemistry-related topics. A careful analysis of the keywords list enabled the identification of relevant keywords for ICT applications in MSWMS. Once the keywords were found in both databases, a new database was built by filtering the relevant works. The word cloud of keywords for the new databases is shown in Figure 1.

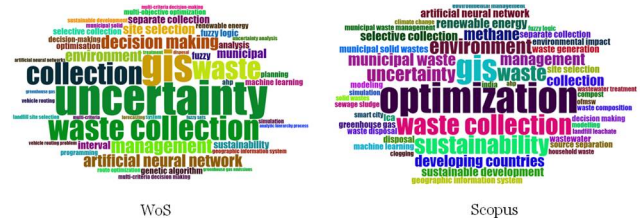


Figure 1. Word cloud obtained with keywords from works dealing with municipal solid wastes from an ICT perspective.

The result obtained with this analysis demonstrates that most works in this field are devoted to optimize waste collection tasks. The most recent waste collection projects in smart cities have demonstrated potential methods for route optimization [18,19]. Some methods concentrate on powerful data analysis techniques to enhance waste collection characteristics (*i.e.*, waste generation prediction, a cyber-physical system for route scheduling, and waste bin mapping). Despite the varied approaches to waste collection optimization, all publications on this topic solely use computational methods to offer a single solution. This method does not require changes to the physical structure since no information from physical measurements are required. On the other hand, because the models' correctness is heavily dependent on the amount of information available, efforts in this direction demand a sizeable amount of data from the organization or municipality in charge of MSWMS. The random nature of the waste formation, however, makes impossible, for even the most sophisticated methods, to estimate waste generation properly for scheduling routes, which can result in the same issues that plagued conventional systems in the past (*i.e.*, visiting empty dumpsters and dumpsters overflowing due to late visits). Still, there are studies in the literature reporting significant improvements in waste collection task by the utilization of this strategy.

Rizvanoglu *et al.* [20] used a geographic information system (GIS) and linear programming to discover the ideal path for waste collection improvement in this technique, demonstrating that the route could be saved by 28% with GIS and 33% with linear programming analysis. In other study, Ramdhani *et al.* [21] showed how one vehicle assignment model might cut the number of trucks needed in Surabaya city from 37 to 13, decreasing the waste collection cost. Wei *et al.* assessed the effectiveness of a mathematical model to improve garbage collection tasks through dumpster reallocation, optimizing both routes based on waste level prediction and also dumpster reallocation. This model includes the waste collection path planning technique and the improved hierarchical agglomerative

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clustering (IHAC) algorithm (GCPP). To determine the shortest route, fewer vehicles were assigned to the collection, and the authors compared the outcomes with their method. Other models suggested in earlier publications didn't perform as well as their model IHAC-GCPP.

Recent positive results in research cases carried out globally have drawn attention to a distinct approach. This technique uses a wireless sensor network to collect data in real-time on the amount of trash existing inside dumpsters [22–24]. In order to aid in decision-making on the required collection and route planning for the collection activity, this information is then stored in the cloud. For sending levels to the cloud, each study takes into account a particular collection of measurement sensors and an IoT protocol. No matter how a physical system is built, the majority of methods for calculating how much trash is in a dumpster take into account variables like load, distance, temperature, and humidity.

With smart garbage collection technologies, some cities and nations worldwide are already leading digital transformations in waste management systems [25]. Brisbane, a city in Australia, and the local garbage management company, worked together to install induction devices and come up with a technique for emptying them according to how much space remained in each bin. The largest telecom company in Denmark, Cisco, invests in SmartBin technology to equip trash cans with sensors and combine data into the digital platform for smart cities. Cisco is one of the world's leading technology companies. The agency in charge of Shanghai's waste management system created a flexible management platform that covers 16 districts and 82 streets. This technology has improved the effectiveness of waste collection by digitizing, enhancing, and visualizing rubbish classification [26].

One smart waste management prototype was created by Oralhan *et al.* [27], that can gauge the amount of rubbish present, the temperature inside the dumpster, and the ratio of carbon dioxide inside the container. Then, utilizing IoT technology, all these characteristics are transmitted to the cloud, and an ant colony optimization algorithm is used to optimize the collection path. Additionally, data mining is used to predict when dumpsters will reach their maximum garbage capacity, which is another helpful information for organizing waste pickup. Their method was implemented in 200 waste containers in Kayseri, Turkey, and resulted in a 30% reduction in waste collection costs. A prototype that can separate garbage at ground level and provide real-time data to the administrator is proposed by Fataniya *et al.* [28]. The improvement of collecting routes is possible with real-time information access. The authors claim that putting their prototype into practice might reduce Ahmedabad's current spending by up to 40%. One method of waste collection optimization that employs IoT technology to communicate information to the server via internet services and afterward use this information for route planning has been demonstrated by Ali *et al.* The authors also equipped their system with fire detection to avoid issues related to fire in waste dumpsters [29].

Despite the strong developments shown in the literature for real-life implementation of solutions, the authors often consider a static scenario. No matter if the work deals with waste level

prediction based on past data or waste collection schedule based on real-time information, the static scenario prevails. However, considering the stochastic nature of waste generation, both approaches could benefit from dynamic route planning, which could change the decision-making regarding routes and improve the system's overall performance. For this reason, there is still room for improvement, with the development and validation of faster algorithms to handle dynamic route planning.

### III. METHODOLOGY

The work performed here was divided into three operating modules: waste level through days, dumpster selection and distance matrix generation, and route optimization. Due to data limitations regarding waste filling profiles inside dumpsters, this work considers a methodology based on demographic factors around dumpsters to simulate waste filling during the period studied. In brief, the initial level inside dumpsters was determined by a uniform distribution probability function. For the next days, the waste level was calculated based on adding an amount of waste in each dumpster that is proportional to the demographic factor. Stochasticity in a waste generation was also considered, as explained in more detail in previous work [30]. Once the first module generates waste levels daily, the second will insert a determined dumpster in the route. The module will select all dumpsters for collection once every 2 days to put the algorithm under pressure. Selected candidates for collection will have the waste level set to 0 the next day so the fulfillment process can continue. The locations (latitude and longitude) of the selected candidates for the collection, along with waste levels, will be passed to the route optimization module, which will return the shortest distance based on execution times varying from 1 to 10 seconds. A long run of 360 seconds was also performed to compare the performance of the fast runs. Each run is performed in triplicate, and the average value is the one reported.

The route optimization module is operating to approach and solve the problem considering the formulation of the Capacitated Vehicle Routing Problem (CVRP) described in previous works [7]. In brief, the objective is to find the shortest path to collect the waste from the selected dumpsters under the following constraints:

- The number of trucks is restricted and uniform.
- Each area receives a single stop from the same vehicle.
- Trucks collect only one type of waste (i.e., paper).
- Trucks must visit the central depot once full capacity is reached.
- Trucks have limited capacity.

### IV. RESULTS

The simulation was carried out for 30 days. Trucks (16 m<sup>3</sup>) and dumpsters (2.5 m<sup>3</sup>) capacities were defined upon information provided by the company. The system considered here is composed of 5 trucks to serve 50 dumpsters, which was chosen to keep the same ratio of dumpster/truck from the real system in the city of Bragança. The distance matrix used as input

in the route optimization algorithm was gathered using the Google Maps API, returning actual distances between the dumpsters. For each collection day, the route optimization algorithm was used to find the shortest path under execution time as criteria stop, from 1 to 10 seconds.

Figure 2 brings the average shortest distances obtained for all collection days considering different execution times. Improvement in distance traveled was observed for all collection days upon increasing the execution time from 1 to 10 seconds. The biggest improvement was achieved by increasing the execution time by at least 4 seconds compared to the standard execution time (1 s). In other words, increasing the execution time from 5 to 10 seconds did not return the same improvement compared to 1 to 5 seconds. This phenomenon is due to the search algorithm's non-linear behavior, which operates based on a stochastic search with penalties to escape local minima.

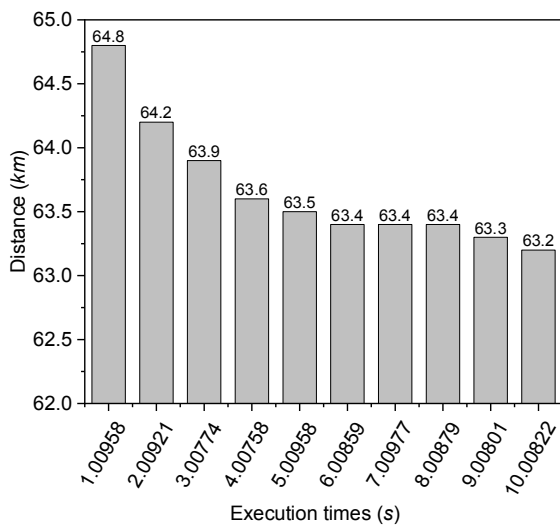


Figure 2. Average shortest distances according to execution times.

Distance savings reach 1.5 km increasing 9 seconds execution time, which would not impact the algorithm's practical dynamic applications in real waste collection scenarios. The results for the long run of 6 minutes were compared in terms of improvement with the solution obtained within 10 seconds for all collection days. The results obtained are shown in Figure 3.

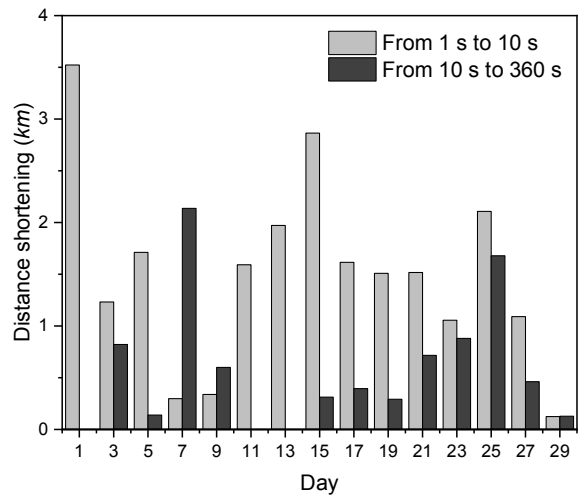


Figure 3. Distance shortening obtained by increasing the execution time.

On average, increasing the execution time from 1 to 10 s returned a distance shortening of 1.5 km, while increasing from 10 s to 360 s resulted in a 0.57 km decrease in distance. The improvement achieved considering the highest execution time would not be feasible for real applications, considering that truck service time for dumpster collection does not take more than 5 minutes. The result shown here also demonstrates that this increase is not cost-effective as well, in terms of time.

Another parameter to be considered to evaluate the algorithm performance on different days is the tightness of the dataset. The parameter represents the relation between the total demand and the total capacity of the fleet to proceed with the collection. In the past, the parameter could not be higher than 1 since trucks could not pursue more collection tasks once they returned to the central depot. However, trucks in this algorithm can visit the central depot, unload, and keep collecting more waste. The old formulation drawback was overcome with the most recent developments in algorithms, but the solutions are still related with the parameter. For instance, the capacity of metaheuristic algorithms to find optimal solutions is deeply connected with tightness. In brief, the optimal solution for tighter datasets is more challenging to overcome using metaheuristic algorithms since they often get stuck in local optima quickly. Other studies already proved the relation between tightness and optimal solution [31], but no work explored the relation between tightness and improvement in solution upon increasing the execution time. Figure 4 brings the analysis result comparing the improvement in distance traveled increasing the execution time from 1 to 10 s according to the dataset's tightness.

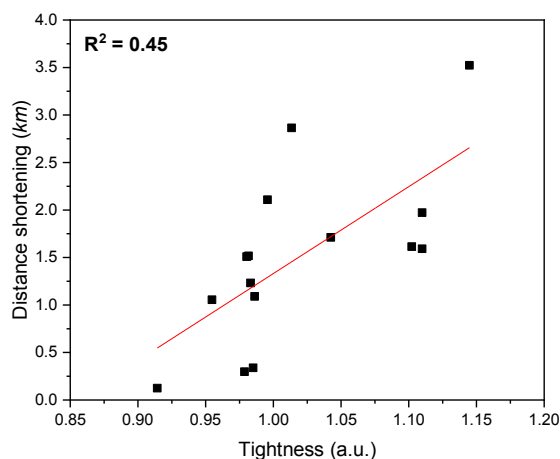


Figure 4. Correlation between tightness and distance shortening increasing execution time from 1 to 10 seconds.

The result shows that, despite the low  $R^2$ , there is a correlation between the dataset's tightness and the solution improvement, increasing the execution time. The relation between the parameters studied here is proportional, meaning that tighter sets returned greater distance improvement giving more time for the algorithm escape local optima. The behavior observed here is related to the higher necessity of time for the algorithm to find the solution in tighter sets, which is why the improvements are more significant for more compact datasets.

## V. CONCLUSIONS

The improvement in distance traveled upon an increase in execution time was demonstrated in this work. It is important to highlight that the times considered in this evaluation are low because high execution times could hinder real applications in dynamic situations. In other words, waste collection research considering dynamic route planning requires fast algorithms to plan routes while trucks perform dumpsters' service. This limits the execution time to less than 20 seconds in some situations. The results obtained here demonstrate that increasing the execution time from 1 to 10 seconds can return significant savings in the distance traveled to perform a service without spoiling the feasibility of the algorithm. Furthermore, comparing the solutions obtained with the long run reveals the best improvement is achieved by increasing from 1 to 10 seconds.

The comparison between the compactness level of datasets with distance shortening, increasing the execution time, revealed possible future branches to be explored. For instance, studying the system used here for more days could return more data to explore the hint given in this work. For future studies, the system used to assess the algorithm's performance will be modified toward a dynamic scenario. At this stage, the trucks leaving the central depot do not have the complete route planned, and dumpsters requiring service can pop up at any moment during the execution of a route. This scenario will be designed to be as much as possible similar to the real situation, in which dumpsters that are not listed to be collected initially can become part of the route.

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