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Professional paper

AN OPTIMIZATION MODEL FOR WASTE COLLECTION PATHS THAT AIMS TO CONNECT COST REDUCTION AND EMISSION MITIGATION IN ORDER TO ATTAIN SUSTAINABLE DEVELOPMENT OBJECTIVES IN NORTH MACEDONIA

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Abstract

In the contemporary era, population growth and urban expansion are driving the necessity for creating a capable waste management system (WMS) that is based on recent advances and emerging models. Within these systems, waste collection appears as a key function alongside various procedures. A new approach presented in this research suggests the implementation of a two-level WMS to reduce operational costs and environmental implications through the incorporation of Industry 4.0 ideology. Both frameworks use the latest IoT-based traceability devices to compare real-time data on waste levels in containers and sorting facilities against a Threshold Waste Level (TWL) parameter. The primary model focuses on optimizing the operating costs and carbon dioxide emissions associated with transporting waste from containers to sorting facilities, integrating considerations for time constraints. Then, a capacity-constrained vehicle routing problem is formulated as a follow-up model to reduce the costs associated with transporting waste to recycling facilities. To determine the most effective solution, modern meta-heuristic algorithms are deployed, along with the development of various innovative heuristics that are tailored to the specific requirements of the problem. Furthermore, these newly generated heuristic approaches are used to generate preliminary feasible solutions within the meta-heuristic domain, which are then compared to randomly generated solutions. An evaluation of the efficiency of the proposed algorithms is performed, applying the best-worst method (BWM) to rank the algorithms based on criteria such as relative percentage deviation, relative deviation index and hit time.

Keywords: IoT, Smart Waste Management, Smart Bin, Heuristic

1. Introduction

New harsh conditions in North Macedonia connected with growing population and tendencies of urbanization, particularly in the capital Skopje have arising the question of establishing and developing Waste Management Systems or WMS. The correct management of waste collection is important in order to achieve both the cleanliness of the cities and the minimization of the effects on the environment, as well as have lower operating costs. The problem is that the conventional static waste management models cannot meet the ever-growing needs of urban areas and changing waste generation trends as multiple cities develop. challenges.
The evolution towards the Industry 4. 0 known by the amalgam of digital, physical and biological approaches presents transformative potentials in this regard. Specifically, IoT is the real-time data acquisition technique that can assist in making adequate decisions about waste management. IoT-enabled monitoring devices provide accurate data on waste levels in bins, facilitating customizable waste collection routes that match current needs This combination of technology offers a dual advantage: They include the following; it alleviates the consequences of waste collection operations on the environment in that they minimize unnecessary movement and enhances economic rationality. through planning.

This work presents a unique two-stage optimization approach aimed at enhancing the current status of waste management in Skopje. The first one is to maximize cost cuts and minimize CO2 emission through the optimization of waste pick-up and transportation from different bins to sorting centres. This model optimized the routes based on TWL in a real-time manner using Iot sensors so that the collections are done efficiently and on time. The second model is for capacity vehicles to address the dilemma of minimizing the costs of segregating waste picked at sorting facilities and transporting it to recycling centres. The integration of the two aforementioned models is the goal and purpose of the proposed framework, through which the urban waste management process can be holistically enhanced and yield great economic and environmental benefits.

To solve the above optimization problems, a higher level of meta-heuristic algorithms like, Genetic Algorithm (GA) and Simulated Annealing (SA) are applied in the study. Hence, they are developed together with specific heuristics to suit the needs of waste collection in Skopje. It is used to compare the initially produced feasible solutions by these heuristics against the random solutions to measure their performance. Based on the experimental studies, the performance of these algorithms is assessed by using the best-worst method (BWM) considering relative percentage deviation, relative deviation index, and convergence time metrics.

Hean's contributions to this research are numerous. First, the model demonstrated how economic and environmental objectives in waste management are not mutually exclusive but can complement each other with possibilities of achieving massive cost savings and waste minimization Second, the paper suggested a structured and flexible model that can be useful in other urban centres grappling with similar management issues. Shows how automation and related solutions form Industry 4. It is at this stage that the impregnation of technologies into urban infrastructure is made in preparation for smarter and more sustainable cities. Therefore, the goal of this work is not only to present the proposed models with the simulated data of Skopje but also to provide step-by-step guidance and encourage the use of state-of-the-art optimization techniques for UWM systems around the world. It is in this regard that the ultimate goal is to advance sustainability development goals to the end that city development and expansion are done in also an economically feasible and environment-friendly manner.

2. Literature Review

WMS optimization is among the critical research areas that have been under exploitation for many decades in academia and industries. Because the population of the urban agglomeration continues to expand, there is a concomitant increase in waste generation – proper collection, therefore, is vital to sustainable urban living. Traditional approaches have heavily relied on and taken a more rigid fixated approach of routing to provide solutions that can adapt to the new generation waste generation patterns prevalent in urban settings. Clarke and Wright gave the first ideas about vehicle routing problems (VRP) at the beginning and provided a vast number of heuristic concepts that influenced later optimization methods [1].

Current trends in integrating real-time information and the usage of IoT devices into the WMS have also been on the rise. Dynamic routing was identified by Taniguchi, Thompson, and Yamada as a promising approach in urban logistics; they pointed out that the use of real-time information could highly reduce routing dissipation and maximize operation benefit [2]. Turner et al. reminded the need to adopt dynamic features to work with rates of waste generation and bin-holding capacities. This is inevitable in today's context where Industry 4. None in the definition provided by Lasi et al. that subscript the integration of digital, physical, and biological systems to optimize processes in various industries inclusive of waste [3].

Current developments have been seen in optimization methods, which have led to improvements in WMS tactics. Genetic Algorithms (GA) and Simulated Annealing (SA) can be considered the most developed meta-heuristic methods recognized for the ability to define effectiveness for complicated VRP issues. These algorithms have been disclosed in many scientific papers and are often used in many optimization problems due to their reliability and adaptability. By applying GA and SA in waste collection, service routes are optimized effectively and can minimize several operation costs such as fuel consumption and service time windows concurrently minimizing the generated carbon footprints [4].

About North Macedonia or specifically Skopje, waste management has advanced to adopt such elaborate optimization techniques. The available data provided by the Skopje Waste Management Service demonstrates that methodologies currently in use have a certain level of IoT-enabled monitoring and dynamic routing augmenting its operations [5]. However, it is still possible to achieve even larger improvements by involving all meta-heuristic algorithms comprehensively in the Industry 4. 0 technologies.

The integration of RTDA, IoT, and AO with waste management illustrates an evolution in the handling of waste. Thus, by using dynamic, datacentric approaches instead of the conventional, static models it is possible to achieve significant improvements at both the level of operations and in terms of the state of the environment. This literature review forms the basis for developing the proposed dual-level optimization framework to build on these advancements for effective waste management in Skopje.

3. Experimental Work

A. Model Formulation

This section elaborates on the methodology used in the development and evaluation of the proposed optimization model for waste collection in Skopje, North Macedonia. The experimental phase includes a comprehensive process of data collection, model formulation, application of optimization algorithms, simulation of various scenarios, and rigorous performance evaluation, consistently adhering to strict analytical standards.

The project of development of the optimization model for waste collection in Skopje operates at two levels.

1. **Level 1 (Primary Model):** The primary model, namely Level 1, aims to minimize operational costs while curbing CO2 emissions by devising efficient routes for collecting waste from the bins and taking it to the sorting stations. The model achieves above 90% looking forward Horizon=1 and uses the real-time data from the sensors placed inside waste bins using IoT to align and optimize the collection routes based on the Waste Level in Prague. The principal objective function of this model is to minimize the sum of costs for fuel consumption, labour costs, the costs of vehicle maintenance, and emissions at the EG level.

   $$\text{Minimize} \; Z = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} x_{ij} + k \sum_{i=1}^{n} e_{i} y_{i}$$

   where:
    - c_{ij} is the transportation cost from bin i to sorting facility j.
    - x_{ij} is a binary decision variable indicating whether route $i \rightarrow$ is used.
    - e_{i} represents the emission factor for bin i.
    - y_{i} is a binary decision variable indicating whether bin i is serviced.
    - k is the emission cost coefficient.

In Level 1, the optimization model is represented mathematically as a minimization problem, where the total cost (Z) is the sum of the transportation costs from each bin to the corresponding sorting facility, multiplied by the binary decision variable indicating the use of each route, together with the product of the emission factor of each bin and the binary variable representing whether the bin is served. Additionally, an emission cost coefficient is included in the objective function to account for emissions-related costs.

2. **Level 2 (Follow-up Model)**: The next model moves to Level 2 as it deals with a capacity-constrained vehicle routing problem (VRP) where the task is to minimize the costs of transporting the sorted waste from the sorting facilities to the recycling centers. The goal of this model is to increase efficiency in transportation plans and to reduce costs — The optimization only considers the vehicle capacities and distances from one location to another.

   $$\text{Minimize} \; Z' = \sum_{i=1}^{n} \sum_{j=1}^{m} c'_{ij} x'_{ij}$$

   where:
   - c'_{ij} is the transportation cost from sorting facility i to recycling center j.
   - x'_{ij} is a binary decision variable indicating whether the route from sorting facility i to recycling center j is used.

   The mathematical formulation of the subsequent model at Level 2 involves the minimization of the total cost (Z') as the sum of the transport costs from each sorting facility to the corresponding recycling center, multiplied by the binary decision variable indicating the use of each route.

B. Data Collection

Concerning the data collection, the data used in the model were simulated using characteristics of an urban area similar to Skopje, North Macedonia. To do this, 500 bins were placed around the city which were placed at both residential and commercial areas. Average waste generation rates were then simulated based on historical data of waste generation and collection. The simulated parameters include:

- **Number of Bins:** 500
- **Average Waste Generation Rate:** 7 kg/day per bin
- **Vehicle Capacity:** 1,500 kg
- **Emission Factors:** 2.64 kg CO_2 per liter of diesel

Calculation	Value
Total Daily Waste	3500 kg/day
Number of Trips per Day	2.33 trips/day
CO_2 Emissions per Trip	132 kg CO_2
Total CO_2 Emissions per Day	307.56 kg CO_2

C. Optimization Algorithms

- **Simulated Annealing (SA):** draws inspiration from the annealing process in metallurgy, where controlled heating and cooling change the physical properties of a material. The process involves:
    - **Initial Solution:** Starting with an initial solution and a high temperature.
    - **Neighbor Solution:** Generating a neighboring solution by making small changes.
    - **Acceptance Probability:** Determining the acceptance of the neighbor solution based on a probability function that depends on the difference in cost and the current temperature.
    - **Cooling Schedule:** Gradually lowering the temperature and repeating the process until convergence.

For SA, the initial temperature was set at 1000, with a cooling rate of 0.93. Two of meta optimization techniques, Genetic Algorithm (GA) and Simulated Annealing (SA) were selected out of many, because they are reliable and adaptive to the problem in routing issues [4],[6].

- **Genetic Algorithms (GA):** GA mimics the process of natural selection, that is select the individuals that are fit and allow them to reproduce in order to generate the next generation population. The process involves:
    - **Initialization**: Randomly generating an initial population of solutions: This step involves the generation of a population of possible solutions from which other better solutions will be evolved.
    - **Selection**: Selecting the right solutions based on the fitness results acquired.
    - **Crossover**: Doubling up of solutions to arrive at children with better solutions to problems.
    - **Mutation**: Teaching new information using whole and part schemes with variations made by changing aspects of a solution randomly.
    - **Iteration**: The (ii) step is performed by using an iterative formula repeating the process until convergence is obtained.

GA parameters employed by this method incorporated a population size of 150 a mutation ratio of 0. 02, and a cutoff rate of 0, 8.

- **Simulated Annealing (SA):** finds antecedents in a process used in metallurgy, known as annealing through heating and controlled cooling of a material to modify its properties. The process involves:
    - **Initial Solution**: Using the initial solution and a high value of temperature as the parameter of the system.
    - **Neighbor Solution:** Deriving a nearby solution from a slight tweaking of the input.
    - **Acceptance Probability**: Implementation of the acceptance rule that is dependent on the probability function of the form P(diff) * exp(-deltaT / T), where deltaT is the difference in cost between the current solution and the neighbor solution, and T is the current temperature.
    - **Cooling Schedule:** Slowly many an isolated sink temperature is lowered and complete many isolated sink temperatures the same process is performed until convergence.

Regarding SA, the initial temperature of 1000 was defined whereas the cooling rate was set to 0. 93.

D. Simulation and Results

To analyze the impact of the models during different conditions and situations, Python and MATLAB simulation models were developed to analyze efficiency during normal waste production and during unusual such as during holidays where there is high production of waste.

Scenario 1: Standard Waste Generation

- **GA Results:** From the analysis it was found that they achieved 25% total optimized cost reduction as compared to baseline static routing and the CO2 emission of a distance was reduced by 18%.
- **SA Results:** In the optimization process, the study brought down the overall total optimized cost by 22% and overall emissions by 16%.

Scenario 2: Increased Waste Generation During Holidays

- **GA Results:** The model proved itself in handling large volumes of waste and in the process cut its costs by 28% and emission by 20%.
- **SA results**: The idea of cutting costs was realized 24% and lowering emissions 18%.

E. Evaluation Metrics

The performance of the proposed algorithms was assessed in the best worst method (BWM) with Relative Percent Deviation (RPD), Relative Deviation Index (RDI) and hit time[6].

Evaluation Metrics:

- **Relative Percentage Deviation (RPD):** Assesses the difference of the solution from the ideal one.
- **Relative Deviation Index (RDI):** Evaluates a general performance considering different factors.
- **Hit Time:** The time it takes to arrive at a good solution.

BWM analysis showed that GA was marginally more effective than SA in all aspects by having a lower RPD and RDI and hit time.

4. Conclusions

In summary, this work showed the feasibility and effectiveness of boosting smart waste collection routing via real-time IoT data edge infrastructure and advanced meta-heuristic algorithms in a city environment in North Macedonia. According to this article in the Journal of Environmental Management, the two-layer Waste Management System (WMS) model drastically decreases operational expenses and ecological footprints, aligning with goals of sustainable development. The case study shows the potential of leveraging IoT-enabled real-time data and advanced meta-heuristic algorithms in the routing of waste collection in Skopje. Specifically, Genetic Algorithm (GA) and Simulated Aging (SA) played a significant role in heightened operational performance and lower environmental impacts. Later works can then continue by applying the algorithms in practice and further tuning the algorithms to improve their adaptive nature to dynamic changes. Future improvements may include the integration of adaptive machine-learning algorithms to increase system responsiveness and effectiveness within dynamic urban landscapes.

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