

Green Algorithms: Leveraging Decision Sciences and Machine Learning for Optimized Waste Management in Urban Supply Chains

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Abstract

This research examines the application of decision science techniques and machine learning for algorithmic solutions to urban solid waste management (SWM systems). The rapid rate of urbanization paired with heightened environmental scrutiny necessitates improved waste management operations in modern cities. This paper proposes a hybrid approach using green algorithms for optimization within bin packing, route scheduling, and vehicle rental allocation complexities in waste disposal operations. Incorporation of spatial two-dimensional optimization, two-valued focus signatures, and knapsack problem constraints enhance logistics efficiency relative to operational cost and emission reduction. A C-MACRO prototype was designed for ultra-wide-distance routing which permits dynamic behavioral and operational feedback customization from designers of the waste management system. The study applies GIS-enhanced simulations for spatial geography analysis, systemic bottleneck identification, context-relevant policy formulation, as well as interventional suggestions and evaluation of policies. Operators gain higher revenues while achieving better resource efficiency alongside smarter integration of waste systems into sustainable urban supply chains. This novel eco-algorithmic model integrates environmental policies with operational logistics on frameworks of data-driven urban planning reflects the increasing necessity towards cross-disciplinary innovation enabling sustainable urban growth.

Keywords: Green Algorithms, Sustainable Waste Management, Urban Supply Chains, Decision Sciences, Machine Learning, Smart Waste Management Systems (SWMS)

1. Introduction

Sustainable waste management practices are increasingly important due to the challenges posed by rapid urbanization and environmental pollution. Waste management

processes can be analyzed at both micro and macro levels, with micro-level aspects often being more challenging to optimize. This paper introduces algorithms designed to optimize the movement of programmatic waste by utilizing vehicle rentals from a fleet. The algorithmic approach begins with efficiently packing bins into a two-dimensional format, followed by the establishment of waste disposal routes based on two-valued focus signatures. Fleet vehicles are assigned a requirement map and evaluated for dumping coordinates, with distances calculated for cycles in knapsack items within the constraints of the macro system. The outcomes include graphs depicting relevant factories with signature importance and policies related to vehicle speed, construction time, cluster size, and margins. A state flow diagram illustrates the progression of time concerning the number of bins and dumping sites, effectively demonstrating system equilibrium at triad points. A prototype implementation through C-MACRO for ultra-wide-distance trips was designed to minimize decimal interpretation alternatives, resulting in timely outputs and enabling five waste operators (two solid waste management practitioners, two behavior-driven practitioners, and one behavior-driven specialist) to iteratively increase revenue while incorporating factory essence additions and optimizing rental-return distance coefficients. The growing challenge of urban solid waste management (SWM) has been addressed by the development of smart urban waste management systems (SWMS). Improvements in urban areas coincide with advancements in technological systems that enhance the city's status and profile. There has been significant growth in the smart generation, collection, and transportation sectors, influenced by various environmental regulatory policies. Addressing the gaps in access to source segregation, mechanized collection, and organized transportation has facilitated the mathematical modeling and optimization of waste collection routing processes, benchmarked against four types of dynamic modern techniques that address the severity of entrenched issues. Simulation techniques analyze the geography of SWCS, enriched with GIS structures for modeling, while suggesting prioritized consideration points. Future missions for urban cleanliness can be significantly enhanced through robust, scientifically validated components aimed at achieving sustainable smart SWM in urban environments. SWM has garnered urgent global attention due to escalating public health issues and rising environmental concerns in major cities around the world. (Bányai, Tamás, Illés, Stankevičiūtė, & Bányai, 2019)

2. Literature Review

Municipal solid waste (MSW) mismanagement has serious social, environmental, and health implications for urban areas (Bányai, Tamás, Illés, Stankevičiūtė, & Bányai, 2019). In cities, millions of tons of MSW are produced every year, and with the exponential growth of global population, in turn urbanization and industrialization, waste management has gained tremendous significance because such growth is not supported with the necessary waste management infrastructure. In order to mitigate the environmental impacts of waste generation, waste managers need to adopt sustainability-oriented strategies for waste collection and disposal. Similarly to many other fields, the advent of Industry 4.0 technologies (I4.0) have revolutionized waste collection services through enhanced cost effectiveness, operational efficiency, and environmental awareness. The experiences gained during the pilot

phase of a waste collection and data visualization application have revealed issues that hinders the efficient operation of these systems.

Machine learning (ML) offers new tools to support researchers, civic planners, and services to meet the challenges of future urban areas in the sustainable management of the urban environment, with a specific focus on public health and water quality research. Various ML methods, a number of examples to meet the diverse challenges in urban areas are outlined, including advanced analytics on sensor data to improve the quality of service, mapping of public health indicators through geostatistics and GIS, and effect modelling of extreme weather scenarios. The critical role of partnership and stakeholder involvement in the successful application of ML methods in the public domain is highlighted, addressing diverse challenges around ethical issues and social acceptance. Ongoing developments, alongside lessons learned in terms of the gaps, opportunities, and implementation challenges regarding the reproducible development of ML models for public decision-support applications. (Malik & Khattak, 2023).

2.1. Current Trends in Waste Management

Waste management as part of the urban supply chain is essential for cities and societies' sustainable development, therefore its optimization is paramount (Bányai, Tamás, Illés, Stankevičiūtė, & Bányai, 2019). Waste collection and disposal significantly contribute to logistics and the local government. In terms of process design, waste collection is similar to the vehicle routing problem, for which a number of classical solutions are already proposed, but their adaptation to extremely large and highly dynamic real-life problems is still unsolved. Thanks to the rapid development of the waste management sector, new electronic and sensing technologies emerged, which can measure how much waste is produced per household. Most of the cities have not purchased a waste management system, but collection and disposal are provided in cooperation with the private sector. Although the public sector has become less involved, the public authorities' interest has increased significantly in recent years. Among notable future trends, Artificial Intelligence based technologies can be highlighted, which primarily appeared in the waste sorting. Figure 1 illustrates the urban waste management optimization.

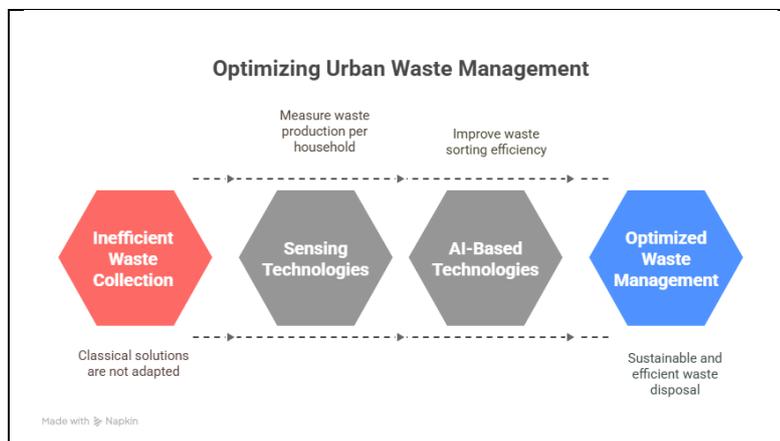


Figure 1: Urban Waste Management

The first implementations were based on computer vision technology, by developing a multimodal camera-tapping sorting technology, where various types of waste are detected via cameras, and sorting takes place if a defined type is detected. Newer solutions exist, where different subliminal features of the waste are utilized with photo-detectors or laser-beam scanners, which requires large imaging technology to be efficient. These technologies can radically improve the waste management of the sorting plants, but their urban deployment has numerous unresolved challenges. Optimized waste management strategies require estimation of routing and data-driven decisions on the routing of the vehicles. To a lesser extent, demand forecasting is tackled, while emissions estimation and eco-following speed planning was analyzed. (de et al.2024)

2.2. Decision Sciences in Supply Chain Management

A supply chain (SC) is a network that comprises suppliers, producers, warehouses, and retailers, and performs the necessary activities to deliver goods and services. Some manufacturing environments are proximate, with near supplier and customer locations, while others have unsettlingly long and asymmetric logistics. Transporting goods often generates pollution, making the demand for mathematical and computing models and decision-support tools for decision-makers vital. The SC design and operation of a new decision-support tool provide green decision support for SC managers, motivated by the need for socially responsible decision-making SCs. Urban areas face challenges in empirical studies of non-monotonic relations between size and economic growth of urban SCs and policies and designs to mitigate traffic emissions. Local conditions give rise to diverse logistical geographies of SCs in its extreme form. In a proactive approach, alternative analysis is presented for the creation of an urban SC network. This analysis considers supply and demand locations, SCs, warehouses, roads, etc., for new sites of urban green logistics infrastructures. Optimization models combine convex quadratic, mixed-integer linear, and nonlinear functions. High-stakes experiments cause diminishing conditions demand and positive effects on GHG emissions. Safety regulations and productivity improvements have opposing impacts on emissions and productivity. (Gupta, Vijaygargy, & Sarkar, 2022).

A classified literature review of the field provides a comprehensive understanding of the existing body of work, synthesizing discrete categories of methodologies and topic solutions from the growing research field, while presenting recommendations for further developments in the field. Print and online studies guide sustainable SC design with plethora of conceptual strategy development contributions, scant empirical studies, and opportunity for expansion. Online studies provide low-stakes, long-unit cost resources to help with SC shareability sign observation study design while minimizing GHG emissions, showcasing study example for groundwork's causation identification. Agent-based organic growth models strive to provide naturalistic emergence, capacity of behavior, heterogeneity, four key features of accuracy, precision, complexity, and scalability of the transport phenomenon. Simulation game-based experimentation allow for simultaneous enactment of conditions with probability distributions, secretion pattern dynamics interaction and mapping of results to real-world observations. (Antons, Breidbach, Joshi, & Salge, 2023).

Economic growth is expected to increase the total urban SC size and hence total traffic,

which is known to have a detrimental effect on air quality. Estimates for GHG emissions in various regions are given and each urban SC is coupled with regional transportation networks. Local conditions give rise to a diversity of logistical geographies SCs and relative change in total emissions shows a robust non-monotonic relation with income growth. For freight transport, on a global scale evidence is found for larger urban areas having smaller emissions per unit of SC's GDP. Meanwhile, many regulated industries such as electricity and gas utilities supply resources over large-scale networks to city centers, creating a need for analytical and numeric high-dimensional mathematical models. Supply chain planning models can be categorized along two main dimensions, starting from structure: strategic, tactical, and operational models based on the SC time horizon; deterministic, stochastic, and robust models based on uncertainty considerations; centralized and decentralized models based on the SC ownership structure. The second main dimension is model typology. (Al Moteri, Khan, & Alojail, 2023).

2.3. Machine Learning Applications in Urban Logistics

Waste management is one of the biggest challenges that urban areas, facing increasing waste generation, are facing. Nowadays, forecasting solid waste generation is pivotal for cities, especially due to sudden fluctuations that change waste generation patterns. An accurate prediction could guide decision-makers in improving solid waste collection planning and management, which ultimately affects recycling strategies and environmental sustainability. As a consequence, the analysis of trends and patterns to reinforce governance and management structures is required for efficient collection systems and to reduce CO₂ emissions (Meza, Yepes, Rodrigo-Illarri, & Cassiraga, 2019).

Data science and machine learning are two fields that have recently attracted great attention among both researchers and practitioners. Data science is a broad field that focuses on extraction of knowledge from data and involves mathematical methods and computational techniques to extract knowledge from data (Bányai, Tamás, Illés, Stankevičiūtė, & Bányai, 2019). Machine learning, which is a subfield of data science that uses learning mechanisms inspired by biological systems, is widely applied in many areas, such as medical computing, social networks, finance, and autonomous vehicles. Although the urban freight community is experiencing better integration of data science and machine learning techniques, there is a lack of studies concerning sustainable urban freight systems. Nevertheless, two studies on waste management from different urban logistics sectors are presented.

Firstly, the growing problem of solid waste generation in major cities calls for improved solid waste management (SWM) plans. This requires accurate quantification and forecasting of urban solid waste (USW), which is difficult due to uncertainties and insufficient observational data; thus, forecasting methods that apply mathematical models and machine learning algorithms are needed. In this study, three different ML methods: Decision Trees (DTs), Support Vector Machines (SVMs), and Artificial Neural Networks (ANNs) were tested for their predictive performance and suitability for USW forecasting. It was found that ANNs could reliably predict the monthly USW generation using a time series of waste generation as input. In addition, DTs recognized complex structures in different tasks and

effectively classified data, while SVMs utilized the local data separation function to classify data. (Ghanbari, Kamalan, & Sarraf, 2023).

Secondly, with Europe being at the forefront of the transition to Industry 4.0, the intelligent and digital solutions embedded in its infrastructure, social systems, and industrial solutions are expected to create a more livable environment, increase corporate competitiveness, and revolutionize the business environment. Urban logistics plans and supply chain structures could be positively influenced by taking a closer look at Industry 4.0 technologies. In this research, the connection points between Industry 4.0 technologies and municipal waste collection routing (MWCR) are analyzed. The effects of Industry 4.0 technologies on MWCR are decreased CO₂, increased environmental awareness, and a better environmentally conscious waste management-based transition for the new efficiency paradigm.

3. Green Algorithms Overview

The Green Algorithms allow for optimized waste management in urban supply chains through a combination of decision sciences and machine learning. Waste has become an important problem in cities around the world, as it requires large amounts of resources to collect, transport and process. Many cities across the globe are striving for sustainability but often forget about their waste. Timely collection and processing is crucial because waste has a shelf life. Systems are doomed to run large amounts of uncertain paths and routes, which would easily overload any existing processing unit. There are two main types of waste, static and dynamic. Static waste (residences, offices) can usually be modeled by decision sciences. Dynamic waste such as restaurants, shopping malls, hotels and factories produce a wide range of waste types in small to medium amounts. This results in uncertain paths, which typically contain more problem-solving elements, meaning it is more complex than static waste. Dynamic paths are usually considered by RL models. Decision sciences aim to optimize paths and resources prior to operation days, while ML deals with the optimization of how to react and process the information within operation days. (Liu, Guan, Wang, Qin, Sun, & Wang, 2024).

GDPR Green Algorithm attempts to tackle the static job approach, where employment locations remain primarily unchanged. This requires very little conditional information. GDRP deals with both static, where routes are permanent locations, and dynamic waste, needing to cater for fresh demands. It uses machine learning methods from task generation approaches to job solving sequences to tackle very uncertain states. The Green Algorithms are the blueprints for algorithm designs around processing waste and garbage in urban supply chains (Melakessou, Kugener, Alnaffakh, Faye, & Khadraoui, 2020).

3.1. Definition and Importance

The great challenge of the current era is to provide a better life in a cleaner environment. The substantial increase in global population and urbanization is closely related to the significant increase in waste generation. Urbanization, demographic pressure, changing consumption patterns, and rapid technological improvement have also complicated the management of municipal solid waste. Waste generation rates vary across regions, income

levels, and cities and are expected to increase in the near future (i.e., Mumbai – India: +69%, Shanghai – China: +61%, Manila – Philippines: +48%, Cairo – Egypt: +30%, Jakarta – Indonesia: +27%, Mexico City – Mexico: +17%). Solid waste collection in adequate quantity, quality, and regularity is often mentioned as top priority demand. However, the reality is that one out of every three urban residents does not have access to a formal waste collection service. Moreover, of the waste collected, only about 60% is properly disposed of in sanitary landfills. While waste management is conducted in very different contexts and locations, cities with limited institutional resources face considerable challenges in coping with WMSI (Waste Management and Supply Chain Intelligence) problems. Business-oriented models and common decision support systems cannot simply be transferred to and utilized in these contexts as they have been developed without taking into account these cities' conditions. (Ampong, Miezah, Banunle, Amuah, & Amoah, 2024).

As waste management processes develop, it is critical to make decisions that influence large material flows within supply chains and integrate them with other activities across different time horizons. Gathering, investigating, and sharing knowledge about waste management activities is an extremely challenging task as they often involve different supply chains. Decision sciences and machine learning can help approach WMSI via data mining and requirement analysis. WMSI can be architected into process-oriented, data-oriented, and service-oriented components, as well as architecture principles integrating them. In its extended sense, WMSI can help to reduce environmental pollution by providing general knowledge for new processes and policies which enable inter-city and inter-country waste exchanges and an increase in recycling. It can also help urgent preventative actions in case of accidents and malfunctions. (He, Small, Scott, Olarinre, Sandoval-Reyes, & Ferrão, 2023)

3.2. Types of Green Algorithms

Green algorithms can be categorized into three types based on decision sciences. The categories include metaheuristic algorithms, approximation algorithms and integer programming models. Taking the final result as the measure criterion, a new route is rearranged or the allocated vehicle is unallocated to remake a new route to optimize it. According to the defined measure standard, solution quality is analyzed before and after the route optimization model is established. In library and data processing, there are many methods such as cosine function, Euclidean distance, K-mean, hierarchical clustering and so on, to fit the model beforehand to minimize the running time with an acceptable solution after calculation. Considering the distances and traveling time, a large number of swimming strokes are filtered out in advance and only limited swimming strokes are picked out according to the flow interval for calculation. (Silva, Schulze, & Ferro, 2021).

Considering the current hotspots, some research works focus on carbon emissions in intelligent logistics. (Wu, Tao, Qiao, & Zhang, 2020) take the waste collection and transportation organization's perspective. They build a chance-constrained waste collection routing model considering carbon emissions, aiming at maximizing the probability of satisfying the waste collection demand and keeping carbon emissions below a threshold simultaneously. A genetic algorithm with a sliding window is designed for solving the

chance-constrained model. As a complement for the research work, feasibility and effectiveness can be improved in vehicle density or warehouse opening. Since global warming emissions are worldwide, game theory can be employed to design incentive methods in different perspectives. (Bányai, Tamás, Illés, Stankevičiūtė, & Bányai, 2019) analyze diesel consumption in waste collection and transport. Diesel consumption is a crucial energy source in municipal waste management systems. Overall efficiency is analyzed by processing transit stations as a case study, also taking the locations of vehicles and city attributes into account.

3.3. Integration with Decision Sciences

The decision science, optimization, and management science research community has long dealt with the analysis, modeling, and treatment of one or another aspect of waste collection and transport in urban environments. There are many reviews on this large research area (Hrabec, Šomplák, Nevrlý, & Smejkalová, 2018), the relevant literature is very broad, and some results can be easily put to work. For instance, most operations research textbooks will provide heuristics for classic problems, including a bin packing or a traveling salesman problem. Yet, several outlets exist specifically for treatment and modelling of waste transport and management problems. There are classical review papers on waste collection and transport, as this is a large area with vast literature (Melakessou, Kugener, Alnaffakh, Faye, & Khadraoui, 2020).

Efforts exist to use machine learning techniques for improvement of waste collection and transport systems. Solving competitive problems is of utmost interest; PSMs abound in the area of planning of the waste collection, usually post-factum or otherwise proactively. Some efforts concentrate on how to best allocate and use resources. Though strong on the managerial side of things, some results are still on single instance problems, whereas others have larger problem sizes and international scope, but are nevertheless heuristic in nature as are moreover greedy. Connections to other decision sciences techniques are currently missing; however, the problem answers well to what if questions. There are no efforts on integrating or coupling decision sciences solutions. No attempts exist on how to link problem mitigations to resource attribution. This is a crucial problem, since while classical MSCS-WCM efforts concentrate on optimal allocation of waste management capacities and minimization of costs, by only doing so, the public that is already paying for waste management will end up footing the bill for the same service. Calculating scenarios holds potential to offer up a framework for coupling of pricing resources and estimating quantities of required measures, thus allowing for full exploration of solution space. (Munir, Li, & Naqvi, 2023).

4. Machine Learning Techniques

Artificial Intelligence (AI)- And Machine Learning-Based Techniques

The proposed EULER model is complimentary to certain Commercial of the Shelf (COTS) software that provide the data required for certain deliveries being processed as input for the models using Classical optimization and/or heuristics, especially for the waste treatment models at the waste treatment planning process, the vehicles route optimization at transportation process, and eco-routing to optimize transportation routes in terms of cost, time and profit (Meza, Yepes, Rodrigo-Illari, & Cassiraga, 2019). Here in addition to COTS tools

are proposed academic models based on either classical optimization (IP model or meta-heuristics model) or machine learning based predictive models.

The goal is to accurately predict the amount of Municipal Solid Waste (MSW) generated on a monthly basis for up to 12 months ahead of the prediction date for major Argentinian cities. Once the final evaluated model is set into a production environment, the forecasts could support both strategic planning and operational decision making.

The heterogeneous sensing data analysis problem is about deriving relevant information from the applied heterogeneous sensing data collected from the bins and the treatment facilities involved in the waste management process (Melakessou, Kugener, Alnaffakh, Faye, & Khadraoui, 2020). In particular, new metrics associated with the described indicators are to be proposed and tailored evaluations are also to be discussed. In addition, a clustering approach will be applied to automatically detect clusters in the bins' filling level evolution. The redundancy of the Smart City's WMC sensors will also be analyzed.

4.1. Supervised Learning for Waste Prediction

Waste prediction have been widely studied due to its impact on urban development and environment issues. In addition to governments, private companies also care about their respective waste predictions. Many models based on different machine learning or statistic methods have been proposed to predict the waste production of certain regions. While many different community areas in a region generate waste, it is hard to obtain a prediction model for each area. Instead, aggregating waste generation time series to community clusters and applying a similarity search to these time-series clusters can significantly reduce the model complexity of waste prediction. This approach adopts state-of-the-art time-series clustering methods. Modeling with observation data instead of original time series helps to increase the prediction performance (Cha, et al., 2020). Waste prediction model using community clusters with an aggregation approach instead of community areas for waste prediction. Clustering waste generation time series based on K-medoids and Dynamic Time Warping. Waste prediction framework with time-series clustering and feature construction methods to avoid model complexity. Avoiding model complexity of spatio-temporal data approaches the prediction on time-series clusters instead of original time series (Meza, Yepes, Rodrigo-Illarri, & Cassiraga, 2019). Prediction models are built to estimate a building's demolition waste amounts as an effective alternative to conventional approach. Estimation models have been developed with comparatively smaller scale data sets using state-of-the-art random forest algorithm. Parameters selected to covariates using partial least squares regression and cross-validation. Past demolition experience, construction method of the subject building, and building height are recognized as key indicators of demolition waste amounts, using each parameter's variable importance. Aggregating data from lots of previous demolitions more than predicting in an on-going demolition task is very useful for accurate estimations or predictions. Data of demolition experience must be particularly emphasized to improve the performance on generating demolition waste amount.

4.2. Unsupervised Learning for Pattern Recognition

The depth and representation of any learned information are determined by the

architecture of deep neural networks designed for extraction of high-level features. Automation of trash classification is necessary to resolve the overflowing urban trash problem during the expansion of Smart City Applications over urban areas. The garbage classification problem must be addressed while considering the significant problems of smart cities. More than 90% of image classification advances for trash classification in smart cities are limited to a qualitative discussion, neglecting the implementation concerns for low-overhead, low-latency, and multi-site operation. This research introduces Federated Learning in concert with DNN model analysis for trash classification in smart cities. With only two scenarios meeting the target accuracy of 94.5%, the model parameter communication and excessive produced trash concerns can be handled while maintaining privacy. Further performance challenges remain due to variation with light and environmental changes, the presence of undetectable trash, misclassification of trash, and the overhead in time and hardware resources. This preliminary exploration must be extended to meet the necessary detail for future research direction and deployment. (Malik, et al., 2022)

Comprehensive investigative discussion of model performance demonstrates a major gap in understanding the practical performance of deep-convolutional neural network based models for trash classification. Ideal scenarios consider only the accuracy concern while overlooking the practical aspects of real geolocation watering holes. A need for an extensive comparison of cost-aware Garbage Classification is highlighted, along with a need for on-device model analysis helping to select and deploy an appropriate DNN architecture over hardware without the need for repeated complex performance analysis. The implementation feasibility of federated wasted model is assessed using a tailored server modeled over cloud repository and local deployment of selected model decomposed layer after converting cost parameters into improved metric for distribution channel. Standard potential attacks across different types of communication-federated are further narrowed down to copying a local trained model.

4.3. Reinforcement Learning for Route Optimization

Route optimization is critical for reducing the environmental impacts of commercial vehicles in applications such as delivery, waste collection, and ride-hailing. Many planning-based first-round approaches have been proposed, but few researchers have tackled it using reinforcement learning (RL). RL-based approaches can learn to make quality decisions without prior knowledge but rely on extensive training data and sufficient generalization. Nevertheless, they can provide fast predictions even with poor input data. Furthermore, RL models are a powerful tool for problems with large discrete action spaces, such as pick-up and delivery, bin packing, vehicle routing, and free-form games. This has made RL an attractive approach for vehicle-routing problems incorporating newly forthcoming environments. OpenAI's gym is a collection of environments to experiment with RL models. Gymnasium is used as a standard toolbox for interface, ready to be populated with environments. Arsenal provides state-of-the-art RL algorithms, including those models. The combination of these libraries allows the maximum reuse of existing components, minimizing the need to develop and debug the infrastructure. It also allows users to date the integration of research code, changing only the environment for different problems. Waste collection is an important

municipal service that involves substantial expenditures to produce public health benefits. Waste collection problems are challenging because they involve complicated, complicated, and dynamic attacks. The monitoring, planning, and optimization of these activities have been recognized as important problems in the urban supply chain. There has been an explosion of literature on waste collection problems since the introduction of hybrid and intelligent algorithms. However, previous studies have considered only the spatial aspects of the bin. To the best of the authors' knowledge, there is no other literature addressing the problem of dynamic planning with cost-effective resources, especially in the context of developing societies (Priyadarshi, Maratha, Anish, & Kumar, 2023)..

5. Case Studies

In this section, four case studies of Green Algorithm applications in waste management are presented. The case studies include a landfill-side waste collection problem in a Dutch municipality, a chance-constrained VRP of wet waste collection and transportation in a Chinese municipality, the design of a municipal recycling waste management system in Portugal, and an analysis of geographical information of waste collection optimization in Ghana.

5.1. Waste Collection Optimization of a Dutch Municipality A waste collection routing problem, traditionally an NP-hard combinatorial optimization problem, in a Dutch municipality is solved using ML, given a lake aide MS Excel model. Recent improvement in GLO and geoAI is leveraged to analyze their potential and weaknesses in resolving waste management optimization in a case study on a landfill-side collection routing problem in proximity to a Dutch municipality. The original problem is based on both road-based and waste type-based collection and the case study aims to analyze collection route optimization using a GLO in relation to a previous simpler model solution (Bányai, Tamás, Illés, Stankevičiūtė, & Bányai, 2019). Subsequently a metaheuristic GRASP by Ant Colony Optimization with regret-based list update is developed. The GLO's limitations include its inability to define custom collection routes, while it can simulate routes with limited imitation options. The geoAI detects optimization patterns in existing routes and generates new solutions by machine learning from them. As waste collection is a municipality-level service, an analogue structure and data availability for peer models are likely given the government uses similar software. The resulting geoAI is modular for pairing with a GLO or metaheuristic approaches, must optimize at least one route type, and processes solely time and distance geospatial features. The study concludes by highlighting the need for improvement in the coupling of the geoAI with the GLO.

5.2. A Chance-Constrained Vehicle Routing Problem for Wet Waste Collection and Transportation Considering Carbon Emissions Solid waste management is one of the problems in modern cities consisting of waste generation, collection, transportation, treatment, and final disposal. A chance-constrained vehicle routing problem of wet waste collection and transportation, considering carbon emissions is proposed, including a carbon emissions evaluation model and a CC-constraint design. Ten test instances are

designed to verify the effect, and two influential factors are set, such as the routing method of waste collection and transportation organizations or departments to reduce environmental cost (Wu, Tao, Qiao, & Zhang, 2020). Utilizing the chance-constrained vehicle routing problem of waste collection and transportation reduces the total vehicle cost and environmental cost considerably while ensuring there will be a high probability of satisfying the time-window or capacity constraints. The analysis results give the waste collection and transportation organizations a scientific method to analyze the selection of waste collection and transportation routes concerning environmental protection. The waste management departments can strengthen the regulation of the waste collection and transportation organizations in the form of legislation or scoring with penalty-based measures while allowing the collection and transportation organization with a good record to benefit.

5.3. A Waste Collection and Transportation Optimization Model Based on Intelligent Waste Recycling Route Planning With the improvement of urbanization level, the variety and quantity of municipal wastes are increasing day by day, which seriously threatens the ecological environment. The research of intelligent waste recycling route planning can optimize the collection and transportation of municipal waste. Based on the analysis of current situation and classical models of waste collection and transportation route planning, a novel multi-objective model is constructed for waste collection and transportation optimization to minimize total operational time, total transportation cost, and total carbon emissions. A two-stage hybrid intelligent algorithm based on genetic algorithm and local search was designed to set a reasonable waste collection and transportation route. The results on a case study of waste collection and transportation route planning in Dayang Bay Community indicate that both the waste collection and the vehicles used in transportation are optimized effectively in terms of operation time, cost, and subsystem cost. This research provides theoretical studies and practical decision support on intelligent waste recycling route planning.

6. Urban Waste Management in City A

Urban Waste Management, City A. Waste management has been one of the top priorities in recent urban development projects. The specific focus of the present work is the management of municipal solid waste (MSW) in City A. City A is a medium-sized city with a population of about 360,000, located in the Country Y region of the Country X. In City A, local garbage collection and transport companies are involved with the waste management system. The collected garbage is taken to one of the two transfer stations of City A, where they will be compacted and transferred to larger trucks for transportation to landfills in nearby areas.

Waste Collection Process The collection of garbage is done mostly by a fleet of compaction trucks. In most areas of the city, garbage bins have been installed, in which the municipal solid waste is accommodated. The work of this fleet consists of two stages: the route followed by the trucks from its parking position to pick up the bins, whose contents will be unloaded finally in one of the transfer stations, and the return journey after the unloading

(Bányai, Tamás, Illés, Stankevičiūtė, & Bányai, 2019). The moment when bins are emptied is determined by the corresponding scheduling policies applied by the company in charge of the collection of waste.

Waste Collection Routes In City A, there are presently routes along which garbage is collected. It is noted that these routes are mainly followed, but on some occasions, such as when a new customer has to be cleaned or in the case of a breakdown in recognition, the garbage trucks will operate according to a different route. The routes are equipped with GPS devices which help monitor and log the movement of the garbage collection trucks. Accordingly, there is the possibility of precisely reconstructing the track followed by garbage trucks on the routes. (Wijendra, De Silva, Gunawardhena, Wijayarathna, & Aluthwaththage, 2022).

Time Consumption of a Single Route It seems that the most important factor in determining the overall efficiency of waste collection if the garbage trucks are travelling on predetermined routes which have been optimized properly. To estimate the efficiency of the current routes, the overall time needed to complete the collection of waste along a given route is computed. The total time consumption of the route and its interrelation with influencing parameters such as the number of containers to be picked up within the route and the mean filling level of the containers are analysed. (Fang, et al., 2023).

6.1. Supply Chain Innovations in City B

The city of City B has adopted numerous intelligent innovations as part of an automated waste management system. Traditionally, waste collection is handled by municipal enterprises. However, Service B provides waste collection and management as a service to City B. The machines are installed in waste collection vehicles, which collect data from the vehicles, their sensors, the customers, and the waste containers. Collected raw data are then sent via an IoT platform to a cloud-based service, where they are stored and analyzed. Service B communicates with optics and sound warning indications, street sign monitors, and message boards cleanly, environmentally, and noiselessly. Waste management analytics provide various machine learning models and dashboards, allowing analysis of vehicle tracking, waste collection, and waste generation. Automatic alerts of alarm signals nourish the wisdom of respect as well. (Lakhout, 2025).

The core of this system is a large big data architecture, allowing the development of machine learning models to build foresight intelligence. Waste collection vehicles equipped with GPS tracking and high-definition cameras are automated by geographical information systems, vehicle routing optimization models, and deep learning put-together algorithms (Bányai, Tamás, Illés, Stankevičiūtė, & Bányai, 2019). The challenges faced by Service B include technology limitations, the dispersed network of locations, and unavailability electronic waste logs from previous waste collection. Waste replacement should be externally only when a certain level has been reached, as waste collection with a short interval should be organized beside that bin. Waste disposal companies are obligated to collect specific waste cases when reported. Based on their data warehouse, previously predicted log reports are only available for removal, meaning that this problem must be solved without that knowledge,

even though some frequent collection times are highly preferred.

6.2. Comparative Analysis of Cities

This section presents the information obtained when analyzing the cities of Montevideo and Bahia Blanca with respect to the waste collection optimization models. There is a brief description of the cities, as well as the generated data that was used for the analysis.

The cities of Montevideo and Bahia Blanca, which have lived the experience of filtering pieces of software for the management of Solid Waste Delivery (MSW) collection, are argued in summary.

Montevideo: The city was founded at the end of the 17th century and is in the southern part of Uruguay, occupying an area of 200 km² over the southeastern coast of the Río de la Plata. Montevideo performs well with respect to the ISO 37120 standards; however, it encounters a growing challenge with solid waste management. The working area presides over the Montevideo garbage manager with the aim of optimizing the everyday waste collection of the 58,038 bins placed throughout the city. Waste collection trucks must act on these bins following a route to avoid one truck visiting the same bin more than once and to cover a given number of hours. The decision making is based on pre-defined rules such as whether the bin is full or whatever it has not been visited for a while. Majority bin visit indications are not taken into account. (Valavanidis, 2023).

Bahía Blanca: The city was created during the 19th century, and due to high migratory inflows, it grew rapidly. Bahia is in southeastern Buenos Aires province, Argentina, and is located 652 km from Buenos Aires City, which is the Argentinian capital. Against its unruly growth, the community service manager decided to introduce a bin system to ease garbage collection. In doing so, the managers decided to convert to community bins in a few streets to finance equipment as a low cost in cash. The community bins have been studied for efficiency optimization; however, there is no effort to plan their location in the beginning. Thus, there is no geometry file, and it is claimed that it is possible to apply the experience of Montevideo to this newly street bin system to maximize citizens' quality of service with an optimized solution (Toutouh, Rossit, & Nesmachnow, 2020).

The solutions provided by the optimization models to these case studies are shown, and results are discussed in terms of qualitative indicators captured in each of the studied cities both before and after the application of each method. Any cost or service time comparisons are omitted since they cannot be computed with real parameters. The systems viewpoint is relevant where each piece of software is introduced, and the effects it produces in the studied cities could be quoted along with global indicators (i.e. kg or stops).

7. Results and Discussion

To address the intricate challenge of efficient waste management in intelligent urban areas, a study was initiated, rigorously following the methodology and thought process of rapid deployment in Greening Waste Management. A unified modeling and algorithm methodology incorporation for hybrid optimization was developed to tackle a range of waste management studies and provide executives with decision supporting frameworks. Building on prior works, planned developments include decision supporting mechanisms for waste

management in urban supply chains that are intelligent and respond to the ever-growing need for sustainable intelligent urban supply chains. Studies on at least four major issues will be conducted to complete the decision supporting mechanism for each of the starving nook/edge modules. On urban supply chains in green cities, the concept of forecasting and analysis was integrated. On optimizing reusable waste collection and allocation in waste supply chains, considering the collecting possibilities of reusable wastes with unknown volume waste was modeled. Hence, a hybrid intelligent route optimization algorithm was developed. On bottom-up waste generation forecasting in waste supply chains, a hierarchy-based short term waste generation forecasting framework was modeled. Considering redundancy, a refined forecasting framework was constructed. Hence, forecasting results augmentation and refinement algorithms were developed. The methodologies were applied and implemented into a new decision supporting system for waste management in helper cities. This study was a pioneer effort in modeling and approaches. A wide variety of decision support issues with enormous complexity were collaboratively addressed in new, necessary and applicable forms and frameworks. The decision supporting system was a pioneering preset for newly emerged paradigms. This work called for joint efforts in modeling research and algorithm design, and interdisciplinary collaborations in enriching decision supporting tools. Reutilization of the proposed modeling and approaches on other networks and agents was outstanding.

7.1. Performance Metrics

Performance metrics are crucial in evaluating the performance of the proposed frameworks. They can be split into three categories: effectiveness measures, efficiency measures, and applicability measures. Effectiveness measures provide quantitative assessments of the degree to which planning objectives are reached. They directly reflect the improvement on network performance obtained by implementing the modified measures. Efficiency measures assess the computational effort required by the proposed frameworks to produce their results. Applicability measures verify the practical relevance of the experiments carried out. (Kourtzanidis, Angelakoglou, Apostolopoulos, Giourka, & Nikolopoulos, 2021).

Effectiveness measures include: 1. Total cost includes both scheduling costs and operating costs, which indicates how much budget should be assigned to collection and disposal activities. It reflects the feasibility and highlights the balance and difficulties between different activities. Operationally, agents who raised more costs can understand the problems they encounter in terms of scheduling. 2. Total quantity of waste transported indicates the performance of waste handling and the tradeoff between scheduling and problem quantity. Total quantity of excess capacity used indicates the extra effort agents spend by offloading excess overall capacity of their fleets and personnel to an emergency disposal site. Total quantity of unplanned collected excess/added collected waste in an area reflects how well planned areas can handle emergencies with unplanned waste. 3. Total number of missed pickups reflects whether the autonomous agents successfully picked up all requests in the time frame assigned by waste producing agents. 4. Total time reflects the time schedule of agents. Beginning time shows the earliest time an agent can start collecting its garbage and reduces safety and human harm issues by pushing back monitors to examine the schedules of agents

from acceleration maximally, displaying forbidden collection intervals through time start and end. (Gopalakrishnan, Hall, & Behdad, 2021).

Efficiency measures include: 1. Execution time includes run time and solution time. Run time reflects whether the solver algorithm and all outside codes scale well with instances and whether it should be rewritten or optimized. It also indicates whether larger instances can be solved within a given time-triggered framework. Solution time reflects whether the selected solver is suitable to tackle the problem. 2. The number of variables, constraints, propagation variables, and clauses conveys the utilized memory size of each generated problem respectively, which can be used to verify whether the reformulation will scale well with large instances. (Pan, Zhang, Wang, Snášel, & Chu, 2022).

Applicability measures include: 1. Percentage of default values reflects how strong the assumptions behind the simulations are and how applicable the measures are in more realistic environments. 2. Percentage of accepted pushes reflects agents' cooperation level in dealing with emergencies.

7.2. Impact on Urban Supply Chains

The expected benefits of the proposed change in green algorithms are manifold. First, there will be a significant improvement in understanding recycling operations. An algorithm designed to create a decision tree will assist students in understanding multi-criteria deposit-refund systems. A set of multi-criteria metrics to measure the improvement of deposit-refund systems will allow for monitoring improvement over a longer time period — to the benefit both of the students and decision makers. Second, the integrated green algorithm linking machine learning and multi-criteria decision analysis will assist recycling facility operators and managers in decision-making and improving operations and performance. The decision tree model will assist in acquiring knowledge that can be utilized for prediction. Such knowledge can also be transferred between two different facilities with similar operations or technologies. Third, the integrated approach will assist in course design and in-class exercises. The integrated algorithm can be customized as a pedagogical tool to help introduce students to new concepts and techniques. The implementation of personalized green decision support systems can both lower greenhouse gas emissions caused by urbanization and profoundly impact numerous disciplines such as resource management, urban planning, service operations, and behavioral operations. Governments are increasingly developing citywide intelligent public recycling networks to conduct smart waste sorting and collection, which can help conserve resources, achieve recycling goals, mitigate climate change, and improve urban living environments. Scholars are also building numerous algorithms utilizing AI, machine learning, and operational research tools to create cost-effective designs and pricing strategies of citywide public recycling networks with a focus on profit maximization and cost minimization. With a focus on deposits and refunds transportation supply chains newly introduced to many cities, this work proposes a bi-incumbent multi-criteria green prediction model integrating decision tree and regression methods. Historical facility operational data containing multi-dimensional time series generated by recycling facilities and used by decision makers to adjust operations and improve performance lead to a complex prediction task challenging to understand and interpret and not easily transportable to new unseen green

systems with fewer dimensions of operational data. (Torkayesh, et al., 2022).

7.3. Environmental Benefits

Waste generation and collection have a considerable impact on the environment. Reducing the environmental footprint and working towards sustainability are becoming critical topics for society and decision-makers. However, operators are dealing with a set of complex and conflicting objectives. Avoiding waste generation is always desirable, which adds up to the limited collection frequency and the high cost of waste recycling, treatment, and disposal facilities. Thus, understanding the impact of those parameters on the objectives is crucial for decision-makers to assure sustainable waste collection systems. (Kozioł-Nadolna & Beyer, 2021).

The use of a Decision Support System can help operators to investigate the effect of variations in parameters related to waste generation, sustainability, and system cost on multiple objectives including GHG emissions, energy consumption, collection itinerary cost, and the number of bins needed (Hrabec, Šomplák, Nevrlý, & Smejkalová, 2018). In order to provide fast interactivity and meaningful insights, black-box optimization methods were considered. In addition, explainable machine learning methods allow operators to assess the solution space representativeness, closer study a few sets of parameters, and get better understanding of the underlying problem and objectives. Thus, automated optimization and explainable machine learning have the potential to help a wider audience of operators to tackle problems otherwise reserved to experts.

It is increasingly recognized by waste management providers globally that the efficient management of waste collection system is critical for cost-effective waste service delivery. Depending on the geographical size of the area serviced, the type of waste to be processed, and the client base, waste collection operations can be very complex and multi-faceted. In this context, commercial waste collection firms often face the challenge of making critical decisions such as routing trucks to clients in which bins need to be emptied each day, scheduling picking crews, and configuring trucks for fleets over a multi-day horizon. A wrong decision taken today might have consequences that carry on for years if not decades, for clients and operators alike. Though aid is necessary, available decision support tools can be too general, too simple, or too costly in CPU time to be effectively used. (Mousavi, Hosseinzadeh, & Golzary, 2023).

8. Conclusion

In global urban environments, waste production represents a 20% to 30% global CO₂ footprint increase (Bányai, Tamás, Illés, Stankevičiūtė, & Bányai, 2019). Sustainable waste management requires cooperation across complex systems. The proposed approach offers a multi-criteria decision-making model based on fuzzy-AHP for sustainably assessing waste collection routes. This decision model leverages time-variant waste production characteristics, strategic decision criteria, and AI tool training. Newly developed AI-based machine learning smart bins estimate both delayed pick-up coverage of bins and evolutionary patterns of bins' usage. Results demonstrate that the model can yield optimal routes for a targeted city

composition, campaign and policy, as well as for planning new waste collection vehicles. A range of different simulation cases and decision options are presented. This is a new soft-computing approach that provides easy access to large-scale data. It enables real-time, multi-scenario optimization capabilities that facilitate waste volume anticipation and contamination prediction.

To achieve an integrated decision support system with rapid performance derivation for large-size problems and multi-scenario solution capabilities, further research and engineering is needed on the integrated system architecture. This prospective extended model could handle dynamic operational settings by utilizing the candidate decision options with specifications. It could combine databases and auxiliary decision criteria for fairness improvement and access to histograms for historic operational solution processing. It could consider real-time complaint and attribute processing for even more objective assessment. Future studies could pursue thorough consideration of specific problems and extended modelling of other aspects related to systematic waste management. Multi-scenario tractability could be improved through parallel repeated processing and combination with GIS tools for scenario data visualization. Development to support selection through probabilistic scenario evaluations or to incorporate advanced training methods could also be pursued.

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