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# The vehicle routing problem as applied to residential solid waste collection operations: Systematic literature review

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A B S T R A C T

The accelerated growth of cities, population increase and economic development have leveraged waste generation globally. This trend is expected to continue, with a significant increase projected in the coming years. Therefore, efficient waste management has become a crucial concern for local, national and international authorities. Transportation plays a key role in waste collection and disposal, being directly related to traffic congestion, fuel consumption and environmental pollution. Despite the existing studies on household waste collection, there is a gap in the literature regarding routing for residential waste collection in medium-sized cities, especially in emerging and frontier developing countries. Therefore, this study seeks through the science tree metaphor and PRISMA methodology, to find studies focused on the vehicle routing problem in waste collection operations, considering aspects such as Modeling approaches and solution techniques, applied Vehicle Routing Problems variants, objective functions, decision variables and constraints, applications in real environments, applied algorithms, and studies considering uncertainty and real conditions. A methodological outline of Vehicle Routing Problems in waste collection operations is presented, where central research topics are identified such as processes developed with Geographic Information System and their integration with exact methods, time windows, multi-objective capacitated vehicle routing problems, the application of stochastic models consider the uncertainty in waste collection, which has allowed including future prediction and optimization as prediction models, based on neural networks, to foresee uncertain conditions of the operations. This article analyzes the evolution in the optimization of municipal solid waste collection routes since 1964, highlighting the transition from iterative models to advanced technologies and multi-objective approaches. The importance of tools such as 3D Geographic Information System and heuristic/metaheuristic algorithms in improving planning and efficiency, despite limitations in the face of uncertainty, is emphasized. The systematic review shows a trend towards sustainable and efficient solutions, indicating future directions for research in urban waste management.



## 1. Introduction

Rapid urbanization, population growth and economic development have contributed to the global increase in waste, with a significant increase projected in the coming years, statistics indicate that 2010 million tons of waste was generated in 2016, which is projected to increase to 3.40 billion tons by 2050 (Kaza et al., 2018). According to recent evidence, transportation plays a fundamental role in waste collection and a costly activity with environmental impacts (Madden et al., 2022). Efficiency in municipal solid waste management (MSWM) has become crucial, especially in expanding cities where poor planning and inadequate operation are common challenges. The complexity of municipal solid waste management requires support tools

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for decision-making, considering variables such as population, waste generation, socioeconomic conditions, and associated costs. In Latin America, collection and transportation costs account for up to 70% of the total budget for solid waste disposal. Improving waste management is essential for waste management organizations, and the need for more efficient approaches has been highlighted. Traditionally, waste collection follows a conventional approach, with a fleet of trucks transporting waste to treatment facilities (Abdallah et al., 2020). Optimizing collection routes is essential to speed up service to citizens, reducing costs and associated problems such as traffic, fuel consumption, and environmental pollution. The determination of incorrect routes without scientific and technological interventions leads to high transportation costs (Akhtar et al., 2017a). Decision makers require various support tools that allow them to decide the best waste management strategy according to the particular characteristics of a given population. These tools must have design conditions that are consistent with the regulations and the different planning elements in force in order to minimize possible errors in the selection of alternatives and to determine assertive measures. This selection must take into account variables such as population, increase in waste generation, socioeconomic conditions, etc., and the need to consider the following factors (Zhang et al., 2022): associated costs, not only with respect to the initial investment of the infrastructure and its operating costs, but also the possible costs to be borne by the users of the cleaning service and their implications. For the operation and final disposal of waste, companies and municipalities spend most of their budget on the collection and transportation of MSW; in Latin America, the associated costs are between 60 and 70% of the total cost (Sáez & Urdaneta, 2014), and the cost of solid waste management is evidenced in total expenses due to salaries, fuel consumption, maintenance, and depreciation. Therefore, methods to improve solid waste management are of great importance to management organizations. The conventional approach to waste collection consists of a fleet of trucks collecting/transferring individual/communal garbage waste to treatment/disposal facilities (Abdallah et al., 2019a), This is evidence that determining the correct route helps municipalities to provide services to citizens more quickly, as well as reducing a significant cost. In addition, problems such as traffic, fuel consumption, carbon emission and environmental pollution would also be reduced. One way to ensure better performance in solid waste collection is to have the shortest or fastest route, for example, between solid waste collection vehicle facilities and disposal sites. Defining incorrect routes, especially without scientific and technological interventions, leads to high transportation costs (Akdas et al., 2021). RRS, especially residential, is a process that has a significant impact on collection and transport operations. This is because of the frequency required to efficiently fulfill the services in cities. For example, a residential route may comprise between 150 and 1,300 households per day, but this is directly dependent on the frequency of weekly service (Kim et al., 2006a). There are two main approaches to collection: one where households place their waste on the street according to a schedule and other where waste is taken to central collection sites. These approaches are applied differently according to regional and national context due to cultural, economic and political factors and vary according to various factors such as climate, geography, community and price of the service, which becomes a challenge for operations. The efficiency of solid waste collection is directly affected by the design of optimal routes for collection trucks. This task involves scheduling and defining the routes that trucks follow during the collection process. Failure to apply scientific or technological approaches to this selection process results in costly and deficient collection systems. Route designs are often based on practical experience and intuitive methods, leading to inefficient and expensive practices.

The implications of not optimizing these routes are multifaceted and affect several aspects:

- Commercial operation: Low productivity and profitability in the business model are direct consequences of inefficient collection systems.
- Public health: Poor management can trigger respiratory risks and the proliferation of disease vectors, such as mosquitoes, flies, and rodents, thereby increasing the risk of diseases transmitted by these animals.
- Environment: Air, soil, and water pollution are serious consequences of inadequate waste management, with negative impacts on the surrounding ecosystems.
- Public service and regulatory compliance: Dissatisfaction with the service, as well as non-compliance with policies and regulations related to public sanitation services.

These multiple effects underscore the critical importance of designing and optimizing solid waste collection routes, not only to improve operational efficiency, but also to safeguard public health, protect the environment and comply with established regulations (Apaydin et al., 2004). Although several case studies have been conducted for household waste collection, and several special characteristics that occur in these problems have been studied, there is no evidence in the literature of a comprehensive analysis that solves the routing problems for residential waste collection in medium-sized cities with situations aligned to emerging and border developing countries, and that meets technical criteria based on emerging technologies for optimal transport systems. In the current literature, waste collection and transportation procedures are mainly studied as routing problems (VRP), which are generally separated into node routing and arc routing problems. In waste management, the former is mainly used to model transportation systems and curbside collection. Case studies have been conducted in a node routing context; for example, Teixeira et al. (2004) and Elbek and Wøhlk (2016) considered the collection of recyclable material by single- and multi-compartment vehicles, respectively, whereas Nuortio et al. (2006) and Tung and Pinnoi (2000a) studied the collection of general waste. In the context of arc routing, curbside collection case studies have been conducted in Ohio (Clark & Lee, 1976), Portugal (Mourão & Almeida, 2000), and Spain (Bautista et al., 2008). Over the years, literature reviews on VRP in collection logistics have been published and structured from different perspectives. The variety of approaches presented in these reviews shows the broad field of study that VRP offers. In other words, this research program can be approached from multiple angles, giving it a multidisciplinary and knowledge-enriching character. A study conducted by (Beliën et al., 2012) summarized and classified the existing publications on solid waste collection into several categories based on the type of waste, solution method (mathematical programming, heuristic, branch and bound, simulation, and others), type of constraints considered, objective of the research, and approached the use of geographic information systems as solution tools for waste collection problems, in which optimality gaps are evident, as most of the studies analyzed were not optimal solutions because they are sensitive to increasing problem dimensions. Finally, it is concluded that future research in this field will be driven by advances in technologies such as GPS, which provides real-time updated information on road congestion.

On the other hand, in a review conducted by (Han & Ponce-Cueto, 2015) different approaches and techniques (classical heuristic and metaheuristic approaches) were used to solve the solid waste collection problem from 1974 to 2014, segmenting searches by collection types, such as residential, commercial, and industrial, and approaches to solving arc and node routing problems. In their analysis, they identified some gaps in the methods of solutions involving modifications of collection schedules, truck optimization, and the incorporation of traffic-related information. They found that future studies should focus on examining opportunities for improvement in the collection system, where one option is data-driven systems supported by new technologies, such as GPS, that help track real data (schedules). Finally, they concluded that there are few studies that seek to combine economic and environmental objectives, a relevant issue today, as it is one of the areas that in transportation is of great importance because of its role in greenhouse gas emissions.

Recently, Liang et al. (2021) analyzed different publications between January 2014 and January 2020, providing a continuity of (Han & Ponce-Cueto, 2015), but extended the knowledge to research that studied heuristics or a combination of heuristics based on Geographic Information Systems (GIS) technologies to solve cases of the waste collection routing problem (WCRP); they then categorized recent studies according to their objective function, vehicle type, constraint type, and the heuristic algorithm used to solve their respective problems. Finally, they generated several ideas for future research that can be used to solve the WCRP problem by addressing challenges such as the uncertain volume of residuals and potentially inaccurate estimates of residuals, as they can lead to scheduling and routing failures when faced with real demand peaks. It is also evident that none of the reviewed articles simultaneously considered other constraints such as WCRP with time windows, generating a gap in both constraints when applying heuristic algorithms to solve WCRP and concluded that future work should seek to optimize the collection and disposal of various types of waste. Studies conducted in the area of solid waste collection have been important for identifying solutions to the routing problem. This study seeks to make further progress in identifying alternative solutions to the WCRP, with a detailed focus on residential solid waste collection operations, where a gap has been found in the literature. None of the above reviews presents a dedicated exploration of VRP models related to municipal solid waste (MSW) collection applications that include analyses of studies that consider uncertainty conditions and studies applied to actual solid waste collection operations; however, their analyses for future work are specifically to search for and analyze these criteria. The objectives of this study were as follows:

- Carefully examine in detail information on scientific and technological advances in the vehicle routing problem in solid waste collection operations.
- Analyze modeling approaches, solution techniques, VRP variants, objective functions, decision variables, and constraints.
- Analyze in detail studies that consider uncertainty conditions
- Analyze studies on applications in real solid waste collection operations.

Accordingly, the following research questions were generated:

Q1: What have been the scientific and technological advances in the vehicle routing problem in solid waste collection operations?
Q2: What modeling approaches, objective functions, and solution techniques have been used to address VRP in solid waste collection operations?
Q3: What studies have considered uncertainty conditions?
Q4: What solution approaches have been applied to actual solid-waste collection operations?
Q5: What are the upcoming trends, opportunities, and avenues of research in the VRP field?

## 2. Methodology

According to (Mallett et al., 2012), by adopting broad search strategies, using predefined search terms, and developing concise inclusion and exclusion criteria, systematic reviews can encourage researchers to explore studies beyond their subject areas and networks. Theoretically, this improves the likelihood of generating a more transparent and objective answer to the proposed research questions. With this in mind, the main objective of this study is to conduct a Systematic Literature Review (SLR) on the topic of WCRP and, thus, evidence which research efforts are considered most influential in this field of research and to identify possible gaps in this literature. To ensure the accuracy and reliability of the results, the scope of this study was defined based on the adequacy of the content for bibliographic analysis. A dataset covering essential developments within the evolution of the subject is considered. In this study, a systematic search was conducted using Web of Science (Wos) and Scopus databases, which have been the leading research platforms in multiple scientific fields and the most reliable publisherindependent global citation databases (Bao et al., 2023). On the other hand, Dimensions and Lens have now gained prominence as open-source repositories of scholarly literature covering various fields of research, providing a more comprehensive coverage compared to subscription-based alternatives that do not support open science (Raji & Demehin, 2023), and were therefore included in this study. The research was divided into two parts, where the information collected was analyzed using different methodologies: the first part is the metaphor of the tree of science, which is summarized as ToS. It is based on an algorithm built in R and Python software that through the use of data analysis and graph theory facilitates the construction of a network of interactions and citations of the sources consulted (Zuluaga et al., 2016)(Valencia-Hernández et al., 2020) and the second from a taxonomic analysis of the nature of the VRP, under PRISMA methodology, which contributes to research as a guide and checklist to improve the quality and transparency of systematic reviews and meta-analyses in scientific research, therefore, it is used as a set of guidelines to plan, conduct and report the review adequately, in order to reduce bias, improve reproducibility of results and ensure that the literature review is conducted systematically, that all the results are included in a systematic manner, and that the results are reproducible, It is therefore used as a set of guidelines for planning, conducting and properly reporting the review, with the aim of reducing bias, improving reproducibility of results and ensuring that the literature review is conducted systematically, that all important steps are included and that it is presented in a transparent and complete manner in scientific articles (Page et al., 2021).

*2.1 Tree of Science - ToS*

The main objective of this analysis is to identify the scientific and technological advances in the problem of vehicle routing in solid waste collection operations over the years, using the metaphor (ToS), which divides the information into roots, stems, and leaves. The first corresponds to those that have founded the knowledge in the investigated área; they are the pioneers of these fields of knowledge. The articles that make up the stems are the different currents that have been consolidated and make up an important structure of knowledge. The leaves constitute the branches of recent research that are beginning to mark paths in the topic explored. A search for publications was initially carried out in the Scopus and WoS databases using the search equation (SE):

*(“Vehicle Routing Problem*" OR "Waste collection Routing Problem" OR "Stochastic Vehicle Routing" OR "Vehicle Routing" OR "Route Optimization" OR "Routing Algorithms”) AND ( "Waste Collection" OR "Waste Management" OR "Solid wastes") .*

In the search fields “article title”, “abstract” and “keywords”. A total of 968 publications were found, 639 in Scopus and 329 in WoS, which were finally cross-referenced and duplicates were eliminated, leaving 707. For their analysis, a tree of science algorithm was used to classify the root, trunk, and leaf articles, and statistics and graphs were obtained from the results obtained in the search for references in the Scopus and WoS databases.

*2.2 Systematic Literature Review (SLR)*

The main objective of this systematic review is to examine in detail the last three years of information on scientific advances, modeling approaches, and solution techniques that have been used to address VRP in solid waste collection operations, thus generating a taxonomic analysis of the focus area of study in this research. This review was conducted according to the following parameters:

- Modeling approaches and solution techniques
- Variants of VRP applied
- Objective functions, decision variables, and constraints.
- Applications in real environments
- Applied algorithms
- Software in use
- Studies considering uncertainty conditions

As mentioned above, the PRISMA methodology was used, based on the following SE:

*(“Vehicle Routing Problem” OR “Waste collection Routing Problem” OR “Reverse Logistics” OR “Stochastic Vehicle Routing”) AND (“Waste Collection” OR “Waste Management” ) AND ( “Household waste” OR “Residential” OR “Residential Waste” OR “Household” OR “Residential waste collection” OR “Municipal Waste” ) AND NOT ( “multiple depots” )*

The PRISMA flowchart of the literature search and article selection process for this study is presented below to develop key sections of the review:

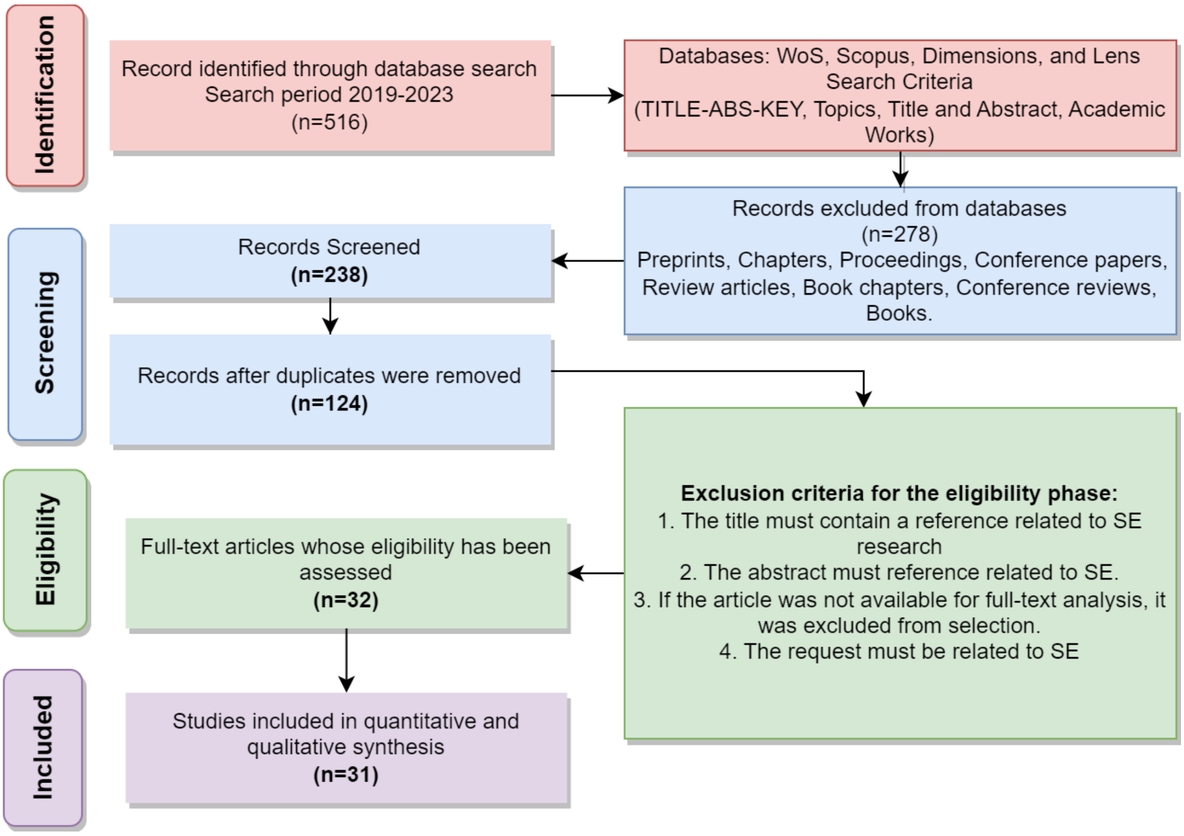


**Fig. 1**. PRISMA flow chart of literature search and article selection to develop the key sections of this review.

Own elaboration

## 3. Results

As expressed in the methodology, this study divides its results into two parts, initially with the application of the tree of science metaphor and algorithm to scientific databases WoS and Scopus, and then an RSL in performed on the databases Wos, Scopus, Lens, and Dimensions. The results are as follows.

### *3.1.1 Tree of Science – ToS*

### *3.1.1 Bibliometrics*

In this study, a comprehensive analysis of 707 articles was carried out, providing solid evidence of the continuous growth in scientific production over the years, as illustrated in Fig. 2. The analysis revealed that scientific production began in 2000 and has experienced steady growth to date, highlighting a significant increase in the Scopus database. In addition, the analysis of citations shows an increase, which reflects the evolution of the influence and impact of this topic among different research focuses. This finding suggests that these lines of research are relevant and interesting.

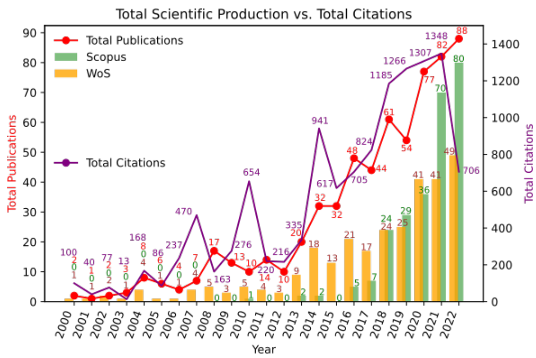


**Fig. 2**. Scientific production applied to household solid waste collection optimization

*Own Elaboration*

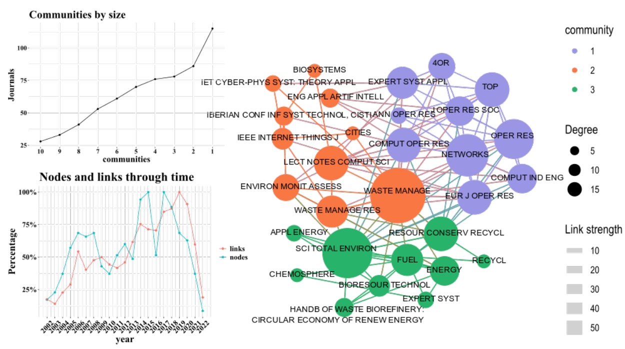


**Fig. 3.** Network Analysis by Journal

Next, the algorithm yields an analysis that shows the networks of the topic under study. The size of the nodes that are part of the network represents the degree of participation, impact, and citation, which are divided by journal (Figure 3), country (Fig. 4), and Autor (Fig. 5). For the analysis by journals, those with the highest impact are reflected; in total, there are 167, where the most relevant are WASTE MANAGEMENT, LECTURE NOTES IN COMPUTER SCIENCE (INCLUDING SUBSERIES LECTURE NOTES IN ARTIFICIAL INTELLIGENCE AND LECTURE NOTES IN BIOINFORMATICS and WASTE MANAGEMENT AND RESEARCH, which are in the orange node and show the networking of the topic of interest. In the analysis by country, the greatest influence is evidenced by the countries of the United Kingdom and the United States; in the green node, the networking between the United Kingdom, Italy and Spain is shown; in the purple node, the relationship of the USA is mainly with China, Japan, and Australia, and despite being in two different communities, the USA and the United Kingdom are very close to each other. The blue node shows joint collaboration between Pakistan, Colombia, Korea, India, Indonesia, and Thailand. According to the Organization for Economic Cooperation and Development (OECD), these countries are the most important in the world (OCDE, 2023), coinciding with socio-demographic characteristics such as the fact that they are emerging developing countries. In addition to being border countries, it should be noted that these countries face the challenge of identifying optimal strategies for the management, utilization, and reuse of materials, waste and residues that have a negative impact on the environment (Gulipac, 2016), making it possible to establish that they have been building research networks due to the characteristics and challenges they share, which makes them suitable and correlatable for waste management studies.

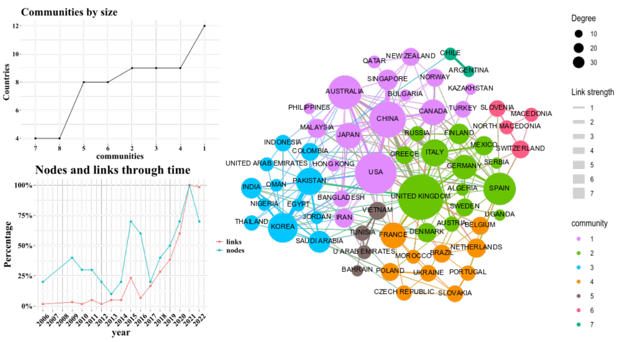


**Fig. 4.** Network Analysis by Countries

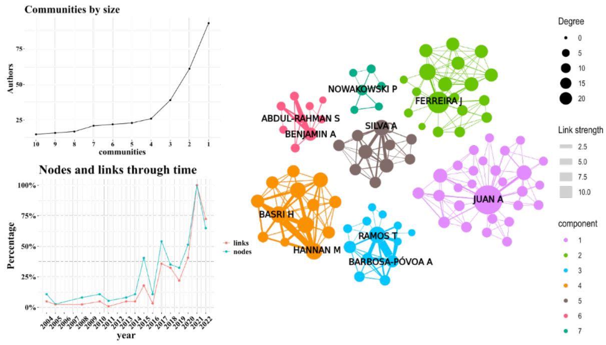


**Fig. 5.** Network Analysis by Author

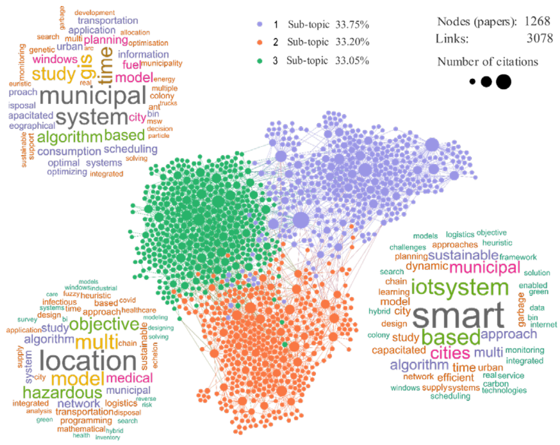


**Fig. 6.** Keyword Analysis (ToS)

*Own Elaboration*

In the analysis by authors, there are 19 authors in 147 studies, which are divided into seven networks; the highest impact is given by RAMOS TRP in 9.5% of the correlated studies, for the same blue node, there is BARBOSA-POVOA AP in 7.53%, and for the purple and orange nodes, there are authors in a proportion of 7.53% and 5.47%, respectively. Finally, among 1268 nodes and 3078 links found (Fig. 6) three clusters were generated which show the sub-themes presented, mainly in the relationship of the networks, for sub-theme 1, purple cluster, 33.75% of the studies are found and the words “IoTS System” and “Smart” are evidenced in greater proportion, reflecting the evolution of the technological capabilities of the studies, “sustainable” is found proving the importance of studies with sustainable approaches; and others such as "Cities", "Dynamic" and "Real Services", which reflect the technological evolution in scientific applications that allow addressing the challenges of solid waste collection operations that should be studied and designed for real environments with dynamic approaches. Sub-theme 2, the orange cluster, represents a proportion of 33.02% of the identified studies, in which “Multi Objective” prevails, which shows the importance of multi-objective studies, on the other hand, words such as “medical”, “healthcare”, “hazardous”, “Location” are present, which reflects a network focused on studies based on medical waste collection operations, a great challenge nowadays due to the biological risk they represent, their types of waste, location, transportation and/or handling. Finally, the green cluster, sub-theme 3 represents 33.02%, where words such as “GIS”, “Municipal System”, “Fuel”, “Consumption” are found.

*3.1.2 Root, Trunk and Leaf Analysis in Research*

One of the most important aspects of ToS metaphor is the classification of articles into roots, trunks and leaves. As mentioned in the methodology, the first ones correspond to those that have founded knowledge in the investigated area; they are the pioneers of these fields of knowledge. The articles that make up the trunk are different currents that have been consolidated and make up an important knowledge structure. The leaves constitute the branches of recent research that are beginning to mark paths in the subject being explored. The list of articles reviewed by the Tree of Science is presented in Table 1 in the Appendix. This section is divided into three main parts, each corresponding to the type of solution procedure employed: modeling approaches (VRP types); solution methods, whether they are exact, heuristic, or metaheuristic methods; and finally, whether they are deterministic or stochastic.

*3.1.2.1 Research Roots*

The roots are made up of 10 publications, which are classic articles that have formed the lines of research, starting in 1964 with the publication of Clarke and Wright (Clarke & Wright, 1964)– with the study "Scheduling of vehicles from a central depot to several delivery points", where an iterative procedure is developed that allows the rapid selection of an optimal or near-optimal route that has been programmed for a digital computer.

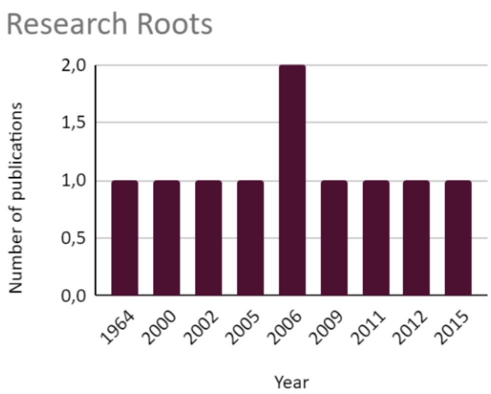


**Fig. 7.** Research Roots

*Own Elaboration*

In 2000, (Tung & Pinnoi, 2000b) incorporate the study "Vehicle route scheduling for waste collection in Hanoi", real application problem of vehicle route scheduling which is characterized as loading and unloading complicated by various time windows and inter-arrival time constraints at each customer point, the problem was formulated as a mixed integer program and a heuristic procedure consisting of construction and improvement phases was proposed Route construction is a modification of Solomon's (Solomon, 1987). In 2002 and 2005, case studies were incorporated, bringing the routing models closer to approximations in real operations, but still deterministic (Angelelli & Speranza, 2002; Sahoo et al., 2005). In 2009, a study was presented in which household waste collection routes were optimized to minimize fuel consumption through 3D GIS modeling from an accurate method consolidated in a geographic information system, which minimized fuel consumption and allowed cost savings of 8% compared to an approach that was limited to calculating the shortest 3D route (Tavares et al., 2009a). In 2011, we began to consolidate "multi-target" optimization models for waste collection with real-time traceability data, generating evidence of possible reductions in emissions from engines, vehicles, and other vehicles (Faccio et al., 2011a). In recent years, solution algorithms have started to be appropriated, which have allowed consolidation of efficient solution techniques, where an adaptive large neighborhood search algorithm was proposed to solve the VRP by time windows. Finally, (Das & Bhattacharyya, 2015) addressed the optimization of municipal solid waste collection and transportation through source separation, and the proposal focused on minimizing the length of waste collection and transportation routes, formulating the problem as a mixed-integer program. A heuristic solution is presented that significantly improves municipal solid waste (MSW) throughput, reducing more than 30% of the total waste collection path length, according to simulations and real testbed results.

Thus, the roots reflect that research on MSW collection and transport optimization has evolved from initial approaches to advanced solutions, incorporating real-world aspects, emerging technologies, and multi-objective approaches, with tangible results suggesting significant improvements in the efficiency of waste management systems.

*3.2.1.2 Research Trunk*

The trunk, which represents those articles that allow the area to grow, is made up of 82 publications, in Fig. 8, there is a consolidation of studies in 2014, 2018 and 2020. Research grows until 2020 but decreases in 2021, which reflects that in those years new leaves or lines are not yet mature because they have recently begun to appear.

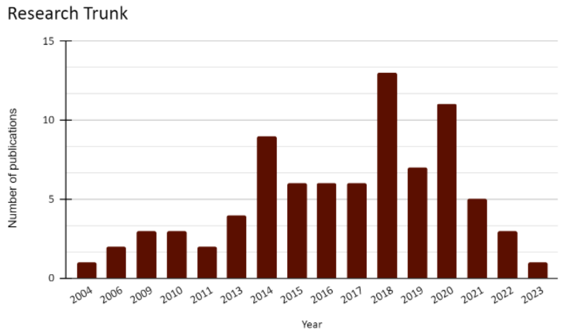


**Fig. 8.** Research Trunk

*Own Elaboration*

The following is a synthesis of the most relevant studies found in the root database and Table 1 consolidates the present solutions. One of the findings is the prominence of case studies developed with GIS, and their integration with exact methods allows taking advantage of the spatial modeling and geospatial analysis capabilities of geographic information systems to improve the accuracy and efficiency of solutions to routing problems. The geospatial representation of locations and the road network helps define the constraints and decision variables in the model more accurately. In this case, exact methods seek to find the optimal solution to a problem, without approximations, and are ideal for initial solutions to more robust problems. Examples of these are (Chalkias & Lasaridi, 2009; Malakahmad et al., 2014), where models based on Geographic Information Systems (GIS) are presented for the optimization of municipal solid waste collection, as they are studies in real operations, using geospatial data to improve route planning in the following areas, in (Tavares et al., 2009b) optimizing fuel, in (Ramos & Oliveira, 2011) delimit areas, and looking for the optimal location of container placement points (Khan & Samadder, 2016; (Erfani et al., 2017). In contrast, another type of study that has been growing is the routing model considering time windows (VRPTW), which is a variant of the classic vehicle routing problem that introduces time constraints for visits to each customer. It is a complete model for RSU applications, first because its objective is to minimize the total distance traveled or the total travel time, which is the mission of this type of reverse logistics. Several solutions have been presented in the literature. In (Kim et al., 2006b) address VRPTW considering multiple elimination trips and driver lunch breaks, providing a solution using Solomon's insertion algorithm. In (Minh et al., 2013), to minimize the total travel time and number of vehicles in the solution, they proposed using a memetic algorithm (MA), outperforming others in the VRP in terms of time windows and conflicts. Other areas that enrich the trunk are multi-objective problems, which have been relevant because, in routing problems, it is necessary to consider and balance several criteria or goals simultaneously. These goals often conflict with one another. Multiobjective problem solving involves finding solutions that represent an optimal balance between these conflicting objectives. One of the present studies is (Faccio et al., 2011b) in which a vehicle routing model integrated with real-time traceability data for the RRSU is presented, demonstrating how the potential benefits of this new approach are both economic and environmental, making it possible to reduce engine emissions, traffic congestion, and noise. Most studies are driven by objectives that address cost optimization and environmental criteria, that is, reduction of greenhouse gas emissions (GHG) (Ramos et al., 2014; Delgado-Antequera et al., 2020; Liu & Liao, 2021). The trunk is also consolidated by the capacitated vehicle routing problem (CVRP), also known as VRP with capacity constraints, which is of great impact in this type of research, as waste collection vehicles have capacity constraints in terms of the amount of waste they can carry. The CVRP considers these constraints to ensure that vehicle capacity is not exceeded and that waste is effectively collected without the need for additional trips. It therefore plays a crucial role in optimizing solid waste collection operations, improving efficiency, reducing costs and contributing to more sustainable and effective waste management practices. Some of the algorithms that provide solutions are backtracking search algorithm (BSA) (Akhtar et al., 2017b), particle swarm optimization (PSO) algorithm [51] and adaptive large neighborhood search algorithm (ALNS) hybrid with whale optimization algorithm (Mofid-Nakhaee & Barzinpour, 2019).

More recent studies have focused on stochastic studies that involve the incorporation of elements of randomness or uncertainty in the routing analysis. Instead of assuming that all the parameters or variables of the problem are known with certainty, the presence of random factors that may influence the outcome of the routing problem is considered, in (Gruler et al., 2017) and (Latorre-Biel et al., 2021) address stochastic demands, in (Guimarans et al., 2018) and (Gruler et al., 2020) address stochastic travel times due to traffic conditions or customer availability by addressing the Vehicle Routing Problem with Stochastic Travel Times (VRPSTT) (Asefi et al., 2019) fleet size, and detailed vehicle routes (i.e., plan/sequence/schedule/route load).

Stochastic studies are relevant in situations where uncertainty plays a significant role in route planning and execution, which is common in real-world applications, such as vehicle fleet management, logistics, and MSW transportation.

*3.2.1.3 Research Branches*

The branches and leaves present 615 articles, which represent recent studies that began to mark paths in the explored topic. The following is a synthesis of the most relevant studies found in the branch databases. Table 1 summarizes the solutions presented in the sintering of the results. The branches present segmented studies on GIS-based topics, given as an accurate solution applied to real cases in cities such as Şanlıurfa, Turkey (Rızvanoğlu et al., 2019), where it is applied using linear programming. In the Santiago área, they generated a solution based on combinatorial optimization, integer programming, and GIS tolos (Arribas et al., 2010), Asalon India generates optimal GIS routes to determine which were the most efficient in terms of cost/minimum distance to transport solid waste to the landfill (Ghose et al., 2006); and (Zamorano et al., 2009) analyzed the municipal waste collection in Churriana de la Vega (Granada, Spain), and described a way to improve the waste collection service, based on the information provided by Geographic Information Systems. The results of our study showed that the municipality had an excessive number of containers for organic matter and residual waste fractions. And some studies used “ArcGIS Network Analyst Extension” (*ArcGIS Network Analyst | Vehicle Routing Problem & Spatial Network Analysis*, n.d.), in (Karadimas et al., 2007) perform a simulation consisting of scenarios of visiting loading points in the municipality of Athens, to collect large items that could not be collected by standard waste collection trucks, due to their size and other prohibitive obstacles. Network Analyst is used to estimate the interrelationships between dynamic factors, such as changes in network traffic (closed roads due to natural or technical causes, e.g., fallen trees, car accidents, etc.) in the area under study and to produce optimized solutions. In (Karadimas et al., 2008), were implemented and discussed two individual metaheuristic algorithmic solutions, ArcGIS Network Analyst and the ant colony algorithm (ACO), for the identification of optimal routes in the case of RRSU. Finally, (Sallem et al., 2021) improved collection efficiency by reallocating collection containers and optimizing vehicle routing in terms of distance or time; the routing optimization process contributed to an expected benefit of 10.11% of the total cost. From the above, ArcGIS Network Analyst's ability to model, analyze, and optimize transportation networks makes it a valuable tool for addressing real-world cases in solid waste collection because it allows the consideration of various network constraints, such as speed limits, street directions, turning restrictions, and other factors that are crucial for accurate and realistic route planning, which generates the ability to Model Complex Networks, taking into account factors such as one-way streets and multi-lane highways. It generates seamless integration with mapping information such as dumpster locations, residential areas, and other data relevant to route planning. Another branch of approach is the use of different algorithms as solution techniques for these problems. There are several stages in the development of solution methodologies for addressing combinatorial problems. First, mathematical models that can solve small-sized problems are presented; however, as the models are refined, approximate methodologies capable of solving medium-sized instances can be designed. It cannot be ignored that before the formal appearance of a mathematical model, the situation is solved based the knowledge of the problem by those who manage with this model daily. Here, we propose heuristic methodologies that can be enhanced with intelligent strategies to develop the search in the space of solutions for larger instances and generally in shorter computational times. In the 1990s, metaheuristics appeared (Sörensen & Glover, 2013) as a solution strategy that, based on the behavior of nature, copied its behavior to manage the search for promising regions to develop good quality solutions. Finally, in the last decade, hybrid techniques such as math-heuristics have been proposed whose philosophy is to divide the problem into stages: one of them is solved in an exact way and the other(s) in an approximate way by using heuristics and metaheuristics or exact solvers and hybrid solution methods. Figure 9 shows the solution techniques and algorithms most commonly used in the branches that have given a solution and development to the different methodologies that solve vehicle routing problems in solid waste collection.

For new lines of study, there is evidence of knowledge generation in the application of route optimization models to estimate emissions from the collection of household organic waste; one case is in Australia (Yazdani et al., 2021). In contrast, in Sevilla (Spain), they presented a mathematical model with an eco-efficient objective function that considers external costs (climate change and air pollution) (Molina et al., 2019). Giang Vietnam proposed the analysis of GIS, integer linear programming (ILP), and mixed integer linear programming (MILP) to optimize vehicle routing and carbon dioxide emissions from municipal solid waste collection, where the proposed ILP is reduced from 7% to 13.7%, and the proposed MILP model is reduced from 15.1% to 21.5% (Dao-Tuan et al., 2018). On the other hand, Artificial Intelligence is beginning to bring more complete and efficient solutions to the table, one challenge of route planning is the type and quantity of, important factors in determining how this waste should be handled, managed and recovered, in (Kontokosta et al., 2018) make use of machine learning and small area estimation to predict building-level municipal solid waste generation in cities, which has the potential to support the optimization of collection truck routes based on expected waste generation rates, generating a forecast of multiple sorting of municipal solid waste using deep time-series learning based on living standards. Another AI approach is given in (Li & Li, 2019) where they apply Deep Neural Network to learning heuristics for combinatorial optimization problems automatically, in (Kool et al., 2018) significantly improve the heuristics learned for the traveling salesman problem (TSP) from reinforced learning, in (Díaz de León-Hicks et al., 2023) explore the use of attention-based neural networks as meta-learners to improve the performance mapping mechanism in the algorithm selection problem and take full advantage of the model's capabilities for pattern extraction.

In (Wang et al., 2022), with the objective of minimizing the total vehicle routing distance, a multiagent deep reinforcement learning model was proposed. In the same way (Yaddaden et al., 2022), NOFSS is first-fraction-of-second order neural deep reinforcement learning approach for capacity-constrained CVRP. NOFSS consists of a hybridization between a deep neural network model and a dynamic programming shortest path (Split) algorithm. Results based on intensive experiments with various neural network model architectures show that such two-step hybridization enables the learning of implicit algorithms (i.e., policies) that produce competitive solutions for CVRP.

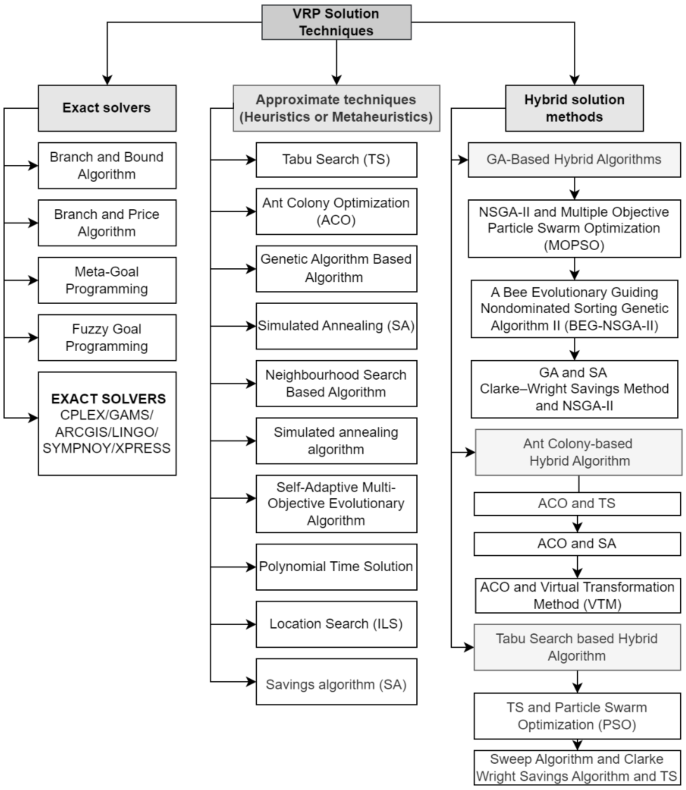


**Fig. 9.** Solution Techniques present in the branches

*Own Elaboration*

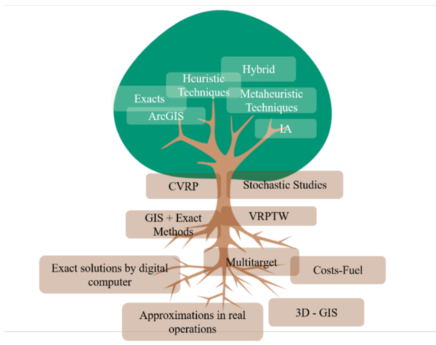


**Fig. 10**.ToS - Optimization of urban solid waste collection

*Own Elaboration*

Although vehicle routing is a classic problem in combinatorial optimization, a large number of exact and heuristic solution methods have been developed in the past. In recent years, machine learning algorithms have been applied to this type of problem with some success, where the three most important in machine learning are reinforcement learning, dynamic attention modeling, and large neighborhood neural search (Vamsi Krishna Munjuluri et al., 2022). It was found that the neural large neighborhood approach provided the best quality solutions, that the dynamic attention model required the most memory and could not be trained for larger instances, and that reinforcement learning provided a good trade-off between execution time and solution quality. AI-based methods show that exploring more complex and advanced performance mapping mechanisms seems to yield good results that could significantly improve the resolution of a problem instance through algorithm selection framework. Finally, the Appendix of Table 1 is presented, where the research is consolidated by modeling approaches, solution methods, and deterministic or stochastic approaches.

**Table 1**
Tree of Science Literature Review (Tos).

| Year | Reference | Modeling approaches | | | | | | Solution Methods | | | Deterministic | Stochastic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TSP | VRPTW | SIG | CVRP | G-VRP | VRPSTT | Exact | Heuristics | Meta-heuristics | | |
| **Roots** | | | | | | | | | | | | |
| 1964 | (Clarke & Wright, 1964) | √ | | | | | | √ | | | √ | |
| 2000 | (Tung & Pinnoi, 2000b) | | √ | | | | | | √ | | √ | |
| 2002 | (Angelelli & Speranza, 2002) | | | | √ | | | | | | √ | |
| 2005 | (Sahoo et al., 2005) | | √ | √ | | | | √ | | | √ | |
| 2009 | (Tavares et al., 2009b) | | | √ | | | | √ | | | √ | |
| 2011 | (Faccio et al., 2011b) | | | | | √ | | | | √ | √ | |
| 2012 | (Buhrkal et al., 2012) | | √ | | | | | | | √ | √ | |
| 2015 | (Das & Bhattacharyya, 2015) | | | | | | | | √ | | √ | |
| **Trunk** | | | | | | | | | | | | |
| 2006 | (Kim et al., 2006b) | | √ | | | | | | | √ | √ | |
| 2009 | (Chalkias & Lasaridi, 2009) | | | √ | | | | √ | | | √ | |
| 2009 | (Tavares et al., 2009b) | | | √ | | | | √ | | | | √ |
| 2011 | (Faccio et al., 2011a) | | | | | √ | | | | √ | | √ |
| 2014 | (Malakahmad et al., 2014) | | | √ | | | | √ | | | √ | |
| 2016 | (Khan & Samadder, 2016) | | | √ | | | | √ | | | √ | |
| 2017 | (Akhtar et al., 2017b) | | | | √ | | | | | √ | √ | |
| 2017 | (Gruler et al., 2017) | | | | √ | | | | | √ | | √ |
| 2018 | (Hannan et al., 2018) | | | | √ | | | | | √ | √ | |
| 2018 | (Guimarans et al., 2018) | | | | | | √ | | | √ | | √ |
| 2019 | (Mofid-Nakhaee & Barzinpour, 2019) | | | | √ | | | | | √ | √ | |
| 2019 | (Asefi et al., 2019) | | √ | | | | | √ | | | | √ |
| 2020 | (Gruler et al., 2020) | | | | | | √ | | | √ | | √ |
| 2021 | (Latorre-Biel et al., 2021) | | | | √ | | | | √ | | | √ |
| **Branches** | | | | | | | | | | | | |
| 2007 | (Karadimas et al., 2007) | | | √ | √ | | | √ | | | | √ |
| 2008 | (Karadimas et al., 2008) | | | √ | | | | | | √ | | √ |
| 2009 | (Zamorano et al., 2009) | | | √ | | | | √ | | | √ | |
| 2010 | (Arribas et al., 2010) | | | √ | | | | √ | | √ | | |
| 2013 | (Sörensen & Glover, 2013) | | | | | | | | | √ | √ | |
| 2018 | (Dao-Tuan et al., 2018) | | | √ | | √ | | √ | | | √ | |
| 2018 | (Kontokosta et al., 2018) | | | | | | | | | | | √ |
| 2018 | (Kool et al., 2018) | √ | | | | | | | √ | | | |
| 2019 | (Molina et al., 2019) | | | | | √ | | | √ | | √ | |
| 2019 | (Li & Li, 2019) | | | | | | | | √ | | | √ |
| 2021 | (Sallem et al., 2021) | | | √ | | | | √ | | | | √ |
| 2022 | (Yazdani et al., 2021) | | | | | √ | | | | √ | √ | |
| 2022 | (Yaddaden et al., 2022) | | | | √ | | | | | √ | | √ |

*3.1.2 Systematic Literature Review*

There are two main areas in scientific literature on this subject: Reverse Logistics (RL) and Waste Management (RM). The first examines the collection and handling of end-use products by consumers. The second area is waste management, defined as "characteristic activities that include (a) collection, transportation, treatment and disposal of waste, (b) control, monitoring and regulation of waste production, collection, transportation, treatment and disposal, and (c) prevention of waste production through process modifications, reuse and recycling". RL and WM clearly overlapped. Both fields study (among other issues) the flows of discarded products leaving the final consumer. For this purpose, a specific definition a reverse waste supply chain is used. Their intersection in both fields (WM and RL) has developed into a broad line of research encompassing theoretical or experimental studies on logistics, waste management, and all levels of network design. Therefore, this review concentrates on the subfield of network design, specifically the optimization of solid waste collection. Therefore, the following is a taxonomic analysis of route optimization from the perspective of the following parameters:

- Modeling approaches and solution techniques
- Applied VRP variants
- Objective functions, decision variables, and constraints
- Applications in real-world settings
- Applied algorithms
- Studies considering uncertainty conditions

The list of articles reviewed by SLR is presented in Table 8 of the Appendix, which is divided into three main parts: modeling approaches and solution methods. In recent years, the Vehicle Routing Problem (VRP) in Municipal Solid Waste (MSW) collection has been widely studied, and numerous contributions have been made in the literature. One of the most important research lines is modeling approaches, as they allow for precise representation, efficient resolution, and adaptability to changing contexts, resulting in significant improvements in efficiency and decision-making, in this case, in the logistics industry. These can be categorized into

## 1. Traditional approaches:

Capacitated Vehicle Routing Problem (CVRP): In the study of solution techniques for routing problems, it is considered that a technique which is efficient for the CVRP can be efficient for any other variant, due to the fact that this represents the fundamental problem of the distribution chain (Ocampo et al., 2020). To develop the mathematical formulation of the CVRP, the following notations are used, as listed in Table 2 (Kumari et al., 2023).

**Table 2**
Notations used in the mathematical model formulation.

| *PARAMETER* | *DESCRIPTION* |
|---|---|
| $O$ | *Depot location* |
| $J$ | *Set of nodes to be serviced J= {j│1, 2, ..., │J│}* |
| $N$ | *Set of depots and nodes N= {n│0,1, 2, ... │N│}* |
| $K$ | *Set of vehicles K= {k│1, 2, ..., │K│}* |
| $D_j$ | *Demand of j* |
| $C_{ij}$ | *Transportation cost from node i to j; i n j ϵ N* |
| $v_{cap}$ | *Vehicle capacity* |

**Problem Formulation**

The main goal of CVRP is to determine the most cost-effective routes while serving a group of nodes scattered across different geographic locations with varying demands. Costs were assessed based on travel distance. Each node was visited once by a single vehicle. All vehicles have identical capacity limitations. A vehicle initiates its route at the depot, covers a sequence of nodes, and then returns to the depot. Each route is allocated to only one vehicle. The objective function is as follows:

$$min\ z: \sum_{i\,\epsilon\,\mathrm{N}}\sum_{\mathrm{j}\,\epsilon\,\mathrm{N}}\sum_{k\,\epsilon\,\mathrm{N}} C_{ij}\, x_{ijk} \tag{1}$$

*subject to:*

$$\sum_{j\,\epsilon\,N} x_{0jk} = 1 \quad \forall\, k \tag{2}$$

$$\sum_{i\,\epsilon\,N} x_{i0k} = 1 \quad \forall\, k \tag{3}$$

$$\sum_{i\,\epsilon\,N}\sum_{k\epsilon K} x_{ijk} = 1 \quad i \neq j \tag{4}$$

$$\forall\, j\ \in N$$

$$\sum_{\substack{i\,\epsilon\,N \\ i \neq j \\ \in K}} x_{ijk} - \sum_{i\,\epsilon\,N} x_{ijk} = 0 \qquad \forall\, j \in J, \forall\, K \tag{5}$$

$$\sum_{i\,\epsilon\,N}\sum_{j\epsilon J} D_j x_{ijk} \leq v_{cap} \quad \forall\, k \tag{6}$$

$$X_{ijK}: \begin{cases} 1\ if\ \ k^{th}\ vehicle\ travels\ from\ node\ i\ to\ node\ j \\ \qquad 0\ if\ not \end{cases} \tag{7}$$

The decision variable is $X_{ijK}$. The primary objective is to minimize the total routing costs, as shown in Eq. (1). Eq. (2) and Eq. (3) ensure that each vehicle departs from the depot, travels through nodes, and returns to the depot. Each vehicle was restricted to travel to each node only once, as shown in Eq. (4). Eq. (5) ensures a flow conservation constraint. The vehicle capacity limitation is defined by Eq. (6), and Eq. (7) indicates that the decision variable is binary in nature. In waste collection, optimization problems are modeled as integer or mixed-integer linear programming problems, and two approaches are widely used in modeling. In the first approach, a CVRP is modeled by considering the exact service points as collection points or nodes to be served. With CVRPs, when the number of service points (nodes) increases, the size of the problem and thus the time required to solve it increases considerably. Therefore, CVRPs are classified as NP-hard problems that are difficult to solve by using algorithms. Real cases of waste collection problems that are modeled as CVRPs are generally solved with heuristic search algorithms that provide near-optimal solutions; in (Rambandara et al., 2022), for example, formulated the problem as a capacitated arc routing problem (CARP) using binary integer programming (BIP) methods, to reassign road segments (arcs) to tractors to minimize the total number of trips and the distance traveled by tractors and in (Priyadarshi et al., 2023) formulated a CVRP in dynamic environments using an Agent-Based Modeling (ABM) approach to maximize waste collection by minimizing the distance to the central depot. On the other hand, in (Alberdi et al., 2020), based on the trained approach, the WCVRP was modeled using a simple but efficient and particularly easy-to-maintain solution. Real data were used and solved using Genetic Algorithm (GA). The computations were performed in two different ways: using a completely random initial population, and including a seed in this initial population. To ensure that the solution is efficient, the performance of the genetic algorithm has is compared with another good performing algorithm, the Variable Neighborhood Search (VNS) algorithm. Three problems of different sizes were solved, and, in all cases, a significant improvement was obtained, resulting in a total reduction of 40% of itineraries with a consequent reduction in emissions and costs. The following is a summary of what CVRP means in this type of logistics focused on solid waste collection.

**Table 3**
Relevant CVRP results in solid waste collection operations

| Modeling approach | Problem type variants | Solution method | Results and improvements | Reference |
|---|---|---|---|---|
| Binary Integer Programming (BIP), Capacitated Arc Routing (CARP) | CVRP | Heuristic algorithms | Efficient reallocation of road segments to minimize trips and distance. | (Rambandara et al., 2022) |
| Agent-Based Modeling (ABM) | CVRP in dynamic environments | Heuristic algorithms | Maximization of waste collection, minimization of distance to the central depot. | (Priyadarshi et al., 2023) |
| Genetic (GA) | WCVRP | GA y Variable Neighborhood Search (VNS) | Significant reduction (40%) of itineraries, emissions and costs with GA compared to VNS. | (Alberdi et al., 2020) |

**Traveler's Problem (TSP):** It is one of the most complex problems known in current mathematical programming because of its computational complexity and is classified within those problems considered NP-Hard. The importance of the TSP lies not only in the number of applications it has, but also in the fact that the research carried out on the TSP is easily applicable to other routing problems that are usually generalized. Several types of routing problems are differentiated by the constraints imposed. In (Ulusam Seçkiner et al., 2021), the study is developed as a capacitated traveling salesman problem (CTSP), which is different from a typical TSP, where the problem statement itself is required to be added. A CTSP is a routing problem in which a vehicle has a limited capacity that prevents it from visiting all locations in one run; therefore, so it needs a second-round trip is required. The ACO algorithm was used to obtain a near-optimal solution. This algorithm is preferable to exact methods for solving combinatorial routing problems. In (Mekamcha et al., 2021), the problem of waste collection in the city of Tlemcen, Algeria was proposed. Because of the complexity of this real-life problem, two known classes of metaheuristics are used, the tabu search algorithm (TS) and a simulated annealing algorithm (SA), indicating that the SA performs better in minimizing the distance traveled in the vast majority of cases.

**Table 4**
Relevant results TSP in solid waste collection operations.

| Modeling approach | Problem type variants | Solution method | Results and improvements | Reference |
|---|---|---|---|---|
| TSP | CTSP (Trained Traveling Salesperson) | ACO Algorithm | CTSP development; Use of ACO to find near-optimal solutions; Focus on combinatorial routing problems. | (Ulusam Seçkiner et al., 2021) |
| Waste collection TSP | TSP | Tabu Search Algorithm (TS) and Simulated Annealing Algorithm (SA) | Application in the real context of the city of Tlemcen in Algeria; Comparison of TS and SA; SA more effective in minimizing the distance traveled in most cases. | (Mekamcha et al., 2021) |

**The VRP with Time Windows VRPTW:** The vehicle routing problem with time windows (VRPTW) can be defined as the choice of routes for a limited number of vehicles to serve a group of customers in time windows.

Each vehicle has a limited capacity. It started at the depot and ended at the depot. Each customer must be served only once. If vehicles arrive before the time window "opens" or after the time window "closes", there will be a waiting cost and a delay cost. In the context of solid waste collection, the VRPTW is of significant importance. Here, time window constraints become critical because of nature of waste collection, where it is crucial to collect waste at specific times to avoid accumulations or to comply with noise or traffic regulations during certain periods of the day. Some types of VRPTW applied to the collection of solid waste are in (Mahdavi et al., 2022) solve the sustainable multi-period, multi-trip vehicle routing problem integrated with relocation models to redesign intermediate transfer stations and find optimal vehicle routes and the best collection frequency for each municipal solid waste generation point, where a MILP model is developed for urban waste collection that considers a multi-trip VRP with time windows, in this study a solution is generated with an SA algorithm to solve the model in small and medium sizes. In (Valizadeh et al., 2022), a new model for municipal waste VRP with time windows and waste-to-energy generation was presented. For this, they presented a bi-objective model with the objectives of increasing the income of waste recyclers and waste-to-energy generation and reducing the emissions of environmental pollutants, and developed a metaheuristic method, such as two non-dominated sorting genetic algorithms (NSGA II) and multi-objective particle swarm optimization (MOPSO) algorithms, where it was found that the NSGA-II algorithm is more desirable based on the number of Pareto solutions and diversity criteria.

Wan et al. (1 C.E.) proposed a multi-model based on Time Windows, with a solution approach based on MILP, where their solution technique is a combination of Clarke and Wright's sparing algorithm and the dynamic task assignment algorithm. Finally, (Abdallah et al., 2019b) appropriated an exact method based on a routing model based on Dijkstra's algorithm, which is the simplest algorithm for determining calculated routes according to expected travel times. The network-based routing tool used in this study was the Network Analyst extension in ArcGIS.

**Table 5**
Relevant results VRPTW in solid waste collection operations.

| Problem type variants | Solution method | Results and improvements | Reference |
|---|---|---|---|
| VRPTW in waste collection | MILP model and SA algorithm | Solution for multi-trip VRP with time windows, considering urban waste collection networks. SA algorithm applied to small and medium size models. | (Mahdavi et al., 2022) |
| VRP of municipal waste with energy generation | Biobjective model, NSGA-II, MOPSO | Increased revenues for recyclers, energy generation and emissions reduction. Comparison of NSGA-II and MOPSO algorithms. | (Valizadeh et al., 2022) |
| Multi-Model based on Time Windows | MILP-based solution, combination of Clarke and Wright algorithm and dynamic tasking | Multi-Model approach with time windows. Solution technique combining Clarke and Wright algorithms with dynamic task assignment. | (Wan et al., 1 C.E.) |
| Dijkstra-based exact method | Routing model based on Dijkstra algorithm and ArcGIS Network Analyst. | Accurate method based on routing model with Dijkstra algorithm and Network Analyst tool of ArcGIS to determine routes according to expected travel times. | (Abdallah et al., 2019b) |

## 2. Solution techniques

As noted in the previous section, base VRPs seek different solution strategies to deploy routing solutions; therefore, heuristic and metaheuristic-based techniques playa an important role in the area and are widely used because of their ability to address complex problems and find acceptable solutions within a reasonable time.

**The Heuristic Approach:** Is strategy or method that, although not guaranteed to find the optimal solution, provides satisfactory or acceptable solutions quickly and practically. These approaches are used in situations in which an exhaustive search for the optimal solution is impractical because the complexity of the problem or time and resource constraints. Heuristic approaches are practical rules based on experience, general knowledge, or simplified techniques that guide the search acceptable solutions. They are often designed to solve complex problems more efficiently than exact methods, although they cannot guarantee the best possible solution. One strategy is given in (Van Engeland & Beliën, 2021), where a model is developed to build tactical waste collection schemes in which a set of trained vehicles visits a set of customers during a given time period based on a heuristic using CG and MILP column generation. The CG technique was used to generate new routes, and the MILP-based heuristic was used to optimize the routes generated by the CG technique. In (Hurkmans et al., 2021), the authors investigated the influence of three objectives: minimum overlap, minimum travel time, and balanced workload, and verified whether they could be contradictory. To this end, they developed an ALNS for this specific problem using a K-means algorithm to generate the initial solution for the territories and discussed the use of various heuristics such as local search, tabu search, cluster first, routing second approach, sweep algorithm, K-means, and insertion by displacement. The Results with all three objectives were shown to be useful for planners seeking to make informed decisions through trade-offs between different solutions with the Pareto frontiers provided, and the ALNS algorithm was shown to find Good-quality solutions in a reasonable computational time. (Shi et al., 2020a), In this study, a heuristic solution method is proposed to address the multi-depot vehicle routing problem (MDVRP) for waste collection. The proposed method involves assigning waste collection points to waste disposal plants according to the nearest distance and then solving the VRP, for each plant respectively. The sector combination optimization (SCO) algorithm is used to generate multiple initial solutions, and then these initial solutions are improved using the merge head and tail removal (MHDT) strategy. After a certain number of iterations, the optimal solution is reported in the last generation.

**Metaheuristic approaches:**

Metaheuristics were developed towards the end of the 1990s and are characterized by the fact that they perform a search procedure to find solutions of acceptable quality, through the application of domain-independent operators that modify intermediate solutions guided by the suitability of their objective function (Rocha Medina et al., 2011). A metaheuristic approach is an optimization problem solving strategy used to find high quality solutions in a complex and large search space. Unlike heuristic methods, metaheuristics are more general and abstract, providing a flexible framework for exploring and exploiting the solution space in search of near-optimal results, although without always guaranteeing the globally optimal solution. These approaches are suitable for difficult or computationally complex problems, where exact methods might be inefficient due to the size of the search space or the presence of multiple local optima.

Some key features of metaheuristic approaches:

- Flexibility: they can be applied to a wide range of optimization problems without the need for extensive adaptations.
- Exploration and exploitation: They allow exploration of the solution space in search of new promising areas (exploration), as well as exploitation of promising areas already found to improve solutions (exploitation).
- Adaptability: They can be adjusted or modified to suit different problems or specific contexts.

**Some common examples of metaheuristic approaches include:**

- **Genetic Algorithms (GA):** Inspired by biological evolution, developed by John Holland and his collaborators in the 1960s and 1970s, is a model or abstraction of biological evolution based on Charles Darwin's theory of natural selection. Holland was probably the first to use crossover and recombination, mutation and selection in the study of adaptive and artificial systems (Yang, 2014). These genetic operators form the essential part of the genetic algorithm as a problem-solving strategy. They use operators such as selection, crossover and mutation to generate new solutions.
- **Simulated Annealing (SA)**: Proposed by Kirkpatrick, it was the first metaheuristic algorithm based on nonlinear physical processes. Proposed in the early 1980s, this algorithm was inspired by the annealing process in materials science, which is concerned with obtaining the material configurations with minimum energy of the material molecules or atoms. SA mimics the annealing process in such a way that the material molecules represent the candidate solution of the optimization problem and the energy of the system is used to represent the fitness function (Chattopadhyay et al., 2023) .
- **Particle Swarm Optimization (PSO):** PSO behavior is inspired by the strategy that bird swarms follow while searching for optimal food sources. During the search process, the direction of a bird's movement is biased by its current movement towards the search for the best food source, where this movement is inspired by the bird's knowledge, the swarm's knowledge and inertia. This procedure is simulated in the PSO algorithm by representing the personal/global best position and inertia for each particle representing a solution. Each particle has a specific position, velocity and target, and tries to reserve the best global value as a function of achieving the best target value, as well as the best global position (Ashour & Guo, 2020).
- **Tabu Search (TS):** Using memory to avoid cycles and explore different neighborhoods of solutions, it is a metaheuristic local search method used for mathematical optimization. Local search methods tend to get stuck in suboptimal regions. TS improves the performance of these techniques by prohibiting already visited solutions or others through user-supplied rules (Tsai & Chiang, 2023).
- **Ant Colony Optimization Algorithm (ACO):** It is inspired by the foraging behavior of ants. At the core of this behavior is the indirect communication between ants with the help of chemical pheromone trails, which allows them to find short paths between their nest and food sources(Ahmed et al., 2020).

Metaheuristic approaches are efficient and flexible search methods used to solve complex optimization problems, providing high quality solutions in a reasonable time, although they do not always guarantee the optimal solution. In (Stanković et al., 2020), address capacity-constrained and distance-constrained vehicle routing problem for municipal waste collection (DCCVRP-MWC), with four metaheuristic algorithms: GA, ACO, SA and PSO, it is important to note that the study takes into account the uncertainty in the waste generation process and use a simulation-based approach to evaluate the performance of the proposed algorithms in different scenarios. The study demonstrates that the proposed algorithms can effectively handle the uncertainty in the waste generation process and provide near-optimal solutions to the problem. On the other hand, (Hashemi, 2021) They take a comprehensive approach by applying fuzzy mathematical programming to design a multi-objective model for a reverse logistics network where they minimize the construction cost of the facilities, the fuel of the vehicles and the environmental damage due to the emission of polluting gases, as well as minimize the sum of the ratio between the non-response demand of the customers and the amount of their demand for all the periods. In order to obtain solutions, a NSGAII and a BCO were applied. Where BCO was able to explore and extract the area to a feasible solution and achieve near optimal responses. In terms of spacing metrics and resolution time, the NSGAII performed better than the bee algorithm. In (Mohajeri et al., 2020) a mathematical model for the reverse supply chain of municipal waste under uncertainty is presented. The model under study is multi-objective and its objectives include minimizing transportation costs and environmental impacts, and maximizing the amount of demand responded to the customer. Experimental sample problems were designed in three groups of small, medium and large size according to the forecasting study. Two whale optimization algorithms were proposed as solutions and the NSGA-II algorithm was compared according to standard indicators of quality, dispersion, uniformity and dissolution time. The results show that, in all cases, the whale algorithm has the ability to explore and extract the possible area of response and achieve near-optimal results. In terms of uniformity and resolution time, the

NSGA-II algorithm performed better than the whale algorithm. In (Akbarpour et al., 2021), a proposed model including two steps is proposed. The first sub-model is applied using VRP to find the best route for waste collection within each area, and the second sub-model is introduced to allocate resources from sorting facilities to the set of recovery plants or landfill. The main contribution of the study is to use the VRP concept in the first submodel and plan LCV and HCV vehicles to collect waste within each area and transfer it to the recovery facility. Random constrained programming along with four different metaheuristic algorithms were used to test the proposed problem. The result showed a good consistency of the applied metaheuristics and GA-PSO showed the best results, among others.

(Gläser, 2022) corresponds to a type-of-service-choice problem (WCPSTO) is modeled as a new variant of a periodic location routing problem and an ALNS solution approach is proposed. This solution approach not only solves the problem just presented, but also outperforms a solution algorithm for a related garbage collection problem seen in the literature, which can be viewed as a special case of the WCPSTO, an ALNS was developed, whose good performance has been demonstrated in tests on both small and large instances. From the modeling point of view, a new set of subtour elimination constraints was proposed to cope with intermediate facilities, where waste is unloaded. In (Armandi et al., 2019), a VRP problem, with a heterogeneous fleet, multiple trips, intermediate facilities and split delivery is developed to address the waste collection problem. A hybrid GA was proposed to solve the VRP and compared with PSO. The GA is used the splitting technique in the VRP evaluation stage and a local search algorithm after the evaluation stage. The selection, crossover, and mutation stages use the Roulette Wheel Selection, Multiple Point Crossover, and Reorganization Mutation techniques, respectively. The GA developed with the LS in this study proved to be more effective and efficient compared to the PSO algorithm in terms of finding the minimum value of the objective function and computational time.

**Hybrid Techniques:**

For example, in (Akkad & Bányai, 2020), an optimization model is presented is twofold: first, the optimal structure of the multilevel collection and distribution system is designed, including design planning and determination of the required transportation resources, such as electric cars, electric bicycles and the use of public transportation; and second, the operational strategy of the multilevel supply chain is optimized, including resource allocation and scheduling problems. Its solution is recorded as a heuristic approach, whose performance is validated with common benchmark functions, such as metaheuristic evaluation. The scenario analysis demonstrates the application of the model and shows the optimal design, resource allocation and operational strategy focusing on energy efficiency and is generated from an evolutionary option of the Excel Solver, which represents a robust algorithm for solving NP-hard optimization problems. This option is based on an evolutionary method, such as genetic algorithm or particle swarm optimization methods. The Solver starts with a random population and uses crossover and mutation operators to avoid local optima, in order to find the near-global optimal solution of the NP-hard optimization problem.

**Table 6**
Relevant results solution techniques in solid waste collection operations

| Reference | Methodology | Key Result |
|---|---|---|
| (Van Engeland & Beliën, 2021) | Heuristics based on CG and MILP | Development of tactical waste collection schemes based on heuristics and CG/MILP. |
| (Hurkmans et al., 2021) | ALNS with K-means and various heuristics | Investigation of conflicting objectives and application of ALNS to address the problem |
| (Shi et al., 2020a) | SCO y MHDT | Heuristic method for MDVRP using SCO, MHDT and iterative improvement. |
| (Stanković et al., 2020) | GA, ACO, SA, PSO | Comparison of metaheuristic algorithms for DCCVRP-MWC with consideration of uncertainty. |
| (Hashemi, 2021) | NSGAII, BCO | Multi-objective model for reverse logistics with NSGAII and BCO. |
| (Mohajeri et al., 2020) | Whale Algorithms and NSGA-II | Multi-objective model for reverse supply chain with algorithm comparison. |
| (Akbarpour et al., 2021) | VRP and GA-PSO | Proposed model with VRP and resource allocation using GA-PSO. |
| (Gläser, 2022) | ALNS | Solving the WCPSTO problem with ALNS approach. |
| (Armandi et al., 2019) | Hybrid GA with PSO and LS | VRP with heterogeneous fleet and hybrid GA compared to PSO. |
| (Akkad & Bányai, 2020) | Heuristic evolutionary approach | Multi-level supply chain optimization with Excel Solver. |

## 3. Stochastic Models

The vehicle routing problem with stochastic demands (VRPSD) is a combinatorial optimization problem. The VRPSD searches for vehicle routes to connect all customers to a depot such that the total distance is minimized, each customer is visited once by a vehicle, each route starts and ends at a depot, and the distance traveled and the capacity of each vehicle are less than or equal to the given maximum value. Unlike classical VRP, in VRPSD the demand at a node is known only after a vehicle arrives at the same node. This means that vehicle routes are designed under uncertain conditions. For example, in (Marković et al., 2020) presents a heuristic and metaheuristic approach to solve the VRPSD making use of heuristic and metaheuristic algorithms where the performance of Clarke and Wright's sparing algorithm, the sweep algorithm and the GA are compared. Their findings showed that the GA outperformed the other algorithms in terms of solution quality and computation time. In (Rahmandoust et al., 2023) a mathematical model with conflicting objects is proposed, at the upper level of the model of maximizing government revenues from waste recycling and at the lower level of minimizing waste collection and recycling costs, which had stochastic parameters and was scenario-based, due to the complexity of the two-level model, the KKT approach was adopted to unify the model. Finally, the relevant calculations were performed based on real information. The results of the case study problem showed the efficiency of the proposed method. Several computational analyses randomly generated different waste recycling rates and obtained significant management results.

(Kůdela et al., 2020) develop a multistage stochastic mixed integer optimization model for developing a sustainable processing infrastructure. The model is designed to capture the planning and decision-making process in selecting waste treatment plant locations and sizes, and the subsequent allocation of waste streams. The model allows sequential decision making and evaluation of various strategies for different future scenarios with specific years, locations, technologies and capacities for the establishment of waste processing infrastructure. While in (Vu et al., 2019), not suggest a traditional stochastic approach, but rather generate scenario from a nonlinear autoregressive ANN model to predict the waste generation rate of the recycling and garbage streams, resulting in mean absolute percentage errors that ranged from 10.92% to 16.51%. What is used as inputs are the modified compositions of the recycling and trash streams, along with the year's generation rates, to create 6 modified and 3 unmodified scenarios that reflect possible future changes in waste composition. These waste stream scenarios are then used as input parameters to determine optimal waste collection routes with minimum travel distance in each of the four subareas using the GIS vehicle routing problem network analysis tool. The results of these 36 scenarios yield changes in distance traveled of up to 19.9% compared to the unmodified composition. In addition, the two-compartment trucks were compared to the single-compartment trucks and were found to save 10.3% to 16.0% in travel distance and slightly reduce emissions, but had a 15.7% to 19.8% increase in pickup time. The results suggest that temporal changes in waste composition and characteristics are important in GIS route optimization studies.

**Table 7**
Relevant results on stochastic models in solid waste collection operations.

| Reference | Methodology | Key Result |
|---|---|---|
| (Marković et al., 2020) | Clarke and Wright Saving Algorithm, Sweep Algorithm, GA | Performance comparison, where GA outperformed in solution quality and computation time. |
| (Rahmandoust et al., 2023) | Performance comparison, where GA outperformed in solution quality and computation time. | Efficiency of the proposed method in maximizing government revenues and minimizing costs. |
| (Kůdela et al., 2020) | Multi-stage model for waste processing infrastructure | Sequential decision making for treatment plant locations and sizing with strategy evaluation. |
| (Vu et al., 2019) | Scenario generation based on waste generation rate predictions. | Changes in optimal collection routes based on modified waste composition scenarios. |

Finally, the Appendix of Table 8 is presented, where the research is consolidated by modeling approaches, solution methods and deterministic or stochastic approach evidenced in the systematic review of the literature.

**Table 8**
Literature review

| Year | Reference | Modeling approach | | | | | Solution method | | | Determinist | Stochastic |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TSP | VRPTW | CVRP | G-VRP | Otros | Exacts | Heuristics | Meta-heuristics | | |
| 2019 | (Abdallah et al., 2019b) | | √ | | | | √ | | | √ | |
| 2019 | (Armandi et al., 2019) | | | | | √ | | | √ | √ | |
| 2020 | (Alberdi et al., 2020) | | | √ | | | | | √ | √ | |
| 2020 | (Shi et al., 2020b) | | | | | √ | | √ | | √ | |
| 2020 | (Stanković et al., 2020) | | | | | √ | | | √ | | √ |
| 2020 | (Mohajeri et al., 2020) | | | | √ | | | | √ | √ | |
| 2020 | (Akkad & Bányai, 2020) | | | | | √ | | √ | √ | √ | |
| 2020 | (Marković et al., 2020) | | | | | √ | | √ | √ | | √ |
| 2020 | (Kůdela et al., 2020) | | | | | √ | | √ | √ | | √ |
| 2021 | (Mekamcha et al., 2021) | √ | | | | | | | √ | √ | |
| 2021 | (Van Engeland & Beliën, 2021) | | | √ | | | | √ | | √ | |
| 2021 | (Hurkmans et al., 2021) | | | | | | | √ | | √ | |
| 2021 | (Hashemi, 2021) | | | | √ | | | | √ | √ | |
| 2021 | (Akbarpour et al., 2021) | | | | | √ | | | √ | √ | |
| 2022 | (Rambandara et al., 2022) | | | | | √ | √ | | | √ | |
| 2022 | (Mahdavi et al., 2022) | | √ | | | | √ | | √ | | √ |
| 2022 | (Valizadeh et al., 2022) | | √ | | | | | | √ | √ | |
| 2022 | (Gläser, 2022) | | | | | √ | | | √ | √ | |
| 2023 | (Priyadarshi et al., 2023) | √ | | | | | | | √ | | √ |
| | (Wan et al., 1 C.E.) | | √ | | | | √ | | √ | | √ |
| 2023 | (Rahmanifar et al., 2023) | | | | | √ | | | √ | | √ |

## 4. Conclusions

### *4.1 Tree of Science – ToS*

The analysis of the science tree provides evidence of a historical evolution in the study of MSW route optimization, from the first publications in 1964 to the most recent approaches. Initial approaches, such as those of Clarke and Wright (1964), focused on iterative procedures for rapid selection of optimal routes, marking the beginning of research in this field, followed by the incorporation of real-world problems as the technological revolution was incorporated, a transition towards the inclusion of real-world problems, such as the complexity of waste collection in Hanoi (2000) and case studies approaching real operational situations in 2002 and 2005. One of the most important processes that has been included over time has been the use of emerging technologies, as in 2009, with 3D GIS modeling to optimize waste collection routes, showing a clear adaptation to advanced technological tools. A clear example is ArcGIS Network- Analyst Extension, a tool that can be an effective solution for route planning and optimization in real cases of solid waste collection, some key reasons is that it allows finding efficient routes to minimize collection time and reduce operating costs, considering network constraints such as speed limits, street directions, turning restrictions, and other factors that are crucial for accurate and realistic route planning in deterministic conditions. It demonstrates the ability to model complex networks owing to its integration with geospatial data and mapping information such as dumpster locations, residential areas, and other data relevant to route planning. However, its effectiveness depends on the complexity and nature of the problem, because its ability to handle uncertainty and variability is not optimal. However, multi-objective approach and real-time data since 2011 highlight the consolidation of multi-objective optimization models that incorporate real-time traceability data, demonstrating the search for more comprehensive and sustainable solutions. This has allowed the appropriation of efficient solution algorithms such as the adaptive large neighborhood search algorithm proposed by Buhrkal et al. in 2012, indicating a trend towards the practical application of advanced computational methods. The scalability and performance of larger and more complex route optimization problems, where a run-time efficient solution is needed, mathematical models, and heuristic and metaheuristic algorithms may be more appropriate in addition to their adaptability to changes in problem conditions and constraints, allowing for faster adjustments and updates. Finally, it is possible to find a solution from the separation at source, where the most recent work (Das & Bhattacharyya, 2015) highlights its importance and proposes an approach that significantly reduces the total length of waste collection routes, which can have a positive impact on the efficiency and sustainability of the system.

### *4.2 Systematic Literature Review*

A systematic review of the literature showed that 66% of the studies were applied to real operations, 60% were multi-objective studies, and 47% were studies based on uncertainty criteria, proposing models based on stochastic realities. Heuristic and metaheuristic approaches offer efficient and effective solutions for solving challenging vehicle-routing problems in waste-collection management. These methods have proven their usefulness in finding near-optimal solutions within reasonable computational times, which makes them relevant and applicable to waste logistics and distribution. The importance of heuristic approaches is evident because they offer acceptable solutions in practical times even though they do not guarantee an optimal solution. On the other hand, metaheuristic approaches, such as genetic algorithms, simulated annealing, particle swarm optimization, tabu search , and ant colony algorithms, explore solutions in complex and large search spaces. Some applications in routing problems propose heuristic and metaheuristic solutions to solve specific waste collection and VRP problems using algorithms such as column generation, evolutionary algorithms, and local search. Several studies have shown that metaheuristic approaches outperform traditional heuristic approaches in terms of solution quality and computational time for waste collection management. Hybrid approaches have been proposed for addressing the complexity of waste management. Finally, stochastic models consider uncertainty in waste collection, which has allowed the inclusion of future prediction and optimization, such as prediction models based on neural networks, to forecast waste generation rates and optimize routes based on possible future changes in waste composition or the generation of scenarios from waste generation rate predictions, among others.

## 5. Future Lines of Research

The exploration and development of advanced models of the Vehicle Routing Problem that integrate multiple objectives, with special emphasis on the incorporation of environmental and economic criteria, is suggested. This line of research seeks to design VRP solutions that respond in a balanced manner to today's sustainability requirements. This demonstrates the importance of the research and development of hybrid solution algorithms to address the complexity of VRP models in the context of solid waste collection operations, with a particular focus on practical applications that encompass multiple objectives. This study focuses on improving the efficiency and effectiveness of solutions in complex scenarios. This highlights the importance of developing VRP variants that incorporate Industry 4.0, tolos, and technologies, with a focus on uncertainty management. This study explores the development of dynamic routing systems that use real-time data and considers various uncertainty factors to improve the adaptability and efficiency of logistics operations.

Finally, artificial intelligence begins to generate optimal scenarios in heuristic and metaheuristic models, which makes it an efficient solution, in addition to generating effective applications for demand and time prediction in routing models.

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