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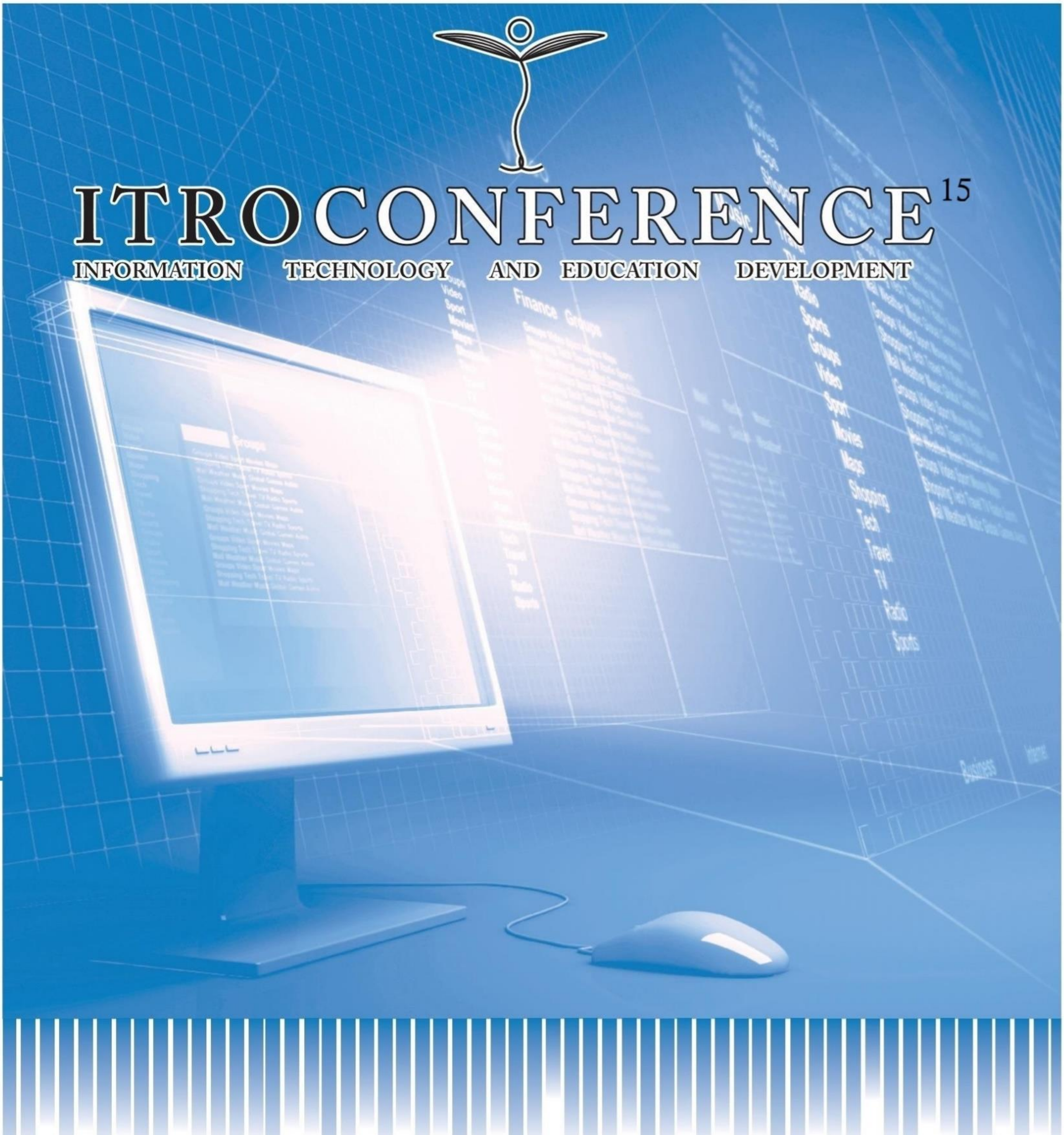
INFORMATION TECHNOLOGY AND EDUCATION DEVELOPMENT



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PROCEEDINGS

ZRENJANIN, November 2024

UNIVERSITY OF NOVI SAD
TECHNICAL FACULTY ”MIHAJLO PUPIN”
ZRENJANIN
REPUBLIC OF SERBIA

XV INTERNATIONAL CONFERENCE OF

INFORMATION TECHNOLOGY AND DEVELOPMENT OF EDUCATION
ITRO 2024

PROCEEDINGS OF PAPERS

XV MEĐUNARODNA KONFERENCIJA

INFORMACIONE TEHNOLOGIJE I RAZVOJ OBRAZOVANJA
ITRO 2024

ZBORNIK RADOVA

ZRENJANIN, NOVEMBER 2024

Publisher and Organizer of the Conference:
University of Novi Sad, Technical faculty „Mihajlo Pupin", Zrenjanin, Republic of Serbia

For publisher:
Milan Nikolić, Ph. D, Professor,
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Circulation: **50**

ISBN: 978-86-7672-383-6

CIP - Каталогизација у публикацији
Библиотека Матице српске, Нови Сад

37.01:004(082)
37.02(082)

INTERNATIONAL Conference on Information Technology and Development of Education ITRO (15 ; 2024 ; Zrenjanin)
Proceedings of papers [Elektronski izvor] / XV International Conference on Information Technology and Development of Education ITRO 2024 = Zbornik radova / XV međunarodna konferencija Informacione tehnologije i razvoj obrazovanja ITRO 2024, Zrenjanin, November 2024 ; [editors of proceedings Marjana Pardanjac, Jelena Stojanov]. - Zrenjanin : Technical Faculty "Mihajlo Pupin", 2024. - 1 elektronski optički disk (CD-ROM) ; 12 cm

Nasl. sa naslovnog ekrana. - Bibliografija uz svaki rad.

ISBN 978-86-7672-383-6

а) Информациона технологија - Образовање - Зборници б) Образовна технологија - Зборници

COBISS.SR-ID 159481865

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The Proceedings have been published in a digital format on the Faculty web site.

INTRODUCTION

This Proceedings present the articles delivered at the international conference Information Technology and Education Development (ITRO 2024), held for the jubilee fifteenth time on November 29, 2024. This international event was conducted in a hybrid format, combining in-person and online participation. The conference continues its tradition of bridging science, professional practice, and educational experiences, with this year's focus on the conditions and perspectives of teachers' digital competencies.

The thematic fields of the conference reflect contemporary trends in education, addressing topics such as: the digitalization of education, education in crisis situations, educational challenges, theoretical and methodological issues in contemporary pedagogy, digital didactics and media, modern communication strategies in teaching, curriculum development for contemporary education, advancements in e-learning, education management practices, methodological approaches in teaching natural and technical sciences, and the integration of information and communication technologies in education.

The conference featured three plenary lectures that explored various aspects of the main topic, with the corresponding articles included at the beginning of this volume.

In total, this edition comprises 57 peer-reviewed articles, evaluated through a double-blind review process. These contributions represent the latest research and advancements in the field.

The conference received financial support from the Provincial Secretariat for Higher Education and Scientific Research, Novi Sad. Hosting and technical support were generously provided by the Technical Faculty "Mihajlo Pupin." We extend our sincere gratitude for this invaluable assistance.

The Organizing Committee expresses its heartfelt thanks to the authors, reviewers, and participants for their contributions, which ensure the success and continued tradition of this event.

We look forward to welcoming you to the next ITRO Conference!

On behalf of the ITRO Organizing Committee
Jelena Stojanov

CONTENTS

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Metaheuristics Methods for Solving Capacity Vehicle Routing Problem: An Overview

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Abstract. The Vehicle Routing Problem (VRP) plays a vital role in logistics, supply chain management, and transportation planning. By providing effective solutions, VRP can significantly reduce costs, lower fuel consumption, and improve customer satisfaction. This makes VRP a critical focus for companies engaged in delivery services, public transit, and distribution networks. Given the NP-hard complexity of the problem, using exact algorithms for large instances is often impractical. As a result, this paper explains a variety of approaches, such as Genetic Algorithms, Tabu Search, Ant System, and Hybrid Metaheuristics. This overview serves as a resource for researchers and practitioners interested in applying metaheuristics to CVRP.

Keywords and phrases: Vehicle routing problem, Optimization, NP-hard complexity, heuristic and metaheuristic algorithm,

1 INTRODUCTION

Optimization is a crucial field of study in both theoretical and applied mathematics, computer science, and engineering, focused on identifying the best possible solutions to problems within a defined set of constraints. The essence of optimization lies in determining the optimal outcome for a given objective function, which could involve maximizing benefits, minimizing costs, or achieving other specific goals. This concept is fundamental across numerous disciplines, including logistics, finance, operations research, and engineering, underscoring its broad importance and wide-ranging applications.

Optimization problems are typically classified based on their structure and characteristics. The primary aim is to either maximize or minimize a function that represents the problem's objective, while adhering to constraints that limit the feasible solutions. These constraints might include resource limitations, physical laws, or other relevant restrictions.

Types of Optimization Problems:

Linear Optimization (Linear Programming): These problems feature linear objective functions and constraints. They are commonly solved using well-established techniques such as the Simplex method or Interior-Point methods (Dantzig, 1963; Wright, 1997).

Nonlinear Optimization: These problems involve nonlinear objective functions or constraints, requiring more advanced methods such as gradient-based techniques, Lagrangian multipliers, or heuristic approaches (Nocedal & Wright, 2006).

Integer Optimization (Integer Programming): In these problems, decision variables must assume integer values. This category includes scheduling and allocation problems, which are often tackled using branch-and-bound techniques or cutting-plane methods (Gomory, 1963; Nemhauser & Wolsey, 1988).

Combinatorial Optimization: This category focuses on finding the optimal solution from a finite set of discrete possibilities. Examples include the Traveling Salesman Problem (TSP) and knapsack problems, which frequently require specialized algorithms or heuristic methods (Korte & Vygen, 2008; Papadimitriou & Steiglitz, 1998).

Optimization problems often exhibit NP-complete or NP-hard complexity, where the number of possible solutions can be immense. The size of the search space represents all possible combinations of states of a solution. NP stands for "non-deterministic polynomial," meaning there is no deterministic algorithm that can find the best solution in polynomial time, but if a solution exists, it can be verified in polynomial time. A good example of this is Sudoku. NP-complete problems lie at the boundary between NP and NP-hard problems. What makes NP-complete problems significant is the "Cook-Levin" theorem, which states that any problem in NP can be transformed into a 3-SAT problem (which is NP-complete) using a deterministic approach in polynomial time. This implies that if a polynomial-time deterministic solution is found for one NP-complete problem, it could be used to solve all problems in this class. This leads to the famous question of whether "P = NP," one of the Millennium Prize Problems. On the other hand, NP-hard problems are those for which there is no known polynomial-time algorithm to find the best solution, nor is there a polynomial-time algorithm to verify whether a given solution is optimal. A classic example is chess: it is not possible to find the best move in reasonable time, and even if a move is proposed, proving it is the best one can take a considerable amount of time.

This paper analyzes the Vehicle Routing Problem (VRP) and several strategies for solving it. Since this problem is classified as NP-hard, obtaining exact solutions for large instances is nearly unfeasible. Therefore, heuristic and metaheuristic techniques are often employed. The paper will focus on the most common and fundamental variant of the problem, the Capacitated Vehicle Routing Problem (CVRP).

This paper presents a review of metaheuristic methods used to address the Capacitated Vehicle Routing Problem (CVRP). It organizes and describes several key approaches, including Genetic Algorithms, Tabu Search, Ant Colony Optimization, and Hybrid Metaheuristics. By offering this structured overview, the paper provides a valuable foundation for researchers and practitioners looking to implement metaheuristic techniques for CVRP.

2 THE VEHICLE ROUTING PROBLEM (VRP)

The Vehicle Routing Problem (VRP) is a combinatorial optimization and integer programming problem that aims to determine the most efficient set of routes for a fleet of vehicles to deliver goods to a specified group of customers. It is essentially an extension of the Traveling Salesman Problem (TSP). The concept was first introduced by George Dantzig and John Ramser in 1959 (Dantzig & Ramser, 1959), who also developed the first algorithmic approach to solving VRP, applying it in the context of gasoline deliveries.

The Capacitated Vehicle Routing Problem (CVRP) is a variation of the Vehicle Routing Problem (VRP) in which a fleet of vehicles, each with a fixed capacity, must serve a set of customers. The objective is to minimize the overall travel distance or cost while ensuring that no vehicle exceeds its capacity and that the demands of all customers are met.

For solving of this problem exist more group of methods:

- **Exact Methods:**
  1. Branch and Bound: Explores all potential solutions systematically.
  2. Branch and Cut: Combines branch-and-bound with cutting planes to reduce the search space.
  3. Dynamic Programming: Breaks down the problem into smaller subproblems, solving them recursively.
- **Heuristic Methods:**
  1. Clarke-Wright Savings Algorithm: A greedy method based on calculating cost savings for merging routes.
  2. Nearest Neighbor: A straightforward greedy approach that always visits the closest unvisited customer.
- **Metaheuristics:**
  1. Genetic Algorithms: Employs crossover and mutation techniques to search through potential solutions.
  2. Tabu Search: Avoids local optima by using a tabu list to keep track of previously visited solutions.
  3. Ant System: Simulates the way ants find optimal paths, applying this logic to routing solutions.

Definition of the problem (VRP): We begin with an overview of the key concepts related to the Vehicle Routing Problem (VRP). A client is an entity with a specific demand that requires service from a vehicle, which can travel between clients and the depot—the location where the clients' demands are initially stored. The fleet refers to the total number of vehicles available. The movement of a vehicle between the depot and the clients incurs a certain cost. A route is a sequence of clients visited by a specific vehicle, starting and ending at the depot. The objective of the VRP is to serve all clients while minimizing the total cost of the routes for all vehicles. A visual example is provided in Figure 1 (note that, for simplicity, the graph in this figure is not complete).

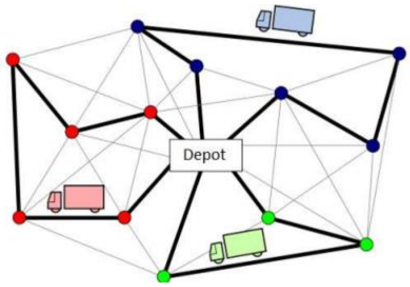

Figure 1. Vizuelization of VRP

The primary structure of the Vehicle Routing Problem (VRP) is a complete graph $G(V,E)$ where the V is a set of vertices and E set of edges. (Ibrahim, Abdulaziz, Ishaya, & Sowole, 2019)

An example of a vehicle routing problem involving multiple vehicles is the Multiple Traveling Salesmen Problem (MTSP), a variant of the Traveling Salesman Problem (TSP) where multiple salesmen are traveling around. We extend the previous detailed list with the following definitions to work towards the definition of VRP:

- m - where $m \geq 1$, is defined as the number of vehicles or the size of the fleet.
- $R_i = \left(v_0^i, v_1^i, \dots, v_{k_i}^i, v_{k_{i+1}}^i\right)$ is a vector that represents the route of vehicle i (with $v_0^i = v_{k_{i+1}}^i = v_0, v_j^i \neq v_l^i, 0 \leq j < l \leq k_i$) which begins and finishes at the depot. The length of the route R_i is a k_i,
- $S = \{R_1, R_2, \dots, R_m\}$ it is the set of routes that represents the VRP solution instance.
- $C(R_i) = \sum_{i=0}^{k_i} C\left(v_j^i \neq v_{j+1}^i\right)$ -it is the route cost R_i.
- $C(S) = \sum_{i=1}^{m} C(R_i)$ – is a total cost of solution S that meets the following conditions: $R_i \cap R_j = \{v_0\}, \forall\, R_i, R_j (1 \leq i, j \leq m, i \neq j), \cup_{i=1}^{m} R_i = V$, to ensure that each customer is served exactly once, the route vectors are treated as a set. The objective of the Vehicle Routing Problem (VRP) is to minimize the cost $C(S)$on the graph $G(V,E)$.

The problem isn't solely about visiting the customers; it also involves addressing their specific demands. In the definitions below, we will outline these additional requirements.

- Demand: $d = (d_0, d_1, \dots, d_{n+1})$ with $d_i > 0$ for each customer and n representing the total number of customers, the demand of the depot is indicated by d_0, which is always set to $d_0 = d_{n+1} = 0$.
- Service time: denoted as δ, is a function that represents the time required to unload all goods at customer v_i for $\{i = 1,2, \dots, n\}$. Typically, δ is influenced by the size of the customer's demand. Therefore, we will use the notation $\delta_i = \delta(v_i)$ consistently moving forward.
- The cost of the route R_i is now defined by

$$C(R_i) = \sum_{i=0}^{k_i} C\left(v_j^i, v_{j+1}^i\right) + \sum_{i=1}^{k_i} \delta\left(v_j^i\right). \tag{1}$$

3 METAHEURISTIC METHODS

In this section, we outline the key metaheuristics that have been effectively utilized to address the vehicle routing problem and provide a brief overview of the metaheuristics employed. Some other reviews are given in (Rezk, Olabi, Wilberforce, & Sayed, 2024) (Montoya-Torres, Franco, Isaza, & Jiménez, 2015)

3.1 Genetic Algorithms

Genetic Algorithms are arguably the most recognized type of metaheuristic algorithms, currently garnering significant attention worldwide. These algorithms are computer-based procedures that apply the principles of natural selection and genetics to develop solutions for a wide range of problems. The foundational concepts were introduced by Holland (1975, 1992), while the effectiveness of Genetic Algorithms in addressing complex issues was demonstrated by De Jong (1975) and Goldberg (1989).

Genetic Algorithms (GAs) work by evolving a population of individuals, represented as chromosomes, through the creation of new generations of offspring in an iterative process until specific convergence criteria are met. These criteria may include a maximum number of generations, convergence of the population toward a set of similar individuals, or the attainment of an optimal solution. Ultimately, the best chromosome produced is decoded to yield the corresponding solution. GAs operates with a population of potential solutions rather than focusing on a single solution, allowing for the simultaneous exploration of multiple paths toward finding an optimal result. Each individual in the population represents a candidate solution to the problem at hand. In Holland's original framework for GAs, these solutions were typically encoded as strings of bits, with the specific interpretation of the bit strings varying depending on the problem being addressed.

The process of creating a new generation of individuals involves three key steps:

Selection Phase: This step entails randomly selecting two parent individuals from the population for the purpose of mating. The likelihood of choosing a particular member is typically proportional to its fitness, which helps prioritize higher-quality genetic traits while still promoting genetic diversity. In this context, fitness is a measure of value, utility, or desirability that should be maximized during the exploration of the solution space.

Recombination Process: In this phase, the genetic information from the selected parents is combined to produce offspring that will constitute the next generation.

Mutation: This step involves randomly altering some genes in an individual to further investigate the solution space and maintain genetic diversity. Mutations generally occur at a low probability, helping to introduce new variations into the population.

To solve the Vehicle Routing Problem (VRP) using Genetic Algorithms (GAs), each solution is typically represented by a single chromosome, which is a sequence of integers. Each integer either corresponds to a customer or a vehicle. The vehicle identifiers act as separators within the chromosome, marking the boundaries between different routes, while the sequence of customer identifiers defines the order of deliveries that a vehicle needs to complete along its route.

In the Figure 2, a possible solution for VRP with 10 customers and 4 vehicles is shown.

$$\underbrace{4-5-2}_{\text{route 1}}-11-\underbrace{10-3-1}_{\text{route 2}}-13-\underbrace{7-8-9}_{\text{route 3}}-12-\underbrace{6}_{\text{route 4}}$$

Figure 2. Sequence of routes

The expression in Figure 1, describes a sequence of routes, where each route is encapsulated within braces and labeled: Route 1:4 → 5 → 2; Route 2:10 → 3 → 1; Route 3:7 → 8 → 9; Route 4:6

The overall path connects these routes through nodes 11, 13, and 12. The flow can be interpreted as starting from route 1, moving through node 11, then following route 2, passing through node 13, continuing through route 3, passing node 12, and finally ending at route 4.

A common fitness function employed for solving the Vehicle Routing Problem (VRP) with Genetic Algorithms (GA) is expressed as:

$$f_{eval}(x) = f_{max} - f(x), \text{ where:}$$
$$f(x) = totaldistance(x) + \lambda \cdot overcapacity(x) + \mu \cdot overtime(x),$$

The overcapacity and overtime functions measure how much the capacity and time exceed the allowed limits. If none of the constraints are violated, the function f returns the total distance traveled. Otherwise, both the excess capacity and time are penalized by the weights λ and μ. The best solutions will have values close to f_{max} , while solutions that violate any restrictions will have their fitness values reduced by the penalties.

3.2 Tabu Search

The core idea behind Tabu Search (TS), as outlined by (Glover, 1986), is that it serves as a meta-heuristic layered on top of another heuristic. TS explores the solution space by iteratively moving from a solution s to the best solution within a subset of its neighborhood $N(s)$. Unlike traditional descent methods, the current solution might worsen from one iteration to the next. To prevent cycles, solutions that share attributes with recently explored ones are temporarily marked as tabu, or forbidden. The period during which an attribute remains tabu is called its tabu tenure, and this can vary over different time intervals. The tabu status can be overridden under certain conditions—this is known as the aspiration criterion, which applies, for example, when a tabu solution is better than any previously discovered solution.

Deviating from a set path might initially appear to be a mistake, yet it can frequently result in positive outcomes. The Tabu method operates on this principle, but unlike random search techniques, it doesn't select new paths at random. Instead, the Tabu search posits that a new solution is only valuable if it prevents revisiting an already explored path. This approach promotes the exploration of new areas within the solution space, helping to avoid local minima and guiding the search toward the optimal solution.

An initial solution is typically generated using a heuristic, such as the cheapest insertion method. Once this starting point is established, local search is applied with one or more neighborhood structures, using a best-accept strategy to improve the solution. Many of the neighborhood structures used in Tabu Search are well-established and have been introduced in the context of various construction and improvement heuristics.

3.3 Ant System

The initial ant system for the Vehicle Routing Problem (VRP) was introduced by (Bullnheimer, Hartl, & and Strauβ, 1997), focusing on the most basic version of the problem: the Capacitated Vehicle Routing Problem (CVRP).

For more intricate variations of VRP, (Gambardella, Taillard, & Agazzi, 1999) created a multiple ant colony system for the Time Windows version of the problem (MACS-VRPTW). This system features a hierarchy of artificial ant colonies that work in succession to optimize multiple objectives: the first colony aims to minimize the number of vehicles, while the second seeks to reduce the total distance traveled. The colonies collaborate by sharing information through updates of pheromone levels.

In the framework proposed by (Bullnheimer, Hartl, & and Strauβ, 1997), the ant system consists of two fundamental phases: the construction of vehicle routes and the updating of trails. The details of the Ant Colony Optimisation (ACO) algorithm are discussed in this context.

Ant System Algorithm: After initializing the Ant System (AS), the two main steps—constructing vehicle routes and updating trails—are iteratively repeated for a specified number of cycles. Regarding the initial placement of the artificial ants, it has been determined that each customer should have an equal number of ants assigned at the start of each iteration. To enhance the quality of the generated solutions, the 2-opt heuristic is employed, which exhaustively examines all possible permutations achievable by swapping two cities, effectively shortening the vehicle routes.

In addition to this straightforward local search approach, candidate lists are introduced to aid in customer selection, determined during the algorithm's initialization phase. For each location d_{ij}, the set $V - \{v_i\}$ is sorted based on increasing distances d_{ij} to create the candidate list.

To tackle the Vehicle Routing Problem (VRP), artificial ants create solutions by sequentially selecting cities to visit until all cities have been included. If selecting an additional city would result in an infeasible solution due to vehicle capacity or the total length of the route, the ants return to the depot and initiate a new tour. In choosing a city that has not yet been visited, two factors are considered: the quality of the previous selection, which is reflected in the pheromone levels τ_{ij} associated with each arc (v_i, v_j), and the attractiveness of the current city choice. This attractiveness, known as visibility and represented by η_{ij}, serves as the local heuristic function guiding the selection process.

Given that $\Omega = \{v_j \in V : v_j \ can\ be\ visited\} \cup \{v_0\}$, the selection of city v_j for visitation occurs in the following manner:

$$p_{ij} = \begin{cases} \dfrac{[\tau_{ij}]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{k \in \Omega}[\tau_{ik}]^{\alpha}[\eta_{ik}]^{\beta}} & , if\ v_j \in \Omega \\ 0 \quad , & otherwise \end{cases} .$$

The probability distribution is influenced by the parameters α and β, which determine the relative impact of the pheromone trails and visibility, respectively. Visibility is defined as the inverse of the distance between cities, and this selection probability can be enhanced by incorporating problem-specific information. For instance, integrating savings and capacity utilization can yield improved outcomes.

Many recent studies combine metaheuristics to obtain more optimal results (Vidal, Crainic, Gendreau, & Prins, 2014). These hybrid approaches in metaheuristics effectively combine multiple optimization techniques to enhance solution quality and computational efficiency for the Capacity Vehicle Routing Problem. In (Lee & Lee, 2006), Genetic Algorithms (GAs) generate a diverse population of potential solutions, which are subsequently refined using local search techniques. Ant Colony Optimization (ACO) may construct solutions based on pheromone trails, followed by local search methods to optimize the routes (Vries & Arentze, 2007). Tabu Search (TS) can be integrated within a GA framework, using TS to refine the best individuals from the GA population (Taillard, 1999).

4 CONCLUSION

Genetic Algorithms (GAs), Tabu Search (TS), and Ant Systems (AS) are effective metaheuristic techniques for addressing complex optimization challenges, such as the Vehicle Routing Problem (VRP). GAs draw on concepts from natural selection and genetics, refining a population of solutions through processes of selection, crossover, and mutation to thoroughly navigate the solution space. Tabu Search enhances local search methods by employing a memory system that avoids cycles, encouraging the exploration of new regions and enabling it to escape local optima, thereby improving solution quality over successive iterations. Ant Systems simulate the behavior of ants in their search for food, using pheromone trails and visibility to probabilistically create solutions while integrating heuristics to boost effectiveness. Each of these approaches offers distinct advantages and can be tailored to various problem scenarios, making them indispensable tools in the realm of optimization. Accordingly, metaheuristic methods have proven to be powerful tools for solving the Capacitated Vehicle Routing Problem, providing a balance between solution quality and computational efficiency. Continued innovation in hybrid strategies and adaptive techniques promises to enhance their applicability in real-world scenarios, pushing the boundaries of optimization in logistics and transportation.

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