Application of Metaheuristic Algorithms to the Traveling Salesman Problem (TSP)

Abstract

Metaheuristics are increasingly vital for solving complex optimization problems where traditional methods struggle. This report presents the application of four key metaheuristic algorithms—Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Tabu Search (TS)—to the well-known Traveling Salesman Problem (TSP). Each algorithm is analyzed based on its approach, performance characteristics, and suitability for different dataset sizes. Comparative metrics and empirical results highlight their effectiveness in finding near-optimal solutions efficiently.

1. Introduction

The Traveling Salesman Problem (TSP) is a benchmark combinatorial optimization problem with numerous real-world applications in logistics, manufacturing, and routing. It asks for the shortest path that visits each city once and returns to the starting point. Exact methods are computationally infeasible for larger instances, making TSP an ideal candidate for metaheuristic approaches.

Metaheuristic algorithms are high-level strategies designed to explore search spaces efficiently and avoid local optima. They are classified into population-based methods (e.g., GA, PSO) and single-solution methods (e.g., SA, TS). This report evaluates their use for TSP based on their theoretical foundations and experimental performance.

2. Methodologies

2.1 Genetic Algorithm (GA)

Genetic Algorithms mimic the process of natural selection. In TSP, each solution is encoded as a chromosome representing a tour. Key operators include:

- Selection: Tournament or roulette-based
- Crossover: Order-based crossover (OX)
- Mutation: Swap-based

GA is highly effective for large-scale TSP due to its diverse exploration capabilities and resilience to local optima (Wirsansky, 2020).

2.2 Particle Swarm Optimization (PSO)

Inspired by social behavior in nature, PSO employs a population of particles (routes) that adjust their position in the search space based on personal and global experience. For TSP:

- Each particle is a route.
- Velocities are updated using cognitive and social coefficients (c1, c2).

Though PSO traditionally suits continuous problems, its adaptation to TSP through rank-based velocity sorting has shown promising results (Talbi, 2009).

2.3 Simulated Annealing (SA)

SA is inspired by the physical annealing process. It uses a probabilistic acceptance criterion that allows worse solutions early on to escape local minima. The temperature gradually cools using:

- Cooling schedule: Exponential decay
- Acceptance function: Metropolis criterion

SA's simplicity and effectiveness in refining a single solution make it suitable for medium-size TSP instances (Luke, 2013).

2.4 Tabu Search (TS)

TS enhances local search by using a memory structure (tabu list) to forbid revisiting recently explored moves. For TSP:

- Neighborhood moves: Swap city positions
- Tabu list: Prevents cycling

TS is deterministic and excellent at intensive exploitation of promising regions, especially effective in small to medium problem sizes (Talbi, 2009).

3. Experimental Setup

Each algorithm was tested across three datasets:

- Small Cities: 10 nodes
- Medium Cities: 15 nodes

- Large Cities: 25 nodes

Metrics evaluated:

- Best/Worst/Median Distance
- Average Computation Time
- Standard Deviation
- Improvement % over unoptimized route
- Convergence curves and visualizations

4. Results and Discussion

Metric	GA	PSO	SA	TS
Best Distance (avg)	High	High	Moderate	High
Speed	Moderate	Fast	Moderate	Fast
Stability	High	High	Variable	High
Local Optima Escape	Good	Moderate	Excellent	Good

- GA provided consistent improvement across datasets and performed best on large instances.
- PSO showed rapid convergence and good scalability.

- SA delivered high-quality results and escaped local minima well but was slower on larger datasets.
- TS produced stable and competitive results, particularly for smaller datasets.

5. Conclusion

Metaheuristic algorithms offer robust, flexible approaches to solving the TSP. Population-based methods (GA, PSO) provide better global exploration, while single-solution methods (SA, TS) are effective for local refinement. The choice of algorithm should depend on the problem size, required speed, and solution quality expectations.

References

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