Optimization of Fuel Distribution Using Simulated Annealing: A Hybrid Approach Integrating CVRP and IRP

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Outline

Objectives

- **Optimize Fuel Routes**: Reduce km/kl ratio through efficient route planning.
- **Develop Hybrid Model**: Implement a combined CVRP-IRP solution addressing **push** and **pull** dynamics.
- **Integrate Polmoni Stations**: Use intermediate Polmoni stations to enhance routing flexibility.
- **Evaluate Routing Strategies**: Compare the impact of various strategies with and without Polmoni stations.
- **Ensure Practical Relevance**: Deliver a scalable solution for real-world applications, particularly for Eni S.p.A.

Introduction

- The optimization of fuel distribution is essential for minimizing costs and enhancing efficiency in energy companies.
- This research addresses the integration of the Capacitated Vehicle Routing Problem (CVRP) and the Inventory Routing Problem (IRP).
- The hybrid approach employs both push and pull strategies:
  - **Push:** Managing inventory levels at Polmoni stations based on demand.
  - **Pull:** Efficiently delivering fuel from depots to service stations.

Introduction

- Polmoni stations, acting as intermediate storage points, enhance flexibility and resource management in the distribution network.
- The study utilizes the Simulated Annealing algorithm to optimize routes and minimize the kilometers traveled per kiloliter (km/kl) ratio.
- This work aims to provide scalable solutions for real-world applications, particularly benefiting companies like Eni S.p.A.

Problem Definition

- Fuel distribution involves depots, service stations, and Polmoni stations.
- Constraints: Depot return, tanker capacity, travel limits (distance and time).
- Objective: Increase efficiency without increasing cost or violating constraints.

Polmoni Stations Concept

- Polmoni stations act as intermediary depots, giving the system more flexibility.
- They allow tankers to optimize loads, reducing empty trips.
- Inspired by the Italian word for "lungs," they provide "breathing space" to the system.

State of the Art

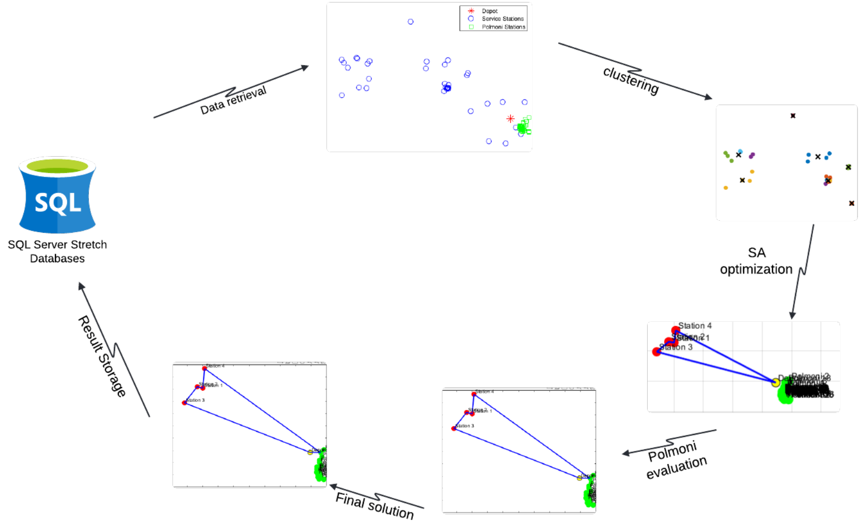
- **Capacitated Vehicle Routing Problem (CVRP)**:
  - Focuses on optimizing delivery routes while respecting vehicle capacity.
  - Key for fuel distribution to ensure efficient tank utilization.
  - Commonly solved by heuristics/metaheuristics (e.g., Simulated Annealing).
- **Inventory Routing Problem (IRP)**:
  - Integrates inventory management and routing.
  - Replenishment decisions are influenced by inventory levels at service/Polmoni stations.
- **Push-Pull Hybrid Model**:
  - Combines push (inventory) and pull (routing) strategies.
  - Few studies integrate both CVRP and IRP in one model.
- **Clustering and Optimization**:
  - Capacitated k-means clustering ensures routes are split efficiently.
  - Explore strategies for incorporating Polmoni stations into routes.
- **Research Gap**:
  - Lack of studies on hybrid routing with dynamic intermediate stops (Polmoni stations).

System's Architecture

High-level system overview:

- Data Input: Location data for depots, service stations, and Polmoni stations, plus demand and constraints
- Clustering: Service stations are grouped based on tanker capacity constraints using capacitated K-means clustering.
- Simulated Annealing: Applied within each cluster to find optimal routes, while considering the addition of Polmoni stations.
- Decision-making process: The system evaluates route efficiency using an acceptance function to determine if adding Polmoni stations improves the km/kl ratio.
- Database storage: Optimized route and results are stored back into the database. Stores data on: Final routes, Stop details (service stations and Polmoni stations), Quantities of fuel delivered

Diagram of System's Architecture



Methodology Overview

- Two-phase approach:
  - Phase 1: Capacitated K-means clustering of service stations.
  - Phase 2: Simulated Annealing for route optimization within clusters.
- Incorporating Polmoni stations:Three strategies to evaluate the impact of Polmoni stations on efficiency.

Capacitated K-Means Clustering

- **Capacitated K-Means Clustering**
  - Focused on respecting constraints, ensuring optimal resource allocation.
  - Two approaches for clustering:
- **Approach 1:**
  - Cluster service stations first, then consider integrating Polmoni stations during the optimization process.
- **Approach 2:**
  - Begin by clustering both service and Polmoni stations together, allowing for a holistic optimization from the start.

Simulated Annealing

- Simulated Annealing Process:
  - Start with an initial solution (route) and iteratively make changes to explore improvements.
  - Temperature: Controls the probability of accepting worse solutions. At higher temperatures, the algorithm is more likely to accept worse solutions, allowing it to escape local optima. As the temperature decreases, the algorithm becomes more selective, focusing on refining good solutions.
  - Acceptance Criteria:
    - If the neighboring solution has a lower cost, accept it as the current solution.
    - If the neighboring solution has a higher cost, accept it with a probability P given by:

$$P = e^{-\frac{\Delta E}{T}}$$

Polmoni Station Integration Strategies

- **First Solution: Optimize Routes First**
  - Optimize routes and then add Polmoni Stations using Simulated Annealing.
- **Second Solution: Impact Calculation**
  - Calculate impact of each Polmoni Station on route distance and select the best.
- **Third Solution: Nearest Polmoni Station**
  - Identify nearest Polmoni Station before route optimization.

Case Study Overview

This case study focuses on optimizing fuel distribution for Eni S.p.A. on March 28, 2023, using specific parameters:

Key Parameters and Constraints:

- Depot ID: 9
- Product Code: "1311N21"
- Tank Capacity: 37,000 liters
- Initial Fuel Level: 0 liters
- Maximum Travel Time: 9 hours
- Maximum Distance: 700 kilometers
- Average Speed: 85 km/h

Objective: Explore the use of Polmoni Stations to optimize routes and fuel efficiency.

Clustering Results

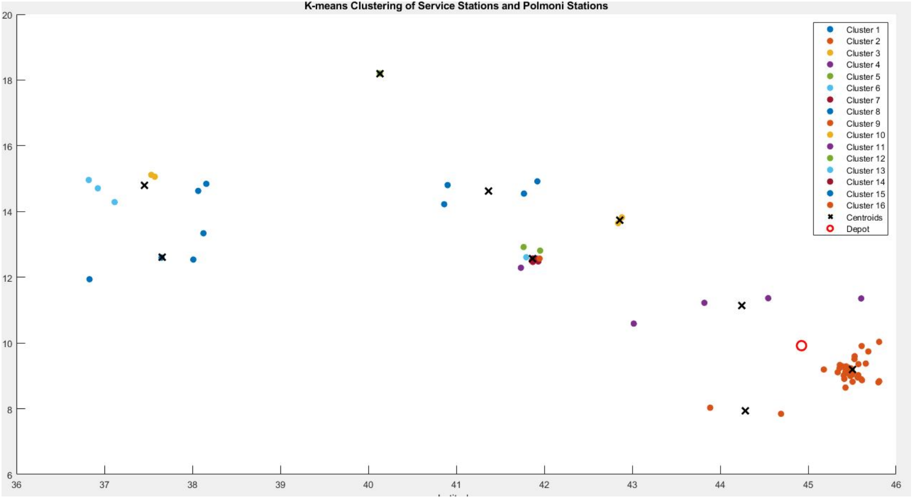


Figure: Clustering Service& Polmoni stations

Clustering Results

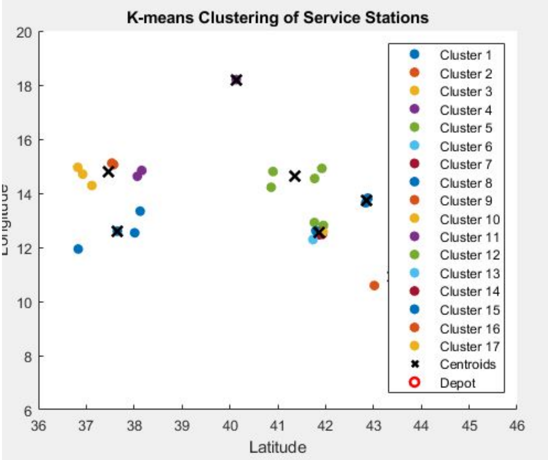


Figure: Clustering Service stations

Simulated Annealing Results

Table: Cost Results Summary for Different Versions

Version	Metric	Initial Cost	Opt Cost	Final Cost	Cost Imp(%)
Version 1	Min	2.78	3.21	3.21	-56.41
	Max	19.22	21.28	21.28	-6.40
	Avg	10.71	12.12	12.16	-17.01
Version 2	Min	2.78	2.79	2.79	-25.15
	Max	19.22	20.50	20.50	-0.037
	Avg	10.71	11.62	11.62	-9.47
Version 3	Min	2.78	2.79	2.79	-25.15
	Max	19.22	20.50	20.50	-0.075
	Avg	10.71	11.65	11.65	-10.18

Table: Km/kl Ratio Summary for Different Versions

Version	Metric	Init. kmkl	Opt. kmkl	Final kmkl	KmKl Ratio Imp.(%)
Version 1	Min	0.1	0.08	0.08	87.07
	Max	2	0.6	0.6	4.24
	Avg	0.8	0.3	0.3	39.6
Version 2	Min	0.1	0.07	0.07	87.48
	Max	2	0.5	0.5	7.77
	Avg	0.8	0.3	0.3	42.53
Version 3	Min	0.1	0.07	0.07	87.48
	Max	2	0.5	0.5	2.11
	Avg	0.8	0.3	0.3	41.93

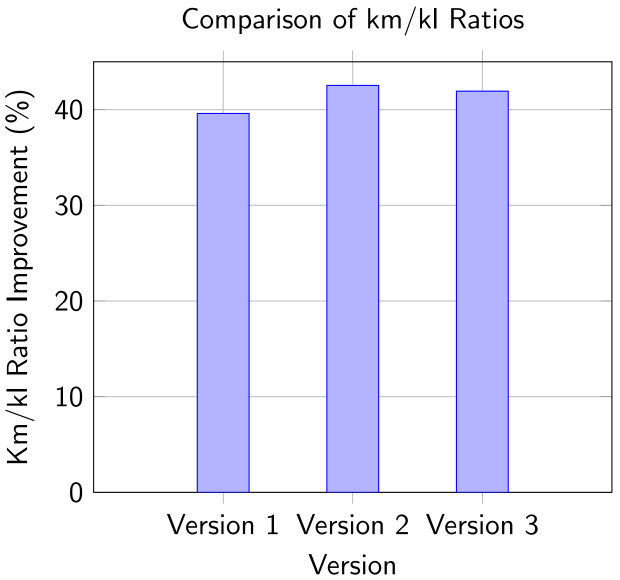
Time results

Table: Travel Time Summary for Different Versions

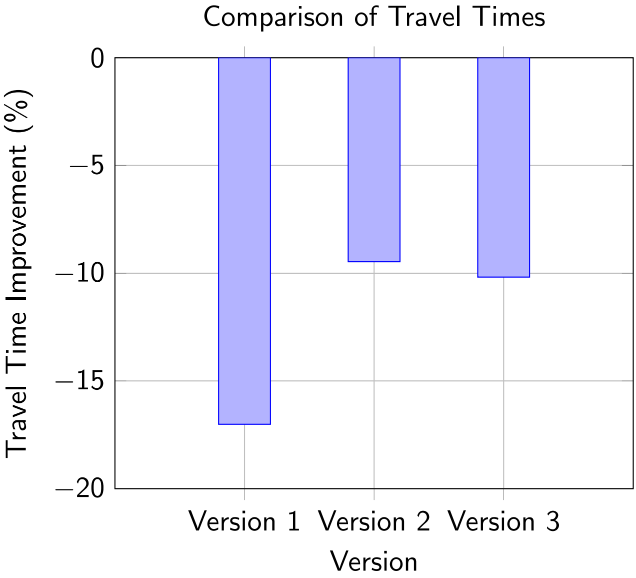
Version	Metric	Init. Time (hrs)	Final Time (hrs)	Time Imp. (%)
Version 1	Min	0.033	0.038	-6.4
	Max	0.23	0.25	-56.41
	Avg	0.126	0.143	-17.01
Version 2	Min	0.033	0.033	-0.038
	Max	0.23	0.24	-25.15
	Avg	0.126	0.136	-9.47
Version 3	Min	0.033	0.033	-0.075
	Max	0.23	0.24	-25.15
	Avg	0.126	0.137	-10.18

Comparing Versions

Comparing Versions



Comparing Versions

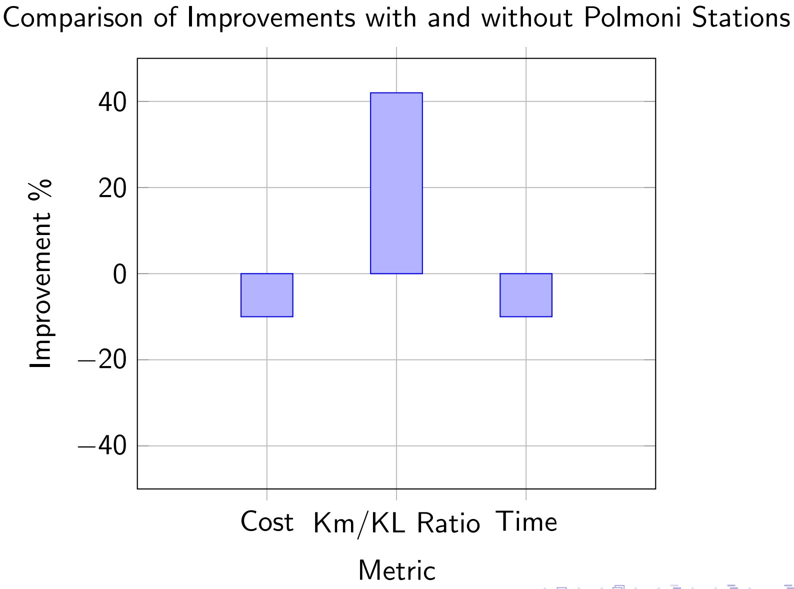


Final Results

Table: Improvement (%) in Routes with vs. without Polmoni Stations

Metric	Improvement %
Cost	(-9.4) - (-17)%
Km/KL Ratio	(39.6) - (42.5)%
Time	(-9.4) - (-17)%

Final Results



Impact of Incorporating Polmoni Stations

Routes with Polmoni stations showed improved fuel efficiency. However, they incurred slightly higher travel times and costs compared to routes without them.

- Improved Efficiency: km/kl ratio improved by 39% to 42%.
- Cost Implications: Cost increases of -9.47% to -17.01% across versions.
- Time Analysis: Average increase in travel times around -10.90%.

Conclusions

Impact of findings:

- Successfully integrated Polmoni stations into the fuel distribution system, improving efficiency.
- Demonstrated the value of a hybrid CVRP-IRP approach for optimizing routes.
- Integrated Polmoni stations improve fuel efficiency and reduce km/kl ratio.

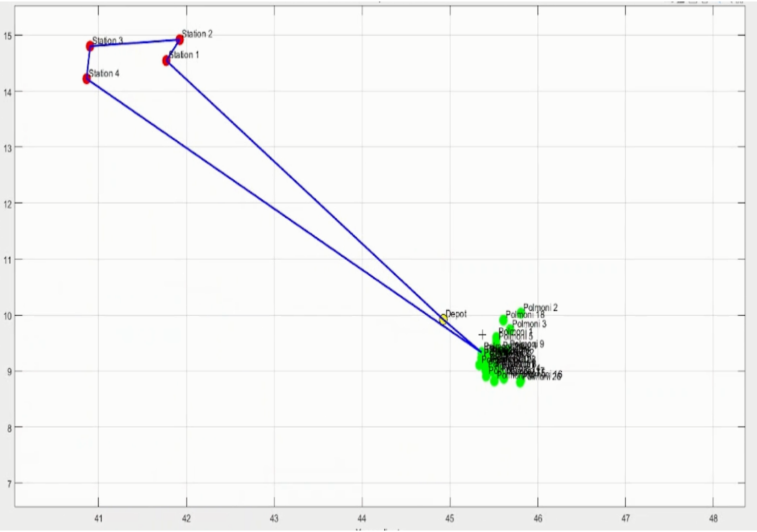
Limitations

- The hybrid CVRP-IRP approach with Simulated Annealing is effective but requires refinement.
- The analysis is based on a limited sample of 17 clusters, which may not capture the full complexity of the fuel distribution network.
- Assumptions in the modeling may not reflect real-world scenarios, and future studies should explore additional methodologies and qualitative metrics for a more comprehensive evaluation.

Future Work

- Improve clustering techniques for more optimal solutions.
- Future research could focus on minimizing the cost and time penalties of using Polmoni stations by enhancing the algorithm or integrating real-time data like traffic and fuel prices.
- Explore other optimization algorithms such as machine learning.
- Scale the model to larger, more complex networks or industries.

Video Streaming



Thank You

Feel free to ask any questions!