Enhancing the Logistics System for a Bottled Water Company

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Abstract

This study investigates the integration of the Minimum Cost Flow (MCF) method with the Traveling Salesman Problem (TSP) to optimize distribution within supply chain networks, addressing inefficiencies in delivery routing. The primary contribution lies in demonstrating how combining MCF with TSM can significantly reduce travel distances and the number of trips required to meet demand. The study employs a hybrid optimization approach, where MCF is used to allocate supplies efficiently to demand nodes, and TSP is applied to optimize the sequence of deliveries, ensuring minimal travel distance. A case study is conducted to compare the performance of using MCF alone versus the combined MCF+TSP approach in a real-world distribution scenario. The results show that the MCF-only method covered a total distance of 289.18 km and required 22 trips to fulfill demand. In contrast, integrating TSP reduced the total distance to 63 km—a 78.21% improvement—and cut the number of trips to just 3. These findings underscore the effectiveness of the combined approach in reducing transportation costs and streamlining logistics operations. The study concludes that while MCF is valuable for balancing supply and demand, its integration with TSM provides a more holistic solution that optimizes both cost and route efficiency. The results highlight the practical implications for supply chain managers seeking to enhance efficiency and sustainability in their operations. Future research is recommended to explore real-time data integration and the scalability of the combined method in larger and more complex logistics networks.

Keywords:

Supply Chain Optimization; Minimum Cost Flow (MCF); Traveling Salesman Problem (TSP); Route Optimization; Logistics Efficiency.

Highlights:

- Integrating Minimum Cost Flow (MCF) and Traveling Salesman Problem (TSP) methods significantly improves logistics efficiency.
- This combined approach reduces travel distance and trip frequency, optimizing supply chain distribution costs.
- The study demonstrates practical applications in bottled water distribution, enhancing both operational efficiency and sustainability.
- The methodology offers a replicable framework for optimizing distribution in various supply chain sectors.
- Results show a 78% reduction in total travel distance, highlighting substantial cost-saving potential for logistics managers.

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1. Introduction

The complexity and dynamism of modern supply chain networks pose significant challenges in efficiently managing the distribution of goods and services. With globalization and technological advancements, supply chains have expanded their reach, leading to more intricate networks involving multiple suppliers, manufacturers, distribution centers, and retailers. This expansion is coupled with rising customer expectations for faster, more reliable, and cost-effective delivery services. In fact, a recent survey indicated that 73% of customers expect fast delivery options, and 55% of customers will abandon their online shopping carts if delivery times are not fast enough [1]. Additionally, logistical inefficiencies account for approximately 20-30% of operational costs in supply chains, highlighting the need for optimized delivery and scheduling strategies [2].

However, traditional delivery and scheduling methods often fail to address these complexities adequately, leading to several inefficiencies such as increased transportation costs, delays, and underutilized resources. Moreover, the lack of effective scheduling methods can result in poor inventory management and underutilization of fleet capacities, which can inflate total costs. As a result, there is a growing demand for more sophisticated approaches to optimize distribution networks, ensuring both cost efficiency and high service levels.

In this context, operations research (OR) methods, specifically the Traveling Salesman Problem (TSP) and Minimum Cost Flow (MCF) models, have emerged as powerful tools for optimizing distribution strategies in supply chain networks. These methods provide systematic, data-driven approaches to decision-making, enabling supply chain managers to tackle complex routing, scheduling, and flow optimization problems more effectively than traditional methods. The TSP, for example, has been successfully applied to optimize delivery routes in last-mile logistics, reducing travel distances and delivery times by up to 30% in urban environments [3]. Similarly, MCF models have been utilized to minimize transportation costs across large-scale, multi-modal supply chain networks, achieving cost reductions of 15-20% while improving delivery reliability [4].

The adoption of these OR techniques is not only driven by the need to reduce costs but also by the increasing emphasis on sustainability and resilience in supply chain management. With logistics operations accounting for approximately 8% of global greenhouse gas emissions, optimizing delivery routes and network flows can significantly contribute to reducing environmental impact [5]. Furthermore, the flexibility of TSP and MCF models allows supply chains to better adapt to disruptions, such as natural disasters or geopolitical events, which are becoming more frequent and severe in today's globalized economy. Recent studies have demonstrated that supply chains utilizing these advanced optimization models can recover from disruptions 35% faster than those relying on conventional methods [6].

This study explores the application of TSP and MCF models in solving distribution problems within supply chain networks, highlighting their potential to overcome the limitations of conventional methods and improve overall supply chain performance. To do so, a mixed integer programing MIP model (MCF) and an integer programing IP model (TSP) are designed to reduce the total travel distance from the supplier node (warehouse) to demand nodes (customers). The model focuses on reducing the number of trips that trucks make in order to fulfill demand needs by providing an optimal route of implementing TSP. Leveraging these advanced OR techniques, businesses can achieve more efficient and resilient logistics operations, ultimately enhancing their competitive edge in a rapidly evolving market landscape. The findings of this research aim to contribute to the growing body of knowledge on supply chain optimization and provide practical insights for practitioners seeking to enhance their distribution strategies.

2. Literature Review

The optimization of distribution processes remains a central challenge in supply chain management, with key issues including efficient routing, cost minimization, and adaptation to changing logistics environments. Two prominent methods for addressing these challenges are the Traveling Salesman Problem (TSP) and the Minimum Cost Flow (MCF) problem. This review focuses on the recent advancements and applications of TSP and MCF models in the field of supply chain management, highlighting their contributions to optimizing routing, distribution, and logistics.

2.1 Traveling Salesman Problem (TSP) in Supply Chain Optimization

The TSP is a classic problem in operations research, where the objective is to find the shortest possible route for a salesman to visit a set of cities and return to the starting point. It is especially relevant to logistics and transportation industries, where minimizing travel distance directly reduces fuel consumption and delivery time. The complexity of TSP arises from the factorial growth of possible routes as the number of locations increases, making it a computationally challenging problem to solve exactly [7].

Golden et al. [8] discussed various heuristic and exact methods for solving TSP, emphasizing the relevance of these methods for practical logistics applications. Their work serves as a foundation for understanding how TSP models can be adapted for modern distribution needs. Among the heuristic approaches, metaheuristic algorithms like genetic algorithms, simulated annealing, and ant colony optimization (ACO) have gained popularity for their ability to find near-optimal solutions efficiently.

Yang et al. [9] introduced a novel ACO algorithm based on game theory principles, which improved the computational performance of solving dynamic TSP instances. This method was particularly effective in scenarios with fluctuating demand and time-sensitive deliveries, making it highly relevant for urban logistics and e-commerce. The study demonstrated that combining ACO with game theory could enhance solution quality, offering better adaptability in real-world applications.

Li et al. [3] examined the application of real-time TSP optimization in e-commerce logistics. With the increasing demand for rapid delivery in the e-commerce sector, their study highlighted the need for TSP models that can dynamically adjust to changes in order volumes and traffic conditions. Their research emphasized the role of TSP in optimizing last-mile delivery, a critical phase where the efficiency of logistics operations directly impacts customer satisfaction.

Zhang et al. [10] focused on the close-enough TSP, a variation where the objective is to find a route that comes within a specified distance of each target location. This variation is particularly useful in urban logistics, where delivery vehicles may not need to stop at every customer location but must come close enough for efficient delivery. The close-enough TSP helps reduce the total travel distance, making it ideal for scenarios where precise delivery locations can be adjusted based on real-time conditions.

The multi-trip split-delivery vehicle routing problem with time windows, as explored by Chu et al. [11], extends the traditional TSP by allowing multiple trips and deliveries to be made within specified time constraints. This variation is beneficial for optimizing delivery schedules and inventory replenishment in retail supply chains, where timely restocking of shelves is crucial. The study highlighted how this approach helps balance the need for speed with the constraints imposed by delivery windows, thus improving overall supply chain responsiveness.

2.2. Advancements in Hybrid and Adaptive TSP Models

The integration of hybrid optimization methods has further enhanced the capability of TSP models to solve complex logistics problems. Sharma and Gupta [12] proposed a hybrid genetic algorithm for solving multi-depot TSP problems, where multiple starting points and destinations are involved. Their approach combined the strengths of genetic algorithms with local search methods, reducing computational time and improving solution accuracy. This hybrid approach is particularly effective in large-scale supply chains with multiple distribution centers, allowing for a more coordinated and efficient routing strategy.

Adaptive scheduling is another key area where TSP models have been applied. Park et al. [13] developed adaptive algorithms for dynamic vehicle routing, which are essential for handling the uncertainties of urban logistics. Their study demonstrated that adaptive TSP models could effectively adjust delivery routes in response to real-time traffic data, significantly reducing delays and fuel consumption. These adaptive models are crucial for logistics companies operating in congested urban areas, where conditions can change rapidly and require quick decision-making.

Herrera et al. [14] explores a transshipment and routing model to optimize the multi-product planning and distribution network of a refreshment company in Bogotá, Colombia. The researchers combined transshipment models with routing techniques, such as the Traveling Salesman Problem (TSP), to address challenges related to efficient delivery routes. The TSP helps to reduce 13% of the total traveling distance.

The Vehicle Routing Problem (VRP) is presented as a logistics model for perishable goods within the "Last Mile" framework, using GAMS Software to optimize distribution routes that maximize profits and reduce transportation times. This model accounts for factors such as the number of vehicles, vehicle types and capacities, demand, and transportation costs.

Furthermore, a heuristic analysis of the same problem is carried out with GAMS software by Fajardo et al. [15], proposing two solution strategies. The first strategy utilizes the Clarke and Wright savings algorithm, where the number of vehicles is a decision variable, aiming to minimize the vehicle count and reduce travel distances. The second strategy applies the TSP optimization model, providing optimal values for distances, costs, and travel times in the process of collecting used lubricating oils in Pereira, Colombia.

Kundu et al. [16] proposed an efficient routing heuristic is for a drone-assisted delivery problem. The study focuses on optimizing delivery routes using drones to enhance efficiency in logistics operations. The authors develop a heuristic method that combines drone and traditional vehicle routes to reduce overall delivery times and costs, aiming to optimize operational efficiency in last-mile delivery scenarios. The paper explores various parameters such as drone capacities, delivery locations, and time constraints to find the most efficient delivery strategies.

2.3. Minimum Cost Flow (MCF) in Supply Chain Optimization

The MCF problem focuses on determining the most cost-effective way to transport goods through a network, considering supply, demand, and transportation costs at each node. MCF models are especially valuable for optimizing supply chain networks where the objective is to minimize transportation costs while meeting demand at various locations [17]. Unlike TSP, which focuses on routing, MCF deals with the flow of resources through a network, making it ideal for applications like inventory distribution and production planning.

Xiao and Liu [6] explored the use of robust MCF models to handle uncertainty in supply chain networks. Their research emphasized the importance of developing models that can adapt to disruptions such as supply shortages or transportation delays. By incorporating stochastic elements into the MCF framework, their approach provided a more resilient solution for supply chains that need to maintain continuity in uncertain environments.

De Souza and Wang [18] similarly highlighted the importance of resilience in supply chain networks, focusing on the role of flow optimization strategies. Their study underscored the need for supply chains to incorporate flexibility into their logistics plans, allowing them to quickly adapt to disruptions like natural disasters or geopolitical events. The integration of MCF models into resilience planning ensures that companies can maintain service levels even under adverse conditions.

Gendreau et al. [19] provided a comprehensive review of continuous approximation models in freight distribution, focusing on their integration with MCF techniques. Their study discussed how continuous models could simplify complex distribution problems, making it easier for companies to manage large-scale operations. This approach allows for a balance between detailed routing models like TSP and broader network flow models, providing a holistic view of supply chain logistics.

2.4. Integrating TSP and MCF for Comprehensive Distribution Solutions

Combining TSP and MCF models offers a comprehensive approach to solving distribution problems, enabling companies to optimize both the routes taken by delivery vehicles and the flow of goods through the supply chain. This integration is particularly effective in scenarios where companies need to coordinate the movement of products from production facilities to multiple distribution centers and then to retail outlets or customers [14].

The World Economic Forum [5] emphasized the role of efficient logistics management in reducing greenhouse gas emissions, highlighting how optimized routing and flow models like TSP and MCF can contribute to sustainability goals. By minimizing the distance traveled and optimizing the flow of goods, companies can significantly lower their carbon footprint, making their supply chains more environmentally friendly.

Deloitte [1] and Gartner [2] both underscored the importance of last-mile delivery optimization in modern logistics. Their reports highlighted how TSP-based solutions are crucial for meeting customer expectations in the e-commerce sector, where timely and accurate deliveries are a competitive advantage. MCF models, on the other hand, help manage the overall flow of goods through the network, ensuring that products are available when and where they are needed.

Integrating TSP and MCF allows for a balanced approach to distribution optimization, ensuring that routes are efficient while maintaining a cost-effective flow of resources. This combined approach is particularly useful for large-scale operations, such as those in retail and manufacturing, where the efficient movement of goods from warehouses to stores is crucial. For instance, using MCF to manage stock levels across distribution centers can complement TSP-based routing for delivery vehicles, creating a more synchronized supply chain.

The significance of using both the Traveling Salesman Problem (TSP) and the Minimum Cost Flow (MCF) methods to solve distribution problems in supply chain networks lies in their complementary strengths in addressing different aspects of logistical optimization. The TSP is particularly effective for optimizing routing and scheduling, which is crucial for minimizing travel distances and delivery times, especially in last-mile logistics and scenarios involving multiple delivery points. On the other hand, MCF focuses on optimizing the flow of goods through a network to minimize overall transportation costs while considering factors such as capacity constraints and varying transportation modes. By leveraging the strengths of both methods, supply chain managers can achieve a holistic optimization strategy that balances cost, efficiency, and service quality. This dual approach not only enhances operational efficiency by reducing transportation costs and delivery times but also improves resilience and flexibility, enabling supply chains to better adapt to disruptions and varying demand patterns. Integrating TSP and MCF models allows for more precise and adaptive decision-making, ultimately leading to a more robust and responsive supply chain network.

3. Model

This study applies two distinct operations research models to address the company's distribution challenges: the Traveling Salesman Problem (TSP) and the Minimum Cost Flow (MCF). Detailed explanations of both models are provided, covering their respective methodologies and applications. Tables 1-3 outline the key notations used in these models, including sets, parameters, and decision variables.

Table 1: Sets

$\mathcal{N}$	Set of nodes {1,…..,n}
$\mathcal{L}$	Set of Commodities
$\mathcal{A}$	Set of Arcs (i, j)

Table 2: Parameters

c_{ij}	Shipping cost of moving from node i to node j.
u_{ij}	Arc (i, j) Capacity.
b_{il}	Net flow at node i commodity l.
M	Unmet demand cost.
d_{ij}	Distance of traveling from node i to node j.

Table 3: Decision Variables

x_{ijl}	Flow of products from i to j for commodity l.
s_{il}^{+}	Unmet demand at node i commodity l.
Y_{ij}	Binary variable that is 1 if salesman travels through arc (i, j) $\in \mathcal{A}$, and if 0 otherwise
U_i	Order of visits on node $i \in \mathcal{N} \setminus \{1\}$ (to resolve subtour)

3.1 THE MINIMUM COST FLOW MODEL

The minimum cost flow (MCF) model focuses on reducing the overall traveling distance while satisfying the demand across various nodes. Eq. (1) serves as the MCF's objective function, aiming to minimize traveling distance during the distribution process incorporating oversupply factors. Eq. (2) represents the flow-balance constraint, ensuring that the difference between the outflow and inflow at each node (i) corresponds to its demand or supply, factoring in any oversupply. Eq. (3) ensures that the flow along any arc (i, j) respects its capacity, meaning that the flow cannot exceed the arc's limit. Lastly, Eq. (4) is a non-negativity constraint, which ensures that the flow value, (x_{ij}), remains an integer, representing the quantifiable units transferred between nodes. Eq. (5) represents the natural status of the oversupply variable.

$$Min\ Z = \sum_{j:(i,j)\in\mathcal{A}} x_{ij}\ d_{ij} + \sum_{i\in\mathcal{N}} s_{il}^{+} M \quad (1)$$

$$\sum_{j:(i,j)\epsilon A} x_{ijl} - \sum_{j(i,j)\epsilon A} x_{ijl} = b_{ijl} - s_{il}^{+} \qquad \forall\ i\ \in \mathcal{N}, \forall\ l \in \mathcal{L} \quad (2)$$

$$x_{ij} \le u_{ij} \qquad \forall\ (i,j) \in \mathcal{A} \quad (3)$$

$$x_{ij}\ \ge 0 \qquad \forall\ i\ \in \mathcal{N} \quad (4)$$

$$s_i^{+}\ \ge 0 \qquad \forall\ i\ \in \mathcal{N}, \forall\ l \in \mathcal{L} \quad (5)$$

3.2 Travel Salesman Problem

Eq. (6) represents the objective function of the TSP which aims to minimize the total distance associated with serving each node. Eqs. (7) and (8) ensure that flow is directed from one incoming node to one outgoing node, meeting the requirement that each node is visited exactly once. Eq. (9) addresses the subtour problem by ensuring that the model passes through all nodes before returning to the starting point. Eq. (10) is a binary condition, where a (Y_{ij}) value of one indicates that the path between node (i) and node (j) is chosen, and a (Y_{ij}) value of zero means it is not. Lastly, Eq. (11) ensures that the capacity of any arc (i , j) remains positive.

$$Min\ Z = \sum_{(i,j)\in\mathcal{A}} d_{ij} Y_{ij} \tag{6}$$

$$\sum_{j\in\mathcal{A}} Y_{ij} = 1 \qquad \forall\, i \in \mathcal{N} \tag{7}$$

$$\sum_{i\in\mathcal{A}} Y_{ij} = 1 \qquad \forall\, j \in \mathcal{N} \tag{8}$$

$$U_i \le U_j - 1 + n\left(1 - Y_{ij}\right) \qquad \forall\, (i,j) \in \mathcal{A} : j \ne 1 \tag{9}$$

$$Y_{ij} \in \{0,1\} \qquad \forall\, (i,j) \in \mathcal{A} \tag{10}$$

$$U_i \ge 0 \qquad \forall\, i \in \mathcal{N}\{1\} \tag{11}$$

4. Case Study, Results, & Discussion

4.1 Case Study

In this case study, a distribution system of an XYZ company is evaluated to find the issues related to its distribution system. The supply chain network of the company was complex and diverse. Thus, we reduce the network and observe the routine processes followed during the delivery processes. This case study consists of a single supplier (a distribution center) and 30 demand nodes (customers) as illustrated in Table 4. The demand nodes were categorized into four groups (A,B,C, and D). Each category requires two commodities: Large and Medium. The supplier capacity and the demand required by each category for each commodity are listed in Table 4.

To address this problem, first, evaluating the current system by observing the number of trips from the distribution center every time a truck leaves the distribution center location and listing which customers to visit in order to measure the total distance the trucks cover to finish the total demand. Then the suggested solution (route) will be calculated to measure the total distance needed to cover to deliver the entire demand avoiding to visit the same customer twice in the route.

Table 4: Partial Percentage of Each Category and Size

Category	Commodity	Demand	Supplier Capacity
A	Medium	2825	15000
A	Large	4675	
B	Medium	500	
B	Large	1000	
C	Medium	498	
C	Large	1002	
D	Medium	2325	
D	Large	2175	

4.2 Results

First, evaluating the current system by calculating the total distance using the MCF problem and visualizing the movement of the truck from/to the distribution center. Evaluating the current system provides insights of the total movements that trucks are covering to deliver the total demands. Following no specific route and move randomly will result in unnecessary trips that the tracks should not do. So, we observed the number of trips and the routs the trucks used to calculate the total distance they covered to meet the entire demands daily.

Based on detailed observations, it becomes evident that the company employs a minimum cost flow approach for managing its distribution operations. This strategy prioritizes meeting the largest quantities required at high-demand nodes before taking into account the distances that need to be covered. Initially, the focus is on fulfilling the demands of nodes with the greatest needs, even if these nodes are farther from the distribution center or warehouse. By doing so, the company ensures that the most significant orders are satisfied promptly. Once these primary, high-volume needs are met, the company then shifts its focus toward addressing the remaining demand at other nodes, which might involve shorter or smaller deliveries.

This approach can ensure that critical demand is met quickly, but it results in certain drawbacks in terms of efficiency. As illustrated in Figure 5, this method results in a substantial number of trips between various demand nodes, which, in many cases, could have been consolidated into fewer trips. Figure 1 highlights instances where vehicles are dispatched on separate trips to fulfill demands. This leads to an increased frequency of trips, which raises fuel consumption and transportation costs and contributes to greater wear and tear on the company's fleet. The total distance covered to meet the demand was 289 km, reflecting the extensive travel required to serve all demand nodes.

The increased number of trips due to this strategy results in what can be considered "redundant trips"—unnecessary journeys that increase direct transportation costs and reduce the overall operational efficiency of the supply chain. Every additional trip increases scheduling complexity, the risk of delays, and the potential for congestion within the network, especially if multiple vehicles are moving simultaneously across similar routes.

Additionally, Figure 2 sheds light on another significant aspect of the company's current distribution practice: the high frequency of trips originating from or destined for warehouse nodes. This pattern suggests that the company frequently returns to the warehouse to restock before continuing to other demand points. The high number of trips between the warehouse and different demand points suggests that there is a potential for optimizing this flow to reduce fuel usage and minimize turnaround times.

Overall, while the minimum cost flow approach ensures that the largest demands are met promptly, it results in a distribution network characterized by a high frequency of trips between nodes and a substantial number of trips between warehouse nodes and demand points. The total distance of 289 km covered highlights the extensive nature of the distribution efforts, indicating that further improvements could be made to enhance efficiency and reduce the overall distance traveled.

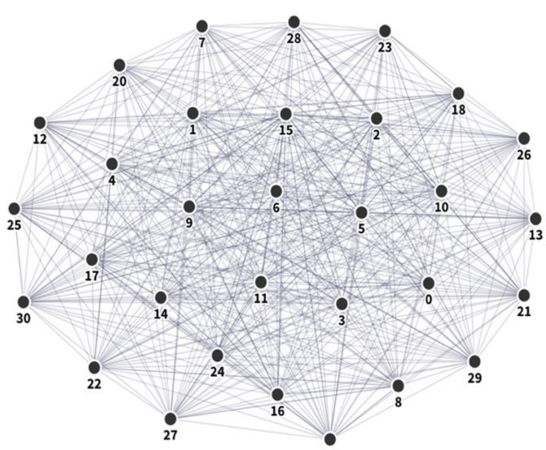

Fig. 1. The Total Trips in the SCN

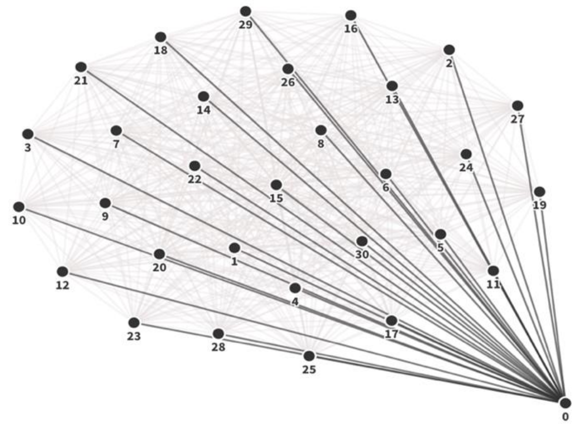

Fig. 2. The Total Trips from/to the Distribution Center Node 0

The implementation of the Traveling Salesman Problem (TSP) alongside the Minimum Cost Flow (MCF) approach has proven to be a highly effective strategy for optimizing supply chain distribution. TSM's focus on determining the most efficient route for visiting multiple demand nodes allows for more streamlined delivery operations, ensuring that delivery paths are as short as possible while meeting demand. By prioritizing the sequencing of visits to each node, TSP minimizes the overlap in travel routes, reducing the time and distance required to complete delivery tasks. This optimization is particularly beneficial when demand is distributed across a broad geographic area, as it helps in clustering delivery nodes into fewer, more manageable trips.

Figure 3 illustrates the optimal route identified using the TSP method, showcasing how the delivery paths were optimized to minimize travel distances between various demand points. The route map in Figure 3 reveals a well-planned path that reduces backtracking and ensures that each delivery covers the maximum number of demand nodes possible within a single trip. The visualization clearly demonstrates how TSP's approach significantly differs from a less-structured method, highlighting the strategic routing that avoids unnecessary loops and overlapping travel paths. The optimized route reduces total distance and time, contributing directly to the overall efficiency of the supply chain network.

Table 5, in terms of the number of trips, the impact of integrating TSP with MCF is evident. The MCF-only method required 22 trips to satisfy all demand nodes, resulting in a more fragmented and less efficient delivery process. Each trip covered relatively shorter distances, but the frequent returns to the warehouse increased the overall operational burden, leading to higher costs and increased time spent managing restocking processes. By contrast, when the MCF approach was enhanced with TSP, the number of trips was reduced dramatically to just 3, offering a far more consolidated and efficient solution. This reduction in the number of trips from 22 to 3 underscores the capability of TSM to optimize delivery routes effectively, enabling a more strategic approach to fulfilling demand.

The relative improvement achieved through the use of both methods is substantial and reflects the value of the combined approach in real-world logistics scenarios, as shown in Table 5. The total distance covered with the MCF+TSP approach was 63 km, compared to 289.18 km using only the MCF method. This resulted in a relative improvement of 78.21%, highlighting the significant savings in travel distance achieved through the use of TSM. Such a considerable reduction in total distance is critical for supply chain operations, as it directly translates to lower fuel costs, reduced wear and tear on vehicles, and a decrease in greenhouse gas emissions, thereby contributing to more sustainable logistics practices. The integration of TSP with MCF helps companies optimize not just operational costs, but also their environmental impact, aligning with contemporary goals of sustainability and efficiency in supply chain management.

$$\text{Relative Improvement RI} = \frac{\text{MCF Pre Applying TSP} - \text{MCF Post Applying TSP}}{\text{MCF Pre Applying TSP}}$$

$$\text{RI} = \frac{289.18 - 63}{289.18}$$

$$\text{RI} = 78.21\%$$

This relative improvement is not just a numerical value but a reflection of the practical advantages that TSP provides in real-world logistics applications. A 78.21% reduction in travel distance means that the same demand can be met using far fewer resources, allowing companies to redirect their efforts and capital into other areas of operation. This also means that companies can better manage delivery times, potentially improving customer satisfaction by providing faster and more reliable service. The ability to meet demand more efficiently without compromising on service levels is a critical advantage in today's competitive market, where customers expect rapid delivery times and minimal delays.

Table 5: Comparison of the MCF and TCP Outcomes

Method	Distance (in km)		No. of Trips from the Warehouse
	A trip	Total	
MCF	13.15	289.18	22
MCF+TSP	21	63	3

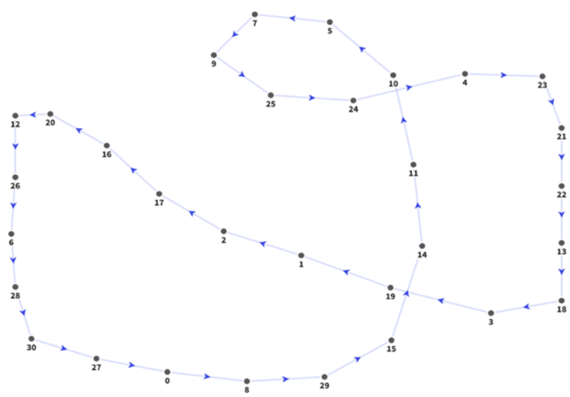

Fig. 2. TSP Output Network

4.3 Discussion

The comparison between the Minimum Cost Flow (MCF) method and the combined MCF with the Traveling Salesman Problem (TSP) reveals distinct differences in their efficiency and suitability for optimizing supply chain distribution. Both methods have their strengths, but their effectiveness varies when applied to real-world logistics challenges, particularly in optimizing delivery routes and minimizing travel distances.

The MCF method is primarily designed to optimize the flow of commodities from supply points to demand nodes, aiming to meet demand in a cost-effective manner. By prioritizing the minimization of costs, it ensures that larger demand nodes are addressed first before focusing on the distance involved. This approach works well for managing the distribution of goods, especially in scenarios where demand varies significantly across different locations. The parameters involved in the MCF model include supply quantities available at each source node, demand quantities required at each destination node, transportation costs associated with moving goods between nodes (which can depend on factors such as distance, fuel prices, or tolls), and network constraints such as capacity limitations on transportation routes. While these parameters allow the MCF to balance supply and demand efficiently, applying the method without incorporating additional route optimization techniques, such as the TSP, can lead to inefficiencies. In this study, the MCF-only method covered a total distance of 289.18 km and required 22 trips to meet the demand across various nodes. The high number of trips highlights a lack of coordination in the physical routing of deliveries, leading to increased transportation costs, higher fuel consumption, and more time spent on managing vehicle schedules.

In contrast, the integration of the TSP method with MCF introduces a powerful layer of route optimization. TSP focuses on determining the most efficient path that visits all demand nodes with the shortest possible travel distance, thus reducing unnecessary travel. The parameters of the TSP model include the set of demand nodes to be visited, the distances or travel times between these nodes, and the requirement to return to the starting point (in the case of a closed-loop system). Additionally, constraints such as vehicle capacity, delivery time windows, and route restrictions can be accounted in MCF model. By leveraging these parameters, the TSP ensures a highly efficient sequence of deliveries that complements the flow optimization achieved by MCF, ultimately enhancing the overall effectiveness of the distribution system. By applying TSP alongside MCF, the combined approach re-sequences the visits to demand nodes, ensuring that the overall travel route is optimized. As a result, the combined MCF+TSP approach significantly reduced the total travel distance to 63 km—a 78.21% improvement over the MCF-only method. The optimization brought about by TSP is evident in the substantial reduction in distance, directly translating into lower transportation costs, reduced fuel consumption, and less wear and tear on delivery vehicles.

Additionally, the number of trips required dropped dramatically from 22 to just 3 when using the combined MCF+TSP approach. This reduction in trips is crucial for streamlining logistics operations, as fewer trips mean less operational complexity and reduced pressure on fleet management. With only 3 trips needed to satisfy demand, the logistics process becomes easier to manage, leading to more predictable and reliable delivery schedules. The fewer trips also reduce the risk of potential disruptions, such as vehicle breakdowns or traffic delays, which can impact the timeliness of deliveries. Furthermore, the decrease in trips helps reduce labor costs as fewer drivers and fewer man-hours are needed to complete deliveries.

The 78.21% improvement in total travel distance achieved by integrating TSP with MCF has several practical implications. This reduction means that the company can achieve the same distribution objectives using significantly fewer resources. The cost savings associated with shorter distances and fewer trips can be redirected to other areas of operation, such as expanding the customer base or improving service quality. In terms of sustainability, the reduced distance and lower number of trips also contribute to a smaller carbon footprint, aligning with the growing emphasis on environmentally responsible logistics. As companies face increasing pressure to adopt greener practices, methods like MCF+TSP provide a way to meet both economic and environmental goals.

The findings of this study emphasize that while the MCF method is effective for managing supply and demand balances, it lacks the precision in route optimization that TSM brings. By leveraging TSP's ability to identify the shortest and most efficient paths, companies can reduce both travel time and costs, achieving more efficient distribution operations. This makes the combined MCF+TSP approach particularly valuable for logistics networks where travel costs are significant or where delivery time is a critical factor.

5. Conclusion and Future Works

This study investigates the Minimum Cost Flow (MCF) method and its combination with the Traveling Salesman Problem (TSP) for supply chain distribution optimization. MCF is effective in balancing supply and demand but lacks route optimization, leading to longer distances and more trips. In this study, MCF alone resulted in a total travel distance of 289.18 km with 22 trips, highlighting its limitations in delivery coordination.

Integrating TSP with MCF significantly improves efficiency by optimizing the sequence of visits to demand nodes. The MCF+TSP approach reduced the travel distance to 63 km, a 78.21% improvement compared to MCF alone. It also decreased the number of trips from 22 to just 3, simplifying logistics operations and lowering transportation costs. This combined method is effective in scenarios where efficiency and cost minimization are crucial. The MCF+TSP approach supports sustainability goals by reducing fuel consumption and carbon emissions due to fewer trips and shorter distances. This dual benefit aligns with green logistics practices, allowing companies to improve their cost structures while meeting environmental objectives.

Future research could focus on integrating real-time data, such as traffic and vehicle availability, into the MCF+TSP model to improve dynamic adaptation. Studies could also assess the method's applicability in industries with time-sensitive or perishable goods, where timely delivery is critical. Incorporating stochastic elements into the model could address uncertainties in demand, supply, and travel times, leading to more robust decision-making under variable conditions. Evaluating the scalability of the MCF+TSP approach in larger networks would provide insights into its performance in diverse logistics scenarios.

Additionally, future studies could compare the hybrid approach with advanced optimization techniques, such as particle swarm optimization or hybrid metaheuristics, to identify the most effective methods for specific logistics challenges. Lastly, research could expand on quantifying the environmental benefits of this approach, such as its impact on reducing greenhouse gas emissions, fostering a more sustainable supply chain. These avenues will ensure that the combined MCF+TSP approach evolves to meet the dynamic needs of modern logistics while addressing computational feasibility.

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