Efficient Route Optimization for US-Global Health Commodity Distribution: A Network Modeling Approach

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Abstract

This report focuses on optimizing U.S. government's Global Health Commodity Support Plan using network modeling approaches. It attempts to build smallest-distance route to ship ARV medications and HIV lab supplies to all targeted countries with two cases being considered: single plane available and two plane available. Using mixed-integer linear programming (MILP) and Gurobi, results show the single-plane model achieves the lowest distance, while the two-plane model ensures better workload distribution. The study highlights trade-offs between efficiency and operational balance, providing valuable insights for sustainable supply chain management.

Keywords: Operations Research, Optimization, Mixed-Integer Programming, Network Modeling, Shipment Problem

Contents

1 Introduction

Nowadays, the shortage of essential medical commodities continues to be a problem that cannot be ignored. Obstacles such as medication shortages, vital medication stockouts, procurement procedures, and inventory management systems continue to hinder the provision of high-quality healthcare services worldwide (Adhikari et al., 2024). Difficulties in the healthcare supply chain arise from the complexity of coordination involving different stakeholders, such as health managers, service providers, drug makers, distributors, information service providers, regulators, and service consumers, creating challenges in the healthcare supply chain (Singh et al., 2016). The U.S. government implements a Global Health Commodity Support Plan to assist nations that are experiencing shortages of vital health commodities. The government provides HIV lab supplies and antiretroviral (ARV) medications to supported nations every year as part of this program. Developing a sustainable global health supply chain is one of the plan's main challenges. Therefore, this motivates this study to concentrate on developing a cost-effective model to deliver all health commodities as scheduled for the US government.

This study will mainly focus on the following research questions: How can a single-plan model be designed to determine the optimal shipment route for minimizing CO2 emissions? How to find the optimal shipment route between two warehouses? Thus, this study's objective is to develop two optimization models by using the network modeling method. In response to answering the research questions and achieving the goal, this study establishes 2 network models to find the optimal shipment routes.

While recognizing the global abundance of research on supply chain problems (AlRuthia et al., 2023), it is still necessary to find out the optimal plan by using the optimization method. Therefore, the purpose of this study is to fill in the gaps in this field of study and tackle this issue using an operations research approach. This study has established two network models to address the route planning issue for health commodity shipments, this frameworks can be applied to other areas. Besides, this examines the feasibility of using network models to solve such problems. In actuality, this study might give upper managers advice on how to set up shipment routes.

The rest of this report is organized as follows: the background is covered in Section 2, which also contains pertinent studies and background information. The network model algorithm will then be used to demonstrate the mathematical modeling in Section 3, which will also include details on the data sources and underlying assumptions. In order to highlight the most important details of our data and model, Section 4 presents the data cleaning procedure and visualizations. Section 5 will explore and discuss the results and findings. It also outlines the study's limits and practical implications. The conclusion will be briefly restated in Section 6 and some further research is presented.

2 Background

This project is based on the background of U.S. government's Global Health Commodity Support Plan, which provides ARV medications and HIV lab supplies to supported countries annually. Given the fact of medical shortage across the world, this program is critical for combating the HIV/AIDS epidemic in underserved countries. Efficient transportation logistics is a key element of this project. With environmental sustainability in mind, the government seeks to minimize the carbon footprint of these shipments by optimizing the total distance traveled by aircraft used in the process.

The Global Health Commodity Support Plan is an initiative by the United States government to address global shortages of essential health supplies. This program provides annual shipments of antiretroviral (ARV) medications and HIV lab supplies to underserved countries, playing a critical role in combating the HIV/AIDS epidemic worldwide. Efficient transportation logistics is a cornerstone of this initiative, ensuring timely and equitable delivery to regions in need.

Key challenges in the program include:

- Designing cost-effective and environmentally sustainable shipping routes.
- Coordinating between multiple destinations with varied logistical needs.
- Balancing resource allocation between warehouses.

With environmental sustainability in mind, the program also seeks to minimize the carbon footprint of these shipments by optimizing the total distance traveled by aircraft. The optimization challenges presented by these goals are equivalent to the well-known Traveling Salesperson Problem, a fundamental problem in logistics and operations research.

Existing methods often rely on heuristic approaches or fail to adequately account for environmental impacts. This study applies advanced optimization techniques to develop mathematical models that address these challenges. By optimizing shipping routes, the study provides actionable insights for improving sustainable global health supply chain management, ensuring that logistical decisions align with the broader goals of environmental and operational efficiency.

3 Method

The optimization problem was modeled using a mixed-integer linear programming (MILP) approach. The objective was to minimize the total shipping distance while ensuring that all destinations were visited. The problem was divided into two phases:

1. **Single-Plane Model**: A single plane departs from JFK and returns to LAX,[1] visiting each destination exactly once.
2. **Two-Plane Model**: Two planes operate independently, one departing from JFK and the other from LAX, each returning to its starting point.

The models were implemented in Python using the Gurobi optimization solver. Lazy constraints were employed to dynamically eliminate subtours, improving computational efficiency.

3.1 Model Assumptions

The following assumptions were made for the models:

- Each plane has sufficient capacity to carry all required shipments in its assigned route.
- The distance between airports is proportional to the haversine distance.
- Planes operate independently and do not visit the other warehouse's starting point.
- All shipments must be completed within a single trip.
- Subtours (cyclic routes) are not allowed since it does not make any sense from take off fuel efficiency perspective nor airport taxes.

These assumptions simplify the problem while maintaining its relevance to real-world logistics.

3.2 Data Source

Two primary data sources were used in this study:

1. **Airport Data**: A dataset (`airports.csv`) containing information on airport codes, coordinates, and locations for all destinations involved in the shipment.
2. **Distance Matrix**: We pre-computed a matrix (`distance_matrix.pkl`) storing the haversine distances between all airport pairs. This matrix was calculated using Python's built in haversine function, part of the geospatial libraries.

The data was pre-processed to ensure consistency, accuracy and a faster compute time. The haversine function was used to compute distances, providing a reliable approximation for real-world air travel distances.

[1] In practice, with the same route, one way would be more fuel-efficient due to the gulf stream currents around the globe. The direction (JFK to LAX or vice versa) also depends on how you interpret the problem.

3.3 Problem 1 - MTZ : Mathematical Formulation

3.3.1 Sets and Indices

- N: Set of countries (excluding JFK and LAX), $N = \{1, 2, \ldots, 44\}$.
- $V = N \cup \{\text{JFK}, \text{LAX}\}$: Set of nodes, including start and end airports.

3.3.2 Parameters

- c_{ij}: Haversine distance between node i and node j, for all $i, j \in V$, $i \neq j$.

3.3.3 Decision Variables

- $x_{ij} \in \{0, 1\}$: Binary variable equal to 1 if the plane travels from node i to node j, 0 otherwise.
- $u_i \in Z$: Position of node i in the sequence of visits.

3.3.4 Mathematical Model

Objective Function:

$$\text{Minimize} \quad Z = \sum_{i \in V} \sum_{\substack{j \in V \\ j \neq i}} c_{ij} x_{ij}$$

Subject to:

1. **Departure from JFK:**
$$\sum_{\substack{j \in V \\ j \neq \text{JFK}}} x_{\text{JFK},j} = 1$$
2. **Arrival at LAX:**
$$\sum_{\substack{i \in V \\ i \neq \text{LAX}}} x_{i,\text{LAX}} = 1$$
3. **Flow Conservation for each country $i \in N$:**
$$\sum_{\substack{j \in V \\ j \neq i}} x_{ij} = 1, \quad \sum_{\substack{j \in V \\ j \neq i}} x_{ji} = 1, \quad \forall i \in N$$
4. **Subtour Elimination Constraints (Miller-Tucker-Zemlin):**
$$u_{\text{JFK}} = 0 \tag{1}$$
$$u_{\text{LAX}} = |N| + 1 \tag{2}$$
$$1 \leq u_i \leq |N|, \quad \forall i \in N \tag{3}$$
$$u_i - u_j + |N| x_{ij} \leq |N| - 1, \quad \forall i, j \in N, \ i \neq j \tag{4}$$
$$u_{\text{JFK}} - u_j + |N| x_{\text{JFK},j} \leq |N| - 1, \quad \forall j \in N \tag{5}$$
$$u_i - u_{\text{LAX}} + |N| x_{i,\text{LAX}} \leq |N| - 1, \quad \forall i \in N \tag{6}$$
5. **Variable Domains:**
$$x_{ij} \in \{0, 1\}, \quad \forall i, j \in V, \ i \neq j$$
$$u_i \in Z, \quad \forall i \in V$$

3.4 Problem 1 - No MTZ: Mathematical Formulation

3.4.1 Sets and Indices

- N: Set of countries (excluding JFK and LAX), $N = \{1, 2, \ldots, n\}$.
- $V = N \cup \{\text{JFK}, \text{LAX}\}$: Set of all nodes, including start and end airports.
- S: Any subset of V such that $2 \leq |S| \leq |V| - 1$.

3.4.2 Parameters

- c_{ij}: Haversine distance between node i and node j, $\forall i, j \in V$, $i \neq j$.

3.4.3 Decision Variables

- $x_{ij} \in \{0, 1\}$: Binary variable equal to 1 if the plane travels directly from node i to node j, 0 otherwise, $\forall i, j \in V$, $i \neq j$.

3.4.4 Mathematical Model

Objective Function:

$$\text{Minimize} \quad Z = \sum_{i \in V} \sum_{\substack{j \in V \\ j \neq i}} c_{ij} x_{ij}$$

Subject to:

1. **Departure from JFK:**

$$\sum_{\substack{j \in V \\ j \neq \text{JFK}}} x_{\text{JFK},j} = 1$$

2. **Arrival at LAX:**

$$\sum_{\substack{i \in V \\ i \neq \text{LAX}}} x_{i,\text{LAX}} = 1$$

3. **Flow Conservation at Each Country $i \in N$:**

$$\sum_{\substack{j \in V \\ j \neq i}} x_{ij} = 1 \qquad \text{(Departure from } i\text{)} \tag{7}$$

$$\sum_{\substack{j \in V \\ j \neq i}} x_{ji} = 1 \qquad \text{(Arrival at } i\text{)} \tag{8}$$

4. **Subtour Elimination Constraints:**

   - For all subsets $S \subset V$, where $2 \leq |S| \leq |V| - 1$, enforce:

$$\sum_{i \in S} \sum_{j \in S, j \neq i} x_{ij} \leq |S| - 1$$

   - *Note:* These constraints are added dynamically during the optimization process when subtours are detected.

5. **Variable Domains:**

$$x_{ij} \in \{0, 1\}, \quad \forall i, j \in V, \; i \neq j$$

3.4.5 Explanation

- **Objective Function:** The objective remains to minimize the total distance traveled by the plane. This is calculated as the sum of the distances between consecutive nodes in the route.
- **Constraints:**
  - **(1) Departure from JFK:** Ensures that the plane departs from JFK to exactly one airport.
  - **(2) Arrival at LAX:** Ensures that the plane arrives at LAX from exactly one airport.
  - **(3) Flow Conservation at Each Country:** Guarantees that each country (airport) is visited exactly once, with one incoming and one outgoing flight.
  - **(4) Relaxed Subtour Elimination Constraints:** Due to the computational complexity of the Miller-Tucker-Zemlin (MTZ) subtour elimination method, which took over 15 hours of runtime before crashing, we replaced it with a more efficient lazy constraint approach. This method dynamically identifies and eliminates subtours during optimization, ensuring that all nodes are part of a single, valid tour without predefining a large number of constraints.
- **Why Relaxation Was Necessary:**
  - The MTZ method introduces an exponential number of constraints upfront, which significantly increases the computational burden for larger problems.
  - In our case, this led to excessive memory usage and runtime, making it impractical for solving the problem within a reasonable timeframe.
  - By using lazy constraints, we allowed the solver to focus only on relevant subtours as they appeared in intermediate solutions, dramatically reducing computational overhead.
- **Variable Domains:** The decision variables remain binary, representing the presence or absence of a direct flight between two nodes.

3.4.6 Implementation of Lazy Constraints

The implementation of lazy constraints was critical for solving the problem within computational limits. By avoiding the upfront addition of all subtour constraints, we significantly reduced memory usage and runtime. To implement lazy constraints, we followed these steps:

1. **Initial Model Setup:** The optimization model was built with the basic flow conservation and departure/arrival constraints, excluding subtour elimination constraints.
2. **Callback Function:** A callback function was used to dynamically add subtour elimination constraints during the optimization process. This function:
   - Extracted the current solution from the solver.
   - Identified subtours (cycles that do not include all nodes).
   - Added constraints to eliminate the identified subtours.
3. **Subtour Identification:** Subtours were identified using a depth-first search on the solution graph. This ensured that all disconnected cycles were detected and eliminated.
4. **Solver Parameters:** The solver was configured to enable lazy constraints:

   ```
   modelNoMTZ.Params.LazyConstraints = 1
   ```

Advantages of Lazy Constraints:

- Reduced the number of constraints introduced upfront, improving computational efficiency.
- Allowed the solver to focus on feasible regions of the solution space.
- Delivered an optimal solution within a reasonable timeframe.

Disadvantages:

- Requires more intricate implementation and debugging compared to the MTZ method.
- May lead to slightly longer optimization times compared to predefining all subtour constraints for very small instances.

3.4.7 Remarks

- The subtour elimination constraints are crucial to ensure that the solution constitutes a single tour that starts at JFK, visits each country exactly once, and ends at LAX.

- Due to the large number of possible subsets S, it is impractical to include all subtour elimination constraints explicitly. Instead, they are added dynamically during the optimization process when subtours are detected, which is implemented in the optimization code using callback functions.

3.5 Problem 2: Routing Optimization with Two Warehouses

3.5.1 Sets and Indices

- N: Set of countries (excluding JFK and LAX), $N = \{1, 2, \ldots, 44\}$.
- $V = N \cup \{\text{JFK}, \text{LAX}\}$: Set of nodes, including both warehouses.
- $K = \{\text{JFK}, \text{LAX}\}$: Set of planes (starting and ending at JFK and LAX).

3.5.2 Parameters

- c_{ij}: Haversine distance between node i and node j, for all $i, j \in V$, $i \neq j$.

3.5.3 Decision Variables

- $x_{ij}^k \in \{0, 1\}$: Binary variable equal to 1 if plane k travels from node i to node j, 0 otherwise, where $k \in K$.
- $y_i \in \{0, 1\}$: Binary variable equal to 1 if country i is assigned to JFK's plane, 0 if assigned to LAX's plane.
- $u^k \in \{0, 1\}$: Binary variable equal to 1 if plane k is used, 0 otherwise (only for the second approach).

3.5.4 Approach 1: Always Use Two Planes

Hypotheses:

- Both planes must always be used, with each plane starting and ending at its respective warehouse.
- All countries are assigned to one of the two planes.
- Balancing constraints ensure an even distribution of countries between planes[2].

Objective Function:

$$\text{Minimize} \quad Z = \sum_{k \in K} \sum_{i \in V} \sum_{\substack{j \in V \\ j \neq i}} c_{ij} x_{ij}^k$$

Subject to:

1. **Each country is visited exactly once:**

$$\sum_{k \in K} \sum_{\substack{j \in V \\ j \neq i}} x_{ij}^k = 1, \quad \forall i \in N$$

2. **Plane Assignment Constraints:**

$$\sum_{\substack{j \in V \\ j \neq i}} x_{ij}^{\text{JFK}} = y_i, \quad \forall i \in N \tag{9}$$

$$\sum_{\substack{j \in V \\ j \neq i}} x_{ij}^{\text{LAX}} = 1 - y_i, \quad \forall i \in N \tag{10}$$

3. **Departure and Return Constraints for each plane $k \in K$:**

$$\sum_{\substack{j \in V \\ j \neq k}} x_{kj}^k = 1, \quad \sum_{\substack{i \in V \\ i \neq k}} x_{ik}^k = 1$$

[2] This approach is most suited to real-world scenarios as it cuts in half the weight of transport, improves fuel efficiency, reduces carbon emissions, minimizes delays, ensures fairness in operational workload, and simplifies planning for future operations.

4. **Flow Conservation for each node $i \in V$ and plane $k \in K$:**

$$\sum_{\substack{j \in V \\ j \neq i}} x_{ij}^k = \sum_{\substack{j \in V \\ j \neq i}} x_{ji}^k, \quad \forall i \in V, \forall k \in K$$

5. **Balancing Constraint:**

$$\sum_{i \in N} y_i \geq \left\lfloor \frac{|N|}{2} \right\rfloor \tag{11}$$

$$\sum_{i \in N} (1 - y_i) \geq \left\lfloor \frac{|N|}{2} \right\rfloor \tag{12}$$

6. **Variable Domains:**

$$x_{ij}^k \in \{0,1\}, \quad y_i \in \{0,1\}, \quad \forall i,j \in V, i \neq j, \forall k \in K$$

3.5.5 Approach 2: Option to Use One or Both Planes

Hypotheses:

- This approach builds on the previous version but allows the model to decide whether to use one or both planes, depending on what minimizes the total distance.
- If a plane is not used, all variables associated with that plane are set to zero.
- The balancing constraint from the previous approach is removed, as the model does not enforce an even distribution of countries between planes.

Additional Decision Variables:

- $u^k \in \{0,1\}$: Binary variable equal to 1 if plane k is used, 0 otherwise.

Objective Function:

$$\text{Minimize} \quad Z = \sum_{k \in K} \sum_{i \in V} \sum_{\substack{j \in V \\ j \neq i}} c_{ij} x_{ij}^k$$

4 Empirical Results and Analysis

4.1 Optimization Results

4.1.1 Problem 1

For problem 1, the U.S. government plans to ship all health commodities in the support plan in one trip. Our model ensures that all countries are visited exactly once, the total distance is minimized, and subtours are dynamically eliminated during the optimization process using lazy constraints. Due to the air transport schedule, we set JFK as our starting point and LAX as our destination.

The optimization model, referred to as the **no-MTZ model**, is implemented using the Gurobi solver. This approach leverages lazy constraints to dynamically eliminate subtours during the optimization process, making it computationally efficient. In contrast, the standard MTZ formulation, without modifications such as lazy constraints, requires more than 15 hours to compute and eventually crashes the kernel. By adopting the no-MTZ model, we achieve a balance between computational feasibility and solution accuracy.

Using the two datasets containing airport information and distance statistics, we identified the minimum distance and optimal routes. Figure 1 illustrates the optimal route for this problem on a world map. This figure shows the locations of all airports and the shipment route graphically. Blue lines indicate the direct connections between airports. These connections represent the optimized paths for the shipment of health commodities.

Based on the graph, the optimal routes proposed satisfy the starting and ending points. This route covers the regions in America, Europe, Asia, and Africa. The results:

- **Objective Value:** 56,828.57 km
- **Plane Route:** JFK → TIP → BEY → KBL → ISB → FRU → ALA → SGN → ADD → KRT → JUB → EBB → KGL → BJM → NBO → DAR → LLW → LUN → HRE → MPM → SHO → MSU → JNB → GBE → WDH → LAD → FIH → DLA → LOS → COO → LFW → ACC → ABJ → OUA → BKO → ROB → FNA → CKY → DSS → GEO → JBQ → PAP → BZE → GUA → LAX

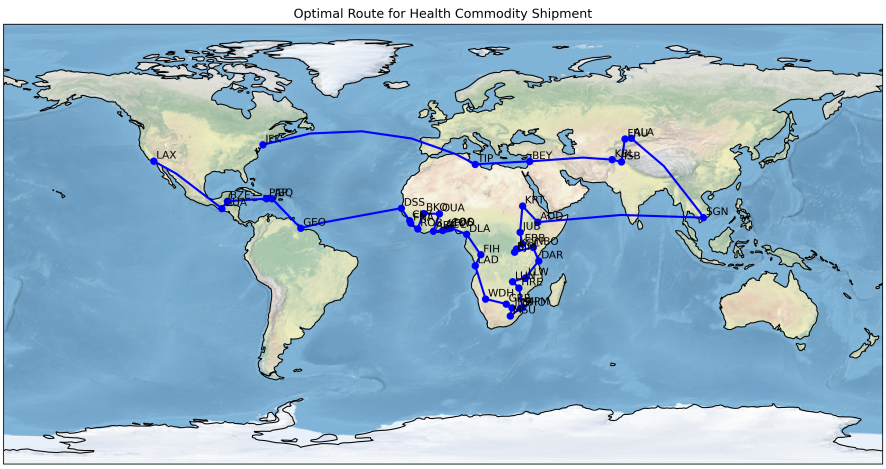

Figure 1: Optimal Route for Health Commodity Shipment - Problem 1

4.1.2 Problem 2

Now, the U.S. government plans to distribute health commodities from two separate warehouses: one near JFK and the other near LAX. To reflect this, we build a new model mentioned in Section 5. In this problem, we still use the Gurobi solver through Python to generate the solution. The solution must be the minimum distance and optimal routes have successfully been found. Figure implements the optimal route on a world map. he visualization highlights an efficient division of destinations to minimize total shipping distances while ensuring that all required locations are visited. The routes are divided between two planes: the blue Route represents the plane starting and returning to JFK, and the red Route represents the plane starting and returning to LAX. The blue plane primarily handles destinations in North and South America, while the red plane covers regions in Africa, Asia, and Europe. The results:

- **Objective Value:** 64700.71 km
- **Route for JFK Plane:** JFK → JBQ → GUA → BZE → JFK
- **Plane fro LAX Plane:** LAX → SGN → ALA → FRU → ISB → KBL → BEY → TIP → KRT → ADD → JUB → EBB → KGL → BJM → NBO → DAR → LLW → LUN → HRE → MPM → SHO → MSU → JNB → GBE → WDH → LAD → FIH → DLA → LOS → COO → LFW → ACC → ABJ → OUA → BKO → ROB → FNA → CKY → DSS → GEO → PAP → LAX

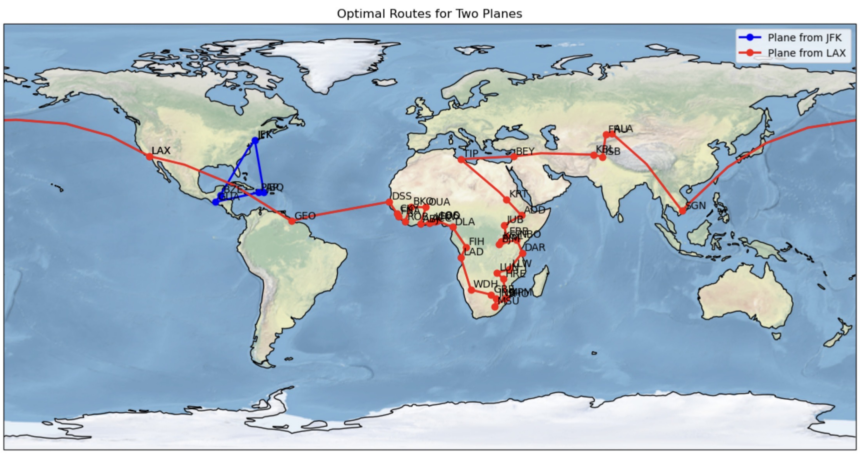

Figure 2: Optimal Route for Health Commodity Shipment - Problem 2

To prevent one plane from being overburdened while the other handles fewer destinations, leading to a more equitable division of the workload, we add a balancing constraint in this case. Holding all else constant, we find the optimal route and the corresponding distance value. The Figure 3 shows the optimal route in this case. The blue route corresponds to the plane departing from JFK, covering destinations predominantly in Africa and Europe, and returning to JFK. Meanwhile, the red route represents the plane from LAX, servicing regions in South America, Africa, Asia, and returning to LAX.

- **Objective Value:** 74,885.13 km
- **Route for JFK Plane:** JFK → BKO → OUA → FIH → LAD → WDH → GBE → JNB → MSU → SHO → MPM → HRE → LUN → LLW → DAR → NBO → BJM → KGL → EBB → JUB → ADD → KRT → TIP → JFK
- **Route for LAX Plane:** LAX → SGN → ALA → FRU → ISB → KBL → BEY → DLA → LOS → COO → LFW → ACC → ABJ → ROB → FNA → CKY → DSS → GEO → JBQ → PAP → BZE → GUA → LAX

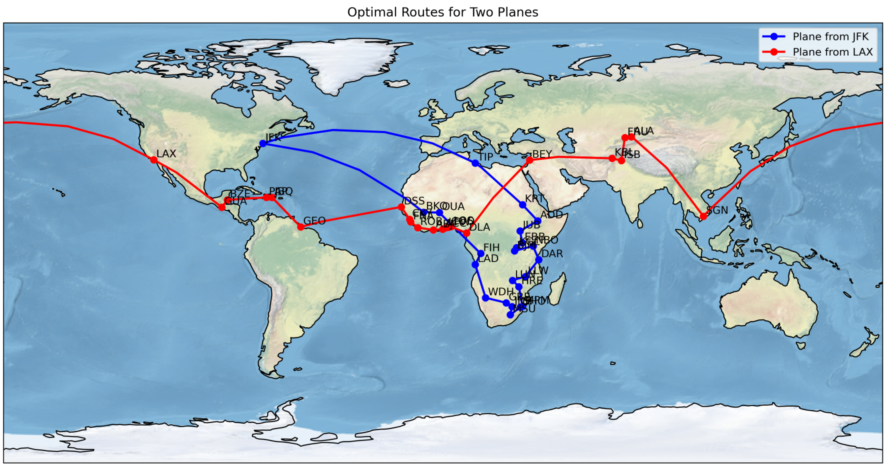

Figure 3: Optimal Route for Health Commodity Shipment - Adding a balancing constraint

In addition, we also try to design an optimization model to decide whether to use one or both plans in this problem. The results show that using one plane that departure from JFK can achieve a lower distance value, and the LAX plane is not be used. Figure 4 states the optimal route we found.

- **Objective Value:** 56,514.55 km
- **Route for JFK Plane:** JFK → BZE → GUA → PAP → JBQ → GEO → DSS → CKY → FNA → ROB → BKO → OUA → ABJ → ACC → LFW → COO → LOS → DLA → FIH → LAD → WDH → GBE → JNB → MSU → SHO → MPM → HRE → LUN → LLW → DAR → NBO → BJM → KGL → EBB → JUB → KRT → ADD → SGN → ALA → FRU → ISB → KBL → BEY → TIP → JFK
- **Plane from LAX is not used.**

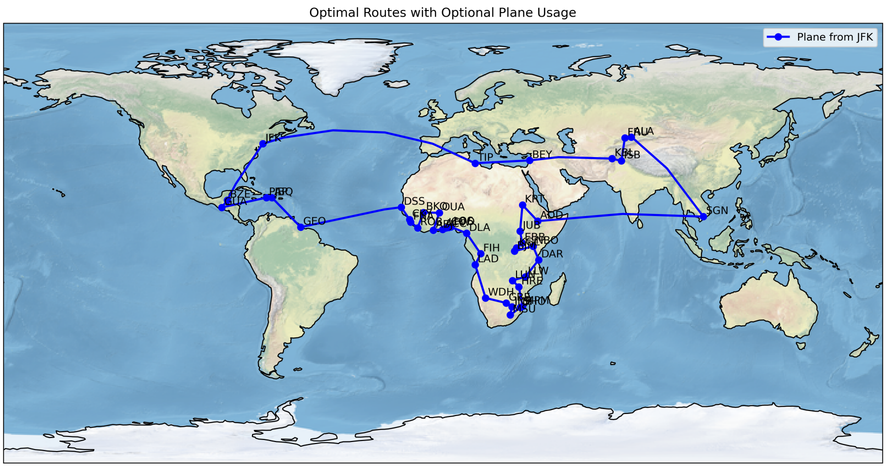

Figure 4: Routes for Optional Plane Usage

5 Discussion

By comparing the two models—one with added balance constraints and one without—we find that adding the balance constraint can increase the minimum distance required. The resulting routes differ significantly, reflecting the trade-offs between operational efficiency and equitable distribution of workload. The inclusion of balancing constraints ensures an equitable distribution of countries between the two planes, reducing operational inefficiencies and promoting workload symmetry. However, this comes at the cost of increased total distance and, consequently, higher operational expenses.

Before planning commences, higher management must determine the aspects to prioritize and their relative importance. Different approaches yield different outcomes based on these priorities, which is crucial for future strategic planning. Additionally, allowing the model to choose between one or two planes leads to a significantly reduced total distance. In Approach 2, the model finds it optimal to use only one plane, starting and ending at JFK, achieving a lower objective value. Conversely, the fixed two-plane approach results in higher costs due to the enforced balancing constraint.

This realization emphasizes the importance of creating systems that dynamically adjust to operational requirements rather than enforcing strict limitations. Flexibility in operational strategies allows for optimization insights to be leveraged effectively, enabling dynamic resource allocation. However, relying on a single plane introduces several considerations:

1. **Operational Risk and Reliability**: Using only one plane increases the risk of operational disruptions. Any mechanical failure or unforeseen event could delay or halt the entire delivery schedule. Utilizing two planes provides redundancy, enhancing reliability and ensuring that deliveries can continue even if one plane encounters issues.

2. **Delivery Times and Efficiency**: With all destinations assigned to a single plane, the total route duration may be longer, potentially delaying shipments to some countries. In contrast, two planes can operate simultaneously, reducing the overall time required to deliver commodities to all destinations.

3. **Environmental Impact Beyond Distance**: While total distance is a key factor in fuel consumption and emissions, aircraft weight also plays a significant role. A single plane carrying all shipments may consume more fuel per kilometer due to the heavier load, potentially offsetting some environmental benefits gained from a shorter total distance.

4. **Capacity Constraints**: The models assume that each plane has sufficient capacity to carry all shipments on its assigned route. In reality, planes have limitations on weight and volume. Incorporating capacity constraints into the model would ensure that proposed routes are feasible given the physical limitations of the aircraft.

5. **Cost Analysis Beyond Distance**: While minimizing distance can reduce fuel costs, other factors such as crew expenses, maintenance, and airport fees also impact total operational costs. A comprehensive cost analysis might reveal that the savings from reduced distance are offset by increased costs in other areas when using a single plane.

5.1 Limitations and Future Work

The limitations of this study stem mainly from the assumptions made. These assumptions simplify the complex nature of real-world logistics to make the problem tractable but may limit the applicability of the results:

- **Simplified Distance Calculations**: The study assumes route lengths are proportional to haversine distances between destinations. This does not account for real-world deviations like air traffic control restrictions, no-fly zones, or weather conditions, potentially underestimating total travel distance. Future work could incorporate more accurate flight path data or use routing software that accounts for these factors.

- **Static Demand and Destinations**: The study considers a static set of destinations and demands, which may not reflect the dynamic nature of global health logistics where new destinations can be added or removed, and shipment sizes may vary over time. Incorporating dynamic modeling techniques or stochastic elements could enhance the model's robustness.

- **Operational Constraints**: Factors such as airport operating hours, time windows for deliveries, crew rest requirements, and maintenance schedules are not considered. Including these constraints would increase the model's realism and practical applicability.

- **Multi-Objective Optimization**: The current model focuses solely on minimizing total distance. In practice, organizations often need to balance multiple objectives, such as cost, time, risk, and environmental impact. Adopting a multi-objective optimization framework could provide solutions that better align with organizational goals.

5.2 Recommendations

Given these considerations, we recommend the following:

- **Incorporate Capacity Constraints**: Modify the models to include aircraft weight and volume limitations to ensure that proposed routes are feasible.
- **Consider Operational Risks**: Evaluate the trade-offs between using one or two planes concerning operational risk and reliability. A risk assessment might justify the additional costs associated with using two planes.
- **Enhance Environmental Impact Assessment**: Include factors such as aircraft weight and emissions per unit distance to more accurately assess the environmental implications of different routing strategies.
- **Adopt Multi-Objective Optimization**: Develop models that can balance total distance with other objectives like delivery time and cost, providing a more holistic optimization approach.
- **Integrate Dynamic Elements**: Explore models that can adapt to changes over time, such as varying demands or new destinations, enhancing the model's utility in real-world applications.

6 Conclusion

This study developed optimization models to enhance the U.S. government's Global Health Commodity Support Plan by minimizing transportation distances, reducing CO emissions, and ensuring the timely delivery of essential medical supplies. For Problem 1, a single-plane model was formulated to determine the optimal shipment route, minimizing total travel distance. For Problem 2, a two-plane model was introduced, incorporating workload balancing between JFK and LAX warehouses. While the balancing constraints in the two-plane model increased the overall transportation distance, they ensured an equitable distribution of resources. Notably, allowing flexibility between single-plane and two-plane configurations demonstrated that a single-plane solution originating and ending at JFK achieved the most efficiency.

The MTZ method addressed subtour challenges in route optimization. Although this approach guarantees precision, its computational complexity is significant. A dynamic subtour elimination approach was adopted to enhance efficiency, significantly improving computational performance while maintaining solution accuracy.

This study's limitations include assumptions of unlimited aircraft capacity, static demand, and idealized travel conditions. Future research should incorporate real-world complexities, such as capacity constraints, dynamic demand variations, airspace restrictions, and weather conditions, to improve model applicability. Integrating heuristic or approximation algorithms with integer programming could provide a practical balance between computational efficiency and solution quality for large-scale logistics problems.

In conclusion, the findings demonstrate the value of advanced optimization techniques in addressing complex global health logistics challenges. By offering data-driven insights and cost-effective solutions, this study provides a foundation for sustainable and efficient supply chain management in support of critical humanitarian initiatives.

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