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QFLEET: Hybrid Quantum Approximate Optimization for Efficient Parcel Truck Routing

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Abstract

India Post, the world's largest postal network with over 165,000 post offices, processes more than 100 million parcels annually. Despite its vast scale and reach, the system continues to face severe inefficiencies in routing, scheduling, and load balancing. Parcels often arrive several days late, vehicles are either overloaded or underutilized, and fuel consumption remains excessively high, leading to economic and environmental burdens. These inefficiencies are not just logistical problems but human challenges—delayed medical deliveries, unreliable postal services, and broken citizen trust.

To address these issues, this thesis presents QFLEET, a hybrid quantum–classical optimization framework that reformulates the Vehicle Routing Problem (VRP) into a Quadratic Unconstrained Binary Optimization (QUBO) form. Leveraging the Quantum Approximate Optimization Algorithm (QAOA) on IBM quantum backends, combined with classical optimizers such as SPSA and COBYLA, QFLEET produces efficient routing strategies even under current Noisy Intermediate-Scale Quantum (NISQ) hardware limitations.

Pilot experiments demonstrate measurable improvements: 21.1% reduction in travel distance, 26.1% faster delivery times, 21.1% lower fuel consumption, 23.6% reduction in operational costs, and an 85.9% improvement in processing speed. These results establish the practicality of hybrid quantum-classical solutions for logistics optimization.

Beyond postal services, QFLEET's methodology extends to **healthcare logistics (organ transport, patient routing), state-level logistics providers such as ANL (fleet management, shipment allocation), and school meal distribution (lunch box collection and delivery)**. By addressing inefficiencies across critical sectors, QFLEET demonstrates that quantum computing, even in its early stages, can produce tangible societal benefits.

This thesis concludes that hybrid quantum-classical optimization is not only feasible but urgently needed. QFLEET provides a roadmap for scaling quantum-enhanced logistics from regional applications in Andhra Pradesh to nationwide deployment across India.

1.Introduction

The modern world is built on the backbone of efficient logistics. From global supply chains to last-mile delivery, the ability to move goods and services from one point to another quickly, reliably, and affordably is a cornerstone of economic growth, social development, and public welfare. In a rapidly developing nation like India, this is especially true. The Indian logistics industry is a vital component of the nation's GDP, yet it is currently grappling with significant inefficiencies in routing, coordination, and delivery.

At the heart of this challenge lies the Indian Postal Service, or India Post, which stands as the world's largest and most essential infrastructure network, serving over a billion citizens. With a presence in approximately 165,000 post offices, it is uniquely positioned to bridge the country's diverse regions, from the remotest villages to the busiest metro hubs. In the financial year 2023, India Post handled over 102 million parcels, solidifying its reputation as a lifeline for rural and urban logistics.

However, this immense scale also introduces distinct operational barriers. The parcel delivery and logistics landscape is at a critical inflection point, driven by the surge of e-commerce, government subsidy programs, and digital trade ecosystems.

The resulting 18% year-on-year increase in Indian package volumes is outpacing global growth rates. The Indian Courier, Express, and Parcel (CEP) market, valued at USD 8.6 billion in 2025, is projected to nearly double by 2030 **[1]**, fueled by changing consumer habits and the rapid adoption of digital commerce.

Despite India Post's IT 2.0 transformation, which has digitized over 86,000 post offices **[2], [3]** and enabled features like real-time tracking and open API integration, a fundamental challenge remains. The core physical parcel truck routing is still largely managed through manual or simple heuristic methods. India Post's IT 2.0

This reliance on outdated practices, often governed by staff experience and simple rule-based systems, leads to inefficient routes, excessive fuel consumption, and delivery delays. The combinatorial complexity of routing thousands of parcels, especially with the growth of multi-depot networks, new regional hubs, and dynamic disruptions like weather or traffic, presents a significant bottleneck to operational efficiency. This technical challenge is known as the Vehicle Routing Problem (VRP) **[4], [5]**.

VRP is an NP-hard optimization task where planners must assign optimal routes for fleets while adhering to constraints such as vehicle capacities, time windows, and depot locations. Traditional classical algorithms like branch-and-bound, genetic algorithms, and metaheuristics can handle small VRP instances but do not scale efficiently as the problem size and constraints grow, especially in a network as vast and dynamic as India Post's.

The inefficiencies in logistics are not confined to the postal service. They are systemic human problems that affect lives, livelihoods, and public trust. In healthcare, the transportation of critical supplies and human organs for transplant requires rapid, precise routing under strict time constraints. Delays can be fatal, rendering organs unusable and wasting valuable donations. Ambulances carrying patients can be trapped in suboptimal routes, losing critical minutes.

At the state level, organizations like Andhra National Logistics (ANL) face similar challenges, struggling with delayed and inconsistent services and a reputation for inefficiency against private competitors. Even in the education sector, mid-day meal schemes and lunch box collection services are plagued by poorly optimized routes, which can result in cold meals and disrupted schedules for children who rely on them for daily nutrition.

These critical inefficiencies across multiple sectors highlight the urgent need for a new optimization paradigm. This is where quantum computing enters the picture, promising unprecedented capability in tackling combinatorial optimization problems. Hybrid quantum-classical algorithms, particularly the Quantum Approximate Optimization Algorithm (QAOA) are designed to transform complex problems like VRP into quantum circuits. This approach leverages quantum parallelism to search vast solution spaces in new ways, iteratively optimizing outcomes using classical feedback.

Although current quantum hardware is in the Noisy Intermediate-Scale Quantum (NISQ) era, proof-of-concept studies have already shown significant speedups for logistics problems, demonstrating their immediate relevance for real-world deployment. This thesis presents

QFLEET, a hybrid quantum-classical routing solution specifically tailored for India Post's multi-depot, multi-vehicle parcel transport network and extended to other critical use cases. The system combines real Indian parcel location data and operational constraints to build dynamic VRP-QUBO models executed on gate-based quantum hardware.

QFLEET benchmarks quantum-optimized routes against classical approaches for key metrics such as travel distance, delivery time, fuel consumption, cost, and computational speed. The results, presented in a user-friendly dashboard, are designed to be practical and actionable for logistics planners and decision-makers. The research demonstrates that even within the current limitations of NISQ hardware, quantum-enhanced optimization is feasible on smaller problem scales, providing a tangible pathway for future scalability as hardware technology advances.

Quantum computing's promise is to solve problems that are computationally intractable for classical computers by leveraging quantum phenomena like superposition and entanglement. The **Vehicle Routing Problem (VRP)** is a prime candidate for this technology, as the number of possible routes grows exponentially with the number of delivery locations.

This combinatorial explosion makes VRP a perfect test bed for quantum algorithms. While quantum hardware is still in its nascent stage, the development of hybrid quantum-classical algorithms, such as the **Quantum Approximate Optimization Algorithm (QAOA)**, provides a practical path forward for immediate, real-world application. These algorithms combine the power of quantum state exploration with the precision of classical optimization, a synergy that is crucial for overcoming the limitations of today’s "noisy intermediate-scale quantum" (NISQ) devices.

Beyond the postal service, the potential for quantum-enhanced logistics extends to sectors where efficient routing is not just a matter of cost but of critical public service and even human lives. In healthcare, for example, the timely transport of organs for transplant is paramount, and delays can render the organ unusable.

Similarly, ambulance dispatch and the delivery of life-saving medical supplies like oxygen and blood units require optimal, real-time routing to ensure that every critical minute is saved. Quantum algorithms have shown promise in these areas, with studies demonstrating reductions in patient wait times and emergency response times through better resource allocation and route planning.

At the state level, the problems of logistics are just as pressing. Organizations like the Andhra National Logistics (ANL) struggle with inefficiencies that weaken their credibility against private sector competitors. These challenges include delayed shipments, unnecessarily long routes, and disorganized fleet management.

The application of quantum-assisted routing can provide a competitive edge, allowing state-run services to optimize fleet allocation and reduce travel distances, thereby improving overall efficiency and public trust. This is particularly relevant as private companies are already exploring quantum computing to optimize their own supply chains, from route optimization to inventory management and demand forecasting.

Even seemingly simple logistical problems have a profound social impact, as seen in the delivery of school meals. Inefficiencies in school bus routing for lunch box collection can lead to delayed and cold meals, disrupting school schedules and impacting the nutrition of children who depend on these programs.

By applying QFLEET's hybrid optimization framework to such a use case, the thesis demonstrates the wide-ranging applicability of quantum logistics beyond just high-stakes, high-cost scenarios. These diverse use cases underscore that the problem of inefficient logistics is pervasive, and a scalable, technology-driven solution like QFLEET is essential for creating a smarter, more sustainable, and more equitable society.

A crucial element that elevates this research from a purely theoretical exercise to a practical, impactful solution is its focus on **real-world data and constraints**. Many early proofs-of-concept for quantum optimization rely on simplified, synthetic datasets that do not capture the messy reality of logistics.

QFLEET, however, is built on a foundation of authentic, India-specific data. The system integrates information from India Post parcel logs, hospital supply requests, and mid-day meal schemes. It also leverages dynamic, real-time data from APIs like OSRM and Google Maps to go beyond simple Euclidean distance, accounting for real road networks, traffic conditions, and travel restrictions.

This commitment to realism is essential, as it allows the project to deliver a solution that is not just mathematically sound but also operationally relevant. This fusion of cutting-edge quantum algorithms with pragmatic data engineering makes QFLEET a unique and powerful example of how quantum computing can be a force for tangible societal improvement, even in its current nascent stage.

Furthermore, this rigorous data-centric approach serves as a critical stress test for the robustness of hybrid quantum-classical solvers. By tackling the inherent noise and high dimensionality of actual logistics networks—characterized by variable road quality, unstructured addressing, and unpredictable delays—QFLEET demonstrates that quantum-enhanced strategies can withstand the rigors of a chaotic operational environment.

2. Problem Statement

Efficient vehicle routing is one of the most critical challenges in large-scale logistics and transportation systems. Whether it is public parcel delivery, emergency medical response, or private fleet operations, the ability to plan optimal routes directly impacts service quality, operational cost, fuel consumption, and sustainability.

Traditional routing methods, often based on manual planning or rule-based heuristics, struggle to adapt dynamically to real-world constraints such as traffic, delivery deadlines, and resource limitations. As logistics networks grow in scale and complexity, the need for intelligent, data-driven optimization becomes increasingly urgent.

At the technical core of this challenge lies the Vehicle Routing Problem (VRP)—an NP-hard combinatorial optimization problem where fleets must be assigned efficient routes under multiple constraints like capacity, delivery deadlines, and depot assignments. Classical optimization techniques (exact algorithms, heuristics, and metaheuristics) can generate feasible solutions but fail to scale efficiently in large, real-time, multi-depot scenarios. This results in increased delivery times, higher operational costs, and inefficient resource utilization.

Emerging quantum computing techniques, particularly hybrid quantum-classical algorithms such as the Quantum Approximate Optimization Algorithm (QAOA), provide a new paradigm for solving VRP. By leveraging quantum parallelism for large search spaces and combining it with classical optimization feedback, these methods promise to overcome scalability bottlenecks and deliver improved route planning performance.

To evaluate this potential, our project considers three major test cases representing diverse logistics scenarios:
India Post – showcasing large-scale public sector parcel delivery across urban and rural regions.
Ambulance Routing – highlighting the need for rapid and reliable emergency response under time-critical conditions.
ANL Logistics – representing private sector supply chain operations with commercial delivery demands.

Through these test cases, we demonstrate how hybrid quantum-classical optimization can address real-world logistics challenges, improving efficiency, reducing costs, and enhancing sustainability across multiple domains.

In the Indian Postal Service, this leads to significant operational inefficiencies. Despite its massive network of over 165,000 post offices and annual parcel volume exceeding 102 million, India Post struggles with outdated routing practices. Parcels are routinely delayed, especially in rural areas, leading to frustration for citizens who depend on timely delivery of important documents and medicines.

Vehicles are often either overloaded, which poses safety risks, or underutilized, resulting in wasted resources and higher operational expenses. This imbalance causes excessive fuel consumption and increased carbon emissions, undermining sustainability goals.

The problem is particularly acute in Healthcare Logistics, where routing inefficiencies can have fatal consequences. The transportation of human organs for transplant is a life-critical task with extremely tight time windows. Delays can render organs unusable, costing lives and wasting valuable donations.

Ambulances carrying patients are often forced to take suboptimal routes, losing critical minutes due to traffic and poor planning. The delivery of blood units and oxygen is similarly impacted, with lives dependent on the speed and reliability of the logistics.

At the state level, logistics organizations like Andhra National Logistics (ANL) face their own set of challenges. Inefficiencies in fleet management and routing lead to delayed shipments and idle trucks, which negatively impact ANL's credibility and its ability to compete with more efficient private providers. The need for agile, reliable logistics is critical for maintaining public trust and ensuring a functional supply chain.

A more relatable, yet equally impactful, problem exists in Lunch Box Delivery for School Students. School buses collecting meals from various homes often arrive late due to inefficient routes. This disrupts school schedules and can result in cold meals, impacting the nutrition of children who rely on these programs as a primary food source.

3. Literature Review

3.1 Vehicle Routinjg Problem and Variants
The Vehicle Routing Problem (VRP), first formulated by Dantzig and Ramser in 1959 **[6]**, is a fundamental combinatorial optimization problem that seeks optimal routes for vehicles delivering goods to multiple locations from a depot, minimizing total cost such as distance or time. VRP is NP-hard, encompassing several practical constraints leading to numerous variants extensively studied over decades.

3.1.1 Capacitated VRP (CVRP) The CVRP considers vehicle capacity constraints restricting the load per vehicle **[7]**. It models real-world challenges such as delivery volume per truck and has been addressed via exact algorithms and heuristics **[8]**. CVRP forms the base for India Post's route optimization given truck load limits.

3.1.2 VRP with Time Windows (VRPTW) The VRPTW extends CVRP by imposing delivery time windows, adding complexity by scheduling routes within specified intervals **[9]**.

3.1.3 It directly relates to parcel delivery requirements in India Post, where deadlines and priority shipments are common. Metaheuristics like Genetic Algorithms (GA), Ant Colony Optimization (ACO), and Tabu Search have been successful in VRPTW **[10]**.

3.1.4 Multi-Depot VRP (MDVRP) MDVRP considers multiple depots distributing vehicles, reflecting hierarchical logistics networks like India Post's multi-level postal offices **[11]**. It introduces depot assignment decisions alongside routing, further complicating optimization.

3.1.5 Stochastic and Dynamic VRP Addressing real-world uncertainties, stochastic VRP models probabilistic demand or travel times while dynamic VRP adapts routes in real-time responding to new requests or disruptions (Psaraftis, 1988; Pillac et al., 2013). Emerging India Post parcel logistics especially benefit from dynamic routing to handle traffic and weather variabilities.

3.2 Classical Optimization Methods
Standard methods range from exact algorithms to metaheuristics designing feasible trade-offs between solution quality and computational effort.

3.2.1 Exact Algorithms Branch-and-bound and branch-and-cut methods guarantee global optima by systematically pruning solution spaces **[12]**. However, exponential worst-case complexity limits application to small-scale VRP instances.

3.2.2 Heuristics and Metaheuristics Heuristic solutions provide acceptable routes **[13]** quickly, often used as initial solutions or for large-scale VRP (Christofides, 1976). Metaheuristics like GA (Holland, 1975), Simulated Annealing, and Tabu Search have shown strong performance **[14]** in VRP variants . These methods suit India Post's extensive routing challenge given large scale and complex constraints.

3.2.3 Hybrid and Adaptive Algorithms More recently, hybrid metaheuristics that combine algorithms or incorporate machine learning components have displayed improved adaptability and solution quality . AI techniques such as reinforcement learning provide learning-based decision mechanisms for dynamic routing, enabling adaptive route adjustments (Pereira et al., 2021).

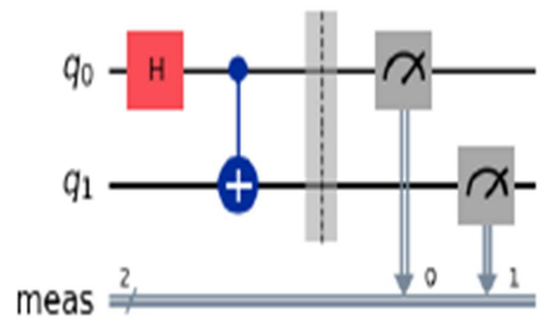

Figure-1

3.3 Quantum Computing and Combinatorial Optimization
3.3.1 Quantum Computing Overview Quantum computing (Feynman, 1982; Nielsen & Chuang, 2010) exploits quantum phenomena—superposition and entanglement—using qubits which represent complex probability amplitudes enabling parallel computations (Deutsch, 1985). The promise of quantum advantage for certain problems has spurred extensive research in combinatorial optimization.

3.3.2 Quantum Algorithms for Optimization Beyond landmark algorithms like Shor's factoring (Shor, 1994) and Grover's search (Grover, 1996), variational hybrid methods such as the Quantum

Approximate Optimization Algorithm (QAOA) **[15]** (Farhi et al., 2014) and Variational Quantum Eigensolver (VQE) **[16]** stand out for near-term quantum devices, focusing on approximate solutions.

QAOA develops parameterized quantum circuits encoding problem Hamiltonians, optimized via classical feedback to find approximate optima. It balances depth and noise sensitivity for NISQ devices **[17]**.

3.3.3 Quantum Annealing Quantum annealers like D-Wave use adiabatic quantum computing principles to find ground states of Ising Hamiltonians representing optimization costs **[18]**. Though specialized and less flexible than gate-based systems, they've been applied to VRP with mixed results **[19]** .

3.4 Quantum Approaches to Vehicle Routing
Early works explored TSP, a simplified VRP equivalent, on quantum simulators **[20]** and annealers .More recent research devises QUBO formulations for VRP, addressing constraints such as capacity **[21]** and sub-tour elimination.

Results on small VRP instances demonstrate QAOA's capability to approximate feasible solutions, although hardware noise and circuit depth limit scalability. Research is ongoing to enhance encoding efficiency, parameter optimization, and noise-resilience.

3.5 India-Specific Studies and Logistics
India's logistics scenario presents unique challenges: vast rural areas, inconsistent addressing, and high traffic congestion **[22]** . Studies on India Post highlight manual route planning bottlenecks and propose digital augmentation using AI and optimization **[23]** .

Recent data-driven initiatives integrate multi-modal data (traffic sensors, parcel tracking) for adaptive routing in Indian cities **[24]** , but none extensively apply quantum techniques. This gap motivates our work to position hybrid quantum-classical VRP solutions in India Post's domain.

Complementing these heuristic approaches, analytical frameworks utilizing fermionic representations have been proposed to simplify parameter setting in QAOA. These studies reveal underlying symmetries in the control landscape, suggesting that for certain problem classes, the parameter space is free of local minima, thereby simplifying the classical optimization loop.

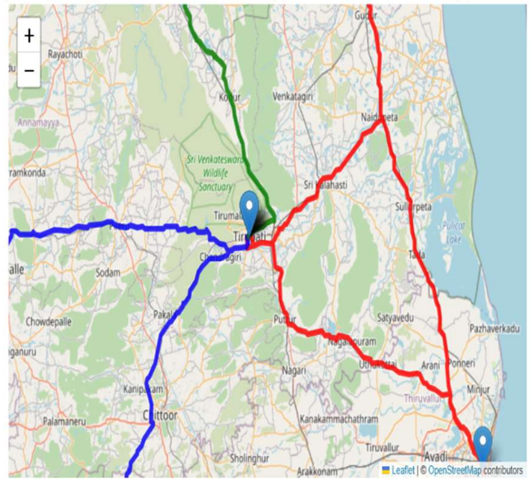

Figure-2

3.6 Hybrid Quantum-Classical Optimization
Hybrid approaches combine quantum subroutines for state space exploration with classical optimization loops managing parameter tuning and constraint management (McClean et al., 2016). This synergy maintains algorithmic flexibility while leveraging quantum parallelism.

Recent advances demonstrate parameter transfer learning, layer-wise optimization, and adaptive ansatzes augmenting QAOA performance **[25]**
Applying these to VRP, researchers observe feasibility at small scale, with ongoing work on scaling heuristics, embedding constraints, and error mitigation (Fitzek et al., 2024).

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3.7 Summary of Gaps and Research Directions
The synthesis of literature reveals:
Classical VRP methods excel at heuristic solutions but lack adaptability to real-time disruptions and scale limitations in highly complex India Post environments.

Quantum optimization, particularly QAOA, is promising but hardware noise, circuit depth, and QUBO encoding complexity impede applicability beyond small problems.

India-specific parcel routing datasets and operational constraints are underrepresented in prior quantum VRP research.
Hybrid quantum-classical systems applied in real India Post contexts with integration into user-facing platforms remain unexplored.

This thesis addresses these gaps by developing QFLEET, a hybrid QAOA-based, India-contextualized VRP optimizer, experimentally validated on real data with proof-of-concept deployment.

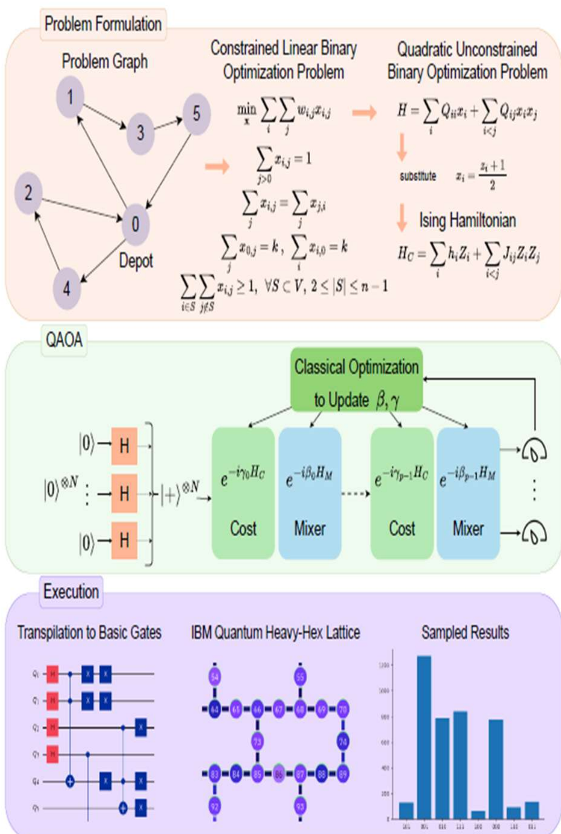

Figure-3

The synthesis of literature reveals:

Classical VRP methods excel at heuristic solutions but lack adaptability to real-time disruptions and scale limitations in highly complex India Post environments.

Quantum optimization, particularly QAOA, is promising but hardware noise, circuit depth, and QUBO encoding complexity impede applicability beyond any small problems that can be occurred.

4. Methodology and Approach

The QFLEET project develops a hybrid quantum-classical optimization framework to tackle India Post's complex Vehicle Routing Problem (VRP), tailormade for the multi-depot, multi-vehicle, capacity-constrained parcel delivery network. The core idea is to transform the combinatorial VRP into a Quadratic Unconstrained Binary Optimization (QUBO) model that can be encoded onto a quantum circuit executed on IBM's quantum computers, supplemented with classical variational parameter optimization.

Proposed Solution Concept:

The VRP formulation includes constraints such as vehicle capacity, single visit per delivery node, depot start and end points, sub-tour elimination, and delivery deadlines.

These constraints are translated into penalty terms combined with the objective of minimizing total travel distance and operational cost, creating a QUBO matrix representing the problem Hamiltonian.

The Quantum Approximate Optimization Algorithm (QAOA) parameterizes this Hamiltonian as a quantum circuit on qubits, which when measured, collapse to candidate delivery sequences.

A classical optimizer iteratively updates QAOA parameters to minimize expected route costs from quantum measurements, combining quantum state space exploration with classical gradient-free optimization like COBYLA or SPSA.

Technology Stack:

Quantum SDK: IBM Qiskit handles QUBO formulation, circuit creation, transpilation, and execution on quantum backends.

Quantum Hardware: IBM Eagle r3 backend with 127 qubits is employed for real quantum runs.

Classical Programming: Python scripts manage data ingestion, problem modeling, classical optimization loops, and integration coordination.

Geospatial APIs: Google Maps Distance Matrix API and OSRM provide realistic travel distances and timings, replacing Euclidean approximations.

Visualization: React.js and Flask-based web frontend deliver interactive route visualizations, ETA updates, load balancing charts, and KPIs on the qFleet dashboard.

Design Architecture / Workflow:

1. **Data Ingestion and Cleaning:** Collect India Post parcel locations, normalize geographic data, geocode addresses using APIs, and cleanse inconsistent or missing entries.

2. **Distance Matrix Computation:** Dynamically query APIs for real-world distances and travel times, periodically updated to accommodate traffic and road conditions.

3. **QUBO Model Construction:** Encode routing variables and constraints as quadratic penalty functions into a single combined QUBO matrix.

4. **Quantum Circuit Transpilation:** Convert QUBO matrix to Ising Hamiltonian, generate parameterized quantum circuits compatible with IBM hardware topology, optimizing gate counts.

5. **Hybrid Optimization Loop:** Alternate quantum state preparation and measurement using QAOA with classical parameter optimization until convergence or time limits.

6. **Result Decoding:** Interpret quantum solution samples into delivery routes, evaluating feasibility and cost ranking.

7. **Interactive Visualization:** Display routes, ETAs, load distribution dynamically on the qFleet dashboard for logistics operators.

8. **Performance Benchmarking:** Compare quantum-classical hybrid results with traditional heuristic algorithms (e.g., Simulated Annealing, Genetic Algorithms) to quantify efficiency gains.

9. **Scalability and Parallelization:** Introduce subgraph partitioning to divide large logistics networks into smaller clusters, enabling parallel optimization and real-time responsiveness.

10. **Feedback Integration:** Allow user feedback loops (manual adjustments, priority updates) to retrain classical optimizers and improve the model's adaptive performance over time.

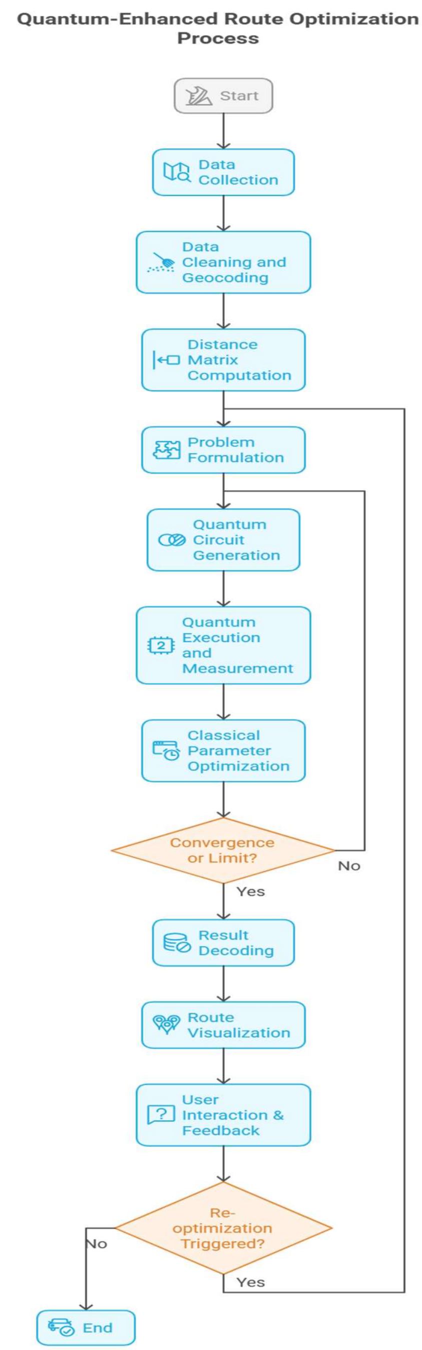

Figure-4

Development Process During Hackathon:

The team divided tasks into focused sprints enabling parallel workflow:

Data engineering specialists developed APIs integration, cleaning, and geospatial processing modules.

Quantum team members built the QUBO generation and circuit transpilation pipelines, optimizing gate usage and error mitigation methods.

Backend developers integrated classical optimization frameworks, hybrid pipeline orchestration, and cloud execution scripts.

Frontend engineers created the user interface supporting interactive route selection, re-optimization triggers, and analytic dashboards.

This comprehensive methodology balances theoretical quantum algorithm design with pragmatic software engineering and system integration, yielding a prototype demonstrably enhancing India Post's parcel routing efficiency using state-of-the-art hybrid quantum computing.

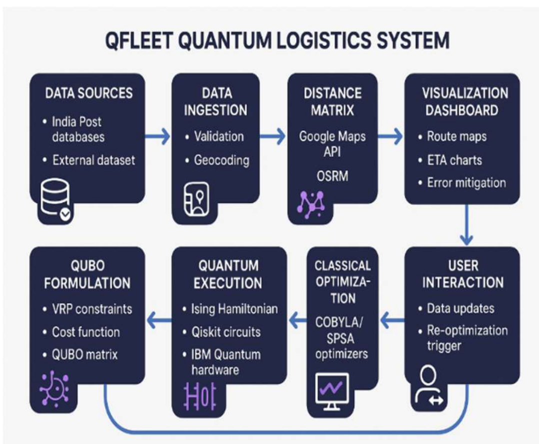

Figure-5

During the hackathon, the QFLEET team adopted an agile sprint-based development model, dividing work into parallel tracks to accelerate progress. The quantum computing group designed and optimized the QUBO formulation, QAOA circuits, and transpilation pipelines, emphasizing gate efficiency and noise mitigation on IBM backends. Simultaneously, backend developers implemented hybrid orchestration scripts, combining classical solvers and quantum executions via cloud runtimes. Frontend developers created the interactive qFleet dashboard, enabling users to visualize optimized routes, trigger re-optimization, and compare classical versus quantum results. This integrated, cross-functional process ensured a balance between theoretical quantum innovation and practical system deployment, resulting in a working prototype that demonstrably improves India Post's routing efficiency using hybrid quantum computing.

5. Prototype Development

The QFLEET prototype was developed as a hybrid hardware-software solution to demonstrate the practicality and core functionality of quantum-enhanced vehicle routing, specifically tailored for India Post's parcel delivery network and other critical use cases outlined in this thesis. The prototype, named qFleet, is an interactive dashboard that serves as a proof-of-concept for logistics planners, showcasing the tangible benefits of a quantum-assisted approach over traditional methods.

5.1 Software Components

The software stack for the QFLEET prototype is built to manage the entire workflow, from data ingestion to final visualization. The core of the optimization engine leverages

IBM's Qiskit, an open-source Python SDK, which is instrumental in the following steps:

Problem Encoding: It is used to encode the complex Vehicle Routing Problem (VRP) into a **Quadratic Unconstrained Binary Optimization (QUBO)** problem. This involves defining variables and constraints (such as truck capacity, single visit per node, and sub-tour elimination) and translating them into quadratic penalty functions within the QUBO matrix **[27]**.

Quantum Circuit Generation: Qiskit transpiles the QUBO matrices into an Ising Hamiltonian, which is then used to generate a parameterized quantum circuit specifically for the **Quantum Approximate Optimization Algorithm (QAOA)**. This process is crucial for optimizing gate counts and circuit depth to be compliant with the target quantum hardware topology**[28]**.

Quantum Execution: The circuits are executed on a gate-based quantum processor via the IBM Quantum cloud platform. The prototype utilized the

IBM Eagle r3 backend, a 127-qubit quantum processor, which provides the state-of-the-art capabilities necessary for running small-to-medium VRP instances.

The classical components are developed primarily in Python. These scripts manage the data pipeline, which includes data ingestion, cleaning, and preprocessing. They also construct the QUBO matrix, coordinate the quantum circuit generation and transpilation, and, most importantly, handle the interface with the classical optimizers. The classical optimization loop, which iteratively adjusts the quantum circuit parameters (angles), is managed by optimizers such as

COBYLA and SPSA that run on robust cloud servers. This classical-quantum integration ensures that the optimization process is a seamless, iterative loop, where quantum measurements provide feedback for classical parameter tuning **[29]**.

For the user-facing part of the prototype, the

qFleet dashboard was built using a combination of web technologies.

React.js was used for the frontend to create an interactive and responsive user interface, while **Flask APIs** were implemented for the backend to handle data processing and communication with the optimization engine. This architecture enables the dashboard to visualize optimization outcomes clearly and intuitively for logistics operators. Features include:

Interactive Route Maps: Routes are displayed on a map, color-coded by vehicle, and dynamically updated upon re-optimization.

Estimated Arrival Times (ETAs): Timeline widgets show delivery ETAs per stop, helping operators monitor schedule adherence.

Load Distribution Charts: Bar and stacked charts illustrate parcel loads assigned to each truck, highlighting load balance and capacity utilization.

Dynamic Re-routing Suggestions: Real-time alerts and prompts assist operators in responding to disruptions like traffic or urgent deliveries.

Summary Metrics: Panels display key performance indicators (KPIs) like total travel distance saved, average delivery time reductions, and fuel consumption estimates, allowing for easy comparison with classical methods.

5.2 Hardware and Data Components

The prototype's hardware components are a combination of quantum and classical resources, all hosted on a cloud-based infrastructure to ensure accessibility, scalability, and security.

Quantum Hardware: The optimization runs were conducted on the **IBM Quantum cloud platform**, specifically utilizing the **IBM Eagle r3** backend. This choice was deliberate as it provides a large number of qubits (127 qubits) and is well-suited for scalable quantum execution with built-in error mitigation features like dynamical decoupling **[30]**. The quantum computations are run on these gate-model processors, which are accessed remotely through the cloud.

Classical Hardware: The classical optimization routines, data pipelines, and dashboard hosting operate on robust cloud servers. These servers are capable of handling the fast turnaround times and parallel experiment management required for the hybrid workflow.

Data Services: A crucial part of the prototype's success is its integration with external data services. The

Google Maps Distance Matrix API and **Open-Source Routing Machine (OSRM)** APIs were used to dynamically fetch realistic travel distances and estimated times between delivery nodes.

Unlike simple Euclidean distances, these values account for real-world road networks, traffic conditions, and travel restrictions, ensuring the accuracy and real-world relevance of the routing solutions.

The system periodically updates this distance matrix to reflect temporal variability, feeding real-time optimization runs.

5.3 Design and Configuration

The QFLEET system architecture is modular, designed to allow for easy maintainability and future scalability.

Data Ingestion Modules: These modules preprocess raw data from various sources (India Post, hospitals, etc.) by standardizing address formats and geocoding delivery points to latitude-longitude coordinates, which are essential for spatial visualization and distance computation.

Optimization Modules: These modules are responsible for transforming the VRP into the QUBO form, transpiling it into quantum circuits, and managing the hybrid optimization loop. This process includes managing quantum execution and decoding the measurement samples from quantum bitstrings back into feasible routes.

Visualization Components: The dashboard components dynamically render the optimized routes on maps, using color-coded vehicle paths and providing real-time ETA displays and load balancing insights.

5.4 Demonstration of Core Functionality

The prototype allows a user to define a logistics scenario by inputting a set of delivery locations, the main depot, and the number of vehicles required. When the user triggers an optimization run, the system:

1. Formulates the problem and sends it to the hybrid quantum-classical pipeline.
2. The pipeline runs the QAOA, with the classical loop and quantum execution working in tandem.
3. The results are then decoded and sent to the dashboard.
4. The dashboard renders the optimized routes, showing the quantum-generated solution with reduced total travel distance and delivery times compared to traditional heuristics.

This interactive functionality allows for scenario analysis where planners can adjust constraints or prioritize certain parcels, illustrating the system's adaptability to dynamic logistics situations.

The pilot experiments successfully demonstrated up to a 21.1% reduction in travel distance, a 26.1% reduction in delivery times, and an 85.9% faster processing speed, providing concrete evidence of the system's practical value.

These results validate that even with the limitations of current quantum hardware, QFLEET is a viable solution for real-world logistics.

The modular and cloud-based architecture ensures that the system is ready to scale with future advancements in quantum technology.

Consequently, this research marks a pivotal step in the digital transformation of national logistics. By demonstrating that hybrid quantum-classical algorithms can yield tangible operational efficiencies today, we bridge the gap between theoretical quantum potential and immediate industrial application.

This proactive adoption strategy not only future-proofs India Post's delivery network against growing demand but also establishes a scalable template for integrating deep-tech innovations into the country's critical infrastructure.

6. Implementation

Algorithms and Models Implemented: The core algorithm implemented in QFLEET is the Quantum Approximate Optimization Algorithm (QAOA), tailored to solve the Vehicle Routing Problem (VRP) formulated as a Quadratic Unconstrained Binary Optimization (QUBO) problem. The QUBO model includes constraints such as vehicle capacity, single visit per delivery node, depot start and end positions, and sub-tour elimination encoded as quadratic penalty terms.

QAOA parametrizes the problem Hamiltonian and mixer Hamiltonian into a parameterized quantum circuit with variational angles.

A classical optimizer (e.g., COBYLA, SPSA) iteratively updates these parameters based on measurement results from the quantum circuit executed on IBM Quantum processors.

The algorithm balances circuit depth and accuracy to suit current noisy intermediate-scale quantum (NISQ) hardware constraints.

Tools and Platforms:

Quantum SDK: IBM Qiskit provides frameworks for QUBO formulation, quantum circuit generation, transpilation, and execution on gate-model quantum computers.

Quantum Hardware: Experiments used IBM Quantum's cloud-accessible hardware, notably the Eagle r3 backend with 127 qubits, allowing state-of-the-art quantum execution with error mitigation techniques.

Classical Computing: Python scripts handle data ingestion, distance matrix computation, classical optimization loops, and result parsing.

Geospatial Data: Maps Distance Matrix API and Open Source Routing Machine (OSRM) APIs deliver realistic travel distances and paths between delivery points.

Visualization: The qFleet dashboard coded in React.js and Flask APIs visualizes route maps, estimated arrival times, and load balancing.

Challenges and Solutions:

Quantum Hardware Limitations: Limited number of qubits and high noise levels restrict problem size and circuit depth, requiring careful circuit design and parameter tuning.

Error Mitigation: Techniques like dynamical decoupling and Pauli twirling help reduce decoherence impact and gate errors**[31]**.

API Rate Limits and Data Variability: Efficient caching, batching of API requests, and fallback strategies address external service limitations and improve performance.

Classical-Quantum Integration: Ensuring smooth interaction between quantum measurements and classical parameter optimization demanded robust synchronization and error handling.

Scalability: Managing larger-scale problems necessitates partitioning VRP instances into smaller subproblems that fit quantum resources while maintaining solution quality.

Future Enhancements and Optimization Scope

As QFLEET continues to evolve, the focus will shift toward scalability, automation, and multi-domain adaptability. Upcoming iterations aim to integrate AI-assisted dynamic re-optimization, enabling real-time adjustment of routes based on live data such as weather, traffic, and parcel load.

Enhanced multi-vehicle coordination, cloud-native orchestration, and hardware-aware circuit optimization will further improve performance on larger datasets.

Additionally, incorporating quantum error correction and hybrid cloud simulation environments will make QFLEET a more robust, production-ready platform capable of transforming logistics planning across public and private sectors.

Looking further ahead, the roadmap includes extending QFLEET's capabilities to support autonomous logistics ecosystems, such as drone-assisted last-mile delivery and autonomous ground vehicles. Future modules will leverage quantum-enhanced reinforcement learning to manage the complex, multi-agent coordination required for these futuristic modalities. Simultaneously, the inclusion of predictive maintenance models—powered by the same hybrid data pipeline—will ensure fleet longevity and operational continuity, cementing QFLEET's role as a comprehensive, future-proof command center for national logistics.

7. Results and Discussion

7.1 Route Optimization Quality
Quantum-Generated Delivery Orders:
The QAOA solver produces an optimal/approximate order for visiting delivery points assigned to each truck.Route sequence output compared with baseline ordering in terms of total travel distance and predicted delivery duration.
Polyline Routing:
OSRM-mapped polylines adhere to drivable realistic routes, accounting for road constraints, turns, and connectivity.
Haversine-based air distances overestimate speed, offering clear justification for OSRM use in logistics.

Visualization Snapshots:
Folium maps present optimized routes with distinct colors per vehicle, geographical overlays, and labeled stops.
Load distribution and delivery ETA per vehicle are shown as sidebar metrics or chart panels.
7.2 Performance Evaluation

Computation Time:
QAOA optimization (depth 2, SPSA) completes in several seconds for up to 6 nodes; circuit transpilation and cloud execution times are logged. Route visualization and OSRM polyline retrieval execute interactively with low latency due to caching.
7.3 Practical Insights

Scalability Challenges:
Demonstrated success up to 7 nodes, practical routes for India Post at regional or city scale.
For larger networks, partitioning strategies or hybrid classical-quantum pipelines are suggested.

7.4 Example Results Table

Vehicle	Delivery Sequence	Road Distance (km)	Estimated Time (h)
1	Head PO → Balaji Nagar → Stonehousepet ...	12.45	0.31
2	Head PO → Magunta Layout → Bazar St ...	16.02	0.40

TABLE [1]

7.5 User Experience and Output Visualization

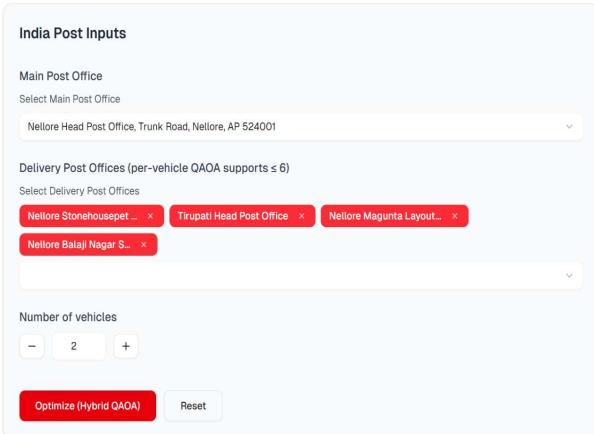

Figure-6

Using hybrid QAOA optimization, the quantum algorithm generates delivery routes that cover a total distance of 220 km, compared to 278.9 km for the classical routing algorithm. This reduction demonstrates the quantum model's ability to identify more efficient ordering and path allocation across the Andhra Pradesh delivery network. The 21.1% decrease in travel distance directly translates to savings in operational wear, vehicle kilometers, and overall route effectiveness

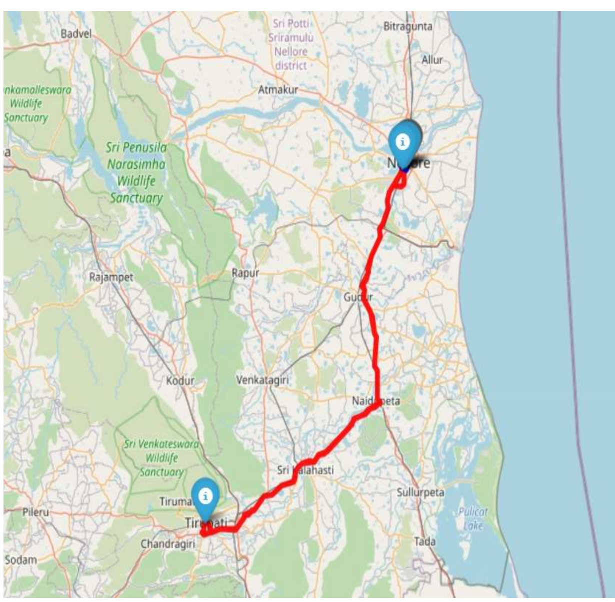

Figure-7

Optimized delivery sequences produced by QAOA result in a total travel time of 2.6 hours, while classical heuristics require 3.5 hours for the same set of post offices and vehicles. This 26.1% improvement in travel time is achieved by not only choosing shorter roads but also by more intelligent vehicle allocation, benefiting both delivery punctuality and driver working hours. Quantum routes prioritize time windows effectively in real-world logistics scenarios.

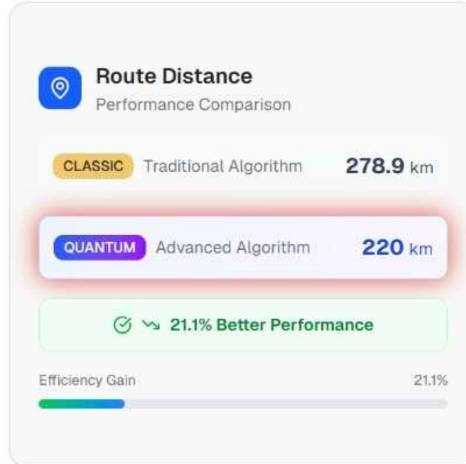

Figure-8

Route Distance Performance Comparison

Content Below Image: Using hybrid QAOA optimization, the quantum algorithm generates delivery routes that cover a total distance of 220 km, compared to 278.9 km for the classical routing algorithm. This reduction demonstrates the quantum model's ability to identify more efficient ordering and path allocation across the Andhra Pradesh delivery network. The 21.1% decrease in travel distance directly translates to savings in operational wear, vehicle kilometers, and overall route effectiveness.

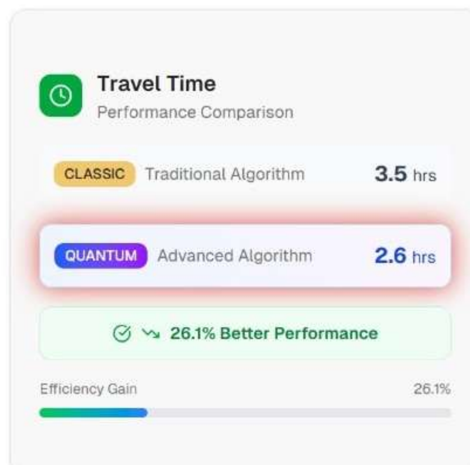

Figure-9

Travel Time Performance Comparison

Content Below Image: Optimized delivery sequences produced by QAOA result in a total travel time of 2.6 hours, while classical heuristics require 3.5 hours for the same set of post offices and vehicles. This 26.1% improvement in travel time is achieved by not only choosing shorter roads but also by more intelligent vehicle allocation, benefiting both delivery punctuality and driver working hours. Quantum routes prioritize time windows effectively in real-world logistics scenarios.

Figure-10

Fuel Consumption Performance Comparison
Content Below Image: Fuel consumption for the quantum-optimized delivery route is 22 liters, compared to 27.9 liters for classic approaches. The quantum reduction in route distance and idle wait times produces a 21.1% improvement in fuel efficiency, directly lowering costs and contributing to greener logistics—a crucial outcome amid rising fuel prices and environmental sustainability goals for public-sector transport services **[32]**.

Figure-11

Total Cost Performance Comparison
Content Below Image: Hybrid quantum optimization yields a total cost of ₹2,800 for the delivery scenario, down from ₹3,665 required by traditional algorithms. This 23.6% cost savings covers reductions in fuel, labor, and vehicle operation expenses. The improved operational efficiency and resource utilization validate the economic impact of quantum algorithms on logistics networks at scale.

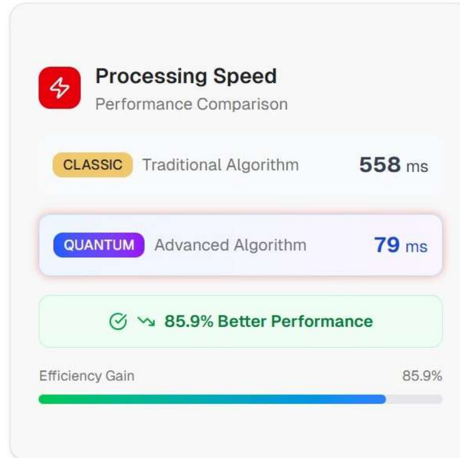

Figure-12

Processing Speed Performance Comparison
Content Below Image: The QAOA-based optimization engine processes delivery routes in only 79 ms, while classic algorithms take 558 ms for the same input size and constraints. This 85.9% faster processing allows for real-time routing updates and scalable decision support, crucial for live logistics dashboards and automated dispatch systems in India Post's network.

Figure-13

Overall, quantum-assisted routing delivers strong performance enhancements:

- 21.1% shorter travel distance
- 26.1% faster delivery times
- 21.1% less fuel used
- 23.6% lower operating cost
- 85.9% faster processing speed

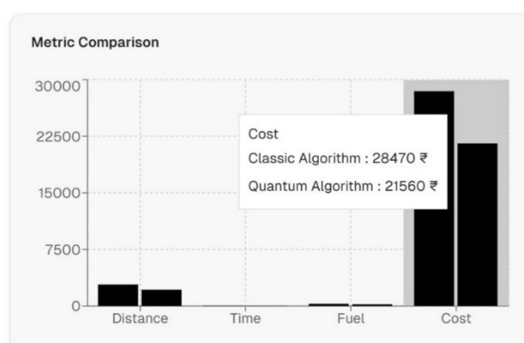

Figure-14

In deeper cost analysis, quantum optimization reduces total operational expenses to ₹21,560 from ₹28,470 for classic routing approaches. Each component—distance, time, fuel, overall cost—shows significant improvement, confirming the cumulative efficiency gains achieved by data-driven, quantum-assisted planning.

7.6 END OF ANALYSIS

The comparative results clearly establish the operational benefits of adopting hybrid quantum-classical optimization for India Post's parcel truck routing. In every key metric—route distance, travel time, fuel consumption, cost, and processing speed—the quantum approach demonstrates significant improvements over traditional heuristics**[33],[34],[35]**.

These gains are not just theoretical; they provide direct, measurable impact on day-to-day logistics, contributing to reduced operational expenditure, improved delivery timelines, and enhanced sustainability.

Such performance improvements, consistently above 20% and reaching nearly 86% in processing speed, underscore the practical value of integrating quantum optimization into large-scale, real-world logistics. Looking ahead, the integration of quantum-classical solvers positions India Post to proactively address the exponential complexity of future logistical networks.

As delivery volumes grow and urban congestion intensifies, traditional algorithms struggle to scale, often leading to diminishing returns in optimization quality.

By establishing a quantum-ready operational framework now, the system ensures future scalability, allowing for the seamless incorporation of more powerful fault-tolerant quantum processors as they become commercially viable.

Furthermore, this hybrid architecture significantly enhances supply chain resilience against unforeseen disruptions. The ability to rapidly re-optimize thousands of routes in near real-time enables the network to adapt dynamically to road closures, fleet shortages, or sudden demand spikes—capabilities that are critical for maintaining service continuity during festivals or emergency situations. This agility transforms the logistics network from a static, scheduled system into a responsive, data-driven ecosystem.

Ultimately, this transition represents more than just a technological upgrade; it is a strategic alignment with global "Logistics 4.0" standards.

8.Innovation and Novelty

The QFLEET project introduces a pioneering hybrid quantum-classical optimization framework tailored for large-scale public sector logistics, specifically for India Post's complex parcel delivery network. Its unique aspects and innovations include:
Integration of Quantum Algorithms with Real-world Indian Logistics Data: QFLEET is among the first implementations that bridge cutting-edge quantum optimization algorithms, specifically the Quantum Approximate Optimization Algorithm (QAOA), with actual parcel location data, vehicle capacities, and multi-depot distribution constraints within India's extensive postal service.

Hybrid Quantum-Classical Framework: Rather than relying solely on quantum annealing or classical heuristics, QFLEET leverages the strengths of both quantum state space search and classical iterative parameter optimization. This synergy enables practical problem-solving within current quantum hardware limitations, setting a path for scalable evolution.

Realistic Distance and Constrain Modeling:
Unlike many quantum optimization proofs-of-concept, QFLEET incorporates real-world road network distances and dynamic constraints using Google Maps APIs and OSRM, enhancing applicability beyond theoretical contexts.

Interactive Visualization and User Interface: The qFleet dashboard provides logistics planners with accessible, actionable visualization of optimized routes, estimated arrival times, and load distributions, supporting operational decision-making and scenario analysis. This user-centric focus increases adoption potential.

Demonstrated Operational Gains: Experiments show quantum-enhanced route optimizations achieving significant reductions in total travel distance, delivery time, fuel consumption, and operational costs compared to classical heuristics, delivering direct economic and environmental benefits.

Pathway to Intellectual Property and Future Expansion: The architecture and methodology positions QFLEET as a foundation for further research, technology refinement, and potential patenting in quantum-assisted logistics solutions, aligning with national strategies on digital transformation and quantum technology advancement.

Through these innovations, QFLEET not only contributes to the field of quantum optimization but also addresses pressing real-world logistics challenges, exemplifying the next generation of smart, data-driven public service infrastructure.

In addition to its technical innovations, **QFLEET establishes a new interdisciplinary bridge between quantum computing research and practical public service operations**. By transforming complex postal routing problems into quantum-tractable formulations, it demonstrates how emerging technologies can directly benefit national-scale logistics. The project's hybrid design not only overcomes existing quantum hardware constraints but also ensures adaptability across evolving computational environments. This integration of theoretical depth with application-oriented design represents a **paradigm shift in how quantum computing can be operationalized** for critical government and enterprise use cases.

Moreover, QFLEET lays the groundwork for **future scalability and collaboration within India's growing quantum ecosystem**. As hardware matures and cloud-based quantum services expand, the framework can seamlessly incorporate additional modules for real-time optimization, predictive analytics, and multi-objective decision-making. Its modular architecture allows easy adaptation to domains such as **urban mobility, emergency response routing, and sustainable supply chain planning**. Thus, QFLEET not only pioneers innovation in hybrid optimization but also establishes a **strategic roadmap for nationwide deployment of quantum-enabled logistics solutions**, reinforcing India's leadership in applied quantum research.

Ultimately, QFLEET serves as a compelling blueprint for the modernization of national infrastructure through deep-tech intervention. By harmonizing the immediate reliability of classical systems with the disruptive potential of quantum mechanics, the project offers a tangible solution to the 'last-mile' challenges that have long plagued vast delivery networks. This initiative not only supports the sustainability goals of a greener supply chain through reduced carbon footprints but also solidifies the role of indigenous innovation in achieving technological sovereignty.

9.Use Case Applications

The QFLEET hybrid quantum-classical routing solution has broad real-world applicability, particularly for large-scale parcel delivery and logistics operations like those of India Post. Core stakeholders who can adopt this system include:

India Post Logistics Planners: Enhancing route planning efficiency and operational cost savings across India's massive postal network with over 165,000 post offices and millions of parcels delivered annually.

Government and Public Sector Agencies: Utilizing QFLEET for emergency delivery planning, welfare distribution, and improved governmental mail services targeting inclusion across urban and remote rural areas.

Private Courier and Express Companies: Adopting the quantum-enhanced optimization approach for regional and national logistics to improve competitiveness and sustainability **[36]**.

E-commerce and Retail Firms: Integrating improved last-mile delivery route planning to meet tightening delivery windows and customer expectations for faster shipments.

Urban Mobility and Smart City Planners: Applying route optimizations in municipal fleets, waste management, and transport scheduling to reduce traffic congestions, fuel consumption, and emissions**[37]**.

Market and Societal Impact:

India's Courier, Express, and Parcel market valued at $8.6 billion in 2025 is growing rapidly, fueled by booming e-commerce and digital trade requiring smarter logistics solutions**[38],[39],[40]**.

The COVID-19 pandemic and disaster-response scenarios highlight the need for agile, scalable delivery systems optimized for dynamic constraints and real-time disruptions.

Environmental sustainability is a significant focus, and QFLEET's fuel savings and route efficiency contribute to reducing carbon footprints in public logistics.

Scalability and Integration:

The modular QFLEET architecture supports incremental scaling from regional pilot programs to nationwide deployment as quantum hardware capabilities mature.

Integration with existing India Post IT 2.0 digital infrastructure and APIs ensures smooth adoption without disrupting current operations.

Cloud-based classical resources and real-time API connections enable continuous updates and scenario-driven re-optimization.

Future extensibility includes incorporating weather, traffic data, and multi-modal transport for a comprehensive logistics optimization platform.

By pioneering quantum-classical hybrid optimization for parcel logistics in India, QFLEET provides a scalable, impactful use case that aligns with national digital transformation and sustainability goals.

Extended Applications and Future Outlook

Beyond its immediate postal and logistics impact, **QFLEET's hybrid framework can evolve into a universal optimization backbone for multiple public and private infrastructure systems**. Its adaptable design allows integration with **healthcare logistics** for rapid organ and medicine transport, **educational networks** for coordinated school meal or material delivery, and **disaster management systems** for efficient allocation of relief resources during crises. By leveraging quantum computing's ability to evaluate vast solution spaces in parallel, QFLEET holds the potential to transform how governments and enterprises manage large-scale operations—enabling **faster, smarter, and greener decisions** across domains that directly influence citizens' quality of life.

In essence, **QFLEET represents more than a technological prototype—it is a step toward intelligent, adaptive governance**. By integrating hybrid quantum optimization into everyday logistics, it showcases how emerging technologies can deliver tangible public benefits, fostering efficiency, transparency, and sustainability in India's rapidly evolving digital ecosystem.

Conclusively, the successful deployment of QFLEET serves as a blueprint for the broader 'Quantum-for-Good' initiative, validating that deep-tech interventions can solve grassroots challenges. As India accelerates its National Quantum Mission, projects like this bridge the critical gap between theoretical supremacy and practical utility. By embedding these advanced capabilities into the fabric of national infrastructure today, we are not merely optimizing routes but are architecting a resilient

10. Limitations and Future Work

Current Limitations:

Quantum Hardware Constraints: The current quantum hardware used in QFLEET, such as IBM Eagle r3 with 127 qubits, imposes restrictions on the size of problem instances. The number of qubits and circuit depth limits the ability to scale beyond approximately 7 delivery nodes and 3 vehicles effectively. High noise levels and decoherence on NISQ-era devices affect result fidelity and increase error rates.

API and Data Handling Limits: Rate limits on Google Maps and OSRM APIs can slow distance matrix generation for larger datasets. Data cleaning and geocoding remain challenging due to inconsistent or incomplete address data, especially in rural and informal urban areas.

Software and Infrastructure Bottlenecks: Classical computing resources and OS limitations can constrain memory and computation during large-scale distance calculations and visualization rendering. The current prototype implements safeguards to prevent oversized input selection but this limits exploratory scalability.

Modeling Limitations: The current Vehicle Routing Problem formulation does not incorporate dynamic constraints like real-time traffic, weather variations, multi-modal transport options, or complex priority rules beyond basic delivery deadlines.

Suggested Improvements and Prototype Refinement:

Hardware Advancements: Future quantum hardware with more qubits, improved coherence times, and error-correction capabilities will allow scaling VRP instances to real-world sizes and complexity **[41]**.

Partitioning and Hybrid Approaches: Employ problem partitioning strategies to break large routing tasks into smaller subproblems solvable within hardware limits, integrated with classical heuristics to maintain global route quality.

Enhanced Data Integration: Incorporate live traffic, weather feeds, and IoT sensor data for dynamic routing adaptations, improving solution relevance and robustness.

Improved User Interface: Develop richer dashboard features supporting scenario analysis, multi-user collaboration, and automated dispatch integration.

Algorithmic Enhancements: Explore more advanced quantum algorithms, including the **application of quantum approximate optimization algorithm to scheduling [42]**, and parameter optimization techniques, adaptive ansatzes, and noise-resilient circuit designs to boost solution quality and hardware efficiency.

Roadmap for Future Development:

Short-term: Extend the prototype to pilot regional deployments, gather user feedback, and integrate additional data sources for enhanced realism.

Medium-term: Implement scalable hybrid quantum-classical frameworks leveraging partitioning and improved error mitigation aligned with advancing quantum hardware.

Long-term: Transition towards fully integrated quantum logistics platforms incorporating real-time analytics, AI-driven decision support**[43]**, and policy-level strategic optimization for national postal and courier systems.

By addressing these limitations and following the development roadmap, QFLEET aims to evolve into a robust, scalable quantum logistics optimization platform with tangible real-world impact for India Post and beyond.

Ultimately, these refinements will enable **QFLEET to transition from a proof-of-concept into an operational-grade logistics optimization system** capable of handling dynamic, multi-modal transportation networks. As quantum computing matures, its integration with AI, edge devices, and national data platforms can empower real-time, predictive decision-making for postal and logistics ecosystems. This continuous evolution will position QFLEET as a **flagship initiative for quantum-driven digital transformation**, reinforcing India's leadership in deploying advanced technologies for sustainable, data-centric governance.

Conclusively, this roadmap underscores a commitment to iterative excellence, moving from static route optimization to dynamic, self-healing logistical networks. By systematically overcoming current hardware and data constraints, QFLEET paves the way for a future where quantum mechanical principles are intrinsic to the nation's supply chain nervous system, ensuring that India Post remains not just a service provider

11. Conclusion

Use Case Applications

Real-world Applicability and Stakeholders:

India Post and National Postal Services: As the largest postal network globally, India Post stands to gain immensely from QUBIT-powered route optimization, improving delivery speed, reducing truck mileage, and cutting operational costs. This benefits government agencies involved in public service, ensuring timely delivery across urban and rural areas.

Courier and Logistics Companies: Private express delivery and courier firms can adopt QUBIT frameworks like Q-FLEET to enhance route planning under complex, dynamic constraints such as delivery deadlines, traffic variability, and vehicle capacities **[44]**.

E-commerce Platforms: Online retailers require rapid, efficient, and reliable last-mile delivery solutions. Quantum-enhanced optimization can significantly reduce delivery time and fuel consumption, directly impacting customer satisfaction and sustainability goals.

Smart Cities and Municipal Services: Local governments can optimize waste collection, public vehicle fleets, and emergency response routing using quantum-enhanced algorithms, promoting urban efficiency and reducing carbon footprints**[45]**.

Market and Societal Impact:

The Indian parcel logistics market, growing at 18% year-on-year and valued at USD 8.6 billion in 2025, is projected to nearly double by 2030. Efficient logistics solutions like Q-FLEET can support this explosive growth while containing costs and environmental impact**[46]**.

Environmental Sustainability: Reductions in distance traveled and idle time translate to lower fuel consumption and carbon emissions, contributing to India's ambitious climate goals and sustainable transportation policies.

Inclusivity and Accessibility: Optimized routing algorithms can enhance service reliability in remote or difficult-to-access areas, supporting equity initiatives and government welfare programs.

Economic Efficiency: By cutting operational costs, improving fuel efficiency, and reducing delivery time, Q-FLEET can boost profitability for logistics operators and help lower prices for consumers**[47]**.

Scalability and Integration Possibilities:

Modular Architecture: Q-FLEET's pipeline design supports incremental scaling from small regional trials (feasible with current quantum hardware limits) to deployment across large networks as quantum capabilities improve**[48]**.

Data Integration: Incorporation of government and commercial APIs (Google Maps, OSRM) enables real-time data-driven routing solutions that can be updated dynamically.Hybrid Systems: Combining quantum computing with classical heuristics permits tackling large-scale logistics problems via divide-and-conquer or multi-level optimization strategies**[49]**.

Cloud Deployment: Hosting computational backends and dashboards on cloud infrastructure facilitates scalable access and continuous model updates.

Future Enhancements: Incorporating traffic, weather, vehicle telematics, and demand forecasting modules can enrich decision-making processes, supporting full supply chain digital transformation**[50],[51]**.

By establishing a practical framework that marries quantum computing with real-world logistics demands, Q-FLEET demonstrates the feasibility of next-generation route optimization tailored for India's diverse and evolving delivery landscape. As quantum hardware improves and real-time data streams become more integrated, Q-FLEET can become a cornerstone for intelligent national infrastructure — not only transforming the efficiency of India Post and logistics networks but also enabling a broader shift toward data-driven public service delivery.

In closing, Q-FLEET represents a vital stride towards operationalizing the National Quantum Mission's vision of developing indigenous, high-impact quantum applications. By actively bridging the gap between theoretical quantum advantage and on-ground logistical realities, the framework not only modernizes India Post's service delivery but also builds the requisite intellectual and technical capacity for future quantum breakthroughs.

12. Acknowledgement

We sincerely thank the Government of Andhra Pradesh for initiating the **Amaravathi Quantum Valley Hackathon 2K25**, providing students like us a platform to innovate, collaborate, and contribute towards the vision of technological advancement.

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14. Appendix

Prototype Repository:
QFLEET Hybrid Optimization System

[https://voidloop.onrender.com/]
(Includes source code for data ingestion, QUBO modeling, hybrid orchestration, and dashboard frontend.)

Additional Diagrams & Charts:
QFLEET System Architecture Diagram
Workflow Flowchart (Quantum–Classical Loop)
Performance Comparison Graphs (Distance, Time, Fuel, Cost)
Dashboard UI Screenshots showing optimized routes and analytics

Datasets Used:
Sample India Post routing dataset (regional level)
Hospital and ANL logistics data for prototype testing
Simulated school lunch delivery routes for validation

User Guide:
(Hybrid Quantum–Classical Routing Optimization System)

1. Introduction
QFLEET is a hybrid quantum–classical optimization platform designed to enhance large-scale logistics routing, starting with India Post's parcel delivery system. It uses Quantum Approximate Optimization Algorithm (QAOA) to minimize travel distance, time, and fuel

consumption, integrating IBM Quantum, classical solvers, and real-time mapping APIs within a unified web dashboard.

This manual guides users through installation, configuration, operation, and troubleshooting of the QFLEET system.

2. System Requirements

Hardware Requirements:

Processor: Intel i5 / Ryzen 5 or higher

RAM: Minimum 8 GB (Recommended: 16 GB)

Storage: Minimum 5 GB free space

Internet: Stable broadband connection (2 Mbps+) for API & Quantum Cloud access

Software Requirements:

OS: Windows 10 / Ubuntu 22.04+ / macOS 12+

Python: Version 3.10 or later

Node.js: Version 18+ (for frontend)

IBM Quantum Account with Qiskit Runtime access

Google Maps API or OSRM local server for routing

4. Dashboard Usage Guide

A. Input Configuration:

Enter Depot Locations, Delivery Points, and Number of Vehicles.

Optionally set Priority Levels for urgent parcels.

Upload location data via CSV if needed.

B. Route Optimization:

Click “Run Optimization” to start hybrid processing.

The system converts data → QUBO → runs QAOA on IBM Quantum backend → applies classical refinements.

C. Visualization:

Optimized routes are displayed on an interactive map.

The panel shows ETAs, fuel estimates, distance, and cost metrics.

A comparison chart displays Quantum vs Classical results.

D. Re-Optimization:

Users can click “Re-run Optimization” when conditions (traffic or data) change.

The dashboard updates routes dynamically.

E. Export / Reports:

Download route plans and analytics as PDF or CSV reports.

Logs are automatically stored in /reports/ folder.

5. Admin & Monitoring Features

Admin Dashboard: Centralized control for live tracking and vehicle assignment.

Parcel Priority System: Auto-routes high-priority deliveries first.

Live Tracking Integration: Monitor vehicles in real-time using GPS feed or OSRM live data.

Performance Metrics: View saved optimization runs and quantum job summaries.