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QUANTUM COMPUTING FOR TRANSPORTATION AND LOGISTICS: OPTIMIZING SUPPLY CHAINS AND OPERATIONAL EFFICIENCY

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ABSTRACT: Quantum computing (QC) presents transformative potential for addressing complex challenges in the transportation and logistics industry, where classical computing often falls short. The ability of quantum systems to perform computations at unprecedented speeds and explore vast solution spaces allows for innovative solutions in air, land, and sea logistics. Key challenges that QC can address include inventory optimization across multiple facilities, route planning, factory and vehicle scheduling, last-mile delivery, fleet management, dynamic pricing, sustainability, and navigation in urban environments. Recent studies and industry trials, including initiatives by Quantum-South, IBM, and ExxonMobil, demonstrate that quantum algorithms can optimize air cargo scheduling, shipping routes, and supply chain allocations, highlighting QC's applicability in real-world logistics operations. Use cases primarily fall under three categories: optimization, simulation, and machine learning (ML). Optimization dominates, focusing on efficient routing, scheduling, and resource allocation. Simulation enables accurate demand forecasting through digital twins of vehicles, warehouses, and factories, improving supply-demand alignment. Machine learning applications focus on pattern recognition, predictive maintenance, and safety monitoring. Across these domains, quantum computing facilitates decision-making in complex, variable-rich environments, including the coordination of thousands of trucks, trains, planes, and ships. While research-oriented applications, such as battery optimization and pollution minimization, remain longer-term, QC's near-term benefits in operational efficiency are substantial. McKinsey estimates that QC could deliver an economic impact of up to $63 billion by 2035, positioning transportation and logistics as early beneficiaries. By integrating quantum technologies, companies can achieve faster, more accurate, and environmentally sustainable operations, paving the way for new business models, improved service delivery, and enhanced competitiveness across the global logistics ecosystem.

Keywords: AI Technologies, Transportation Simulation, Improved Services, Cost Control

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Quantum computing offers intriguing solutions to supply chain and logistics challenges that classical computers cannot completely solve. It also offers the possibility of significantly faster computations. Both advantages can spur the imagination to new solutions, new quantum use cases, and new business models for all parts of the transportation and logistics industry — air, land, and sea. Challenges to be addressed include optimization of inventory across many facilities, route planning, minimization of manufacturing costs, last-mile delivery, factory and truck scheduling, dynamic pricing algorithms, fleet management and maintenance, sustainability and green logistics, energy systems, control of autonomous vehicles, and navigation within modern cities (e.g., traffic flow, parking). McKinsey estimates that quantum computing (QC) could have an economic impact of as much as $63 billion by 2035,3 and the supply chain and logistics industry is positioned to be one of the earlier benefactors of quantum technology.

The literature suggests that quantum computing offers advantages in three primary areas for logistics and transportation: optimization, machine learning (ML), and simulation. Many companies are already exploring these potential applications. For example, Quantum-South has tested the use of quantum algorithms to optimize air cargo and IBM and ExxonMobil have collaborated to explore the use of quantum computers to optimize shipping routes amidst a vast number of maritime complexities, such as scheduling and minimizing distance traveled.

QC DECISION MAKING IN LOGISTICS: A majority of the 83 use cases identified (72%) centered around using quantum computing to help with decision making. Physical supply chains are very complex with many variables, and understanding how to make good operational decisions is hard. The combinations of movement for thousands of trucks, trains, planes, and ships are difficult or impossible to model using classical computing. Thus, most of the workshop's discussions centered around either problems that seek to optimize allocation of resources (e.g., trucks, people) or the need to simulate market demand and reflect that simulation on supply (e.g., trains, planes, labor). The participants also discussed the use of machine learning to find patterns in performance information in order to make good or better decisions. Only a few of the use cases identified noted the use of quantum computing for research, such as to develop better batteries/power sources for vehicles or to minimize pollution, but the timelines for achieving those were farther out because of the hardware advances needed in QC technology.

- **Optimization**: As noted, the majority (46 of the 83 use cases, 55%) of the use cases described optimization as the key need. There were several variations of optimization noted. Many focused on a routing problem — finding the most efficient ways for multiple vehicles to travel that reduces travel times and maximizes customer service. Variations of routing included finding better scheduling tools for manufacturing and efficient routing of vehicles to minimize traffic congestion. Other optimizations focused on efficient loading and unloading in a complex environment, such as scheduling the loading and creation of railcars and loading an airplane to maximize the load carried. Questions were raised about whether optimization could also apply to government compliance burdens such as lowering CO_2 emissions or expediting PFAS remediation efforts.

- **Simulation**: The next most popular approach (22 of 83, 26%) in the identified use cases was simulation. Examples tended to center around simulating or forecasting demand that in turn would allow transportation assets to be optimized to meet the simulated forecast. One use case called for the creation of a full digital twin, i.e., a virtual representation of a factory, truck, train, etc. created to simulate demand and supply planning.

- **Machine Learning:** A smaller number of use cases (11 of 83, 13%) noted how ML could help with pattern recognition, especially for monitoring vehicle performance for maintenance and safety. For a few use cases for which optimization was the primary approach identified, experts noted that simulation and ML would likely also play a role, for example, with assigning fleets and crews and managing on-time deliveries.

quantum computing reach in logistics projections

QC IN TRANSPORTATION ESTIMATION	SOURCE
Estimated economic impact by 2035: Up to $63 billion in logistics and supply chain sectors.	McKinsey & Company
Global quantum computing market size in 2024: $1.3 billion, projected to reach $5.3 billion by 2029.	MarketsandMarkets

UK Department for Transport's projection: Quantum-enabled traffic and route optimization could unlock up to $10.24 billion in value by 2035.	UK Department for Transport
Annual emissions savings: Potential $3.58 billion in reduced congestion costs through quantum optimization.	UK Department for Transport
QED-C's 2024 study: Identified 83 use cases in logistics, with 72% focusing on decision-making, primarily in optimization.	Quantum Economic Development Consortium (QED-C)

source: prepared by author based on sources

Quantum computing is poised to revolutionize transportation and logistics by enabling faster, more efficient decision-making across complex supply chains. Its primary near-term applications focus on optimization, such as route planning, fleet scheduling, and inventory management, delivering measurable economic and operational benefits. As the technology matures, it also offers opportunities for sustainable, data-driven logistics and smarter urban mobility solutions.

LOGISTICS PROBLEMS AND QUANTUM TECHNOLOGIES: Following ten problems in Logistics are presented for which quantum computing technologies are possibly applied to find the desired result for efficiency.

1.Fleet & Vehicle Scheduling

Problem: Optimizing schedules for trucks and autonomous vehicles to minimize downtime and maximize throughput.
Quantum Technology: Quantum annealing, QUBO formulations.
Example: Quantum-enhanced scheduling of Automated Guided Vehicles (AGVs) to reduce travel time and task completion time.

2. Route Optimization

Problem: Determining the most efficient routes for delivery vehicles, considering constraints like capacity and traffic.
Quantum Technology: Quantum annealing, hybrid quantum-classical algorithms.
Example: Real-time route optimization using quantum annealing strategies to solve the Capacitated Vehicle Routing Problem (CVRP).

3. Labor & Workforce Planning

Problem: Scheduling and assigning tasks to workers to optimize labor costs and efficiency.
Quantum Technology: Quantum optimization algorithms.
Example: Optimization of labor plans across multiple facilities to enhance operational efficiency.

4. Demand Forecasting

Problem: Predicting customer demand to optimize inventory and supply chain operations.
Quantum Technology: Quantum machine learning, variational quantum circuits.
Example: Utilizing quantum-enhanced algorithms for more accurate demand forecasting.

5. Warehouse & Inventory Management

Problem: Optimizing storage, retrieval, and restocking processes in warehouses.
Quantum Technology: Quantum optimization, QUBO models.
Example: Applying quantum computing to optimize warehousing operations, including layout and inventory control.

6. Disaster Recovery & Network Restoration

Problem: Restoring transportation networks efficiently after disruptions, with a focus on equity.
Quantum Technology: Quantum optimization, hybrid quantum solvers.
Example: The Q-RESTORE framework uses quantum computing to prioritize restoration efforts in underserved communities.

7. Autonomous Vehicle Control

Problem: Enhancing decision-making and coordination in autonomous vehicle systems. **Quantum Technology**: Quantum neural networks, quantum image encoding. **Example**: Development of a Quantum Neural Network for Vehicle Road Cooperation Systems (QNN-VRCS) to improve traffic prediction and system optimization.

8. Traffic Flow & Urban Mobility

Problem: Managing and optimizing traffic flow in urban environments. **Quantum Technology**: Quantum optimization, real-time data processing. **Example**: Quantum Shuttle project used quantum computing to optimize bus routes during high-traffic events, demonstrating real-time traffic navigation.

9. Sustainability & Green Logistics

Problem: Reducing environmental impact through optimized logistics operations. **Quantum Technology**: Quantum optimization, energy-efficient algorithms. **Example**: Applying quantum computing to minimize carbon footprint in logistics operations.

10. Dynamic Pricing & Revenue Management

Problem: Adjusting pricing strategies in real-time based on demand and supply. **Quantum Technology**: Quantum machine learning, optimization algorithms. **Example**: Implementing quantum-enhanced dynamic pricing models to maximize revenue.

CONCLUSION: Quantum computing offers unprecedented opportunities for improving transportation and logistics operations through enhanced optimization, simulation, and machine learning capabilities. Key applications include fleet scheduling, route planning, labor allocation, demand forecasting, warehouse management, disaster recovery, autonomous vehicle control, urban traffic flow, sustainability, and dynamic pricing. By enabling faster computations and modeling highly complex supply chain networks, QC supports better decision-making, reduces operational inefficiencies, and promotes sustainable practices. Near-term applications focus on operational optimization, while longer-term research may address energy systems, pollution control, and advanced materials. Early adoption of QC in logistics can significantly enhance competitiveness, resilience, and innovation across the industry.

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