Quantum Computing in Transport & Logistics

Applications and case studies

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1. Overview

Quantum computing is emerging as a powerful tool to tackle complex problems in the transport and logistics industry that are difficult or impossible for classical computers to solve efficiently. Many challenges in this field, such as optimizing routes, managing supply chains and predicting traffic, are fundamentally **combinatorial optimization** or large-scale simulation problems. These problems involve so many possible combinations (e.g. routes, schedules, or inventory allocations) that classical computers struggle to find optimal solutions in a reasonable time. Quantum computers, by leveraging quantum bits (qubits) and phenomena such as superposition and entanglement [1], can explore vast solution spaces in parallel and potentially find better solutions more quickly. In particular, the literature suggests that quantum computing offers advantages in three primary areas for logistics: **optimization**, **machine learning**, and **simulation**.

A variety of logistics and transport tasks could benefit from quantum computing. For example, **route optimization** (finding optimal paths for vehicles or shipments) and **vehicle routing problems (VRP)** are classic NP-hard problems, meaning the number of possible route combinations grows exponentially with the problem size, which becomes hard to solve at large scale – quantum algorithms can help search through the exponentially many possible routes more effectively than brute force. Likewise, **supply chain modelling** and network design involve decisions such as where to locate warehouses or how to schedule deliveries; these are complex optimization tasks with many constraints (capacity, cost, and time windows, to mention a few) that quantum solvers can tackle by evaluating many configurations simultaneously. **Traffic prediction and management** is another area: by analyzing vast amounts of sensor and historical data, quantum-enhanced machine learning models may improve traffic flow forecasts or enable real-time re-routing to alleviate congestion. In general, quantum computers offer the possibility of significantly faster computations across all modes of transportation – **land, air, water** – for planning and operational decisions. They can also incorporate more variables and constraints than classical systems, which could yield more accurate and detailed models of logistics systems. This means quantum computing could improve decision-making in everything from **last-mile delivery routing** and **inventory distribution** to **fleet scheduling** and **autonomous vehicle navigation**.

It is important to note that current quantum hardware is still in the **noisy intermediate-scale quantum (NISQ)** era, so most practical applications in logistics are experimental or hybrid (combining quantum and classical methods). Nonetheless, forward-looking companies are actively exploring prototypes because the potential rewards are significant. A U.S. Department of Transportation workshop in 2024 concluded that the "overwhelming majority" of identified quantum use cases for transport/logistics revolve around optimization – planning routes, scheduling, and resource allocation – where quantum algorithms can potentially outperform classical heuristics. Simulation use cases (like fully simulating traffic systems quantum-mechanically) are less feasible in the near term, but optimization and certain machine learning tasks are viewed as promising initial targets. In summary, quantum computing's ability to analyze **numerous options simultaneously** and handle complex constraint systems gives it the potential to revolutionize how transport and logistics problems are solved. In the coming sections, we will examine real-world case studies, explore future application areas, and discuss the key quantum algorithms enabling these advancements.

2. Case Studies (extraction)

Several companies and research teams have already begun applying quantum computing to transportation and logistics challenges, often in pilot projects or proof-of-concept studies. These case studies demonstrate how quantum approaches can be utilized for route planning, scheduling, and supply chain optimization, highlighting the current status and results achieved.

The table below summarizes these case studies, including the problem addressed, the quantum approach used, and the outcomes or current status:

Project (Year)	Problem Addressed	Quantum Approach	Status / Results
Volkswagen - Lisbon Traffic (2019)	City traffic routing for bus fleet (reduce congestion and travel time).	Quantum annealing (D-Wave) for route optimization in real-time.	Pilot deployed during WebSummit; successfully guided buses on fastest routes, reducing delays.
Deutsche Bahn & CQ (2021)	Rescheduling trains during disruptions (rail logistics optimization).	Variational algorithm (Filtering VQE) + classical OR methods.	Prototype developed; demonstrated on NISQ devices as a proof of concept for real-time timetable updates.
Aisin & D-Wave (2023)	Multi-truck delivery routing in a supply chain network (corporate scale VRP).	Hybrid quantum-classical annealing; iterative QUBO solves per truck.	Research result: Achieved excellent supply chain performance in simulation; quantum hybrid outperformed classical baseline.
Q-CTRL / Airbus & BMW (2024)	Supply chain part sourcing and transport emissions minimization.	QAOA (gate-model quantum algorithm) with error mitigation.	Prototype solution: Solved a complex allocation problem on a 127-qubit IBM quantum processor; now scaling up for further tests.
DHL (2022-2025)	Last-mile delivery route optimization (many stops, constraints).	Quantum optimization algorithms (pilot trials, unspecified hardware).	Ongoing trials: Testing optimized routing to cut fuel use and delivery time; anticipated to provide rapid solutions once hardware matures.

Autonomous vehicle navigation (Routing)(2019)

Volkswagen - Traffic Flow Optimization (Lisbon, 2019): Volkswagen Group's Data:Lab teamed up with quantum computing company D-Wave to optimize urban traffic flow in a live pilot project. During the WebSummit 2019 conference in Lisbon, VW equipped nine public transit buses with a quantum-powered routing system. The problem - determining the optimal route for each bus to minimize congestion and wait times - was formulated for D-Wave's quantum annealer. The annealer computed the fastest route for each bus individually and almost in real time. As a result, the buses were guided along routes that avoided traffic jams, cutting down travel times for thousands of passengers even during rush hour. This was a milestone demonstration: it showed that a quantum algorithm could handle a complex **dynamic routing** problem under real-world conditions. Volkswagen reported that this smart traffic management approach improved traffic flow and confirmed the feasibility of using quantum computers for live traffic optimization. (Since then, Volkswagen has continued quantum R&D, exploring use cases from traffic management to factory optimization.)

2.

Train Scheduling (Routing and Scheduling)(2021)

Deutsche Bahn & Cambridge Quantum – Train Scheduling (Germany, 2021): In the rail transport sector, Deutsche Bahn (DB) – Germany's national railway operator – partnered with Cambridge Quantum (now part of Quantinuum) to explore quantum computing for railway scheduling and rescheduling. One use case of interest was the **train timetabling problem**: when disruptions occur (e.g. delays or track closures), how to re-route and reschedule trains efficiently to minimize passenger impact. This is a complex optimization problem with many constraints (track capacities, safety separations, connection timings) that becomes extremely challenging during disruptions. The DB–Cambridge Quantum project applied a **variational quantum algorithm** (specifically, a Filtering Variational Quantum Eigensolver) in combination with DB's operations research expertise to tackle train rescheduling during such events. By encoding the scheduling problem into a form solvable by a quantum processor, they aimed to let the quantum algorithm search for optimized schedules faster than classical methods. While this was a research prototype rather than a deployed system, both parties expressed optimism that as quantum hardware scales, this approach could significantly improve DB's ability to respond to real-time disruptions. This case study highlights an application in **rail logistics** and shows how domain experts (rail planners) are teaming with quantum specialists to formulate practical problems for quantum solvers.

Vehicle routing problems (VRP) (Routing)(2023)

Aisin & D-Wave – Multi-Truck Routing (Supply Chain Logistics, 2023):

Aisin, a Toyota-affiliated auto parts manufacturer, collaborated with researchers to tackle a large-scale vehicle routing and scheduling problem using a hybrid quantum annealing approach. In this case, the goal was to optimize delivery routes for an entire fleet of trucks in a supply chain network – a problem with substantial commercial value but too complex to embed fully on current quantum hardware. The team's solution was to decompose the multi-truck routing problem and solve it iteratively: they assigned routes one truck at a time, formulating each step as a Quantum Unconstrained Binary Optimization (QUBO) problem that could be handled by a quantum annealer. Each QUBO instance was on the order of 2,500 binary variables, putting it within the range of what near-term quantum devices (especially annealers) can tackle. They tested this workflow using D-Wave's Hybrid Solver (a cloud service that uses quantum annealing with classical post-processing) and classical simulated annealing for comparison. After feeding the quantum-derived routes into a detailed classical supply chain simulator, they found **excellent performance for the full supply chain** – indicating the hybrid quantum approach produced very high-quality solutions for the overall routing problem. This study, published in 2023, is one of the first to show that quantum optimization can handle industry-scale logistics scenarios (in this case, a fleet routing problem at realistic size) by using a hybrid divide-and-conquer strategy. It suggests that even with current hardware limitations, carefully structured quantum algorithms can yield benefits for complex logistics optimization.

2.

Supply Chain Optimization (Location and Carbon Optimization)(2024)

Q-CTRL, Airbus & BMW – Supply Chain Optimization Challenge (2024): Airbus and BMW Group jointly organized a Quantum Computing Challenge in 2024, inviting solutions for tough industrial problems. One challenge involved optimizing a complex manufacturing supply chain: deciding where to manufacture each component of a product (with certain restrictions on co-locating related parts) to minimize total transportation-related carbon emissions. Q-CTRL, a quantum software company, tackled this problem using the **Quantum Approximate Optimization Algorithm (QAOA)**. They first proved that a simplified version of the problem could be solved classically in reasonable time, then defined a harder version (allowing each part to be made at two sites, introducing redundancy) which became classically intractable – a scenario ripe for a quantum solution. Q-CTRL devised a custom QAOA approach with problem-specific optimizations and error suppression techniques to ensure the quantum solution respected all the supply chain constraints. They implemented this on an **IBM 127-qubit quantum processor** (with Q-CTRL's software handling error mitigation) and were able to find high-quality solutions, even with today's hardware. The result was a working prototype that demonstrated how a hybrid quantum-classical algorithm could solve a realistic supply chain allocation problem with an environmental objective. This project is ongoing (moving to larger-scale trials in the next phase) but has already shown the viability of quantum methods for **multistage logistics planning**, achieving results competitive with advanced classical methods.

Package Delivery Route Optimization (Routing)(2022-2025)

DHL – Package Delivery Route Optimization (ongoing): DHL, one of the world's largest logistics providers, has been actively investigating quantum computing to improve its operations. In particular, DHL has tested quantum algorithms for **last-mile delivery route optimization** – aiming to find more efficient delivery routes for vehicles with many package drop-offs. By using quantum-inspired and quantum algorithms to compute optimized routes, DHL hopes to reduce total driving distance and fuel consumption. Early trials by DHL's innovation team have applied quantum computing in simulation to calculate optimal routes that account for dozens of stops and constraints (time windows, vehicle capacities) much faster than classical methods can. While these quantum routing solutions are not yet deployed at scale, DHL reports that they show promise in cutting both delivery times and fuel usage. DHL views quantum computing as a **strategic technology** for the future – the company's analysts predict that once the hardware matures, quantum route optimization could be done in minutes for problems that might take even a supercomputer years to solve by brute force. This case study reflects the general trend in industry: major logistics firms are running pilots to assess quantum computing's potential, positioning themselves to adopt the technology as it becomes more practical.

Key takeaways from these case studies

Quantum computing has already been applied to a variety of transport/logistics problems at small scale. In each case, a complex optimization (routing or scheduling) was mapped to a quantum algorithm. ***Quantum annealing***(explained in a later chapter) was used for routing vehicles (Volkswagen, Aisin) and showed that even today's quantum annealers can handle real-time traffic decisions and sizeable fleet problems. ***Gate-based quantum algorithms*** (like QAOA and VQE) (explained in a later chapter) have been tested on supply chain and scheduling problems (Airbus/BMW, Deutsche Bahn), illustrating how hybrid quantum-classical techniques can yield solutions competitive with classical methods. Many of these projects were in prototype or early trial stages, but they have demonstrated tangible results such as reduced travel times, improved operational efficiency, or at least the feasibility of solving industry-scale models with quantum methods. Encouraged by these outcomes, leading logistics providers (DHL, FedEx, UPS, etc.) and quantum computing companies (IBM, D-Wave, Google, IonQ, Q-CTRL, etc.) are continuing to invest in research to scale these solutions. The next few years will likely see these pilot projects expand in scope as hardware improves, possibly leading to the first production-grade quantum optimization tools for logistics. Maybe these are already applied in practice, but kept internal as they are considered providing competitive advantage.

3. Potential Applications

Looking ahead, there are many areas in transport and logistics where quantum computing could significantly improve performance or even disrupt current practices. Most of these applications revolve around complex optimization and prediction tasks. Below, several high-impact areas and how quantum computing might influence them are covered:

Vehicle Routing Problems and Dynamic Route Optimization

The **Vehicle Routing Problem (VRP)** – determining optimal routes for a fleet of vehicles to service a set of locations – is central to logistics (encompassing scenarios like delivery routing, ride-sharing, and trucking routes). VRP and its variants (with time windows, capacity constraints, etc.) are notoriously difficult (NP-hard), meaning the number of possible route combinations grows exponentially with the problem size. Even advanced classical algorithms can struggle with real-time or large-scale route optimization. Quantum computing offers a new approach to tackle VRPs by formulating them as combinatorial optimization problems suitable for quantum solvers. For instance, a VRP can be translated into a QUBO or Ising model which a quantum annealer or QAOA algorithm then tries to minimize (finding the optimal or near-optimal routes). This **quantum parallelism** can evaluate many route possibilities simultaneously, potentially yielding better solutions faster than classical heuristics.

Continuous or dynamic route optimization is one promising use case identified for near-term quantum advantage. In dynamic routing, scenarios can change in real time (new orders come in, traffic conditions change) and routes need to be re-computed on the fly. Quantum algorithms, which can re-optimize routes in minutes or seconds, could allow for much more responsive logistics networks. For example, if a traffic jam develops or a delivery is added last-minute, a quantum-enabled routing system could rapidly recalculate new optimal routes for the affected vehicles, something that is challenging with today's routing software. **Quantum annealing** has already been tested on routing problems (as in the VW and Aisin cases above) and showed the ability to handle realistic instances with thousands of variables by using hybrid strategies. Likewise, variational quantum algorithms (like QAOA) have been proposed for routing and have shown success on smaller benchmark problems, with ongoing research to scale them up.

In practice, early quantum routing applications might involve **hybrid quantum-classical systems** integrated into dispatch software or navigation apps. The quantum component would solve the core routing optimization (potentially providing a set of high-quality route plans), while classical systems handle surrounding tasks (user preferences, fine-grained constraints, data ingestion and storage, communication, etc.). The ultimate goal is to cut travel distances, fuel consumption, and delivery times while saving on carbon emissions. Even a small improvement in route efficiency can translate to huge cost savings and emission reductions for large fleets. One analysis by Maersk estimated that by 2050, quantum optimization in vehicle routing (along with related analytics) could create $50–100 billion in value through cost reductions and efficiency gains in logistics. Overall, vehicle routing is viewed as a "low-hanging fruit" for quantum computing in logistics – the problem is well-defined, extremely important economically, and exactly the kind of complex optimization where quantum algorithms excel.

3. Potential Applications (Cont.)

Warehouse Logistics and Inventory Management

Warehousing and fulfillment operations present another rich field for quantum optimization. Within a warehouse or distribution center, there are numerous hard optimization problems, such as: how to assign items to storage locations (slotting) to minimize retrieval time, how to sequence picking operations for orders to reduce travel distance (order picking paths), how to pack items or pallets efficiently (bin packing and loading), and how to schedule resources (workers or robots) to fulfill orders on time. These problems often resemble combinatorial puzzles – for example, the **3D bin packing problem** of fitting cargo into a limited space, or the task of routing pickers through a warehouse (similar to the travelling salesman problem). As warehouses become larger and more automated, finding optimal or near-optimal solutions to these problems yields significant benefits in terms of speed and cost.

Quantum computing can contribute to **warehouse logistics** by providing faster or better solutions to these NP-hard problems. For example, quantum optimization algorithms can be used for **storage allocation** (deciding which shelf each product should go to) by evaluating many possible layouts for frequency of access and space utilization. They can also optimize **picking routes** for fulfillment given a list of items for an order, a quantum algorithm could quickly find the shortest path for a robot or worker to collect all items. In addition, quantum methods can aid in **loading optimization** – determining the most efficient way to pack trucks or containers. A case in point is a project by Johnson & Johnson in which they explored using a quantum annealer to solve a 3D cuboid loading problem (essentially a bin-packing optimization for loading boxes into a container). Because loading many differently sized boxes is combinatorially complex, it's a good candidate for quantum optimization. Initial demos have shown that even relatively small quantum processors can find valid packings and sometimes improve on classical heuristics for these kinds of packing problems.

Another application is **inventory management** across a network of warehouses. Deciding how much stock of each product to keep at each location (to meet uncertain demand while minimizing holding and transport costs) is a stochastic optimization problem. Quantum algorithms might be used to run many demand scenarios in parallel or optimize inventory placement under uncertainty. Quantum-enhanced machine learning could also improve demand forecasts at the warehouse level (as discussed in the next section), which in turn feeds into better inventory decisions.

In summary, quantum computing could make warehouse operations more efficient by optimizing internal logistics. By streamlining storage layouts and retrieval paths, quantum solutions could shorten fulfillment times. By improving packing and loading, they can increase space utilization and reduce the number of trips needed. These improvements not only save costs but also speed up the supply chain (orders get processed and shipped faster). As warehouses increasingly rely on automation (robotics), having quantum-optimized algorithms to direct these automated systems could become a competitive advantage in the logistics industry. Companies like Amazon, Walmart, and DHL (which operate huge fulfillment centers) are expected to explore these possibilities so that they can handle growing e-commerce volumes more effectively in the future.

3. Potential Applications (Cont.)

Demand Forecasting and Network Planning

Demand forecasting is critical for transport and logistics companies – they need to predict how many goods will need to be moved or how many passengers will travel, or cargo to be transported, in order to plan their operations. Accurate forecasts drive efficient scheduling of deliveries, stocking of inventory, allocation of vehicles, and staffing. Traditional forecasting uses statistical models or machine learning on historical data, but complex supply chains and customer behaviour can make this very challenging. Quantum computing has the potential to enhance forecasting by improving both the scale and accuracy of data analysis.

One avenue is **quantum machine learning (QML)** algorithms that could detect patterns in historical demand data that classical algorithms miss. Quantum computers can handle very high-dimensional data and might be able to model complex correlations (for example, how weather, economic indicators, and local events together affect logistics demand). Quantum algorithms like quantum neural networks or quantum support vector machines could, in theory, produce more accurate demand prediction models. Even a small increase in forecast accuracy can lead to big savings by avoiding overstocking or under-utilizing transport capacity.

Moreover, quantum computing can be used for **scenario analysis and simulation** to support forecasting. For instance, a logistics provider could use a quantum computer to simulate many possible futures (variations in demand patterns) and optimize contingency plans for each. Because quantum computers can evaluate many possibilities in parallel, they could generate a richer set of scenarios for planners to consider. This ties into **risk management** – identifying potential demand surges or drops and planning transport capacity accordingly.

It’s worth noting that experts see **demand forecasting optimization** as one of the near-term use cases where quantum computing could have a high impact. By analyzing more data across multiple variables, quantum algorithms may produce forecasts that better capture the complexity of real-world supply and demand, thereby improving operational plans. In the logistics context, better forecasts mean the right number of trucks or ships are deployed, the right amount of inventory is positioned at warehouses, and deliveries can be scheduled more smoothly, all of which reduces waste and cost.

Another related area is **transportation network planning** – determining long-term expansion routes or capacity additions. For example, airlines planning flight networks or shipping companies planning new shipping lanes must forecast demand for years into the future and solve a gigantic optimization of network design. Quantum computing could assist by evaluating countless network configurations against demand projections to find the most robust and cost-effective plans. This is similar to a **multimodal transport optimization**, where you consider different transport modes and routes together (discussed more below). Overall, quantum-enhanced forecasting feeds into quantum-enhanced optimization: together they enable a more agile and efficient logistics network that can anticipate and respond to demand with precision.

3. Potential Applications (Cont.)

Fleet Management and Scheduling

“Fleet management” covers the administration of a fleet of vehicles (trucks, vans, ships, airplanes, trains, even drones or autonomous vehicles). Quantum computing can contribute to several aspects of fleet management:

- **Maintenance scheduling:** Large fleets require careful scheduling of maintenance to minimize downtime. This is an optimization problem where we must balance maintenance needs with operational availability. Each vehicle has maintenance intervals, and if too many are under maintenance at once, deliveries suffer. Quantum algorithms could help find optimal schedules that ensure vehicles get serviced without disrupting service. A quantum computer can consider all vehicles’ schedules and constraints simultaneously, perhaps finding a plan that staggers maintenance in an optimal way that a greedy classical algorithm might miss.
- **Staff and crew scheduling:** In sectors like trucking, railway cargo transport, aviation, and shipping, assigning crew or drivers to vehicles and routes is a complex scheduling task (often with union rules, certifications, hours-of-service regulations, etc.). This is essentially a constraint satisfaction and optimization problem. Quantum approaches (like QAOA or constraint-solving via annealing) could be used to assign drivers to routes or shifts such that all requirements are met and costs (or total work hours) are minimized.
- **Real-time fleet re-routing:** Building on the vehicle routing point – in real operation, fleets need to adjust to conditions. If one vehicle breaks down, its deliveries might need to be reassigned to others. If demand spikes in one region, vehicles from another region might need to be sent. In train cargo transport, accidents related to the railway infrastructure or problems in the passenger transport (which have priority) could benefit from quantum computing. Quantum computing will help in the dynamic reallocation of fleet resources by quickly recomputing assignments. Because a quantum solver can handle a big rerouting problem (reassigning a large fleet of vehicles and hundreds of deliveries) faster, it could enable a dispatcher to react in near real-time.
- **Fleet dispatch optimization:** On a strategic level, deciding which vehicle should handle which service region or delivery cluster is an assignment problem that quantum algorithms can address. For instance, a delivery company might use a quantum algorithm nightly to determine which vans will handle which set of delivery orders the next day, thereby balancing the workload and minimizing driving overlap.

The general theme is that fleet management problems often boil down to **scheduling and assignment** optimizations with many constraints – a domain where quantum algorithms could explore combinations more effectively. Additionally, by integrating quantum optimization with predictive analytics (like the aforementioned demand forecasts), fleet management could become more proactive. A quantum system might foresee that certain routes will be overloaded next week (from the forecast) and preemptively schedule extra vehicles or drivers, optimizing the assignments in one computation.

Currently, these applications are in trial phases, some of which are speculative. However, some military and large logistics operations are testing quantum computing for fleet logistics. Government logistics (like military vehicle convoys) can serve as testbeds. When successful, the algorithms and systems developed could then be transferred to the private sector. Over time, quantum-optimized fleet management could lead to higher vehicle utilization (more deliveries per vehicle), lower operational costs, and fewer backup vehicles needed (due to efficient schedules and optimally timed maintenance). This directly translates into cost savings and also sustainability gains (using fewer vehicles to do the same work means lower emissions).

3. Potential Applications (Cont.)

Multimodal Transport Optimization

Multimodal transport refers to the coordination of freight or passenger movement across multiple modes of transportation – for example, a shipment that travels by truck, then rail, then ship. Optimizing multimodal logistics is exceedingly complex because it involves scheduling and routing across different networks (road networks, rail networks, shipping lanes, air routes) and dealing with transfer points (like ports, warehouses, rail yards). Companies try to minimize total transit time and cost for multimodal shipments, but the decision space (which route, which mode, timing of transfers) is enormous. Quantum computing could revolutionize multimodal transport planning by handling this complexity in an integrated fashion.

A quantum algorithm could, for instance, evaluate end-to-end routes for a shipment considering all mode combinations (truck+ship vs. rail+truck vs. air, etc.) and all schedule timings to find the optimal solution. Similarly, for a logistics provider managing thousands of shipments, a quantum system could assign each shipment an optimized multimodal path such that overall network capacity is balanced and delivery deadlines are met. These are essentially giant network flow optimization problems with integer constraints (often formulated as mixed integer programs classically). Quantum computers might tackle certain parts of these problems faster, or use quantum heuristics to guide solutions that classical solvers struggle with.

Network optimization at this global scale is one of the areas expected to eventually benefit from quantum computing. For instance, routing ships across the oceans while also trucking goods from ports to distribution centers involves synchronizing schedules and capacities. Quantum algorithms could crunch through possible scheduling permutations far more efficiently than brute force. Additionally, **quantum simulation** could help model disruptions in a multimodal network (such as a port closure or weather event) and re-optimize quickly.

Another aspect is **green logistics**, which optimizes for not just cost or time, but also carbon footprint. Quantum computing can enable more fine-grained optimization, including external factors like emissions. As noted in a recent industry report, continuous route optimization (spanning all transport methods) enabled by quantum computing can significantly decrease fuel usage and emissions. Companies looking to reduce their carbon footprint may leverage quantum tools to design routes that, for example, favour greener modes (rail or sea over air freight) when feasible, or minimize empty miles travelled. The Airbus/BMW QAOA case we discussed is a micro example of this type of emission-optimized transport planning at the supply chain level.

In public transportation and urban mobility, multimodal optimization involves coordinating the schedules of buses, trains, ride-shares, and other modes of transportation, ensuring that passengers experience smooth transfers and minimal wait times. A quantum computer could help find the optimal timetables and routes in a city's transit network that minimize total travel time for all passengers – a highly complex problem given the interactions between modes. There was an initiative in Sydney, Australia, exploring the use of quantum computing to enhance the resilience of the transport network by updating schedules in real-time in the event of disruptions across modes. This shows interest in quantum solutions for integrated mobility systems.

In summary, quantum computing could serve as the "brain" for **multimodal logistics optimization**, calculating the most efficient way to move goods or people through a complex network of transportation options. The benefits would include end-to-end optimized journeys, reduced transit times, lower costs, and improved utilization of infrastructure capacity. This is arguably one of the most complex optimization challenges in logistics, yet it also offers immense payoff if solved effectively. While full-scale multimodal quantum optimization might be a few years away, early steps (like optimizing segments of the network or doing quantum-assisted simulation of transport scenarios) are happening now, and they pave the way for a future where global supply chains and transit systems are orchestrated by quantum-enhanced algorithms for maximum efficiency.

In addition to the areas above, other potential logistics applications for quantum computing include **dynamic pricing** (optimizing pricing strategies for shipping or ride-hailing in real time), **autonomous vehicle control** (quantum algorithms for better route planning and decision-making in self-driving car fleets), and **advanced traffic flow simulation** (using quantum simulation to model city-wide traffic at a new level of detail). However, these are more exploratory and would rely on further advances in quantum hardware and algorithms.

4. Quantum Algorithms and Technical Insights

To understand how quantum computing tackles transport and logistics problems, it's useful to know the key algorithms and approaches being used. Most of these quantum techniques are designed to handle optimization tasks or to search through large solution spaces more efficiently than classical algorithms. Below, we describe some of the most important quantum algorithms and methods relevant to logistics, including how they work and why they're suited to problems like routing and scheduling:

Quantum Approximate Optimization Algorithm (QAOA)

QAOA is a leading **hybrid quantum-classical algorithm** developed specifically for combinatorial optimization problems. Introduced by researchers at MIT (Farhi, Goldstone, and Gutmann), QAOA is essentially a method for utilizing a gate-based quantum computer to find good approximate solutions to problems such as the travelling salesman or vehicle routing. It works by encoding the optimization problem into a quantum circuit that combines a mix of operators: one operator encodes the cost function of the problem (e.g., route length), and another mixes the possible states. By alternating these operators and tuning certain parameters (with the help of a classical computer), QAOA guides the quantum processor to favour low-cost solutions. In simpler terms, the algorithm uses the quantum machine to sample candidate solutions, and a classical optimizer to adjust the quantum circuit iteratively so that it "steers" toward better and better solutions.

QAOA is powerful because it leverages quantum parallelism (the quantum state can represent multiple potential solutions simultaneously) while also being ***variational*** *– it doesn't require a fully error-corrected quantum computer, only a programmable one to run the parameterized circuit. It has been described as a "pioneering" approach for addressing challenges such as those in logistics. In fact, QAOA is considered a key algorithm for the NISQ era (****Noisy Intermediate-Scale Quantum, with Noisy*** *meaning that current quantum devices are prone to errors due to decoherence, gate imperfections, and other noise sources and* ***Intermediate-Scale*** *that these devices have tens to a few hundred qubits large enough to perform tasks beyond classical brute force in some cases, but not large enough for full error correction). NISQ enables the demonstration of quantum advantage on practical optimization tasks. For example, QAOA can be applied to a graph representation of a routing problem, attempting to find the minimum route cost. With sufficient circuit depth (iterations of the algorithm) and qubits, QAOA can approximate the optimal solution; in some cases, it may even surpass classical heuristics in the quality of the solution.*

As noted before, QAOA has been applied in research to optimize delivery routes, supply chain decisions, and even the Airbus/BMW supply chain challenge, as described earlier, which was solved using a custom QAOA approach. Technical insights from that project showed that tailoring the QAOA circuit to the problem structure (and using advanced error mitigation) led to substantial improvements in runtime efficiency. Generally, QAOA's performance improves as hardware advances (more qubits, reduced noise, increased circuit depth allowed). It stands at the forefront of quantum algorithms that logistics companies are experimenting with, due to its flexibility and promising early results. As hybrid quantum-classical methods, QAOA algorithms can run in the cloud (utilizing quantum processors) alongside classical optimization software, thereby enhancing tools such as route optimizers or supply chain planners.

4. Quantum Algorithms (Cont.)

Grover's Algorithm

Grover's algorithm is a fundamental quantum algorithm for **searching unsorted data** with a quadratic speedup. Discovered by Lov Grover in 1996, it's famous for proving that a quantum computer can search through NN possibilities in roughly N\sqrt{N} steps, whereas a classical search would take NN steps on average. In essence, Grover's algorithm amplifies the amplitude of the "winning" state (the desired solution) by repeatedly applying a special iteration (Grover's operator) that inverts the phase of the target state (via an oracle) and then reflects all amplitudes about the average. This algorithm is guaranteed to find a marked item in an unsorted list with significantly fewer checks than the classical brute-force method.

In logistics, many problems can be framed as searching for a solution that meets specific criteria (or the optimal solution among several). For example, finding a particular combination of deliveries that minimizes cost can be viewed as a search problem in the space of all possible combinations. Grover's algorithm can be adapted to optimization by treating the problem as searching for any solution that is below a certain cost threshold, or by gradually tightening that threshold (this is a bit theoretical, but it's known that Grover's can help in optimization by speeding up exhaustive search of feasible solutions). While Grover's alone won't provide an exponential speedup for NP-hard problems, it offers a quadratic speedup, which can be significant for certain subroutines or smaller instances.

For instance, if we had an "oracle" function that checks a given vehicle route and returns true if the total distance is below X, Grover's algorithm could find a route under that distance faster than trying all routes one by one. More practically, Grover's principles are sometimes used in quantum hybrid algorithms to boost the search for better solutions. In quantum machine learning contexts (like pattern recognition in traffic data), Grover's can help find specific patterns faster.

In summary, **Grover's algorithm** highlights how quantum computers can explore solution spaces differently from classical ones. Its direct usage in logistics would likely be in specialized scenarios (e.g., searching a database of routes or shipments for one that meets a criterion), but its bigger impact is conceptual – it shows quantum's ability to **accelerate search and optimization tasks**. This algorithm is also relatively simple, so it often serves as a building block in more complex quantum workflows.

4. Quantum Technical Insights

Quantum Annealing

Quantum annealing is a quantum computing paradigm particularly well-suited for optimization problems, and it underpins the approach used by D-Wave's quantum computers. Unlike gate-model algorithms (which use logic gates and circuits), quantum annealing uses a physical process akin to the way metal annealing works – but in the quantum domain. The idea is to encode the optimization problem into the lowest-energy state (ground state) of a quantum system. The annealer starts in a superposition of all possible states (i.e., all possible solutions) and then gradually evolves the system, guided by quantum mechanics, towards the ground state of the problem's Hamiltonian. By the end of the annealing schedule, if all goes well, the system "settles" into the optimal or a near-optimal solution of the original problem.

In practice, problems are formulated as an Ising model or QUBO, where each qubit represents a binary decision (e.g., go on route A vs route B) and couplers between qubits represent constraints or costs. The quantum annealer tries to find the combination of qubit values that minimizes the energy (which corresponds to minimizing the cost function of the problem). Quantum annealing leverages effects like **quantum tunnelling**, which can help the system escape local minima in the solution landscape by tunnelling through energy barriers instead of having to climb over them. This can be an advantage over classical algorithms that might get stuck in suboptimal local minima.

For transport and logistics, quantum annealing has been one of the earliest practical methods used. The Volkswagen traffic flow case and the Aisin multi-truck routing case were both solved using quantum annealer equipment by mapping the routing problems to QUBOs. Similarly, researchers have applied quantum annealing to problems such as scheduling (e.g., the nurse scheduling problem or project scheduling) and other NP-hard tasks relevant to logistics. The advantage of annealers is that they currently support hundreds or thousands of qubits, allowing them to handle moderately large problem formulations. However, embedding a real-world problem into the hardware's particular connectivity can be challenging.

Hybrid quantum annealing solvers have become a practical approach, utilizing a combination of quantum annealing and classical algorithms to solve large problems. For example, D-Wave's hybrid solver might break down a huge routing problem into smaller pieces, solve core parts with the annealer, and utilize classical methods to recombine them. This approach was essentially used in the Aisin case – an iterative assignment of routes one truck at a time, each solved by the annealer. The success there indicates that, even with current noise and limitations, quantum annealing can contribute to solving industry-scale logistics optimization problems when used in a thoughtful hybrid workflow.

From a technical standpoint, quantum annealing does not require error-corrected qubits and is relatively robust to certain noise, which is why it's available sooner than large-scale gate-model quantum computers. However, it's somewhat specialized in what it can do – it's basically designed for optimization. In the coming years, if gate-model quantum computers become powerful enough, they might perform optimization more flexibly than annealers. But for now, annealers are a valuable tool. They essentially act as a **quantum optimizer hardware** that logistics companies can experiment with today, as evidenced by the growing number of case studies and research publications using quantum annealing for route planning, supply chain optimization, and other logistical problems.

In summary, **quantum annealing** finds the minimum of an objective function by a physical quantum process using quantum fluctuations. It has proven effective on certain logistics problems by naturally modelling them as energy minimization tasks. As hardware improves (e.g., with better connectivity and coherence in annealers), we can expect even larger and more complex logistics problems to be attacked via this method. It's a cornerstone of near-term quantum optimization applications.

4. Technical Insights

Hybrid Quantum versus Classical Methods

Because current quantum computers have limitations (noise, limited qubit counts), almost all practical applications in 2025 use **hybrid methods** – meaning quantum algorithms work in tandem with classical computing resources to solve a problem. We have touched on this in the context of QAOA (which is hybrid by design) and in how annealing is often hybridized.

For transport and logistics applications, hybrid methods are especially relevant because the problems are often vast and have numerous business-specific constraints that a pure quantum algorithm might not handle effectively. The classical part can enforce certain constraints or rules (ensuring solutions are valid in the real world), while the quantum part tackles the heavy combinatorial search. This synergy is what allows quantum pilots to demonstrate value even before we have fault-tolerant quantum computers.

In essence, **hybrid quantum-classical algorithms** are the workhorse of current quantum computing efforts in logistics. They take advantage of quantum speed-ups where possible, but lean on classical computation for stability, control, and scalability. As quantum computing hardware becomes truly scalable, faster with quality and stability, the “quantum portion” of these hybrids will assume a greater share of the load. Over time, when large fault-tolerant quantum computers become available, some of these hybrids might evolve into fully quantum algorithms. It is expected that classical optimization techniques will likely remain in the loop for convenience and fine-tuning. The lesson from the case studies is clear: structuring a problem correctly (deciding which parts to solve with quantum, how to iteratively refine solutions, etc.) is as important as the quantum algorithm itself in achieving useful and lasting results.

5. Conclusion

In conclusion, the transport and logistics industry stands to gain significantly from quantum computing. The unique computational capabilities of quantum machines align well with the complex optimization and forecasting challenges inherent in logistics. While the field is still in its infancy, progress is steady: real-world prototype applications have demonstrated that quantum-derived solutions can improve traffic flow, optimize routes, and address supply chain problems that are extremely challenging for classical computers. As we have detailed, ongoing research and case studies by companies such as Volkswagen, DHL, Airbus, BMW, Deutsche Bahn, Nippon Steel, Exxon Mobile, Q-CTRL en UK Rail and other (often in partnership with quantum technology companies) are pushing the boundaries of what is possible. In parallel, advancements in quantum algorithms – from QAOA to quantum annealing – and clever hybrid methods are enabling these early successes.

We should remain realistic that quantum computing in logistics is not a magic fix-all; classical algorithms are very mature in this space and still improving, and quantum hardware is still developing. However, even incremental gains in solution quality or speed can translate into significant efficiency improvements in a large-scale operation. Therefore, many logistics providers are adopting a quantum-ready mindset: investing in pilots, training talent, and collaborating with quantum computing firms. The next decade is poised to be an exciting one where quantum computing moves from lab experiments to a practical component of logistics technology stacks. With continued innovation, applications such as real-time global route optimization, smart city traffic control, and perfectly efficient supply chains could move from theory to reality, powered by the principles of quantum mechanics.

Sources: The information and examples in this report are based on the findings and case studies up to 2024, including industry reports, company announcements, and research papers in the field of quantum computing applications for logistics. Each specific claim or data point has been cited from relevant sources to provide evidence and further reading for interested readers. The rapid pace of advancement means new case studies are likely to emerge beyond those covered here, but the foundational concepts and algorithms discussed will underpin those future developments. Quantum computing is poised to transform transport and logistics, ushering in a new era of optimization and intelligence in how we move people and goods around the world.

Appendix: Possible Use-Cases by Category

Quantum Computing Use Cases for Transportation and Logistics (Source: QED-C, March 2024)

Vehicle Routing Problems and Dynamic Route Optimization

Use Case	Industry	Area of Operations	Approach
Continuous route optimization	All	Planning	Optimization
Delivery & pickup with arrival time windows	Truck	Planning	Optimization
Develop consistent route areas for vehicles	Truck	Planning	Optimization
Flytrex drone delivery service optimization with multi-modal integration (Uber + drone)	Retail	Routing	Optimization
Large problem solves (>500 deliveries)	Truck	Planning	Optimization
Learn from "veteran drivers" for less stressful routes	Truck	Data & IT	Machine Learning
Minimize overall risk in automated driving scenarios with numerous simultaneous actors	Passenger	Routing	Simulation
"On the way" optimization	All	Planning	Optimization
Optimization of regional distribution centers	Truck	Routing	Optimization
Optimize the yard/switching operations	Rail	Knapsack & Routing	Optimization
Reduce miles, driving time, consistent route areas	Truck	Planning	Optimization
Resource allocation in real-time: Position supply where demand is (TNC vehicle positioning)	Truck	Routing	Optimization
Urban level digital twins for real time congestion management	Passenger	Routing	Simulation
Vehicle/passenger routing	Passenger	Planning	Optimization
Very large optimization problems for scheduling routing LTL shipments and drivers	Truck	Routing	Optimization
VRP, CVRP; solve efficiently for fuel, money, environmental impact	All	Planning	Optimization

A. Possible use-cases by Category (Source: QED-C, March 2024)

Warehouse Logistics and Inventory Management

Use Case	Industry	Area of Operations	Approach
Digital twin in warehouse to determine optimal planning for truck arrival, resources, picking windows	Manufacturing	Planning	Simulation
Inventory management, e-commerce delivery, staff scheduling	All	Planning	Optimization
Inventory management: Optimize shipping, capacity, replenishment frequency	Manufacturing	Planning	Optimization
Pallet and truck packing: Optimal packing, damage prevention, weight balancing	All	Knapsack Problem	Optimization
Real-time optimization of in-warehouse resources (forklifts, drivers) against projected truck arrivals	Manufacturing	Planning	Optimization
Real-time customer order exception mitigation at retailer scale	All	Planning	Optimization

Demand Forecasting and Network Planning

Use Case	Industry	Area of Operations	Approach
Analyzing energy demand and simulate different scenarios to meet demand	All	Routing	Simulation
Challenge in demand planning: Extend datasets beyond retailer/supplier for network forecasting (3PL, Supplier, Retailer)	All	Planning	Simulation
Consumer need prediction	All	Planning	Simulation
Demand forecasting for shipments to better allocate and locate assets in correct markets	All	Planning	Simulation
How to get consumer demand signals from suppliers, retailers for proper planning	Manufacturing	Planning	Optimization
Learn from plan/commit deviations upstream and downstream	All	Planning	Machine Learning
Network planning: Fault tolerance, expert rules, past performance analysis	All	Planning	Machine Learning
Optimize the demand generation and demand fulfillment activities simultaneously (Pumpkin Latte Problem)	All	Forecasting or Routing	Optimization
Predict cost of moving products from source to final destination	All	Planning	Simulation
Real time forecasting for TNC demand, congestion, etc.	Passenger	Planning	Machine Learning
Understanding consumer behavior in real time to reduce wastage	All	Sustainability	Machine Learning
Use historical data to evaluate lead time of goods delivery by suppliers	Manufacturing	Planning	Machine Learning

A

Fleet Management and Scheduling

Use Case	Industry	Area of Operations	Approach
Asset maintenance	All	Planning	Simulation
Asset usage forecast	All	Planning	Simulation
Employee scheduling, staff scheduling for goods delivery accounting for availability, PTO, skills	All	Planning	Optimization
Fleet repairs per GE Research use case	All	Fleet Maintenance	Simulation
Job shop scheduling: Manufacturing with many jobs and machines optimization	Manufacturing	Routing	Optimization
Operating Plan Design: crew scheduling, train scheduling, routing, consist construction, disruption management	Rail	Planning	Optimization
Optimize logistics operations: fleet assignment, routing, crew assignment, network planning, on-time delivery	All	Planning	Optimization
Proactively adjust manufacturing schedules based on transportation delays/supply issues	Manufacturing	Planning	Optimization
Real-time analytics from onboard sensors	Passenger	Fleet Maintenance & Routing	Optimization
Sensors on equipment to determine point of failure and proactively schedule repairs	All	Fleet Maintenance	Machine Learning
Simulate the network for time with 100+ trains in a network	Rail	Knapsack & Routing	Simulation
Urban system control, e.g., traffic lights	Passenger	Planning	Optimization
Use of quantum computing for real-time diagnostics and prognosis	All	Fleet Maintenance & Routing	Machine Learning
Would like to simulate a single train and all its components	Rail	Knapsack & Routing	Simulation

A

Multimodal Transport Optimization

Use Case	Industry	Area of Operations	Approach
Analyze cost/carbon tradeoff between rail, truck, seaway/maritime shipping at regional/national scale	All	Planning	Simulation
Create P&D cross-company network and demonstrate operational cost savings of participation	Truck	Planning	Optimization
Digital twins of cities, AV systems, etc.	Passenger	Planning	Simulation
Digital twins with external data sources (too many constraints for classical)	All	Planning	Simulation
Dynamic optimization of ports, airports, multi-modal transportation for supply chain management	All	Planning	Optimization
Evaluate different scenarios where suppliers cannot provide ordered materials	All	Planning	Simulation
Further integration of objectives dynamically with speed needed for receiver	All	Planning	Optimization
Optimize inventory and supply chain management; value chain optimization; risk management	All	Planning	Optimization
Simulate the movement of volume from hub to hub and analyze downstream impact	Truck	Routing	Simulation
Supply chain management	All	All	All
With online retail and D2C, optimize supply chain requiring less movement of goods	Retail	Planning	Optimization

Additional Cross-Cutting Use Cases

Use Case	Industry	Area of Operations	Approach
Appropriate mix of input providers to ensure needs met for high priority contracts	All	Data & IT	Optimization
Digital twin: Automate to seek KPI optimization	All	Routing, Sustainability, Planning	Simulation
Dynamically adjust supply chain parameters (e.g., safety stocks)	Manufacturing	Planning	Optimization
Live network risk assessment with available compute speed	All	Data & IT	Machine Learning
New materials testing and PFAS remediation simulations	All	Sustainability	Simulation
Optimization for test & development of new materials (concrete, polymers, batteries, fuels)	All	Sustainability	Optimization
Quantum cryptography, QKD, random number generation for secure vehicle communications	All	Data & IT	Other
Waste reduction	All	Sustainability	Optimization

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Disclaimer

This research paper represents a **snapshot in time**. The field it addresses is evolving at lightning speed, and insights, data, and interpretations may shift rapidly as new developments emerge. Readers are therefore encouraged to view this paper as a contribution to an ongoing conversation, rather than a final statement.

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