Quantum Computing for Transportation and Logistics

March 2024

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About QED-C

QED-C is an industry-driven consortium managed by SRI International. With a diverse membership representing industry, academia, government, and other stakeholders, the consortium seeks to enable and grow the quantum industry and associated supply chain. For more about QED-C, visit our website at quantumconsortium.org.

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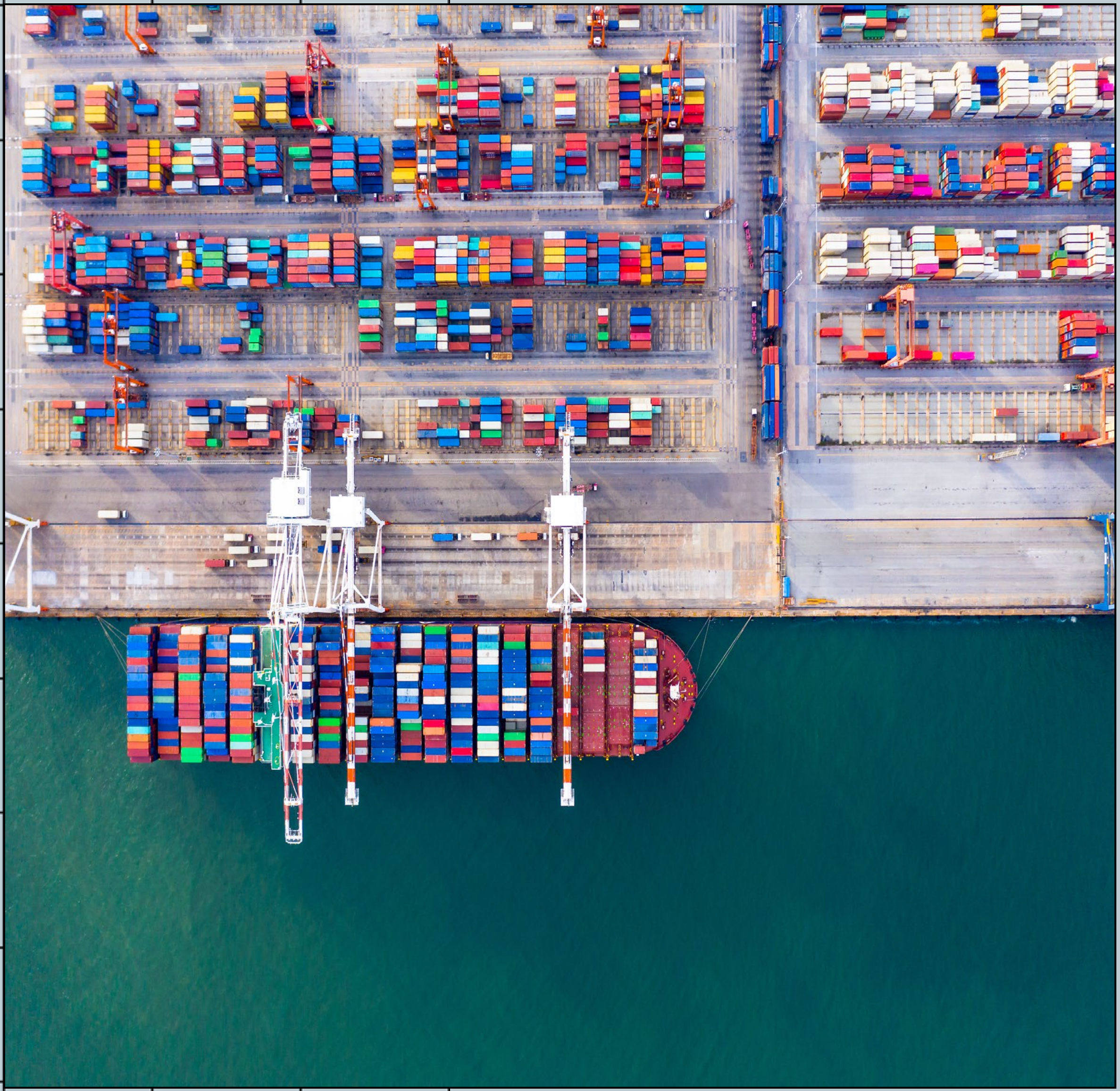

Executive Summary

To assess the current state and future possibilities of quantum computing and the transportation and logistics industry, QED-C's Use Cases Technical Advisory Committee led this study based on a workshop exploring the feasibility and impact of different use cases.[1] Quantum computing (QC) offers intriguing solutions to supply chain, transportation, and logistics problems that classical computers cannot completely solve. It also offers the possibility of significantly faster computations, with applications in all modes of the transportation and logistics industry — air, land, and sea.

The challenges faced by the transportation and logistics industry 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. The literature suggests that quantum computing offers advantages in three primary areas: optimization, machine learning, and simulation.

As part of this study, experts from both the transportation and logistics industry and the quantum communities convened at a workshop to identify use cases at the intersection of the two fields. The overwhelming majority of use cases identified were ultimately optimization problems, most of which came down to planning operations. In contrast, use cases applying a simulation (from a logistics industry perspective) approach were seen by experts as less feasible and impactful than most optimization problems. Several companies have demonstrated small-scale prototypes that apply QC algorithms to different classes of logistics problems.[2]

From analysis of the current state and the feasibility and impact of use cases of quantum computing for transportation and logistics applications, four use cases emerge as those that could have the greatest impact in the relatively near term:

- Optimization of labor plans
- Continuous route optimization
- Optimization of warehousing
- Demand forecasting

In addition, this report puts forward five recommendations for boosting development and adoption of QC technologies by the transportation and logistics industry:

[1] The study methodology, identified use cases, and workshop participants are presented in Appendices A, B, and C.

[2] See, e.g., Sean J. Weinberg, Fabio Sanches, Takanori Ide, Kazumitzu Kamiya, and Randall Correll 2023. Supply chain logistics with quantum and classical annealing algorithms. *Scientific Reports* 13: 4770, doi: 10.1038/s41598-023-31765-8; Christopher D. B. Bentley, Samuel Marsh, André R. R. Carvalho, Philip Kilby, and Michael J. Biercuk. 2022. Quantum computing for transport optimization. arXiv, arXiv:2206.07313; and Crispin H. V. Cooper. 2022. Exploring Potential Applications of Quantum Computing in Transportation Modelling, *IEEE Transactions on Intelligent Transportation Systems* 23, no. 9: 14712–20, doi: 10.1109/TITS.2021.3132161.

- **Increase operational efficiency for businesses:** Quantum computing offers possible solutions for increased business efficiencies via better routing programs, efficient cargo loading, optimized manufacturing processes, and optimal labor scheduling. However, QC adoption can be prohibitively expensive and risky, especially for smaller companies. To overcome this barrier, QC companies could offer discounted rates for small logistics companies to trial the technology and see the business efficiencies that can be gained. This would also provide valuable feedback and data to the QC company to improve their product. This cross-industry collaboration could even facilitate the development of quantum-enabled route planning and other optimization tools.

  Relatedly, Manufacturing USA is a network of institutes that each have a distinct technology focus but with a common goal: to secure the future of US manufacturing through innovation, education, and collaboration. Emerging technologies like quantum computers could impact all of the technologies, ranging from flexible electronics to biomaterials. The Manufacturing USA program should disseminate information about quantum computing and other emerging technologies across the network to ensure broad incorporation as advanced manufacturing processes are being developed.

- **Increase supply chain security and resilience:** There are broad dependencies between the security and resilience of national and global supply chains. Two measures can support continued innovation in this area: (1) identification of the weakest links in supply chains and direction of enhancements to those areas, and (2) increased capabilities for contingency planning tools. QC technologies could analyze more data across more variables and constraints than can classical computers, enabling the development of more accurate and comprehensive forecasts and operating plans that better protect against supply chain threats. Government can boost these capabilities of quantum computers by creating testbeds and sandbox programs focused on demonstrations, proofs of concept, and pilots of near-term applications for supply chain management.

- **Address sustainability:** Climate change is a top concern of companies and nations, and transportation-based emissions are a leading contributor. Any potential for increases in efficiencies that reduce emissions should be explored and developed. One of the most impactful uses of quantum computers in transportation and logistics is continuous route optimization, which can decrease emissions and fuel usage across transport methods. As companies increasingly look to cut their carbon footprint, they should consider the impact that QC technology adoption can have by helping them better optimize routes and processes for maximum fuel efficiency. As an added bonus for companies, using quantum computing to optimize this way will likely lead to cost savings as well.

- **Optimize government logistics missions:** Government can be an early adopter of QC solutions in optimizing its own fleets and missions. For example, the US Postal Service could use QC technology to better plan fleet maintenance, schedule staff, and design more fuel and time efficient routes. By adopting QC technologies in its earlier stages, government can guarantee revenues to help sustain private QC companies.

- **Create a skilled workforce:** QC technology is evolving quickly, creating demand for skilled workers who are able to contribute to the field. This includes opportunities for the end users of the technology, such as operating plan developers and route designers, to shape its development and key features and functions. However, most supply chain workers today are not well versed in quantum technology. Including QC education in industrial and supply chain engineering degree programs could increase understanding and adoption of this new technology. Training could also be extended to the existing transportation and logistics workforce by collaborating with professional organizations to provide knowledge, skills, and access to the latest QC tools. This training could be especially useful for the workers who focus on route planning, operating plan design, and forecasting, i.e., the tasks that could most benefit from quantum computers.

Introduction

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 US transportation industry faces numerous challenges that must be solved for the US economy to continue to grow and thrive over the next decade and beyond. Traffic congestion on the nation's capacity-constrained highway infrastructure; rail service quality; workforce planning and work-life balance; inventory planning and production management; delay propagation mitigation across interconnected, multicarrier supply chains; and greenhouse gas emission reduction are all challenges that cannot realistically be solved solely by increased capital expenditures, new vehicle propulsion technologies, or new regulations. Solution options to these problems are limited and in some cases extremely expensive, which can prevent business adoption. The unmatched utility that the potential of quantum computing offers presents an exceptional opportunity for US leadership. Quantum computing's relevance, promise, and economic viability in this solution space cannot be ignored.

The literature suggests that quantum computing offers advantages in three primary areas for logistics and transportation: optimization, machine learning (ML), and simulation (see sidebar). Many companies are already exploring these potential applications. For example, Quantum-South has tested the use of quantum algorithms to optimize air cargo,[4] 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.[5]

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[3] Gao, Scarlett, Timo Möller, Niko Mohr, Alexia Pastré, and Felix Ziegler. 2023. Gearing up for mobility's future with quantum computing. McKinsey & Company, September 13. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/gearing-up-for-mobilitys-future-with-quantum-computing.

[4] Dargan, James. 2022. Quantum-South Explores Quantum Algorithms for Air Cargo Optimization. *The Quantum Insider*, December 2. https://thequantuminsider.com/2022/12/02/quantum-south-explores-quantum-algorithms-for-air-cargo-optimization/.

[5] Fretty, Peter. 2021. Could Quantum Computing Solve Maritime Complexities? Industry Week, March 31. https://www.industryweek.com/technology-and-iiot/article/21159784/could-quantum-computing-solve-maritime-complexities.

Defining the term "simulation"

Supply chain and logistics experts use the term "simulation" to mean Monte Carlo-style discrete event simulation mostly for modeling demand for logistics services. This differs from the quantum industry definition, which generally refers to simulation of quantum mechanical systems (most commonly chemistry and material science). Further, while the simulation described by logistics experts is usually solved using machine learning algorithms in a quantum computer, the logistics experts involved in this study used the term "machine learning" to label problems of pattern recognition in data — which is a classical computing definition. In this paper, the definitions of "simulation" and "machine learning" follow the logistics experts' definition. [a]

[a] For a history of the use of the terms "simulation" and "optimization" by industry, see Jean-François Cordeau, Paolo Toth, and Daniele Vigo, "A Survey of Optimization Models for Train Routing and Scheduling," *Transportation Science* 32, no. 4 (1998): 380–404, doi: 10.1287/trsc.32.4.380.

Many governments are supporting the development and application of quantum technologies. In the United States, for example, Sandia National Laboratories is developing QC algorithms to solve supply chain optimization problems.[6] Furthermore, the US Congress called for a review of what applications can be developed in the near term using today's quantum technology; in response to this, QED-C detailed how public-private partnerships should be used to advance application development.[7] Additionally, Congress is reauthorizing the National Quantum Initiative Act[8] with new language that focuses support on near- and mid-term application development through testbed programs.[9] Congress also passed the National Defense Authorization Act (NDAA) in January 2023,[10] which includes a pilot program to develop quantum applications. Both pieces of legislation encourage collaboration with industry, including consideration of quantum annealing, gate model, and quantum-hybrid technologies, to move the most promising of quantum technologies out of the lab and into commercial applications. Other countries investing in QC technologies to develop quantum applications include the United Kingdom's call for quantum application

[6] Law, Marcus. 2023. How quantum computing can solve supply chain challenges. *Supply Chain*, February 16. https://supplychaindigital.com/pr_newswire/how-quantum-computing-can-solve-supply-chain-challenges.
[7] Quantum Economic Development Consortium (QED-C). 2022. *Public Private Partnerships in Quantum Computing: The Potential for Accelerating Near-Term Quantum Applications*. Arlington, VA. https://quantumconsortium.org/ppp22/.
[8] US Congress, House. 2023. A Bill to reauthorize the National Quantum Initiative Act, and for other purposes (HR 6213). Washington. https://www.congress.gov/118/bills/hr6213/BILLS-118hr6213ih.pdf.
[9] US Congress, House Committee on Science, Space, and Technology. 2023. HR 6213 - The National Quantum Initiative Reauthorization Act: Passed by full committee, November 29. Washington. https://science.house.gov/2023/11/the-national-quantum-initiative-reauthorization-act.
[10] US Congress. 2023. National Defense Authorization Act for Fiscal Year 2024. January 3. Washington. https://www.congress.gov/118/bills/hr2670/BILLS-118hr2670enr.pdf.

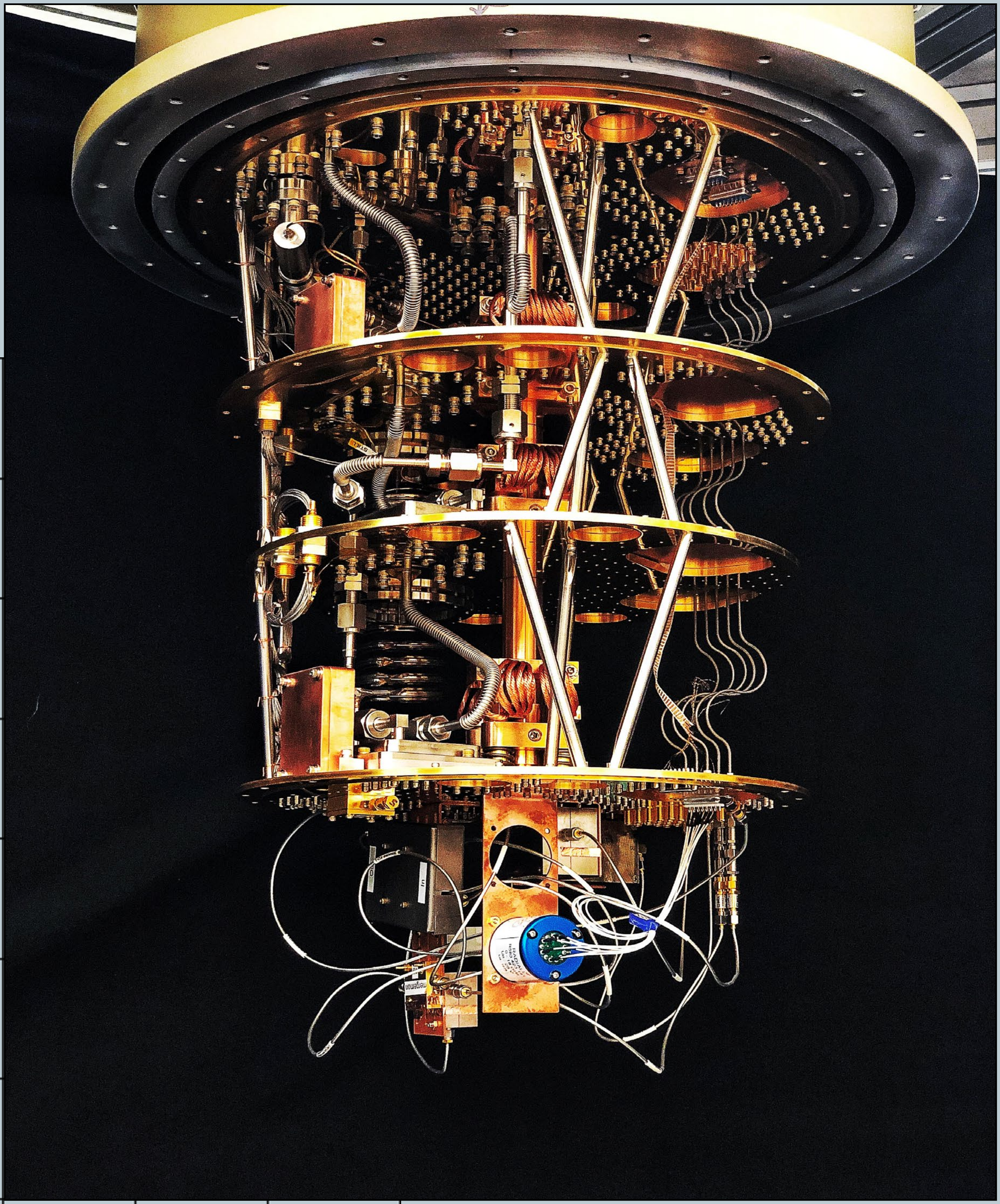
feasibility,[11] Australia's efforts to utilize quantum computing for transportation network optimization,[12] Japan's vision of a quantum society,[13] and a report released by the Council of Canadian Academies that identified several industries, including transportation and logistics, that can benefit from quantum computing.[14]

In alignment with the potential for significant economic impact and implications related to climate and other policies, it is important to explore key questions pertaining to quantum computing in the transportation and logistics industry:

- What are classes of problems in logistics and transportation that may benefit from quantum computing? What is the relevant scale? What is the anticipated business impact of such QC solution? What is the likelihood or feasibility of deploying this solution?
- What is the state of high-performance computing and QC in the logistics and transportation sector? For example, is it commonly used at scale, is the industry well educated on the technology, are there strong partnerships?
- What constraints do logistics and transportation companies face when adopting emerging technologies? Constraints might include low profit margins, lagging technology, high computing energy costs, and/or lack of skills. Which constraints can QC offerings help to address?

In seeking to answer these questions, experts from both the transportation and logistics industry and the quantum communities convened at a workshop to explore the types of quantum computing systems available, the algorithms and methods they use, the use cases that they show promise in addressing, and the business and government actions that can be taken to progress the field forward.

[11] GOV.UK. 2023. Funding Competition: Feasibility Studies in Quantum Computing Applications (February 13–March 29). London https://apply-for-innovation-funding.service.gov.uk/competition/1468/overview/3e95c2d9-70ba-4a06-880f-c814422bb1f1.
[12] Transport for New South Wales. 2021. Quantum Technology. Sydney. https://www.transport.nsw.gov.au/system/files/media/documents/2021/Transport%20for%20NSW%20and%20Quantum%20Technology%20-%20WCAG%20version.PDF.
[13] Secretariat of Science, Technology, and Innovation Policy. 2022. Vision of Quantum Future Society. Tokyo. https://www8.cao.go.jp/cstp/english//outline_vision.pdf.
[14] Council of Canadian Academies. 2023. *Quantum Potential*. Ottawa. https://www.cca-reports.ca/reports/quantum-technologies/.



Source: National Institute of Standards and Technology

Decision Making in Supply Chains with Quantum Computing

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.

Use Cases Impact and Feasibility

We analyzed the 83 use cases for quantum technologies in logistics identified by experts and consolidated them into 15 examples (see **Figure *2***). We further ranked the use cases as those expected to have the greatest impact and those judged to be the most feasible. The average impact and feasibility scores of each use case from this assessment are presented in the graphics below. There is a clear linear relationship: The feasibility and impact of a use case are often similarly ranked, though this could be caused in part by an unconscious bias people may carry that the more feasible use case will also be the more impactful one. Still, we conclude from this assessment that there are key opportunities that are relatively prepared to leverage quantum technology for logistical purposes.

The use case ranked the most feasible and impactful is *continuous route optimization*, making it the best target for research. High impact and high feasibility imply less time is required to develop a working solution than is required for other concepts. *Continuous route optimization* is a broad concept that is relevant to all transportation modalities. Route optimization is an old problem, first described by Leonhard Euler in the 1700s, and research since World War II is extensive.[15] There are algorithms for classical computers to solve routing problems, but workshop participants noted that the problems either take too long using conventional computing or are simply too big for the computers, requiring end users to reduce the number of variables or constraints inputted into the model.

The concept rated the second most feasible is *operating plan design and train scheduling*. This concept refers to a process of forecasting needs for a fleet, including the crew, vehicles, and load, and developing a plan to meet the needs. Operating plans are comprehensive, often considering factors such as train scheduling and routing, train car construction, car distribution, and fleet management. However, this concept was rated only the fifth most impactful. This use case perfectly illustrates the amount of complexity that should be addressed in an optimal solution; routing, loading, personnel scheduling, maintenance schedules, construction, weather disruptions, and more are all possible factors to try to account for.

[15] Euler, Leonhard. 1741. Solutio problematis ad geometriam situs pertinentis, *Commentarii academiae scientiarum Petropolitanae* 8: 128–40.

Figure 1: Impact and feasibility of the 15 consolidated use cases

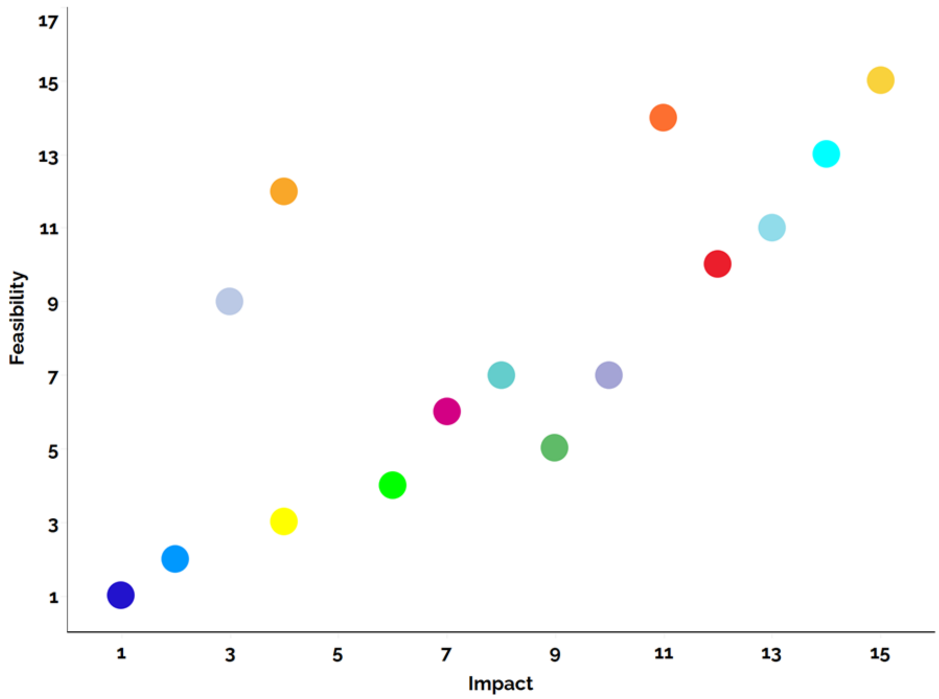


Figure 2: The 15 consolidated use cases, categorized by topic, type of problem, and relevant quantum technology

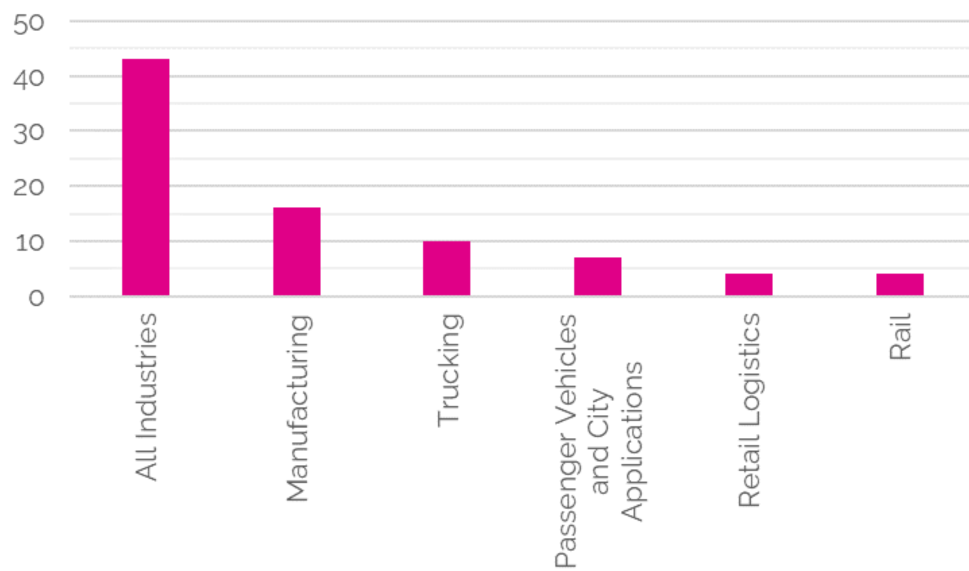
Use Case Topic	Type of Problem	Relevant Quantum Technology
Quantum materials, like fuels, batteries	Optimization	Gate model
Load planning optimization in the intermodal facility	Optimization	Annealing, quantum-hybrid
Operating plan design: Crew scheduling, train scheduling, train routing, train consist construction, disruption management, car distribution, train makeup, fleet management, railcar pipeline management	Optimization	Annealing, quantum-hybrid
Optimize the yard/switching operations	Optimization	Annealing, quantum-hybrid
Continuous route optimization	Optimization	Gate model, annealing
Demand generation and fulfillment optimization	Optimization	Annealing, quantum-hybrid
Real-time optimization of in-warehouse resources (like forklifts and forklift drivers) against near-term projected truck arrivals	Optimization	Annealing, quantum-hybrid
Dynamic optimization of ports, airports, and multi-modal transportation for supply chain management and optimization	Optimization	Annealing
Demand forecasting for shipments so carriers can better allocate and locate assets in the correct markets (e.g., intermodal rail containers, chassis, etc.)	Simulation	Annealing
Pallet and truck packing	Optimization	Annealing
Job shop scheduling: manufacturing setting where there are many jobs and machines that would benefit from optimized scheduling across functions	Optimization	Annealing
Tracking of material ingredients in goods, components	Simulation	Annealing, quantum-hybrid
Optimize logistics operations: fleet assignment, routing, crew assignment, network planning, on-time delivery scheduling	Optimization	Gate model, annealing, quantum-hybrid
Optimization of production floor and manufacturing	Optimization	Annealing
Real-time twinning of a system	Simulation	Annealing, quantum-hybrid

Classification

The 83 use cases have been classified by industry, algorithm approach (e.g., optimization, ML, simulation), and area of operations (department).

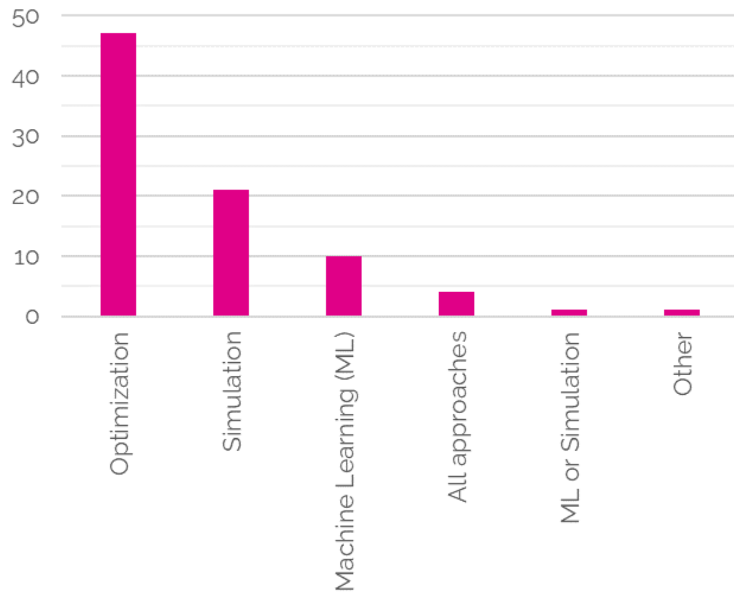
Industry: Classification by industry is generally organized by mode of transportation (truck, train, plane, ocean), manufacturing, or passenger vehicle applications. Just over half (43 of 83, 51%) of the use cases could be applied to all industries. The rest are identified as specific to a portion of the supply chain: 16 use cases for manufacturing, 10 for trucking, 7 for passenger vehicles and city applications, 4 for retail logistics, and 3 for rail.

Figure 3: Number of use cases classified in each industry



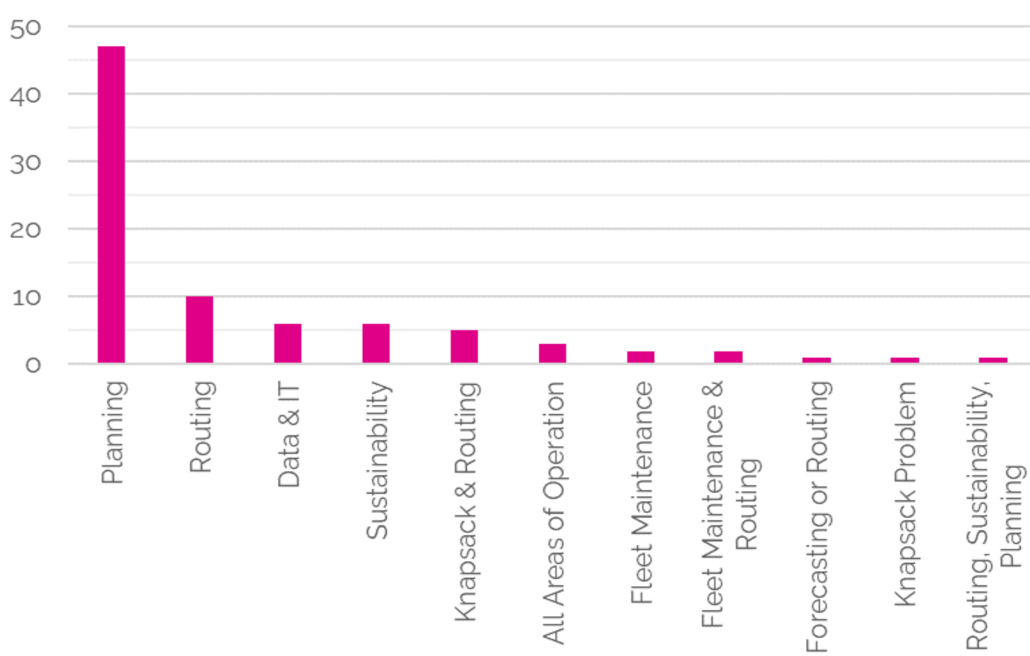
Type of problem: The data are classified by problem approach. The workshop participants were asked to use optimization, simulation, and machine learning as their initial choices, and this default was supported by the workshop's end results: The vast majority of use cases are classified primarily as an optimization problem.

Figure 4: Number of use cases classified in each primary type of problem



Area/department that benefits from a quantum solution: The data are also categorized by department or area of operations. Congruent with the focus on optimization, most problems are in some way related to the planning function in a company; only 6 use cases are problems likely to be assigned to an IT/data team and another 6 would be ascribed to a group working on sustainability issues.

Figure 5: Number of use cases classified in each area of operations/department



Note: "Knapsack" is the generic term for problems related to loading (e.g., filling a truck, airplane, train).

Impact and Feasibility by Relevant Industry

The feasibility and impact of the 15 consolidated use cases are shown in **Figure 6** and **Figure 7**. Use cases specifically for the rail industry have a high feasibility, while those specific to manufacturing have moderate to low feasibility with current QC technology. This difference could be attributed to the wide range of classical computing solutions focused on manufacturing — because manufacturing is a larger segment of the economy, there is more competition to solve manufacturing problems and therefore the incumbent technology is harder to outperform.

Figure 6: Use cases most relevant to the rail industry

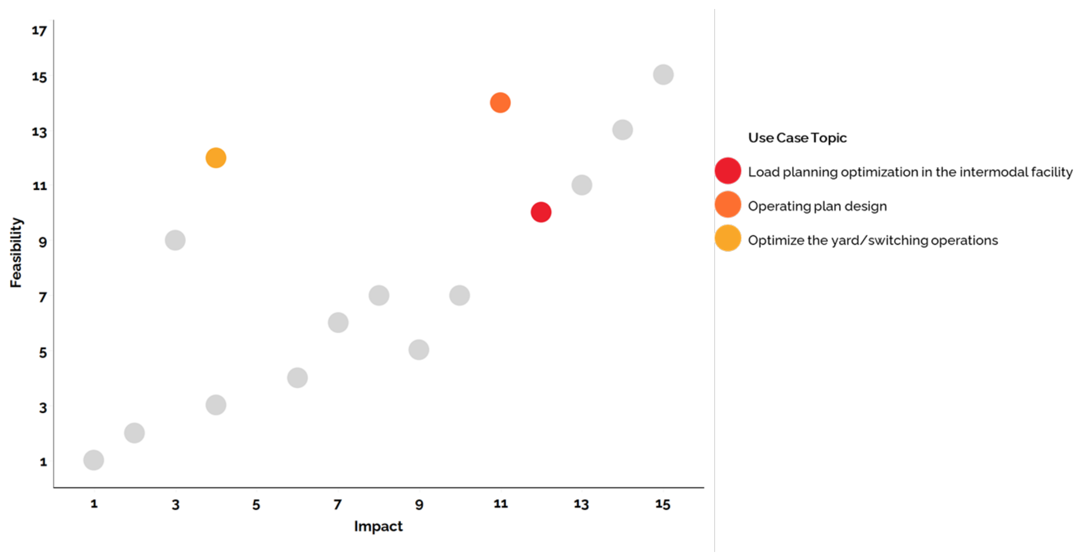
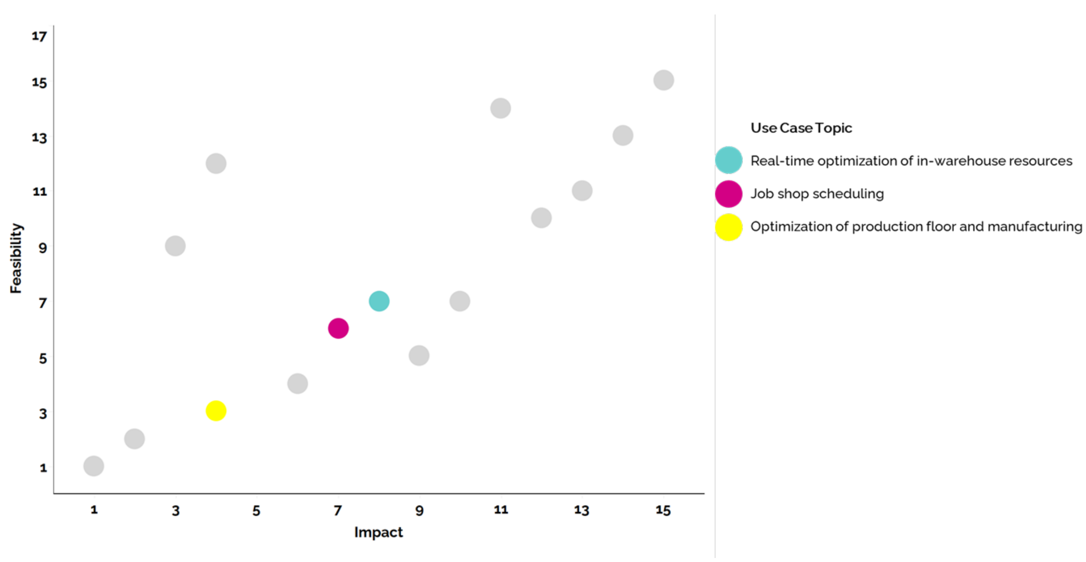


Figure 7: Use cases most relevant to manufacturing



Impact and Feasibility by Approach

With most use cases primarily using an optimization approach, the impact and feasibility of these is spread across the range. Still, all five of the use cases in the top right corner — those with the highest impact and feasibility — use an optimization approach. Approaches using a simulation approach were in the lower half of the feasibility ranking. This may be not only because optimization is considered so important but also because good forecasting requires (generally) more data for a solution than optimization. One of the simulation use cases, demand forecasting, was ranked sixth highest in impact but in the bottom half for feasibility.

Figure 8: Use cases employing an optimization approach

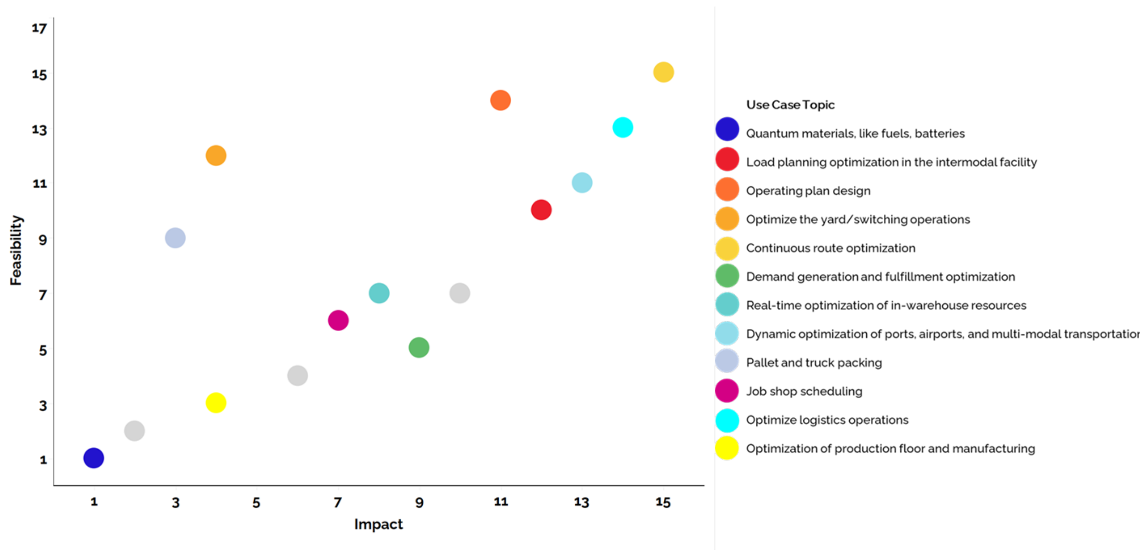
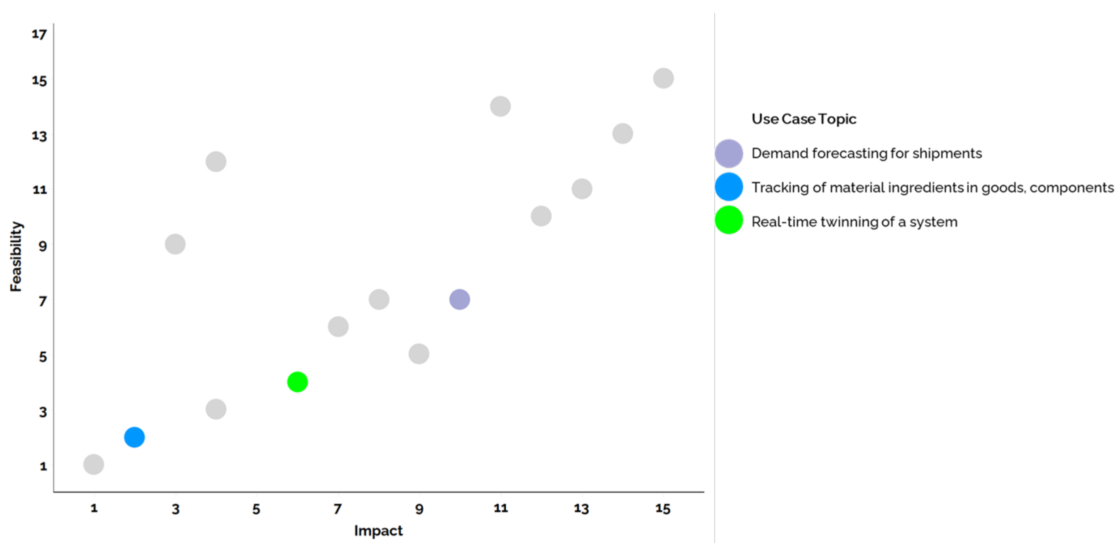


Figure 9: Use cases employing a simulation approach



Impact and Feasibility by Area of Operation

All of the highest-ranked use cases on both impact and feasibility focused on planning. Both use cases focused on the "knapsack problem" had a low impact but moderate to high feasibility. "Knapsack problems" are generally small in scope — optimizing the load in a single truck or airplane requires fewer variables than other problems. The sustainability and forecasting areas of operation each had one applicable use case. The use case for sustainability — quantum materials — was the lowest-ranked use case for both impact and feasibility.

Figure 10: Use cases focused on the planning area of operation

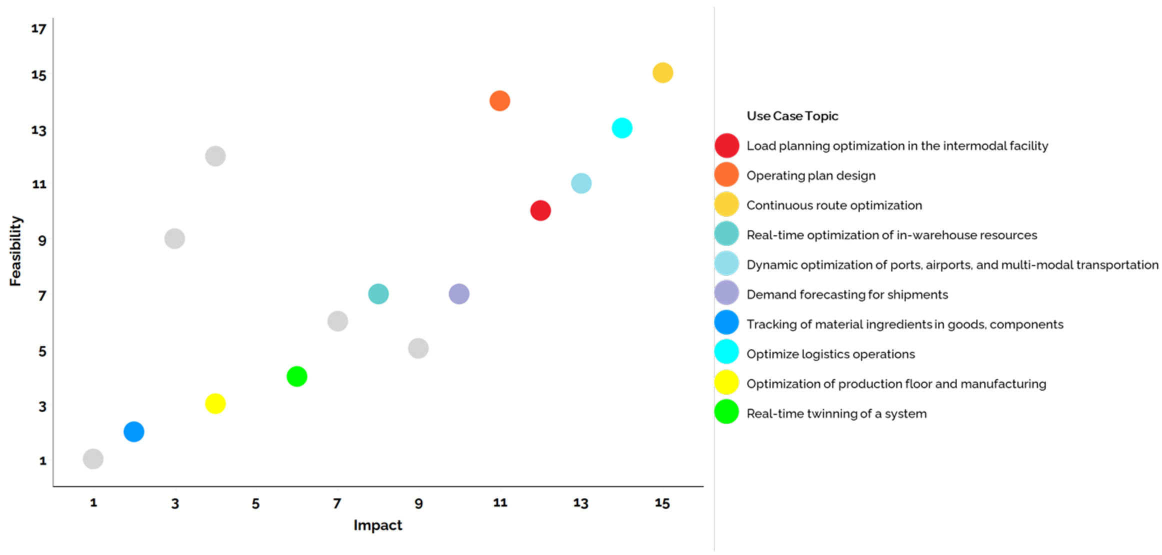


Figure 11: Use cases focused on the routing area of operation

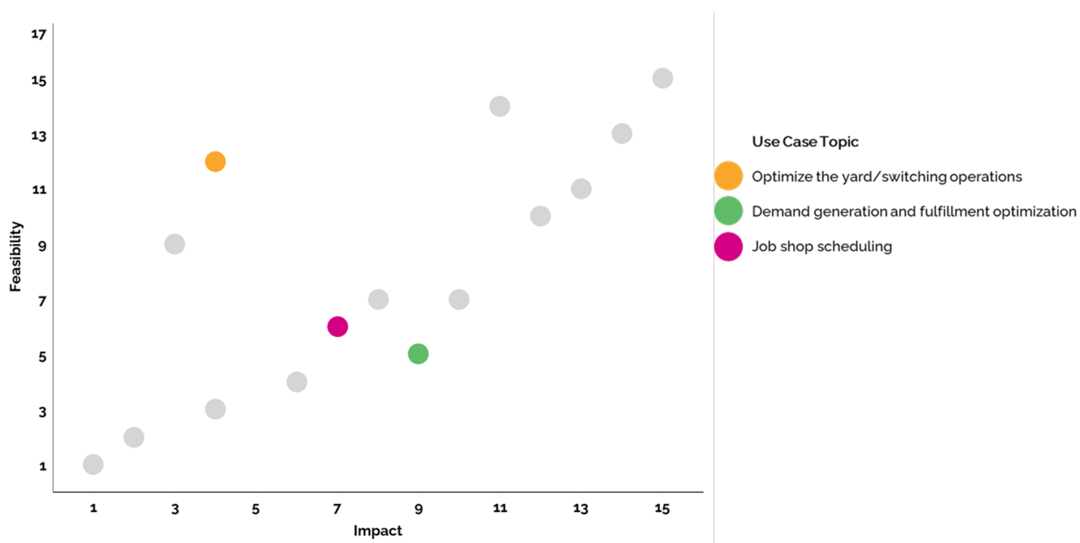


Figure 12: Use cases focused on knapsack area of operation

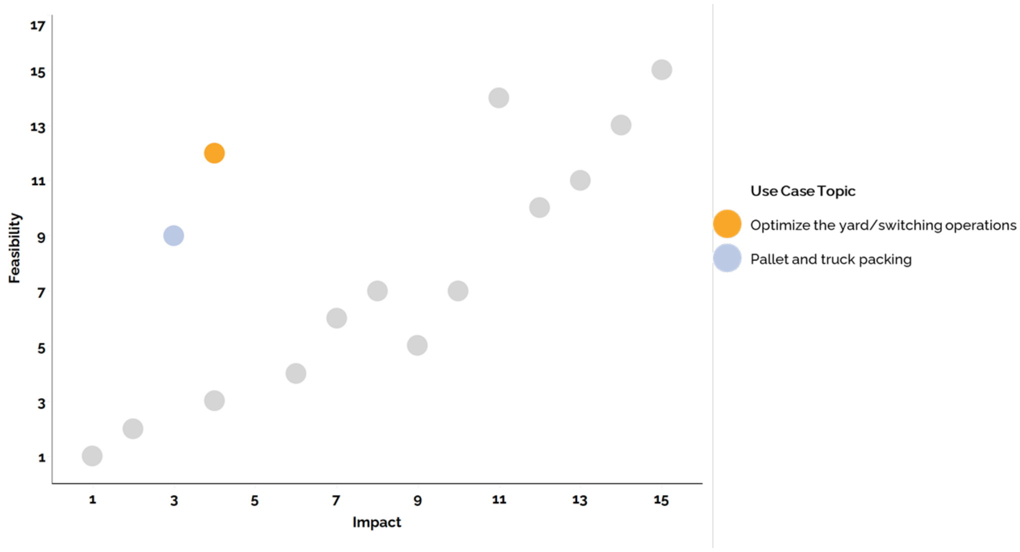


Figure 13: Use case focused on the sustainability area of operation

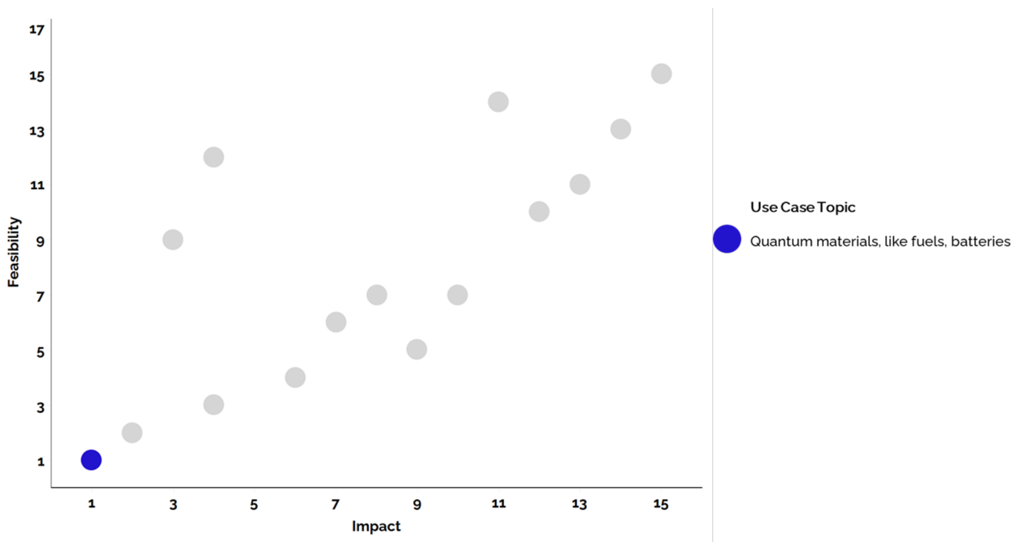
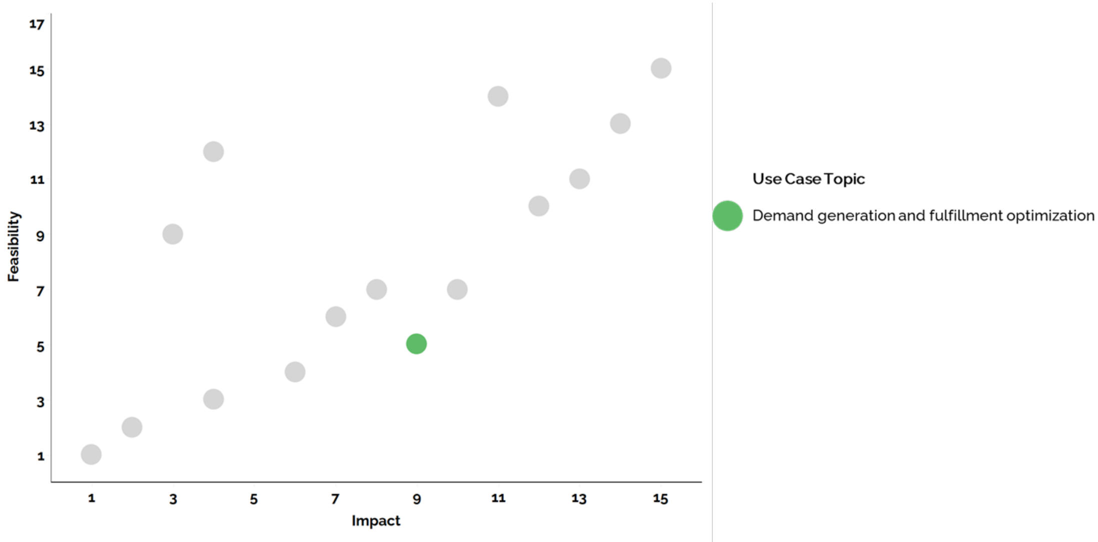


Figure 14: Use case focused on the forecasting area of operation



Priority Use Cases

After assessing the impact and feasibility of use cases and consolidating them further, four broad transportation, supply chain, and logistics use cases emerged as those most ready to benefit from QC technology adoption:

1. **Optimization of plans (labor, materials, etc.).** To explore load planning optimization for intermodal facilities combining rail and trucking, more specific information is required for each real-world scenario. Once that information is available, a 360-degree analysis could map the classical approach to a quantum computing approach. Two key issues were identified as needing to be addressed in the feasibility phase: the IT department would need to be ready with clean data, and an application for integrating load planning data into a quantum architecture would need to be developed. A representative quantum analytical model could then be built.
2. **Continuous route optimization.** Live deliveries that require active replanning entail a heavy computational burden. A research phase of 6–8 months would be required for specific investigations on quantum options, followed by the model building phase, estimated to be another 8–14 months. The development time of a production-ready solution is estimated to take an additional 18–24 months. Thus, the total time estimated from start to real-world deployment is a minimum of 32 months.
3. **Optimization of warehousing (labor, forklifts, robots, etc.).** Planning assets and resources for warehouses would require particular expertise from the logistic industry, especially when considering manual and automated synergies before a quantum model can be constructed. A timeline for outcomes requires additional investigation.
4. **Demand forecasting.** Predicting shipments and market movement requires a large cross-functional team including industry and quantum technology expertise. It is estimated that initial research would require 6–12 months and creation of a working quantum model an additional 6–12 months.

Table 1: Concept details for most impactful and feasible use cases

Title	Operating plan design	Continuous route optimization	Real-time optimization of in-warehouse resources against near-term projected truck arrivals	Demand forecasting for shipments
Description	Build a better customer experience and improved employee morale through enhanced resource and operational / capacity planning	Rerouting deliveries; optimizing nodes vs. optimizing routes; using quantum technology to create new edges mid-flight (dynamic graph); optimizing for constraints (dynamic or static) on vertices and edges	Real-time simulations that could help with planning all assets & resources, such as trucks, people, movement of goods. Allows third-party logistics firms to charge more, as they're more competitive, can handle higher volumes.	Demand forecasting for shipments so carriers can better allocate and locate assets in the correct markets (e.g., intermodal rail containers, chassis) Restatement: Demand generation and fulfillment optimization
Persona	Railroad operators (transportation company) (multilevel and iterative between operations and plan); people doing the work / managers	Delivery companies; any group doing route planning; government agencies (recycling routes, supply chain)	Warehouse workers, through greater efficiency; customers; suppliers — more predictable performance leads to efficiency gain	Operations planner; financials (accounting) planner
How it works	Railroad operators feed in data (demand from endpoints/users [predictive forecast], GPS, scanners, schedules, labor availability, maintenance, car scheduling); clean data; feed it into a solver; and then deploy that information with an iterative learning component (feedback)	Define the topics where there is a quantum advantage; define constraints; evaluate real-time contingencies; set parameters; use quantum algorithms to optimize real-time execution.	Inputs · Transportation arrival information · What goods are on the trucks, number of trucks · Calculate which door to put the truck in based on warehouse inventory classification · Current staffing level (or ability to plan for staffing) · Outbound orders: visibility to demand · Outbound planning schedule: which	1. Gather the demand components (data sets); classic data warehouse problem: piping the source system into the modeling system. A company that already has forecasting in place ensures that all the sources are met to be integrated into the model (reference architecture); establish a baseline for running algorithms in the classical system.

			outbound orders need to go on which trucks? · Truck size Outputs · Picking execution (varies by type of picking) · Variability - resilience in the system; exception handling · Length of time it takes to fill truck	2. Develop and run the model: ML algorithms; distributions (whether in classical models or deep neural networks); support vector machine algorithms that are not forecasting; optimization algorithms: forecast, plan to meet forecast, apply optimization algorithm (currently using a hybrid-model algorithm). 3. Match to available supply.
Features	Capable of short- and long-term planning; all-in-one resource planner (crew, locomotive, shop, train; track assignment [more trains than tracks available]) factors in regulations and instructions on how trains are to be operated and actions in course of movement	Push-centric data collection; continuous data monitoring; taking a pulse on the opportunities and exception areas	Data history (longer than 2 weeks); expanded compute power	Can use data in ML; can create a forecast, then use the forecast to optimize in the success metrics then run simulations with what-if scenario (does not need to be a linear process, but should be used in the aggregate)
Problem space	Information unique to the client (not all clients have the data necessary to build useful models) Problem frequency: level-dependent (overall schedule: monthly / quarterly; others: daily)	Things change over time as new information becomes available; can't plan for everything; need to optimize during the execution; requires real-time access to the quantum application; outperforms classic as more constraints and parameters are added; regulatory burdens (e.g.,	Time; cost; availability of information (accurate data); access to all the data	Either ML or optimization; apply multiple commercial off-the-shelf products and compete the tools against each other to formulate your prediction. Currently apply multiple models at once, which can become computationally dense. Possible use simulations. Biggest challenge with

		emissions and fuel use, time at port)		classical: creating a model with a lot of data. Currently there are too much data with a lot of variables. If demand is known, how can that be matched to a supply? What is realistic on the supply side? How can a company allocate assets in a particular lane with so many assets? Do they optimize for service or for profits? Is there a compromise? Information sharing among partners in the supply chain that cannot be controlled. Understanding the constraints on both the supply and demand.
Success metrics	Customer ETA (consistency in delivery and accuracy); improved velocity across network; resource planning vis-à-vis classical / current operations	Reduction in cost, less maintenance, time savings, better and more accurate arrival times	Labor cost reduction; predictability; reliability; scalable; case pick per worker-hour (maximize labor metrics); on-time in-full delivery (OTIF)	Can you maintain or increase your margin with the tool? Can you fulfill the customers demand on time and in full? Can you minimize the error of your forecast?

Recommendations

Based on the current state of the industry and the experts' assessment of the feasibility and impact of 15 use cases for quantum computing in transportation and logistics, the organizing committee developed five recommendations for ways to grow and support this technology application:

- **Increase operational efficiency for businesses:** Quantum computing offers possible solutions for increased business efficiencies via better routing programs, efficient cargo loading, optimized manufacturing processes, and optimal labor scheduling. However, QC adoption can be prohibitively expensive and risky, especially for smaller companies. To overcome this barrier, QC companies could offer discounted rates for small logistics companies to trial the technology and see the business efficiencies that can be gained. This would also provide valuable feedback and data to the QC company to improve their product. This cross-industry collaboration could even facilitate the development of quantum-enabled route planning and other optimization tools.

  Relatedly, Manufacturing USA is a network of institutes that each have a distinct technology focus but with a common goal: to secure the future of US manufacturing through innovation, education, and collaboration. Emerging technologies like quantum computers could impact all of the technologies, ranging from flexible electronics to biomaterials. The Manufacturing USA program should disseminate information about quantum computing and other emerging technologies across the network to ensure broad incorporation as advanced manufacturing processes are being developed.

- **Increase supply chain security and resilience:** There are broad dependencies between the security and resilience of national and global supply chains. Two measures can support continued innovation in this area: (1) identification of the weakest links in supply chains and direction of enhancements to those areas, and (2) increased capabilities for contingency planning tools. QC technologies could analyze more data across more variables and constraints than can classical computers, enabling the development of more accurate and comprehensive forecasts and operating plans that better protect against supply chain threats. Government can boost these capabilities of quantum computers by creating testbeds and sandbox programs focused on demonstrations, proofs of concept, and pilots of near-term applications for supply chain management.

- **Address sustainability:** Climate change is a top concern of companies and nations, and transportation-based emissions are a leading contributor. Any potential for increases in efficiencies that reduce emissions should be explored and developed. One of the most impactful uses of quantum computers in transportation and logistics is continuous route optimization, which can decrease emissions and fuel usage across transport methods. As companies increasingly look to cut their carbon footprint, they should consider the impact that QC technology adoption can have by helping them better optimize routes and processes for maximum fuel efficiency. As an added bonus for companies, using quantum computing to optimize this way will likely lead to cost savings as well.

- **Optimize government logistics missions:** Government can be an early adopter of QC solutions in optimizing its own fleets and missions. For example, the US Postal Service could use QC technology to better plan fleet maintenance, schedule staff, and design more fuel and time efficient routes. By adopting QC technologies in its earlier stages, government can guarantee revenues to help sustain private QC companies.
- **Create a skilled workforce:** QC technology is evolving quickly, creating demand for skilled workers who are able to contribute to the field. This includes opportunities for the end users of the technology, such as operating plan developers and route designers, to shape its development and key features and functions. However, most supply chain workers today are not well versed in quantum technology. Including QC education in industrial and supply chain engineering degree programs could increase understanding and adoption of this new technology. Training could also be extended to the existing transportation and logistics workforce by collaborating with professional organizations to provide knowledge, skills, and access to the latest QC tools. This training could be especially useful for the workers who focus on route planning, operating plan design, and forecasting, i.e., the tasks that could most benefit from quantum computers.

Conclusions

Our findings show there is a need for, and real interest in, the use of quantum computing to address challenges across the logistics and supply chain environments. The challenges described are real issues, based on daily tasks, for operations personnel — none were theoretical or postulated. The level of complexity and the number of variables that the transportation and logistics industries try to factor into optimization and simulation challenges make this field a prime candidate for applying quantum computing solutions.

We suggest exploratory next steps that can bring together businesses and researchers to discover impactful solutions that could be tested and run on current and future quantum systems. Additionally, we offer recommendations that identify outcomes that government and industry alike can strive toward to bolster the resilience and efficiency of the transportation and logistics industries in support of supply chain security.

Additionally, the ranked use cases suggest where applying quantum computing could be both feasible and impactful. This means even noisy intermediate-scale quantum (NISQ) solutions, while not perfect, can be explored to discover usefulness in the short-term. New investments in quantum computing targeted to the logistics ecosystem could accelerate exploration and expand benefits for business operations and sustainable supply chains.

Appendix A: Methodology

This report explores quantum computing as it relates to logistics and supply chain and is largely informed by a virtual workshop organized by the QED-C Use Cases Technical Advisory Committee (TAC) and held on October 24, 2023. The workshop was attended by 48 representatives from the supply chain and/or quantum computing (QC) industries, government, and academia (the list of participants is in Appendix C). This study focused on use cases that cannot be solved using a classical computer or for which the processing time to solve via classical methods is impractical and where a quantum-hybrid application could provide added benefits. Notably, the study excluded from scope quantum-inspired algorithms run on classical hardware.

Workshop participants were instructed to leave aside other quantum problems (e.g., cybersecurity) for this workshop. Instead, they looked at several QC modalities (annealing, gate model, and quantum-hybrid) and their ability to solve current challenges in the transportation and logistics industry. Participants identified 83 specific use cases, which are listed in full in Appendix B.

The overwhelming majority of the use cases identified were primarily optimization problems, such as routing or scheduling. The subset of use cases attached to a specific mode of transportation or supply chain area were led by railroad problems, manufacturing use cases, and trucking challenges. A few of the use cases focused on machine learning (ML) approaches and/or simulation, though experts noted that many optimization use cases could also involve ML and simulation.

Workshop Goals: Surface high-impact, feasible ideas

- Capture many ideas on how to use quantum technology to solve current supply chain and logistics problems in order to create a diverse set of concepts to investigate.
- Clearly define and refine popular ideas and match to quantum approaches for future exploration including timeline to realization.
- Isolate the ideas with the highest impact and feasibility; then identify a path to bring these ideas to fruition.

Structure: Encourage collaboration, fresh thinking

The workshop was designed to maximize collaboration opportunities among attendees with knowledge of supply chain and logistics and attendees familiar with quantum technologies. It was important that the groups be self-sufficient, finding answers quickly to their own questions so that they could complete all the exercises.

Facilitators and attendees from the quantum sector were invited to a briefing on the workshop structure and tools several days before the event to ensure smooth operations. All participants were sent materials (articles and video) describing how quantum might help with supply chain problems. The workshop began with five short presentations from groups working on quantum solutions for logistics and supply chain. The presentations covered trucking, rail, air, and sea transportation and all described working models or early production solutions.

Alex Luna, founder and CEO of AlphaRail, gave a lightning talk on the usefulness of optimization in railways. Railroad logistics have several overlapping layers of combinatorial problems that must be addressed to achieve optimal scheduling, including train routes, train scheduling, and crew scheduling. Luna's demonstration of the AlphaRail Platform showing a small, Class II railroad illustrated how a quantum computer would be used to solve the daily scheduling and execution of a rail network. While small railroads can be optimized today using cutting-edge classical algorithms, quantum solutions offer the possibility of solving and scheduling national or even international rail systems.

Ed Heinbockel, cofounder, president, and CEO of SavantX, discussed recent successes his firm has had in using quantum computers to solve complex optimization problems of intermodal transportation by land, sea, and air. SavantX's approach has been to combine classical and QC methods by beginning with a classical digital twin on which to run millions of simulations. Analysis of the simulated data has facilitated identification of specific problems that are good candidates for quantum optimization. By running these optimizations on a quantum computer, SavantX has been able to provide real-time solutions that yield improvements to crane operation and cargo flight scheduling efficiency.

Carl Dukatz, managing director of Accenture's Next Gen Compute, provided several examples of how quantum optimization can improve logistics planning. For problems involving multiple vehicles, pick-ups, and drop-offs, Accenture's system can both generate vehicle routes and calculate key metrics such as total time to operate the generated plan and its mileage cost. Additionally, there is an opportunity to use quantum optimization for fleet management of electric vehicles and their required charging schedules.

Annarita Giani of GE Research gave a talk on applying quantum annealing technology to asset sustainment with a focus on airplane engines, an area with relevant parallels to other parts of the transportation and logistics industry.

Sal Certo of Deloitte presented a quantum application that touched on optimization of a vehicle routing problem.

These talks provided background information and case studies to set the stage for robust discussions of the potential use cases — and their shortcomings — for quantum computing in the transportation and logistics industry.

Following the lightning talks, workshop participants split off into groups that were intentionally structured to ensure a balance between attendees from the supply chain and logistics industry, those from the quantum technology industry, and academics.

Value chain matrix: A bidirectional flow

The primary tool to guide conversations during the ideation session was a supply chain-focused value chain matrix:

	A. Supplier	B. Manufacturer	C. Distributor	D. Transport Provider	E. Retailer
Quantum Method	• Provide Goods or services that are essential for the production, operation, or fulfillment of other businesses • Ensuring the smooth flow of materials, components, and service to meet the needs of manufacturers, distributors, retails and ultimately end customers.	• Transform raw materials, components or intermediate goods into finished products. • Adding value to raw materials and creating product that meet the demands of the market	• Serve as an intermediary between manufacturers or suppliers and retailers or end customers. • Efficiently move products from the source to the final destination.	• Offers services related to the movement of people, goods, or materials from one location to another. These services can encompass various modes of transportation (ground, air, rail, water)	• Serve as the final link in the supply chain, facilitating the sale of products or goods to end consumers • Making products available to the public, meeting consumer demands, and providing a range of services to enhance the shopping experience.
Optimization					
Machine Learning					
Simulation					

Operations: Other activities which enable the value chain to run efficiently									

The matrix column headers note the principal actors in the supply chain: suppliers, manufacturers, distributors, transportation providers, and retailers. This organizational structure was not intended to restrict thought but rather provided participants with starting points to think of specific use cases that could benefit from quantum computing. The components of the value chain were not meant to be considered independent of each other. Attendees were also encouraged to think about how the categories interact and which processes and operations touch multiple parts of the value chain. The left side of the matrix shows the categories of quantum approaches considered by the participants: optimization, machine learning, and simulation.

Workshop process: Idea generator

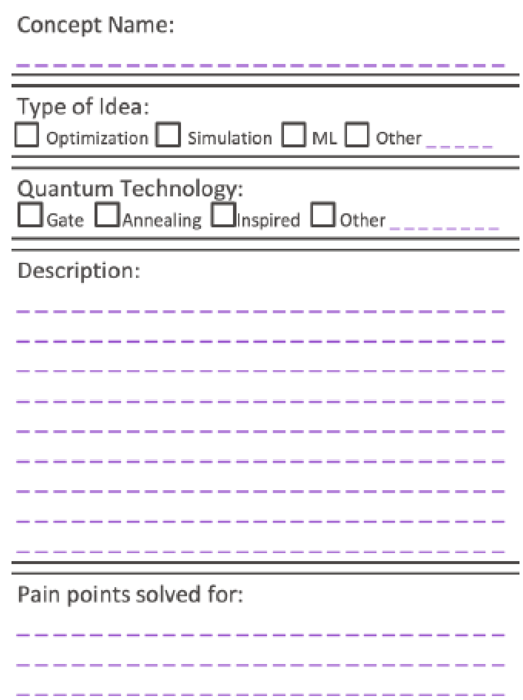
The workshop was designed to create as many ideas as possible up front, methodically select ideas that the participants thought would be the most important, and develop them into meaningful and actionable concepts. This process yielded three content pieces: ideas, concept cards based on the ideas, and concept posters built from the concept cards.

Ideas: Brainstorm, analysis, selection

Workshop participants were placed in small groups for a 45-minute ideation session. First, each participant generated ideas in a 15-minute individual brainstorm and placed them onto the value chain matrix under the actor category and quantum method they felt was most applicable. The groups then took 25 minutes to discuss their ideas, and finally 5 minutes to vote for the ideas they thought had the most potential. The groups came up with a total of 83 ideas. The ideas were well distributed across the grid areas, but, the majority were optimization challenges.

Concept cards: Winnowing ideas

Each group selected the ideas that had the most votes and created a “concept card” for each idea. As depicted in the figure to the right, these concept cards included the name of the concept, the type of idea, the quantum technology best suited to execute the idea, a description of the concept, and the pain points for the concept addressed. The groups had 15 minutes to fill out the concept cards. Each group ended up with between one and five cards that they then presented to the whole workshop audience. To make the next step easier, similar ideas were consolidated into 15 summarized concepts.


Concept Name:

Type of Idea:
☐ Optimization ☐ Simulation ☐ ML ☐ Other

Quantum Technology:
☐ Gate ☐ Annealing ☐ Inspired ☐ Other

Description:

Pain points solved for:

A flexible rating system to promote expansive thinking

Attendees used an online survey tool to rank each of the 15 consolidated concept cards based on the impact and feasibility the attendee judged them to have. A weighted average of the concepts’ ranking on each dimension was then used to graph the group’s overall rating of the impact and feasibility of all 15 concepts.

Concept posters: How to execute

After further discussing the feasibility and impact of the ideas summarized on the concept cards, the workshop participants agreed to focus on the six concepts that ranked the highest on impact and feasibility to further develop as concept posters, as shown below. However, when attendees self-selected the concept they wished to work on developing, only four of the six were chosen.

Attendees were instructed to use the idea’s original concept card as a basis for the concept poster, each of which included a description of the concept (copied from the summarized concept cards), how it works, the problem space it occupies, key features, types of personas the concept will affect (e.g., truckers, rail operators, warehouses), and metrics and outcomes to measure success. The concept posters also identified potential team members and suggested a timeline to complete the project.

Concept Name:

Persona:

Description:

How it works:

Features:

Problem Space:

Success Metrics/Outcomes:

Team Members:

PI	Mathematician	Physics Theorist	Scientific Computing	Modeling & Sim	Interface Developer	Data Scientist	Backend Developer	ML Specialist
Project Sponsor	Project Lead	Business Specialist	Q Algos Designer	Quantum Developer	IT Architect	Transport Planner	Transport Procurement	

Timeline:

	Start								Finish
Research									
Solve									
Develop									

Appendix B: Quantum Computing Use Cases for Transportation and Logistics

The table below contains the full list of potential uses cases for quantum computing in the transportation and logistics sectors that were identified by workshop participants.

Idea	Industry	Area of Operations	Approach
Analyze cost/carbon tradeoff between rail, truck, and seaway/maritime shipping on a regional/national scale at high resolution. Determine the value of carbon credits required to incentivize the "greenest" options.	All	Planning	Simulation
Analyzing the energy demand and simulate different scenarios to meet those demand	All	Routing	Simulation
Appropriate mix of input providers to ensure needs met in the event of high priority contract	All	Data & IT	Optimization
Are there feature selection that could benefit from quantum computing?	Retail	Planning	Machine Learning
Asset maintenance	All	Planning	Simulation
Asset usage forecast	All	Planning	Simulation
Challenge is demand planning: Beyond the 4 walls of a given retailer/supplier relationship, how could we extend those datasets to get forecasting capabilities in a network? (3PL, Supplier, Retailer)	All	Planning	Simulation
Collecting past data and impact of external factor to optimize the ML. Many providers do not have good data to start with.	All	Data & IT	Machine Learning
Consumer need prediction	All	Planning	Simulation
Continuous route optimization	All	Planning	Optimization
Create P&D cross-company network and demonstrate operational cost savings of participation based on all combinations of potential players - "coopetition opportunity"	Truck	Planning	Optimization
Delivery & pickup with arrival time windows	Truck	Planning	Optimization
Demand forecasting for shipments so carriers can better allocate and locate assets in the correct markets (e.g., intermodal rail containers, chassis, etc.). Different optimization algorithms that are competing against one another to obtain a scored output, which lead to large tables of information. How do you run large, complex, problems quickly? Improve margins, time, and allocations.	All	Planning	Simulation
Develop consistent route areas for vehicles	Truck	Planning	Optimization

Idea	Industry	Area of Operations	Approach
Digital twin in a warehouse to determine most optimal planning for truck arrival, resources, picking windows, etc.	Manufacturing	Planning	Simulation
Digital twin: Automate to seek KPI optimization	All	Routing, Sustainability, Planning	Simulation
Digital twins of cities, AV systems, etc.	Passenger	Planning	Simulation
Digital twins with external data source (too many constraints for classical)	All	Planning	Simulation
Dynamic optimization of ports, airports, and multi-modal transportation for supply chain management and optimization (Case study-I: Port of LA in 2020-2021 by Amazon & AWS for delayed supplies) (Case study-II: Port Authority of NY & NJ + digital twins) and supporting infrastructure; digital print of entire system utilizations	All	Planning	Optimization
Dynamically adjust supply chain parameters (e.g., safety stocks)	Manufacturing	Planning	Optimization
Employee scheduling, staff scheduling for delivering goods, efficient scheduling accounting for staff availability, PTO, skills, requirements for satisfaction of order requirement and staff satisfaction	All	Planning	Optimization
Employees identify biggest obstacles and then look for quantum solutions	All	All	All
Evaluate different scenarios in which one or more suppliers cannot provide the ordered materials	All	Planning	Simulation
Evaluate the best strategy for manufacturing plant operation according to different objective functions: time, reliability, and the available raw material	Manufacturing	Planning	Optimization
Finished goods depending on Bill of Material complexity. It would be helpful to have visibility to the suppliers goods in-transit to create customized solutions for a customer (ex. Nike Build your own shoe) Inputs: Customer design patterns from Nike website Outputs: Raw material demand	Manufacturing	Planning	Machine Learning or Simulation
Fleet repairs per the GE Research use case	All	Fleet Maintenance	Simulation

Idea	Industry	Area of Operations	Approach
Flytrex is a drone delivery service in my city, it takes 1hr or more to get food delivered. Optimization could be order food, have Uber pick up and drop off to launch pad, and then drone delivers, all scheduling issues and discounted information.	Retail	Routing	Optimization
Further on in the network, how are you integrating objectives dynamically, with the speed needed for the receiver?	All	Planning	Optimization
How do I get consumer demand signals from the suppliers, retailers in order to plan properly to meet their needs? The supplier does not usually have retailer info.	Manufacturing	Planning	Optimization
How to design quantum algorithm for constrained optimization problem	All	All	Optimization
How to design the quantum algorithm to handle the continuous variables in the optimization problem	All	Knapsack & Routing	Optimization
Inventory management, e-commerce delivery, staff scheduling	All	Planning	Optimization
Inventory management: How do you ship out your inventory, how are you optimizing your inventory? Customers might have different requirements: What is the capacity of the inventory, how often do you need to replenish inventory? Mathematical models, the classical technologies are not able to handle the volume/scale of the challenges/problems.	Manufacturing	Planning	Optimization
Job shop scheduling: Manufacturing setting where there are many jobs and machines in which you want to optimize scheduling across functions. Semiconductor manufacturing where there are many machines and many components that need to be produced. Best way to schedule production?	Manufacturing	Routing	Optimization
Large problem solves (>500 deliveries)	Truck	Planning	Optimization
Learn from "veteran drivers" for less stressful route	Truck	Data & IT	Machine Learning
Learn from plan / commit deviations upstream and downstream	All	Planning	Machine Learning
Limiting hot order impact with dist./TP/supp	Manufacturing	Planning	Optimization
Live network risk assessment speed of the compute available—network risk assessment. The amount of data available to solve problems, currently ML.	All	Data & IT	Machine Learning

Idea	Industry	Area of Operations	Approach
Manufacturer, if unionized, ensuring "problems and solutions" are not divorced from efficient solutions and buy-in bargaining for economic or cultural reasons	Manufacturing	Planning	All
Minimize overall risk in automated driving scenarios with numerous simultaneous actors	Passenger	Routing	Simulation
Network planning: Fault tolerance expert rules and experience, past performance on product line. Granularity of detail to be able to determine how prepared you are for challenges.	All	Planning	Machine Learning
New materials may need gate-model system. Are there simulations that can be done with today's technology? PFAS remediation and cleanup efforts?	All	Sustainability	Simulation
On headings, consider approach of company is vertically integrated	Manufacturing	Planning	Optimization
On retailer ensuring correct product and GTM	Retail	Planning	Simulation
"On the way" optimization	All	Planning	Optimization
Operating Plan Design: crew scheduling, train scheduling, train routing, train consist construction, disruption management, car distribution, train makeup, fleet management, railcar pipeline management	Rail	Planning	Optimization
Optimization for test & development of new materials, e.g., concrete, polymers, batteries, fuels, etc.	All	Sustainability	Optimization
Optimization of regional distribution centers. Similar to SavantX port use case, can there be optimization at distribution centers?	Truck	Routing	Optimization
Optimize inventory and supply chain management; value chain optimization; risk management	All	Planning	Optimization
Optimize logistics operations: fleet assignment, routing, crew assignment, network planning, on-time delivery scheduling	All	Planning	Optimization
Optimize the demand generation and demand fulfillment activities simultaneously and continuously, AKA the "Pumpkin Latte Problem"	All	Forecasting or Routing	Optimization
Optimize the yard/switching operations	Rail	Knapsack & Routing	Optimization
Optimizing to lower CO_2 emissions or to address workforce shortages, or tackle other government regulatory burdens?	All	Sustainability	Optimization

Idea	Industry	Area of Operations	Approach
Pallet and truck packing: How do you optimally pack into a pallet or other means for shipping, ensure that the item is not damaged, how do you manage weight balancing, etc.	All	Knapsack Problem	Optimization
Predict cost of moving products from the source to the final destination. This is based on the mean of transportation and the current situations (geographical socio-political).	All	Planning	Simulation
Proactively adjust manufacturing schedules based on near-term transportation delays and/or short term supply issues for input components	Manufacturing	Planning	Optimization
Product design; production planning; workforce management; optimal resource allocation	Manufacturing	Planning	Optimization
Production process optimization model	Manufacturing	Knapsack & Routing	Optimization
Quantum cryptography, QKD, random number generation, etc. As our cars communicate out more & more, what can we do to secure communications?	All	Data & IT	Other
Real / synthetic data science inform feature selection	All	Data & IT	Optimization
Real time forecasting for TNC demand, for congestion, etc.	Passenger	Planning	Machine Learning
Real-time analytics from onboard sensors	Passenger	Fleet Maintenance & Routing	Optimization
Real-time customer order exception mitigation: Small team operating at a retailer scale, expert roles and over communications. Retailer w/ k's of good that take times. How do you optimally approach many issues that happen at the same time?	All	Planning	Optimization
Real-time optimization of in-warehouse resources (like forklifts and forklift drivers) against near-term projected truck arrivals	Manufacturing	Planning	Optimization
Reduce miles, driving time, consistent route areas	Truck	Planning	Optimization
Resource allocation in real-time: Position supply where the demand is, e.g., TNC providers can optimize vehicle positioning based on demand. All shared systems face the repositioning problem due to asymmetry in demand patterns.	Truck	Routing	Optimization
Sensors on equipment to determine point of failure and proactively schedule repairs	All	Fleet Maintenance	Machine Learning

Idea	Industry	Area of Operations	Approach
Simulate the movement of volume from hub to hub and analyze the downstream impact	Truck	Routing	Simulation
Simulate the network for time with 100+ trains in a network	Rail	Knapsack & Routing	Simulation
Supply chain management	All	All	All
Understanding consumer behavior in real time and take decision to reduce the wastage	All	Sustainability	Machine Learning
Understanding the constraints that could be involved with manufacturing. Could be a government regulation, such as lowering emissions; could be scheduling of employees; etc.	Manufacturing	Routing	Optimization
Urban level digital twins for real time congestion management	Passenger	Routing	Simulation
Urban system control, e.g., traffic lights	Passenger	Planning	Optimization
Use historical data to evaluate lead time of delivering of goods by the suppliers	Manufacturing	Planning	Machine Learning
Use of quantum computing for real-time diagnostics and prognosis. It is predominantly a machine learning problem.	All	Fleet Maintenance & Routing	Machine Learning
Vehicle/passenger routing	Passenger	Planning	Optimization
Very large optimization problems for scheduling routing LTL shipments and drivers. There are many applications with large optimization problems—scheduling, forecasting. High capacity computing to get solutions.	Truck	Routing	Optimization
VRP, CVRP; be able to solve efficiently; fuel, money, environmental impact	All	Planning	Optimization
Waste reduction	All	Sustainability	Optimization
With online retail and D2C, the role of different stakeholders is changing. How can supply chain be optimized further, requiring less movement of goods?	Retail	Planning	Optimization
Would like to simulate a single train and all its components	Rail	Knapsack & Routing	Simulation

Appendix C: Workshop Participants

Thank you to the following individuals who participated in the workshop for sharing their time and perspectives:

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