In collaboration with Accenture

Quantum Technologies: Key Opportunities for Advanced Manufacturing and Supply Chains

WHITE PAPER

OCTOBER 2025

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Advanced manufacturing and supply chain leaders are at a pivotal moment. Emerging quantum technologies present unique opportunities to transform operations and build resilience in an increasingly complex global landscape. The challenge lies not only in harnessing these technologies but also in identifying the strategies and enablers that will unlock their full potential. By exploring actionable pathways, organizations can drive innovation, enhance precision and secure a competitive advantage through quantum advancements.

The World Economic Forum and Accenture have been collaborating through the Quantum Application Hub and Industry Track to accelerate the adoption of quantum technologies across industries and inform policy development. This report comprises the insights of manufacturing experts, technology leaders and policy stakeholders, gathered through roundtables, interviews and cross-sector dialogues. It highlights early case studies, readiness pathways and key enablers, from policy and standards to talent development, that will shape the future of quantum in industrial ecosystems.

We extend our sincere gratitude to all contributors to this report. We hope it serves as a valuable resource for decision-makers seeking to navigate the quantum frontier and unlock new opportunities for advanced manufacturing and supply chain systems.

Executive summary

Evolving quantum technologies are reshaping manufacturing and supply chains, creating opportunities that require strategic foresight.

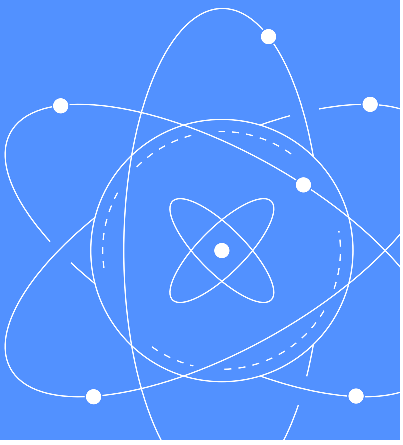
Manufacturers and supply chain leaders are facing unprecedented disruption fuelled by rapid technological advancements, global volatility and evolving customer demands. Quantum technologies are emerging as a transformative opportunity, unlocking groundbreaking capabilities in simulation, optimization, precision sensing and secure communications. These innovations are reshaping product design, factory operations and supply chain adaptability.

This white paper provides a pragmatic overview of quantum's relevance to industrial operations, showcasing early case studies with measurable benefits such as efficiency gains, cost savings and improved resilience. It outlines readiness pathways to help leaders transition from exploration to execution and stay ahead in a competitive landscape. For deeper technical insights, readers are directed to complementary resources from the World Economic Forum on quantum fundamentals,[1] the quantum economy[2] and quantum security.[3]

FIGURE 1 **Key takeaways for leaders**

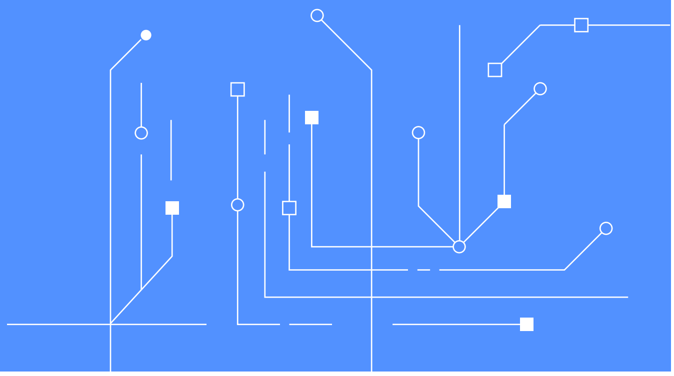
Quantum is real and relevant

Early implementations are delivering measurable impact.



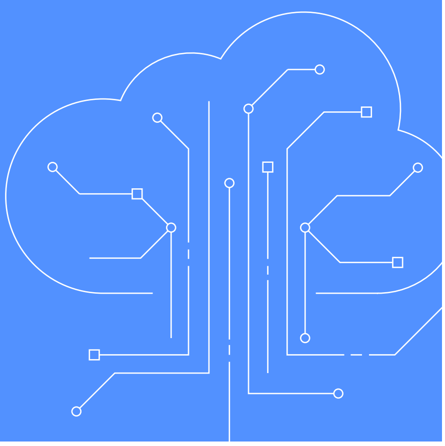
Start building readiness now

Talent, partnerships and pilot programmes are essential to stay competitive.



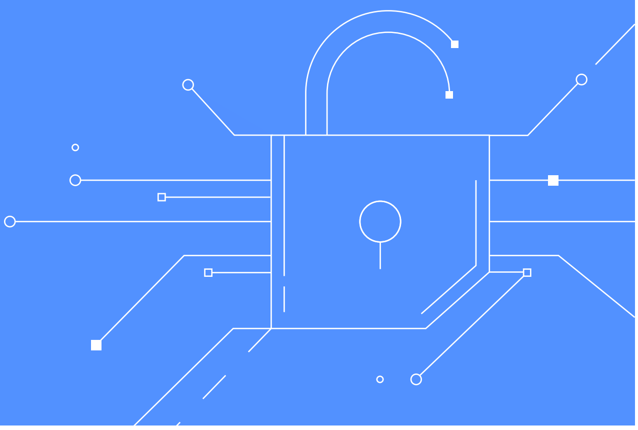
Hybrid platforms offer low-risk entry

Cloud-based quantum tools enable experimentation without major investment.



Security is urgent

Quantum-safe cryptography is critical to protect industrial systems from future threats.



1 What is the quantum imperative?

Quantum technologies are unlocking new industrial capabilities where classical systems fall short.

In 2024, global supply chain disruptions rose by 38% year-over-year, driven by extreme weather, geopolitical tensions and labour strikes.

The manufacturing and supply chain sector is experiencing its most turbulent period in decades, with disruption now being the norm rather than the exception. In 2024, global supply chain disruptions rose by 38% year-over-year, driven by extreme weather, geopolitical tensions and labour strikes.[4] The Panama Canal drought cut transit capacity by 33%, delaying shipments by up to two weeks and adding an estimated $1.1 billion in annual transport costs.[5] In Europe, a summer heatwave caused over $10 billion in losses, forcing factory shutdowns and triggering shortages across food and consumer goods.[6] Meanwhile, cybersecurity threats against industrial organizations surged 87%, with manufacturing as the top target, accounting for 69% of ransomware attacks and causing significant disruptions to operations.[7]

Amidst the global phenomena, the pace of technological change is accelerating, bridging the gaps in real-time decision-making, cross-functional orchestration and industrial cybersecurity. Leaders are now called to operate not only as production experts but also as stewards of complex digital ecosystems – balancing efficiency with resilience, performance with transparency and growth with responsibility. These challenges, rooted in immense complexity and vulnerability, are precisely where quantum technologies offer a new paradigm of solutions. The potential of quantum technologies (quantum computing, quantum sensing, and quantum security and communications) is becoming increasingly relevant, not as a distant or academic pursuit, but as a powerful new set of tools that could unlock competitive advantage in precisely those domains where conventional technologies are reaching their limits. Figure 2 illustrates the key areas where quantum is advancing, highlighting their potential strategic impact on industrial operations, along with the critical enablers that are essential for driving successful adoption and integration.

FIGURE 2 | **Quantum technologies driving the next industrial leap**

Quantum computing

- Offers breakthrough capabilities in solving complex optimization and simulation problems not solvable by conventional methods
- Use cases include production planning, supply chain network design and materials discovery, among many others

Quantum sensing

- Enables unprecedented precision in measuring physical properties, especially in environments where conventional sensors fall short
- Use cases include quality control, predictive maintenance and process monitoring

Quantum security and quantum communications

- Provides future-proof protection by addressing the impending threat posed by cryptographically relevant quantum computers (CRQCs)
- New methods such as post-quantum cryptography (PQC), quantum key distribution (QKD) and quantum random number generators (QRNG) can be used to protect sensitive data

Efficiency | **Resilience** | **Competitiveness**

Enablers

Quantum readiness and platforms
Build quantum-ready platforms and infrastructure to support adoption and scalability

Standards and interoperability
Develop standards and interoperability frameworks to ensure seamless integration across systems

Business alignment
Focus on aligning quantum initiatives with clear business goals and outcomes

Talent development
Develop policies and programmes to build a quantum-trained workforce

Advancements in complementary tech
Cryogenics, error correction and control systems are also expected to advance to support quantum evolution

Collectively, quantum technologies represent a step change in capability, positioning companies for the next wave of industrial growth and competitiveness.[8] Leading industrial organizations are already taking steps to prepare for quantum readiness and must act decisively to stay ahead in this transformative technological shift. For instance:

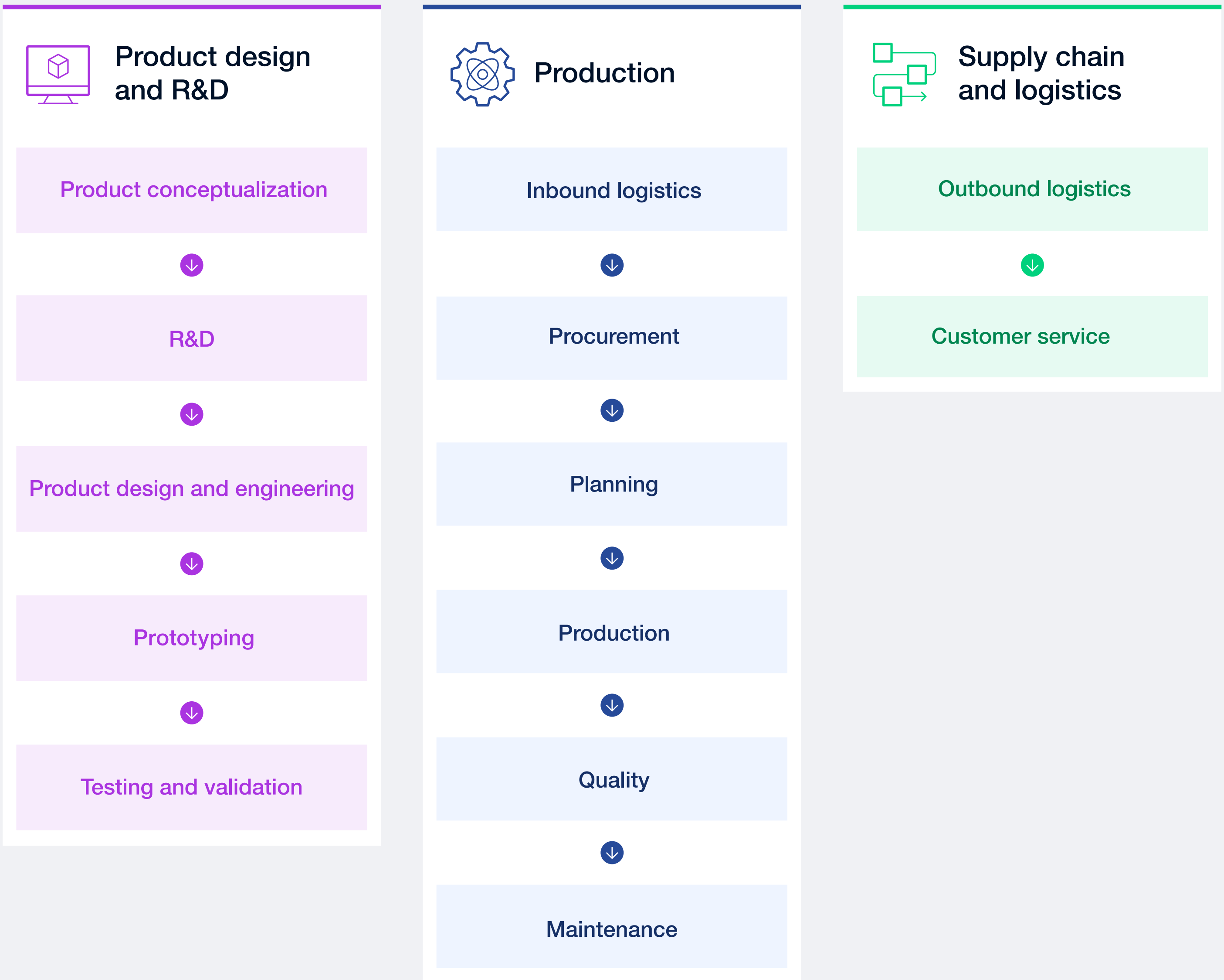
- **Ford Otosan**, an automotive company, demonstrated a 50% reduction in vehicle manufacturing scheduling time at one of its sites by leveraging hybrid classical-quantum annealing.[9]
- **The Taiwan Semiconductor Manufacturing Company (TSMC)** claimed that quantum sensors based on synthetic diamonds could offer greater precision than conventional sensors, drastically transforming the semiconductor industry by improving failure analysis for the next generation of integrated circuits.[10]
- **The Port of Rotterdam**, one of the world's largest and most critical logistics hubs, has piloted a quantum-secured communications network based on quantum key distribution (QKD), enabling secure, real-time communication between users without disrupting workflows.[11]

2 Where do quantum technologies create value?

Quantum unlocks new efficiencies, product capabilities and operational resilience across the entire value chain.

While the field is still maturing, recent progress in hardware, algorithms and use case development has shifted the conversation from "if" to "when and where". The following chapters explore key areas of opportunities across manufacturing and supply chains (see Figure 3) – starting with innovation in R&D and product design, moving into production and factory operations, and then addressing broader applications across logistics, transport and entire supply chains.

FIGURE 3 **Simplified manufacturing and supply chain value chain and its core functions where quantum can deliver transformative impact**



Note: This simplified manufacturing and supply chain value chain is non-exhaustive.

2.1 Innovations in product design and R&D

How quantum advances material discovery, product design and secure R&D from molecular structures to computational models

Product design and R&D form the foundation of competitiveness in the manufacturing sector. The ability to discover new materials, engineer high-performance components, simulate complex behaviour and collaborate securely across ecosystems defines frontrunners in a fast-evolving industrial landscape. This is where quantum technologies reveal their transformative potential. Figure 4 illustrates some of the opportunities in this area, mapping specific challenges across the different functions in the design phase and highlighting how quantum technologies are poised to address them.

FIGURE 4 **How quantum technologies are transforming product design and R&D applications (five key examples)**

Value chain functions	Challenge	Quantum innovation
Material discovery (R&D, prototyping)	Lengthy and expensive R&D cycles due to slow material validation processes	Quantum computing can natively simulate molecular interactions at an atomic scale, enabling faster development of advanced materials.
Product design and engineering	Fragmented design workflows delay launches and increase costs	Quantum-enhanced optimization can streamline design iterations and improve cross-domain engineering decisions, supporting faster, more efficient product development.
Process simulations (prototyping; testing and validation)	Low-fidelity simulations limit performance and quality assurance	Quantum computing offers higher-precision simulations of complex physical processes, with long-term potential to improve accuracy in areas like fluid dynamics and thermal behaviour.
Component validation and performance testing (testing and validation)	Conventional sensors miss subtle defects and stress factors	Quantum sensors provide ultra-sensitive detection of magnetic, thermal and pressure variations, enabling earlier fault detection and better quality control.
Secure collaboration (product conceptualization, R&D)	Sensitive R&D data is vulnerable to cyberthreats, including future quantum attacks	PQC, QRNG and QKD ensure secure data sharing and protect intellectual property (IP) across collaborative networks.

Quantum computing · Quantum sensing · Quantum security and communications

> While today's quantum computing hardware is still evolving and not yet ready for production-scale deployment, quantum computing use cases scale favourably and are already unlocking new possibilities.

Unlocking simulation and optimization at the atomic scale with quantum computing

As industries evolve and product requirements grow more complex, traditional design tools are becoming increasingly inadequate and limited.[12] One of the most compelling applications of quantum computing lies in molecular modelling, relevant to developing advanced materials like metal-organic frameworks (MOFs) for carbon dioxide (CO_2) capture.

Leading firms in automotive, energy and materials science are already piloting quantum algorithms to guide experimental design and reduce R&D cycles. While today's quantum computing hardware is still evolving and not yet ready for broad, production-scale deployment, quantum computing use cases scale favourably and are already unlocking new possibilities. Meanwhile, hybrid classical-quantum approaches are starting to bring measurable value. In this model, certain parts of a problem that are well-suited to quantum algorithms are processed on a quantum computer, while the remaining parts are handled by a classical computer. This approach is particularly useful today, as current quantum computers are limited in size and capability, making them most effective when used alongside powerful classical systems.

Bringing new precision to engineering and testing through quantum sensing

In the prototyping and testing phase of product development, quantum sensors offer an unprecedented ability to measure physical properties with extreme precision and stability over time. This need for precision and adaptability is particularly acute in sectors such as aerospace, automotive and electronics, which are leading adopters of advanced design and simulation tools.

Enabling secure and collaborative R&D ecosystems with quantum security and communications

Conventional encryption faces growing vulnerabilities from poor configurations, outdated protocols and weak key management. Quantum computing amplifies these risks, enabling retroactive decryption, compromising secure communications and threatening data privacy, operational continuity and global economic stability.

As R&D ecosystems become more global and interconnected, protecting intellectual property (IP) and ensuring trusted collaboration is paramount. To retain security in the quantum era, there is room for several methods. Post-quantum cryptography (PQC) should be used globally to enhance the current cybersecurity infrastructure. For example, new post-quantum algorithms should be used in transport layer security (TLS) and other internet applications. Quantum random number generators (QRNGs) can be used to generate improved random keys for encryption. QKD can add an extra layer of security for applications requiring long-term security.

These technologies are essential to secure data exchanges across research networks, test facilities or between industrial partners, especially in the face of future quantum-enabled cyberthreats. This is relevant in all manufacturing sectors, where embedding quantum-secure infrastructure now can de-risk future digital collaboration models and support more open, cross-disciplinary innovation.

Early quantum technology case studies (non-exhaustive) in product design and R&D

Quantum computing

CASE STUDY 1

Computational simulation of corrosion for materials durability

Corrosion in aircraft materials poses a major challenge, weakening structural components, shortening lifespan and increasing maintenance costs. The ability to simulate material behaviour at the atomic level with very high accuracy enables researchers to rapidly evaluate potential materials for corrosion resistance, accelerating the discovery process by focusing on the most promising candidates of new alloys and coatings. This not only extends the lifespan of aircraft components but also enhances safety and reduces maintenance costs.

To improve the durability and safety of aerospace materials, Boeing needed to simulate corrosion reactions in them. Classical computing methods were slow and limited in accuracy to identify the specific properties that make certain materials more resistant to corrosion. To overcome these limitations, Boeing used variational quantum algorithms to simulate how water molecules interact with magnesium surfaces, a key reaction that triggers corrosion in lightweight aerospace metals. These models, which were run on commercially available cloud-based quantum computers, allowed for more precise energy calculations and reaction dynamics. Boeing's research team focused on reducing the complexity of the quantum models by up to 85%.[13]

The study highlights how quantum computing can accelerate material discovery for aerospace platforms. Additionally, the findings could benefit steel-intensive industries like maritime transport, automotive and industrial machinery.

> **We are investing time now to learn how quantum computers can help us model these complex reactions in the future. We expect this investment will enable us to find better material systems faster and reduce the cost to develop high-performing aerospace materials.**
>
> John Lowell, Principal Senior Tech Fellow, Boeing Research and Technology

CASE STUDY 2

Accelerated R&D cycles of drug discovery for pharmaceutical manufacturing

Messenger RNA (mRNA) therapeutics are a new way to help the body make its own medicines. Instead of giving a drug directly, scientists design mRNA molecules that tell our cells how to make helpful proteins. mRNA is made up of building blocks called nucleotides. These are small molecules that link together in long chains, forming the mRNA sequence. Designing effective mRNA drugs is challenging as it involves simulation of how long chains of nucleotides fold into functional shapes. The folding patterns affect drug effectiveness and safety.

Imagine trying to fold a very long piece of paper into a tiny box – there are countless ways to fold it and finding the best way is extremely tricky. Regular computers struggle with this because there are many possible shapes to check, especially for longer mRNA sequences, slowing down R&D cycles.

Quantum computers can look at many possible folding patterns at the same time. Recent advances by Moderna have shown that quantum computers can predict mRNA shapes up to 60 nucleotides. For mRNA sequences with 200 nucleotides, traditional methods can take hours or even days for comprehensive analysis, and to save time they often simplify the process by skipping over key details. While this approach is faster, it risks missing critical insights that could impact results. Quantum computing, on the other hand, can handle complexity without cutting corners, delivering deeper insights into folding patterns in a fraction of the time.

Better understanding mRNA folding enables more effective drugs with fewer side effects and faster development during health emergencies. Reduced time-to-market means lower costs for developing new treatments. This technology helps bring new, life-saving medicines to people faster, supporting global health and well-being.[14]

Early quantum technology case studies (non-exhaustive) in product design and R&D (continued)

Quantum computing (continued)

CASE STUDY 3

Advancing industrial R&D with quantum computing

Aramco, a global leader in energy and chemicals, faces complex industrial challenges such as materials discovery for carbon capture, large-scale process optimization and subsurface modelling (which simulates underground geological formations to optimize resource extraction and environmental management). These domains push the limits of classical computing and supercomputing, creating bottlenecks in efficiency and innovation. To address these challenges, Aramco partnered with Pasqal to deploy a 200-qubit quantum computer in Saudi Arabia by the end of 2025. With this on-premises infrastructure, Aramco aims to accelerates joint R&D efforts in quantum algorithm development for logistics, predictive maintenance and energy distribution that can drive greater efficiency, resilience and sustainability across interconnected value chains.

The partnership exemplifies cross-border ecosystem collaboration, bringing together a global quantum technology innovator and a regional industrial champion. The project is expected to catalyse knowledge transfer, joint R&D and the creation of a local quantum innovation ecosystem.

Recognizing the global shortage of quantum expertise, the agreement includes commitments to train local engineers and scientists in quantum programming, hardware maintenance and algorithm development. As quantum solutions mature, the lessons learned from Aramco's deployment will inform the best practices for other industrial players seeking to integrate quantum technologies into their operations.[15]

Quantum security and communications

CASE STUDY 4

Secure transfer of sensitive data between remote industrial facilities

The National Composites Centre (NCC), a world-leading composite R&D facility, and the Centre for Modelling & Simulation (CFMS) have been connected through the UK's first industrial quantum-secure QKD network. Previously, sensitive data was physically transported via portable storage devices between the sites, which was time-consuming and posed security risks, especially in the context of increasingly distributed supply chains and digital transformation.

The solution allows highspeed encrypted data transfer and supports a 10 gigabytes per second (GBps) quantum-secure tunnel over a 7km optical fibre link. Quantum keys are generated at high throughput, which enables the continuous encryption of data. To eliminate the need for costly dedicated infrastructure to transmit quantum keys, NCC and CFMS implemented multiplexing, which enabled both data and quantum keys to be transmitted on the same standard fibre.

This deployment showcases the transformative potential of QKD in enabling distributed offsite control of factories and unlocking the internet of things (IoT). This initiative also positions the UK as a leader in quantum-ready manufacturing, paving the way for connected smart factories and the Fourth Industrial Revolution, and underscores the commercial importance of quantum-secure networks in safeguarding data and driving innovation in advanced manufacturing.[16]

Note: See the appendices (A2) for other notable case studies.

2.2 Enhancing precision and productivity in factory production

Harnessing quantum innovations to overcome complexity, optimize operations and secure smart factories

As manufacturing operations grow increasingly digital, connected and complex, the modern factory is expected to deliver more than just throughput. Leaders are tasked with creating agile, precise and sustainable production systems capable of adapting to shifting demand, supply variability and regulatory requirements in real time. Lighthouses – advanced factories and industrial sites enabled by AI, IoT and Fourth Industrial Revolution technologies – are already delivering on this transformation.[17] Yet even the most advanced digital tools are starting to confront hard computational limits in optimization, monitoring and predictive decision-making. Quantum technologies offer a new class of solutions that could overcome these boundaries and unlock the next frontier in operational excellence.[18]

FIGURE 5 **Exploring quantum technologies to revolutionize production processes (eight key examples)**

Value chain functions	Challenge	Quantum innovation
Process planning and scheduling (planning)	Inefficient resource allocation and delayed response to disruptions	Quantum computing optimizes workflow and production sequencing by solving complex combinatorial problems.
Smart factory operations (production)	Inability to dynamically optimize production, leading to reduced agility and suboptimal AI performance	Quantum-enhanced AI improves predictive analytics and decision-making.
Precision manufacturing (production)	Inconsistent quality and scalability issues	Quantum algorithms can fine-tune manufacturing parameters for accuracy and throughput.
Inventory management (inbound logistics)	Stockouts, overstock and poor supply visibility	Quantum computing can optimize inventory and improve supply chain insights.
Quality assurance and process monitoring (quality, maintenance)	High defect rates and reactive maintenance	Quantum sensors enable real-time, high-precision defect and anomaly detection.
Infrastructure integrity (maintenance)	Undetected structural risks	Quantum gravimeters monitor facility stability via gravitational shifts.
Environmental monitoring (maintenance)	Inaccurate readings in sensitive zones	Quantum sensors deliver high-accuracy environmental data.
Secure production systems (procurement, maintenance)	Cyberattackers targeting industrial networks	PQC, QKD and QRNG secure machine-to-machine and cloud communications.

Quantum computing · Quantum sensing · Quantum security and communications

Quantum-secure technologies are becoming essential for safeguarding production systems, ensuring compliance and encouraging customer trust.

Solving complex process and scheduling problems through quantum computing

Quantum computing has the potential to transform factory operations by enabling advanced optimization and enhanced precision.[19] In the future, quantum algorithms could optimize workflows, production scheduling and real-time decision-making, offering unparalleled computational power for dynamic production environments.

These applications will pave the way for smarter, more efficient and resilient industrial processes, as quantum systems advance towards commercial readiness for production-scale workloads in the coming years.[20]

Unparalleled precision and quality enabled by quantum sensing

In addition to quantum computing, sensing technologies can be used to enable real-time quality checks, predictive maintenance and facility stability monitoring.[21] Embedding quantum sensors into factory operations enables non-invasive, continuous monitoring systems that enhance safety, minimize unplanned downtime and ensure regulatory compliance.

Securing the factory of the future with quantum security and communications

The rise of smart factories and digital operations create a growing surface for cybersecurity vulnerabilities, especially in operational technology (OT) environments where downtime or manipulation can lead to physical damage, compromised product integrity or safety risks. Quantum-secure technologies are becoming essential for safeguarding production systems, ensuring compliance and encouraging customer trust.

Early quantum technology case studies (non-exhaustive) in production

Quantum computing

CASE STUDY 5

Enhancing manufacturing operations efficiency through advanced scheduling optimization

Ford Otosan, a global leader in commercial vehicle production, faced growing complexity in production sequencing of over 1,500 highly customizable vehicle variants of Ford Transit vehicles. Each change in specifications, such as roof height or wheelbase, required reprogramming welding robots across 250 stations, often leading to delays and reduced response to supply chain disruptions. Scheduling production runs for 1,000 vehicles with limited constraints can take up to 10 minutes using conventional computing, and even longer with open-source tools, creating bottlenecks in the manufacturing process.

To address this, Ford Otosan adopted a new scheduling approach that uses hybrid classical-quantum computing using quantum annealers. This solution enabled the company to generate high-quality, feasible production schedules in under five minutes, even managing up to 16,000 constraints for a single production run. When a similar run was executed on traditional setup, it could not be executed within a reasonable timeframe. As a result, Ford Otosan has significantly transformed its scheduling processes, improved its ability to adapt to real-time changes and enhanced overall manufacturing flexibility.

The new scheduling system also allows Ford Otosan to reclaim valuable manufacturing time, enabling the production of approximately one additional vehicle every 10 hours during periods of high demand, boosting overall output. Ford Otosan plans to extend this optimization approach to paint shops and assembly zones, as well as to upstream and downstream processes. This case highlights how advanced scheduling optimization can deliver tangible operational benefits in large-scale, highly variable manufacturing environments, supporting greater agility, efficiency and resilience across the value chain.[22]

Quantum sensing

CASE STUDY 6

Transforming quality assurance in semiconductor manufacturing

As semiconductor architectures grow increasingly complex, traditional inspection methods face limitations in detecting nanoscale defects and process variations. These hidden anomalies can compromise device yield, reliability and time-to-market, especially as manufacturers push the boundaries of miniaturization and integration density.

To address these operational pain points, leading semiconductor manufacturers are adopting advanced quality control solutions in their workflows. One such approach leverages quantum diamond sensors to identify subtle magnetic signatures associated with nanoscale defects and material variations, enabling non-invasive, high-resolution inspection during early production stages. This approach allows manufacturers to identify faults before they propagate, significantly reducing rework, scrap and downstream failures. Embedding quantum sensing into in-line inspection systems enables manufacturers to support the development of next-generation devices with tighter tolerances and more complex architectures, ensuring competitiveness in a rapidly evolving market.

Beyond semiconductors, this technology holds promise across the broader electronics manufacturing sector, supporting the reliable production of components critical to 5G, IoT and high-performance computing. As quantum sensing solutions become more accessible and scalable, they are poised to drive greater efficiency, sustainability and innovation across the electronics supply chain.[23]

Early quantum technology case studies (non-exhaustive) in production (continued)

Quantum sensing (continued)

CASE STUDY 7

Ultra-high accuracy for automated testing in manufacturing of mission-critical systems

To better manage ignition and improve safety, over a decade ago, the ArianeGroup, part of the European Space Agency (ESA), transitioned from traditional electrical control systems to advanced optical networks. Optical systems offered clear advantages such as lower costs, reduced weight, improved safety and strong resistance to electromagnetic interference. However, the complexity of these fibre-optic systems, with dozens of lines and multiple connectors, introduced new challenges for real-time monitoring and quality assurance.

To address these challenges during assembly and launch, ArianeGroup partnered with ID Quantique to develop a cutting-edge solution based on quantum sensors known as superconducting nanowire single-photon detectors (SNSPDs). These sensors are extremely sensitive to light and, when paired with specialized lasers and electronics, they can detect even the smallest anomalies within the networks in real time. An automated software platform manages the entire testing process, from execution to instant reporting. It identifies and localizes faults within the fibre network, generating real-time pass/fail reports with precise diagnostics. This ensures end-to-end validation of the fibre optic network without exposing ignition systems to risk.

The impact of this innovation is profound. Ariane 6's inaugural flight in July 2024 and 2025 validated this approach, marking the first industrial application of SNSPDs in aerospace. The technology's capabilities in enhanced precision and automation in complex networks are directly applicable to sectors such as automotive, electronics, and high-tech manufacturing, where system integrity and speed are critical.[24]

Quantum security and communications

CASE STUDY 8

Efficient cryptographic verification for secure software delivery

As advanced manufacturing systems become increasingly software-driven and connected, securing firmware updates is critical. The rise of quantum computing threatens traditional encryption, exposing production systems to new cyber risks.

NXP Semiconductors and Denso Corporation have taken a pioneering step by integrating PQC into their software delivery pipeline. PQC-upgraded digital signatures were implemented in the vehicle networking systems to verify authenticity of over-the-air (OTA) firmware updates. The solution was deployed on NXP's Hardware Security Engine (HSE), which acts as a tamper-proof root of trust. With the enhancement, signature verification required less than 3 kilobytes (KB) of memory. This is a 90% improvement over previous implementations and completes in just 11 milliseconds, which is extremely small. It ensures security enhancements do not compromise user experience or system throughput, a crucial requirement for embedded systems not only in automotives, and is also relevant for robotics, energy systems and medical devices.

This kind of analysis is crucial for industries transitioning to quantum-safe cryptography, as it helps determine how to deploy these new algorithms for secure software delivery without disrupting existing workflows or compromising security. It also aligns with emerging global compliance standards, helping manufacturers future-proof their operations against quantum threats. By mitigating risks, the solution reinforces trust across digital ecosystems and delivers strategic assurance to executive stakeholders.[25]

2.3 Achieving agility and security in supply chains

Quantum technologies' role in real-time optimization, resilient routing and secure distribution for advanced manufacturing supply chains

While digitalization has improved visibility and responsiveness, traditional computing systems are beginning to reach their limits in handling the scale, variability and complexity of today's dynamic, global and deeply interdependent supply chain environments. By design, quantum technologies are uniquely suited to address this complexity, offering new capabilities for optimization and prediction.

FIGURE 6 **Transforming supply chains in outbound logistics value chain segment with quantum technologies (seven key examples)**

Value chain functions	Challenge	Quantum innovation
Transport and route optimization	Insufficient routing and scheduling in dynamic traffic	Quantum optimization algorithms can optimize vehicle routes and schedules for faster, adaptive logistics.
Warehouse and distribution hub operations	Inefficient resource use and throughput	Quantum-enhanced simulations can optimize labour allocation, equipment use and cargo loading by analysing complex constraints.
Inventory allocation and demand forecasting	Inaccurate forecasts and limited inventory visibility	Quantum models improve forecasting and optimize stock levels by analysing datasets with complex interdependencies.
Quality assurance and environmental monitoring	Difficulty in detecting damage, spoilage or leaks	Quantum sensors enable the real-time monitoring of product and environmental conditions.
Last-mile delivery and navigation	Navigation challenges in GPS-denied areas	Quantum sensing improves precision tracking and autonomous delivery reliability.
Warehouse infrastructure monitoring	Difficulty in detecting structural risks in fulfilment centres	Quantum gravimeters detect subtle changes in facility integrity for safer operations.
Secure data exchange	Cybersecurity risks in supply chain communications	Quantum-safe encryption ensures secure and tamper-proof data exchanging while strengthening blockchain security.

Quantum computing Quantum sensing Quantum security and communications

The quantum advantage in supply chain operations with many variables and multiple constraints is being realized today through hybrid quantum-classical algorithms.

Quantum computing's unique advantage in solving hyper-complex supply chain problems

Quantum algorithms have the potential to support continuous optimization of routes, vehicle assignments and delivery schedules by processing real-time data such as traffic, weather and network constraints. While these capabilities are still in development, they could eventually help minimize delays and reduce operational costs once quantum systems reach commercial maturity.[26] The quantum advantage in supply chain operations with many variables and multiple constraints is being realized today through hybrid quantum-classical algorithms that are improving efficiency, reducing costs and enhancing resilience.

In parallel, quantum-enhanced simulations may improve labour allocation, optimize the use of logistics assets, and space utilization by dynamically adjusting workflows based on demand. Hybrid quantum-classical machine learning models are also being explored to improve forecasting and inventory planning, enabling supply chains to respond more proactively to fluctuations and reduce waste.[27]

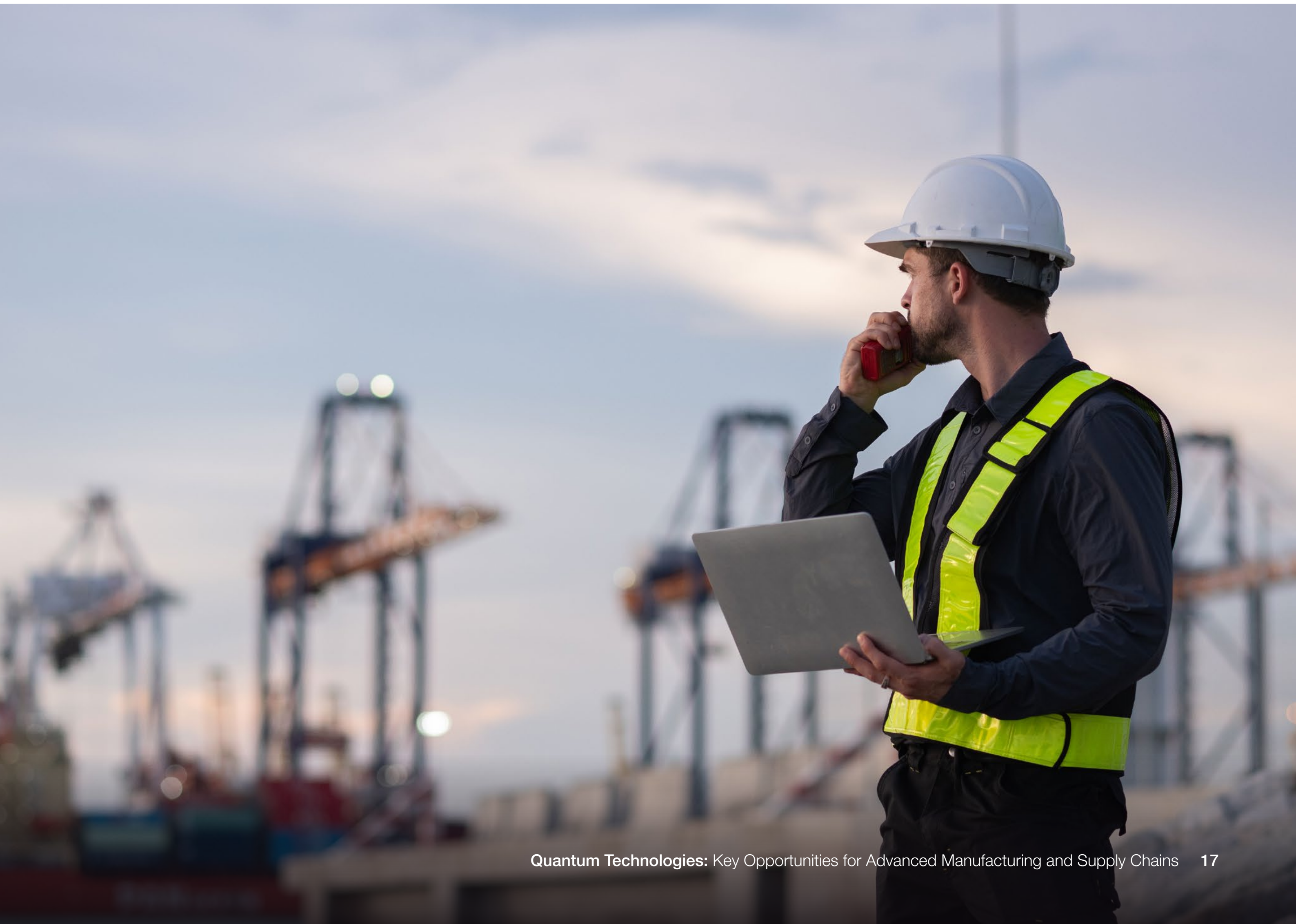
Enhancing visibility, traceability and environmental monitoring with quantum sensing

Quantum sensing technologies have strong potential to enhance environmental and product quality monitoring throughout the delivery process. Moreover, they may enable non-invasive detection of spoilage or damage and support high-precision tracking and navigation, even in environments where GPS is unavailable. Such innovations are critical for maintaining quality standards and enabling autonomous delivery systems.

Securing the data backbone of modern supply chains with quantum security and communications

Modern logistics and supply chain operations rely on the secure exchange of sensitive data.

> **Adopting quantum security in advanced manufacturing and supply chains is an investment in business continuity and growth. The organizations that act now are not only protecting themselves against an inevitable technological shift but also positioning strategically for long-term success. Quantum security enables businesses to build future-proof digital ecosystems, maintain regulatory compliance and adapt seamlessly to the transformations ahead.**
>
> Alina Matyukhina, Global Head of Cybersecurity for the Business Unit, Siemens



Early quantum technology case studies (non-exhaustive) across supply chains

Quantum computing

CASE STUDY 9

Optimizing supply chain logistics using quantum computing at the Port of Los Angeles

The Port of Los Angeles, the largest container port in the US, serves as a critical hub for global supply chains. With over 10 million containers processed annually, even small inefficiencies can cascade into major delays and significant costs for manufacturers and logistics partners. Traditional scheduling systems at the port struggled to adapt to dynamic conditions, leading to long truck wait times, excessive crane movements and underused resources. To address increasing volumes, unpredictable arrivals and growing complexity in scheduling, the team at Pier 300, one of the port's largest terminals, reimagined their logistics strategy.

Pier 300 implemented a new optimization engine based on hybrid quantum computing annealers, which have 99.999% availability. This system simulates and analyses over 100,000 cargo-handling scenarios and optimizes truck-to-crane assignments.

Resource use improved significantly when compared to the scheduling system previously in use, with crane use reduced by nearly 40%, leading to lower labour and equipment costs. Operational productivity increased, as each crane's average daily travel distance dropped by nearly one-third, and container deliveries per crane rose by more than 60%. For truckers and logistics partners, average pickup times fell by nearly 10 minutes per visit, and in some cases, wait times reduced by up to two hours. These gains translated into substantial business value, including tens of millions of dollars in annual savings and increased asset value for the terminal. This case study demonstrates that quantum computing can unlock new levels of efficiency in complex supply chain environments.[28]

> **Layering quantum optimization into our truck-to-crane appointing process proved remarkably effective. Every few minutes across two shifts daily, a D-Wave quantum computer intelligently appoints trucks to specific cranes, solving these hard optimization problems in real time. We've achieved measurable efficiency gains with solid KPIs, demonstrating quantum computing's practical value in logistics.**
>
> Ed Heinbockel, Chief Executive Officer, SavantX

Quantum sensing

CASE STUDY 10

Strengthening of manufacturing and supply chain operations with quantum-enabled navigation

Modern manufacturing and supply chain operations increasingly depend on precise navigation systems to ensure efficiency, safety and continuity. However, the growing threats such as GPS jamming and spoofing have exposed vulnerabilities in satellite-based navigation, posing critical operations at risk across sectors such as aerospace, automotive, electronics and logistics. To address these challenges, industry leaders and government agencies are validating alternative solutions that can operate independently of satellite signals. One such approach involves quantum magnetometer sensor-based navigation, which uses the Earth's magnetic field to provide robust, un-jammable positioning.

A leading example is the US Air Force's validation of this technology through over 200 hours of flight tests, more than 40 sorties, and participation in large-scale exercises across diverse aircraft and geographies. These trials demonstrated the technology's ability to deliver reliable navigation in GPS-denied environments and its readiness for integration into critical platforms.[29] The implications extend beyond aerospace. As autonomous vehicles and advanced robotics become central to logistics, companies require navigation systems that are resilient to signal interference and adaptable to diverse environments. Embedding quantum navigation modules into vehicles and industrial systems supports safer operations, real-time asset tracking and uninterrupted workflows. Hence, by adopting quantum-enabled navigation, manufacturers and supply chain operators can reduce operational risk, enhance product reliability and support the digital transformation of their industries.

Early quantum technology case studies (non-exhaustive) across supply chains (continued)

Quantum security and communications

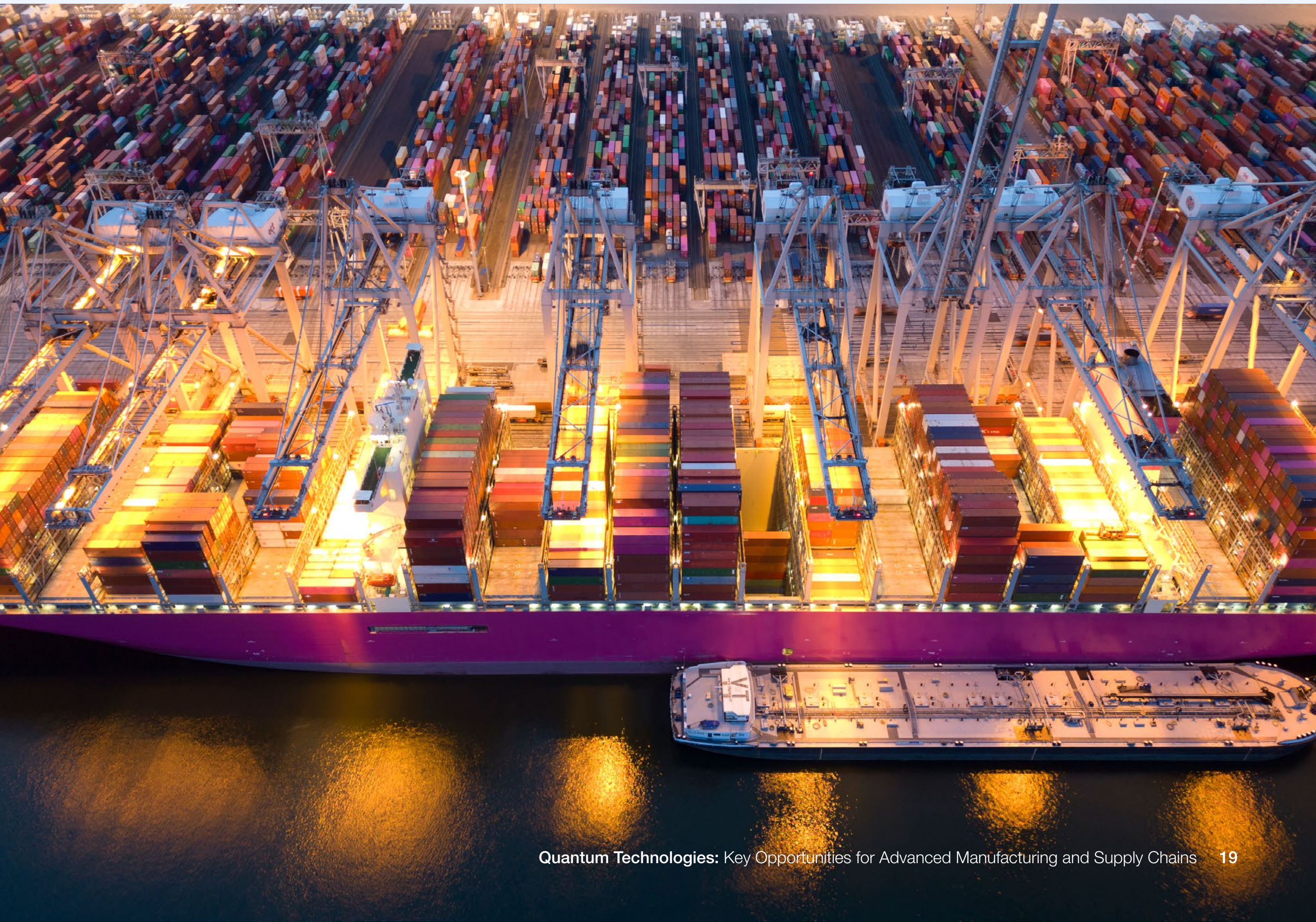
CASE STUDY 11

Untappable multi-user communications network at the Port of Rotterdam

As one of the world's largest logistics hubs, the Port of Rotterdam handles nearly 500 million tons of cargo annually and contributes over 8% to the Dutch gross domestic product (GDP). Ensuring secure and uninterrupted operations is imperative for its extensive network of manufacturers, logistics providers and supply chain partners. Recognizing the possible vulnerabilities of conventional data security methods, especially considering emerging quantum computing threats, the port partnered with Dutch connectivity provider Eurofiber to pilot a quantum-secured fibre-optic network based on next generation QKD technology.

The trial connected a central data hub to several regional users via classical fibre, spanning up to 70 km in the port area. It successfully demonstrated uninterrupted, secure, real-time data exchange across the network, even under simulated cyberattacks without disrupting existing workflows or requiring extensive retraining. Quantum communication across high-quality terrestrial fibre makes it impossible for nefarious states or cybercriminals to penetrate the network. The network's architecture supports seamless integration with classical networks and allows rapid onboarding of new users, a key advantage for dynamic port operations.

The trial also demonstrated that QKD can be effectively deployed within a 200 km radius, offering a reliable model for operational resilience in the port area. By prioritizing secure communications, the Port of Rotterdam has set a new standard for supply chain resilience, offering a replicable model for other ports, logistics hubs and critical infrastructure worldwide.[30]



3 How can leaders scale quantum adoption?

Adoption necessitates a shift from exploration to execution in the journey.

We introduce a pragmatic framework to help leaders assess the relevance of quantum technologies to their organizations, identify high-impact use cases and guide early adoption efforts, enabling decision-makers to prioritize investments and build organizational readiness. Subsequently, we examine the broader enablers and ecosystem shifts that must evolve to realize the full potential of quantum technologies in manufacturing and supply chains operations.

3.1 Building quantum readiness and platforms

Proactive investment in quantum capabilities today will determine tomorrow's leaders.

The quantum era is here, as evident by the recent announcements from Google, IBM, Microsoft and other leading technology companies.[31] As these technologies transition from research labs into real-world applications, manufacturers and supply chain leaders must prepare for their adoption. This journey begins with cultivating quantum awareness at the leadership level, identifying high impact use cases, co-creating solutions with cross-functional teams and technology vendors, and investing in workforce development and strategic partnerships.

Industrial organizations should identify a C-level sponsor to lead these efforts, ensuring alignment with core business goals while keeping experimentation anchored to strategic needs. For instance, leading chemical manufacturers can focus on developing more efficient catalysts to improve production yields and minimize environmental impact in competitive markets. Technology executives are encouraged to take a hands-on, iterative approach by piloting projects on available quantum hardware platforms, experimenting with quantum algorithms tailored to industry challenges, and evaluating both full quantum and hybrid quantum-classical solutions. Engaging with technology providers on pilot initiatives helps build internal understanding, identify promising applications and prepare organizations for informed decisions as quantum technology matures.

To support this measured approach, leaders in advanced manufacturing and supply chains can explore targeted initiatives across key quantum domains where it is delivering value today. Figure 7 provides an overview of these areas and offers a starting point for organizations to assess relevance, build internal alignment and position themselves for immediate opportunities in quantum innovation. For example, global logistics providers can assess pressing supply chain challenges and explore quantum optimization for effective solutions.

Cloud-based quantum platforms now allow companies to experiment without large upfront investments.[32] They allow operations executives to test quantum computing algorithms and quantum circuits on specific challenges while building expertise. By running low-risk pilots leveraging hybrid computing approaches and cloud-based platforms, organizations can focus on measurable outcomes and position themselves to lead, not follow, in the quantum age.

Leaders in advanced manufacturing and supply chains can explore targeted initiatives across key quantum domains where it is delivering value today.

FIGURE 7 | **Focus areas, strategic initiatives and benefits of quantum technologies**

	Priority areas	Strategic initiatives	Benefits
Quantum computing	Advanced simulation, design optimization Production scheduling, sequencing and resource allocation Supply chain and logistics optimization	Deploy hybrid quantum-classical platforms Integrate quantum simulations into R&D pipelines Establish quantum pilot programmes in smart factories	Efficiency gains in production and logistics through better optimization Accelerated materials innovation Improved forecasting and planning via quantum machine learning and simulation
Quantum sensing	Precision quality assurance, automated defect detection, process control Asset tracking, safety, traceability	Embed quantum sensors in quality control systems Pilot quantum sensor-based navigation systems	Very high precision in measurement and defect detection Enhanced reliability in critical systems Real-time visibility into asset condition and location
Quantum security and communications	Create awareness in protecting sensitive data and IP Ensuring data integrity and confidentiality in supply chains	Inventory current cryptographic assets, assess quantum exposure Use PQC in IoT, enterprise networks to secure software delivery pipelines Explore QKD use cases for secure industrial networks	Future-proof cybersecurity against quantum-enabled attacks Compliance with evolving regulatory frameworks for critical infrastructure Enhanced trust and transparency in supplier ecosystems

Each quantum domain is advancing along distinct maturity curves, offering unique capabilities for resilient digital infrastructure. Appendix 1 explains indicator levels across these domains, highlighting differences in readiness for deployment and required expertise. Executives should align pilot projects and investments with the maturity and risk appetite appropriate for their organization.

Building on the focus areas and strategic initiatives outlined above, Figure 8 presents a strategic roadmap for a phased integration of quantum technologies into manufacturing and supply chain operations. This roadmap highlights key milestones and enabling factors, providing a practical framework for organizations to navigate the journey from initial awareness to full-scale deployment.

FIGURE 8 | **Roadmap for quantum integration in manufacturing and supply chain**

Immediate actions	Medium-term strategy	Long-term vision
Establish quantum technology assessment teams to evaluate relevant use cases Priority applications include supply chain optimization, production scheduling, quality control enhancement and cybersecurity strengthening Strategic partnerships with technology providers for capability development without requiring deep in-house expertise	Pilot projects in high-impact areas while building internal capabilities Develop metrics to measure return on investment (ROI) Partner with universities to develop a quantum-skilled workforce Plan seamless integration with existing infrastructure Ensure interoperability with supplier quantum implementations	Position organizations as quantum-native by embedding quantum capabilities into competitive strategies and redefining industry standards Drive a cultural shift to embrace quantum technologies while cultivating a workforce skilled in quantum applications Establish strategic partnerships that go beyond traditional manufacturing boundaries to create a future-ready ecosystem

3.2 Enabling quantum innovation through policy, standards and organizational readiness

A holistic approach combining policy, standards, strategy and talent is essential to enable quantum innovation across global supply chains.

The journey towards quantum adoption cannot be undertaken by industry leaders alone. Ecosystem partners, including policy-makers, regulators, technology developers and research institutions, must work together to create enabling conditions for responsible and scalable adoption. This chapter explores the key regulatory, security and policy-related imperatives that manufacturing and supply chains businesses must deal with when adopting quantum technologies, and how these can be addressed through multistakeholder collaboration and collective action.

Ecosystem partners, including policy-makers, regulators, technology developers and research institutions, must work together to create enabling conditions for responsible and scalable adoption.

1 Collaborate on standardizations and interoperability frameworks

One of the most pressing policy and regulatory challenges in the adoption of quantum technologies is the absence of universally accepted international standards.[33] This lack of standardization creates uncertainty, complicates compliance efforts, hinders interoperability across systems and makes vendor selection more complex and risk-prone.

To mitigate these risks and future-proof investments, industrial consortia should actively participate in standard-setting bodies and pilot interoperability frameworks that can guide the responsible and scalable integration of quantum technologies.

For instance, Quantum Technology & Application Consortium (QUTAC), a German consortium, is working to build early standards by fostering cross-industry collaboration, piloting real-world use cases, developing reference architectures and contributing to international standardization efforts.[34]

Many quantum solution providers, often early-stage start-ups, lack the industrial-grade compliance infrastructure required to meet enterprise and regulatory standards. Certification frameworks modelled after established standards, such as those from the International Standards Organization (ISO) or the National Institute of Standards and Technology (NIST), would help validate vendor readiness, build trust, and streamline procurement and integration processes across the quantum sector.[35]

2 Ensure security and cryptographic readiness

Recent research suggests that cryptographically relevant quantum computers (CRQCs) capable of breaking current asymmetric key encryption standards like Rivest-Shamir-Adleman (RSA) could emerge within five to 10 years. Symmetric key encryption protocols, such as the Advanced Encryption Standard (AES), on the other hand, remain more resilient but require larger key sizes to maintain security.

To stay ahead of emerging threats, businesses should initiate quantum-safe pilot programmes now, particularly in high-risk areas and laying the groundwork for a secure quantum future.

Migration to quantum-safe cryptography may take a decade or more for complex enterprise systems, so delays in quantum preparedness could lead to widespread vulnerabilities in high-risk areas such as software delivery pipelines, IoT device security and enterprise communications.[36]

The transition to quantum-safe cryptography is becoming increasingly urgent, driven by recent government mandates and regulatory expectations. The US, for example, has taken a leading role by mandating migration to PQC algorithms and setting clear regulatory expectations for their adoption, where NIST has proceeded to standardize the first round of PQC algorithms.[37] In other countries, such as China, South Korea and Singapore, implementing PQC as well as QKD is under way.[38] In Europe, a more academic quantum communication infrastructure, known as European Quantum Communication Infrastructure (Euro-QCI), is being built.[39] These developments underscore the urgency for organizations to align their security strategies with quantum-safe standards.

However, many businesses, particularly small to medium-sized enterprises, remain unaware of the urgency or lack the readiness to begin this transition. Guidance from regulators and proactive leadership from C-level executives are essential to accelerate adoption.

To stay ahead of emerging threats, businesses should initiate quantum-safe pilot programmes now, particularly in high-risk areas and laying the groundwork for a secure quantum future. For instance, mobility companies Continental and Elektrobit have joined forces with several partners to investigate how automotive devices can be protected from quantum computer threats.[40] Manufacturers and industries using building automation and control networks (BACnet)/Secure Connect (standardized protocol for communication between devices and systems) should proactively adopt quantum-resistant security measures to future-proof their systems from quantum attacks.

3 Demystify hype and align with business goals

The rapid rise of quantum technologies has sparked significant excitement, but it also carries a risk of inflated expectations regarding timelines and scalability, which can lead to misinformed strategies and poor investment decisions. Lessons from previous technology waves, such as AI and machine learning, underscore the importance of balancing enthusiasm with realistic expectations.[41] Leadership teams, including chief information officers (CIOs), chief technology officers (CTOs) and chief information security officers (CISOs), play a critical role in navigating this emerging wave effectively. Strategic training tailored to quantum technologies can empower these leaders to make future-ready decisions that align with both technological realities and long-term business goals.

4 Develop talent and a trained workforce policy

A critical barrier to the widespread adoption of quantum technologies is the global shortage of quantum-literate professionals, particularly those with expertise in applying quantum principles to real-world industrial contexts.[42] Bridging this skills gap requires coordinated action from both government and industry. Initiatives such as the Quantum Mobility Quest, sponsored by Airbus and BMW Group, exemplify how global challenges can connect quantum experts with industry leaders to accelerate workforce development.[43] Policy-makers and industry leaders must co-develop specialized curricula, fund hands-on training programmes, and support the growth of quantum R&D centres. Additionally, implementing upskilling programmes for existing professionals and fostering a "quantum-aware" culture within organizations can ensure broader understanding and adoption of quantum technologies. Public-private collaborations should treat workforce development not merely as an educational initiative, but as a strategic imperative for industrial competitiveness in the quantum era.

Equally important is ensuring that the workforce is ready and willing to learn and adapt to emerging technologies. This requires the implementation of humane change management processes that prioritize transparent communication, ongoing support and inclusive engagement. Fostering a culture of continuous learning and resilience empowers individuals to embrace technological change and contribute meaningfully to the evolving quantum ecosystem.

Conclusion

As quantum technologies transition from theory to real-world application, manufacturing and supply chain leaders have a unique opportunity to act decisively and secure a leadership position before the market becomes more established. The convergence of technical maturity, market availability and economic necessity creates an unprecedented opportunity for quantum-enabled competitive advantage, but this window will not remain for long.

Rapid advances in these technologies position quantum as a catalyst for greater agility, resilience and sustainability in industrial operations. Early adopters will shape industry standards, attract top talent and forge new partnerships across the quantum ecosystem. Quantum-as-a-service platforms are democratizing access, enabling even mid-sized firms to experiment and develop expertise without significant upfront investment. However, the path to quantum adoption is not without obstacles. To navigate these challenges and capture the quantum opportunity, refer to the implementation pathway outlined in Figure 8.

The quantum revolution is not a distant possibility; it is an immediate opportunity that demands executive attention and strategic action. Leaders who act decisively today will define the competitive landscape of tomorrow. Early engagement in standards, policy and talent development will position organizations as leaders, not just adopters, in the quantum economy.

As quantum technologies evolve, industries in manufacturing and supply chain organizations must remain agile, grounded in practical feasibility and committed to continuous learning. Through multistakeholder collaboration and adaptive policy frameworks, the sector can drive sustainable growth, resilience and global leadership in the quantum era.

Appendices

A1 Explanation of indicators

These indicators also influence one another, with risk being particularly affected by the combined impact of all other factors.

TABLE 1 **Indicator explanations**

Indicator	Explanation of indicator levels	Quantum computing	Quantum sensing	Quantum communications and security
Maturity level How developed and ready the technology is for practical use **High** is desirable	**Low** – Experimental stage, mainly theoretical, no real-world use cases **Medium** – Some proven applications, but large-scale deployment is limited **High** – Well-developed, widely adopted and integrated into various industries	**Medium**	**Medium**	Between **medium** and **high**
Scalability The ability of the technology to expand and handle increasing workloads **High** is desirable	**Low** – Limited scalability due to hardware, cost or environmental requirements **Medium** – Some expansion possible, but significant improvements needed **High** – Easily scalable, deployable across industries with minimal barriers	**Medium**	**Medium**	Between **medium** and **high**
Level of expertise required The effort and expertise required to adopt and use the technology **Low** is desirable	**Low** – Easy to learn and integrate, with user-friendly tools and widespread training available **Medium** – Specialized knowledge required (but practical applications are more intuitive) **High** – Very complex, requiring deep expertise in quantum physics and engineering	Between **medium** and **high**	**Medium**	Between **low** and **medium**
Implementation time and cost The resources required to deploy the technology **Low** is desirable	**Low** – Cost-effective and quick to implement at scale **Medium** – Moderate cost and time commitment, with potential long-term ROI **High** – Expensive, long-term investment with slow deployment	Between **medium** and **high**	**Medium**	Between **low** and **medium**
Risk level Potential challenges or negative outcomes from adoption or non-adoption **Low** is desirable	**Low** – Minimal risk, well-established technology with clear benefits **Medium** – Some uncertainties, but risks can be managed with strategic planning **High** – Significant risks, including high costs, security vulnerabilities or potential disruptions.	**Medium** (for both adoption and inaction)	Between **medium** and **high** (for both adoption and inaction)	**High** (for inaction)

A2 Other notable case studies

Below are additional case studies to take notice of:

BOX 1 Quantum computing

- Amerijet International has partnered with Quantum-South to optimize cargo loading using quantum computing. By analysing 451 flights, they identified loading alternatives that increased payload by up to 30% and volume by 76%, demonstrating significant efficiency gains in air cargo operations.[44]

- Einride, a freight mobility platform that combines software, autonomous vehicles, charging infrastructure and electric mobility, has partnered with IonQ to leverage quantum computing for optimizing large-scale routing and scheduling.[45]

BOX 2 Quantum security and communications

- Abu Dhabi Maritime Academy, part of Abu Dhabi Ports Group, has partnered with ID Quantique to develop maritime-specific quantum-safe cybersecurity services.[46]

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