Citi GPS

SUPPLY CHAIN TECHNOLOGY

Improving Efficiency, Resilience, and Transparency

Citi GPS: Global Perspectives & Solutions

October 2023

Authors

Martin Wilkie
Co-Head, Industrial, Technology & Mobility Super-Sector
Citi Research

+44-207-986-4077 | martin.wilkie@citi.com

Wenyan Fei
Analytical Insights Team
Citi Global Insights

+44-20-7986-3543 | wenyan.fei@citi.com

Anuj Gangahar
Analytical Insights Team
Citi Global Insights

anuj.gangahar@citi.com

Tahmid Quddus Islam
Analytical Insights Team
Citi Global Insights

tahmid.quddus.islam@citi.com

Anita McBain
Head of ESG Research, EMEA
Citi Research

+44-20-7508-4361 | anita.mcbain@citi.com

Monique Pollard
Co-Head European Internet Team
Citi Research

+44-20-7508-0686 |
monique.pollard@citi.com

Sathish B Sivakumar
Head of EMEA Transportation Team
Citi Research

+44-20-7986-1926 |
sathish.babu.sivakumar@citi.com

Christian Wetherbee
Global Head of Transportation Sector
Citi Research

+1-212-816-9051 |
christian.wetherbee@citi.com

Rob Garlick
Head of Innovation, Technology, and the Future of Work
Citi Global Insights

+44-20-7986-3547 | robert.j.garlick@citi.com

Gopinath Govindaraj
SVP, Partnerships and Innovation, Global Trade and Working Capital Solutions
Citi Trade and Treasury Solutions

+353-1-622-6071 | gopinath.g@citi.com

Ronit Ghose, CFA
Head of Future of Finance
Citi Global Insights

+971-4-509-9586 | ronit.ghose@citi.com

Andrew Kaplowitz
Co-Head, Industrial, Technology & Mobility Super-Sector
Citi Research

+1-212-816-0642 | andrew.kaplowitz@citi.com

Graeme McDonald
Head of Pan-Asia Capital Goods Sector
Citi Research

+81-3-6776-4614 | graeme.mcdonald@citi.com

Michael Rollins, CFA
U.S. Communication Services & Communication Infrastructure Analyst
Citi Research

+1-212-816-1116 | michael.rollins@citi.com

Amy Thompson
Social Economist
Citi Global Insights

+44-20-7508-7674 | amy1.thompson@citi.com

SUPPLY CHAIN TECHNOLOGY

Improving Efficiency, Resilience, and Transparency

Kathleen Boyle, CFA
Managing Editor, Citi GPS

One of the more interesting observations about the COVID-19 pandemic era was the way in which it expanded words and phrases used in general conversation. Prior to the pandemic, it was unlikely that people routinely talked about the effectiveness of mRNA vaccines or how long a virus could stay viable on a shopping bag. And conversations about the daily trip to the supermarket suddenly incorporated phrases like “supply chain disruptions.”

We started writing about supply chains back in December 2021 in our report *Global Supply Chains: The Complicated Road Back to Normal*. At the time, global markets were unbalanced. There was strong demand for goods, as many who were sitting home due to lockdowns or remote work were clicking on “Add to Cart.” On the supply side, border closings and lockdowns kept production sites shuttered. At the time, we noted that because there was more than one cause or event that had gotten us into that situation, one single solution would not relieve the stress.

Then came the armed conflict between Russia and Ukraine, which added a new layer of supply chain pressure and new challenges for the global economy. Together with the issues from the pandemic, the supply chain management practices that prevailed in the years before the pandemic were questioned, especially whether global supply chain structures were robust, cost-effective, and reliable, and whether the demand for goods was relatively smooth and predictable.

With vulnerabilities in supply chains exposed, we noted that many firms would feel the need to take the lessons from supply chain disruptions on board and adjust their operations. One of our suggestions was to embrace digitalization and technology more broadly throughout the supply chain.

Although technology had been slowly added over the year into the production and distribution areas of the economy, we believe the recent supply chain disruptions are proving to be a catalyst for technology adoption.

From robotics in manufacturing and automated guided vehicles in warehouses, new technologies in the production area of the economy can help to automate processes, increase productivity, and lower costs. In the delivery sector, technology can help decrease delivery times and novel transportation solutions can lower delivery costs. New technology such as artificial intelligence and machine learning can help companies bring products to market faster and more efficiently. Finally, digitization and documentation can help keep supply chains running smoothly.

In the report that follows, we look at some 20 different areas of supply chain technology that could help companies enhance their supply chain management practices. Some are technologies that are already used in practice, while others are more conceptual. All are likely to help lead to a more stable global supply chain.

Hopefully supply chain technology can ensure that future conversations about the trip to the market will center around what’s for dinner instead of what’s missing on the shelves.

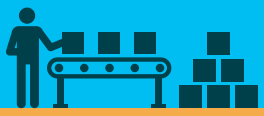
The Dawn of Digital Supply Chains

PRODUCTION AND STORAGE

While humans still perform 72% of manufacturing tasks, the use of robots is on the rise, including Automated Mobile Robots (AMRs) and Automated Guided Vehicles (AGVs). Lower costs and higher speeds can be achieved through technologies such as Robots-as-a-Service (RaaS) subscriptions and 3D printing. While warehouses are still largely manual, the use of Automation Storage and Retrieval Systems (AS/RS) is growing.

60%
of warehouses have limited or no automation

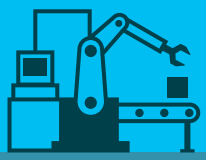
Only 1%-2%
are fully automated ("lights out")



AS/RS market penetration is expected to more than double to

36% over 10 years

Source: LEK Consulting



Robots

53%
increase in global sales of AMRs and AGVs in 2022

Hourly rates

RaaS robots:
$2-$8/hr

U.S. factory worker:
$17.40/hr

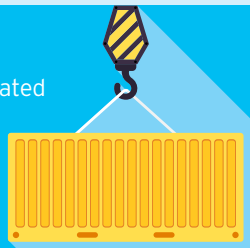
Sources: IFR, MiR, BLS

DELIVERY AND RECYCLING

Globally, automation at container terminals remains low despite evidence it increases throughput and reliability while reducing costs. Other technologies such as autonomous trucks, hyperloop transport, automated parcel sorting, and automated last-mile delivery technologies can produce further efficiencies in logistics.

Port automation:

- Only 4% of global container terminals are automated
- Labor accounts for ~50% of port operator costs
- Automated Port of Rotterdam has 2x the productivity of non-automated ports



Autonomous vehicles:

the most likely automated solution for last-mile delivery

Hyperloop:

Enables faster cargo transport, reducing inventories and freeing capital

Autonomous trucks:

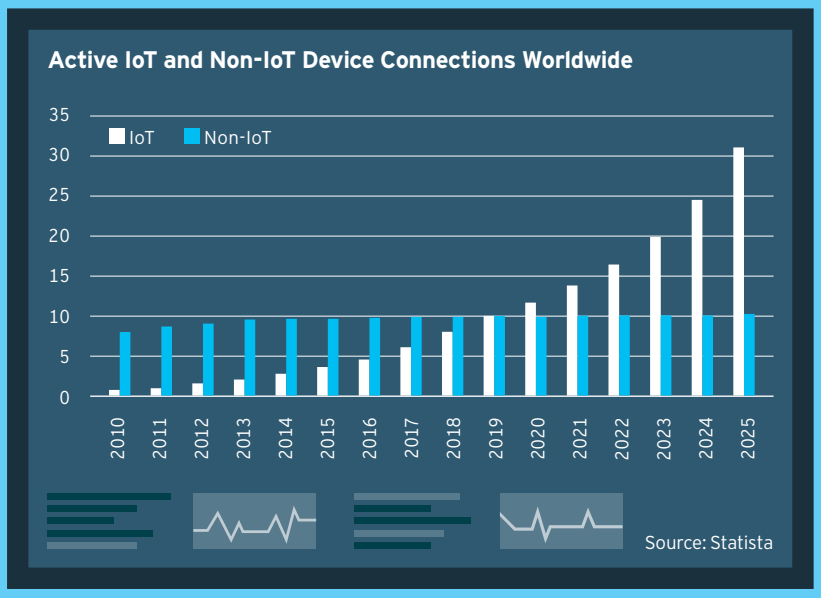
May alleviate the driver shortage, set to double by 2028

Automated parcel sorting:

Improves efficiency at fulfillment centers, reduces impact of seasonality, and enables faster delivery

DECISION MAKING

The Internet of Things (IoT) is providing greater visibility over supply chains and enables better decision making through artificial intelligence (AI) tools. Greater connectivity from 5G enhances these capabilities, with quantum computing expected to further optimize supply chains. As sensor costs fall, the number of IoT-connected devices is expected to rise significantly.

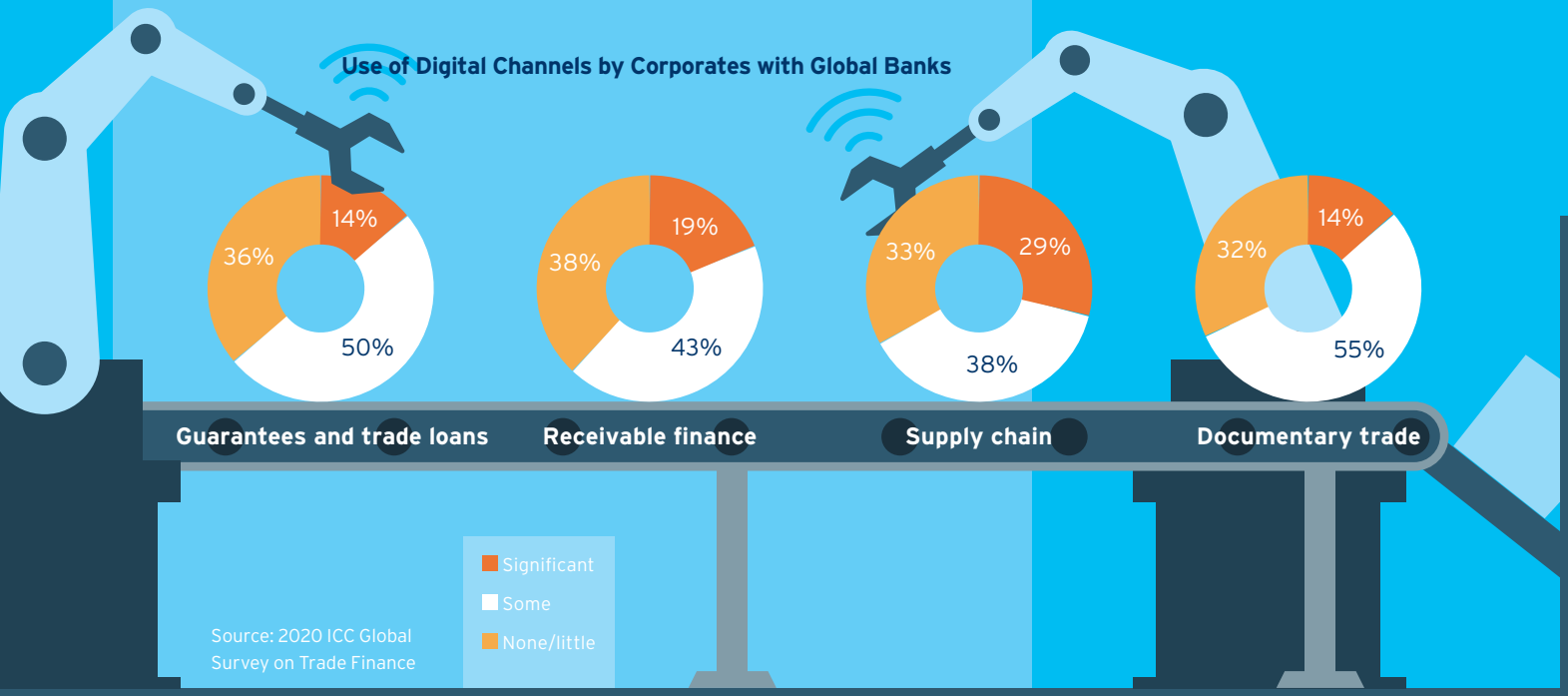


The Use of 5G in Smart Manufacturing

- Enables communication between devices on factory floor
- Generates data to help optimize production
- Monitors environmental factors
- Enables end-to-end tracking of supply chain

DIGITIZATION AND DOCUMENTATION

Less than 10% of trade documents are fully digitized, but this is changing with the Digital Documentation Initiative (dDOC). Interoperable Digital ID systems and digital payments (including blockchain and tokenization) in the supply chain may bring further change, helping to improve supply chain resilience and increasing transparency to stakeholders.



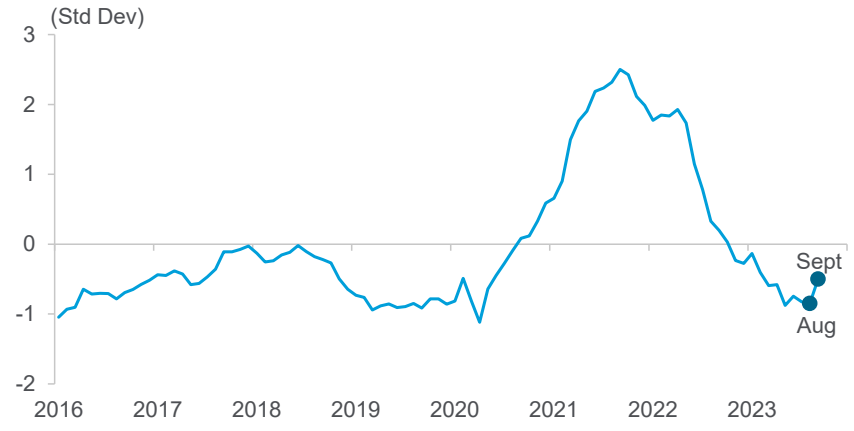
Contents

Introduction

Over the course of the past two years, we published a series of reports on global supply chains, most recently on the role of supply chain finance (see the Citi GPS report *Supply Chain Finance: Uncertainty in Global Supply Chains Is Going to Stay*) in an environment of rising interest rates and financing costs. In our first Citi GPS report, *Global Supply Chains: The Complicated Road Back to "Normal"*, a key takeaway was that corporates would take time to review their supply chains and make changes based on lessons from the pandemic. Potential areas of focus include embracing digitization, placing a greater emphasis on long-term alliances and partnerships with suppliers, holding larger inventory buffers, and bringing supply chains closer to home. Technology can be a key driver of this reconfiguration, and the report that follows examines a range of new technologies to improve supply chain efficiency, speed, and transparency while reducing risk.

We cannot ignore the fact that 2023 has been a transition year. The full impact of government programs has yet to be realized, and new orders for some supply chain technologies have declined sequentially as lead times have eased and record backlogs that built up in 2021-22 have started to normalize. Some companies have reported that at the height of the post-pandemic supply chain bottlenecks, several industrial customers moved from ordering three months' worth of product to ordering two years' worth. This boosted backlogs for many supply chain technology companies and meant that orders have (inevitably) declined in the short run as lead times have normalized. This means that while we see clear long-term structural growth, there is some near-term cyclical pressure.

Figure 1. Citi Global Supply Chain Pressure Index



Source: Citi Research, Bloomberg

Technology developments in automation, software, and connectivity mean that supply chains can, in theory, be digitized and automated in novel ways. However, technology adoption has not historically been as fast as we think is possible. We believe the global events of the last few years — and subsequent policy actions — can now reshape supply chains in many industries and drive adoption in new technologies that not only lower costs, but also increase flexibility, transparency, and resilience.

More than 20 years prior to the pandemic, industrial companies began outsourcing production to emerging markets and decreasing their vertical integration. This was globalization at work. Many of the moves were a response to growing demand in emerging economies such as China, but they also reduced asset intensity for manufacturers, lowered production costs, and boosted returns on capital for many U.S. and European companies. For decades, production became increasingly outsourced as firms decreased vertical integration or simply avoided it in the first place. Firms benefited from relocating production expenses to low-cost countries as well as moving assets to supplier balance sheets from their own. Occasionally, events (especially natural disasters) would briefly highlight the risks of unknown interdependencies, but the just-in-time model of inventory management — in which firms keep as little inventory on hand as possible — was not seriously questioned before 2018. Since then, the model has started to be questioned, especially in the immediate aftermath of the post-pandemic recovery when inventories in many cases ballooned on component shortages, lengthening lead times and increasing backlogs.

In the globalized supply chain model, production was sent to the location of lowest marginal cost, with some industries chasing the lowest labor rate around the world. But what if unexpected frictions appear, as happened with U.S./China trade tariffs in 2018? Or if new incentives appear to produce locally — as is now happening with semiconductors and some green technologies? If supplier production sites simply become inaccessible, as happened during COVID-19, the “sole source” model is called into question. Earthquakes, wars, and other tragedies have also highlighted hidden risks within supply chains.

As supply chains become longer, the risk of a “bullwhip effect” also increases. This long-known pattern identifies that demand and supply imbalances get amplified and delayed down the length of a supply chain. The shock of COVID-19 led to a bullwhip effect like no other in certain markets, where the demand rebound was fast but incremental supply additions were slow. Notably, in semiconductors, the effects are still being felt.

Disentangling supply chains may not be easy — complex and integrated ecosystems have developed, especially in electronics, and most famously in smartphones. Technological disruption, however, can act as a catalyst for change — i.e., the supply chain of flat-screen televisions looks very different from that of its cathode ray tube predecessors. Arguably, this is where the opportunity lies in emerging green technologies: areas in which the supply chain has yet to mature or even fully establish itself.

Today we are entering a new era of domestic support and national champions. Semiconductors, green technologies, and critical materials are all being targeted, notably in the U.S. and increasingly in Europe. The U.S. Inflation Reduction Act (IRA) is the most prominent, but not the only, example of the shifting landscape.

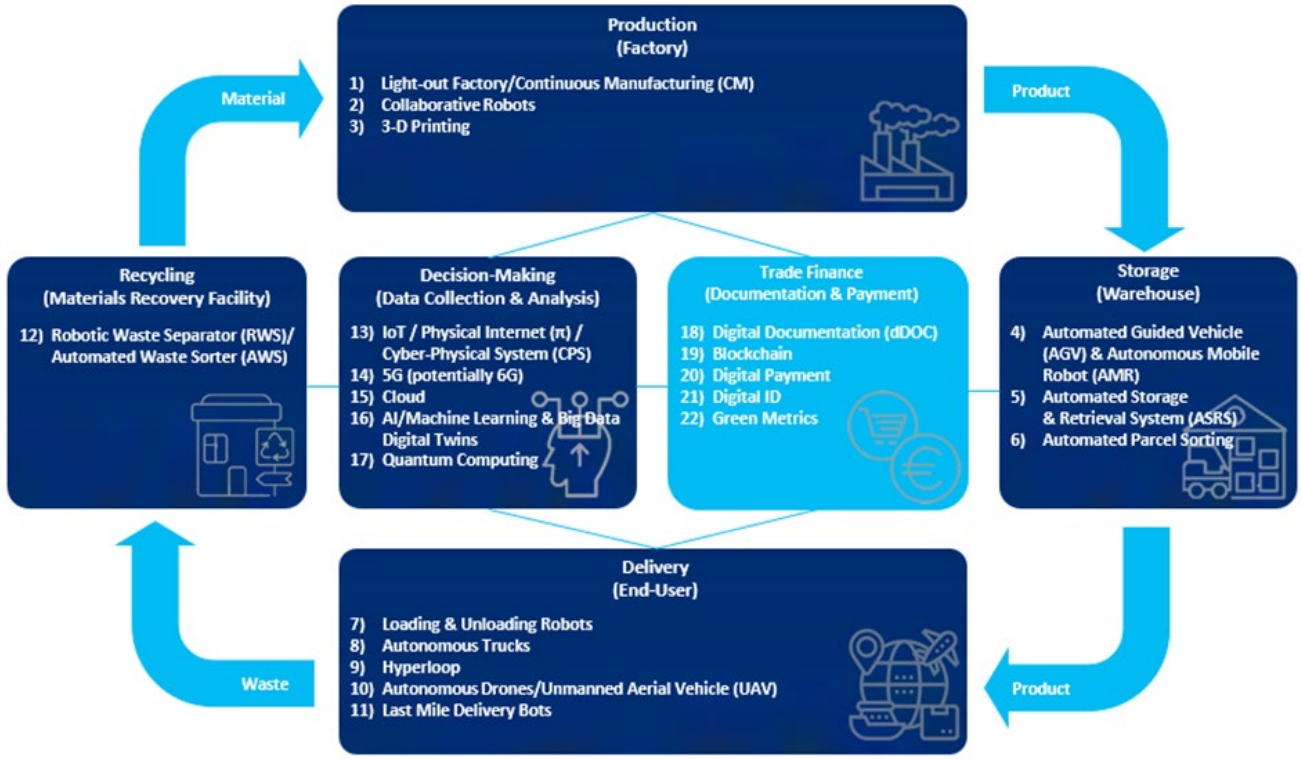
Protectionism and security of supply are the key drivers behind this new era of domestic support, but they also create a snowball effect. It is hard for one region to remain open and trade-barrier free if others are not, as Europe is now discovering in its attempt to respond to the U.S. IRA.

Despite the changes, local ecosystems for raw materials, suppliers, and know-how matter and make production and supply chains sticky. Technological disruption, however, can act as a jolt to this dynamic. In the early 1900s, auto manufactures owned rubber plantations, but by the 1980s and 1990s they had begun to carve out their in-house component suppliers. Now, with the shift to electrification, auto companies are looking to secure battery metal supplies, as they did with rubber in the 1920s. Combined with the impact from incentives, the supply chain for the next few decades is being formed differently than it has been over the last few decades. One talking point at the automation expert panel at Citi's 2023 Global Industrial Tech and Mobility Conference was about a "once in a generation" greenfield buildout in electric vehicles (EVs), batteries, and semiconductors. This is not reshoring or onshoring — it is not moving capacity from one region to another — but simply the creation of inaugural capacity for fledgling industries. We see these structural changes as drivers in the automation and digitization of supply chains, which are becoming digital in design, in testing, in production, in transit, and in use.

While geopolitics and domestic support are significant drivers of change, demographic changes should not be overlooked. In China, the total population has peaked, and the total working-age population is already past its peak. China's mass internal migration from rural areas to cities, a huge source of incremental labor, cannot be repeated. Meanwhile in the West, high labor costs and low labor availability will likely drive higher penetration of automation.

The opportunity in supply chain automation is huge. Around 80% of warehouses are still not automated, and in the early days of post-pandemic economic re-opening, delays in port throughput had as much to do with warehousing and trucking as with port capacity. Data matters too; in an era of "Scope 3" carbon emission measures, where companies must report on CO_2 emissions embedded not only in their own operations but also up and down their value chain — from their supply chain, through to consumers using their products — digital supply chains become key. Even in areas where automation penetration is high, there remains significant untapped potential in connectivity to the cloud.

Figure 2. Technology-Empowered Supply Chain



Source: Citi Global Insights

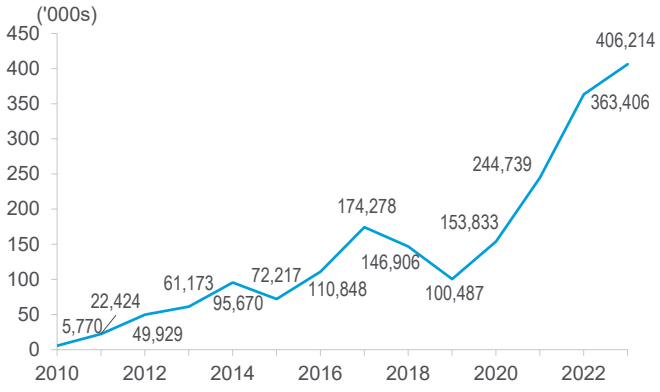
The catalyst effect from government policy and stimulus is largely in front of us. In the U.S., the CHIPS and Science Act of August 2022 is intended to strengthen American manufacturing and supply chains. According to the White House, the Act aims to provide more than $50 billion in funding "to bring semiconductor supply chains home" and has sparked over $200 billion in private investment, according to the Semiconductor Industry Association. The act has already driven a spike in U.S. manufacturing construction, led by computer, electronic, and electrical manufacturing, although even the first semiconductor facilities will not be up and running until 2024 — the full supply chain impact is yet to come. Similarly, the U.S. IRA has already driven announcements for $110 billion of private investment in clean energy projects, mostly related to EVs. An August 2023 project tracker by the American Clean Power Association for projects in solar, storage, and wind estimates that most on-line dates for these renewable energy facilities will be beyond 2023.

According to the nonprofit group Reshoring Initiative, EV batteries and semiconductors were the most active sectors to see jobs reshored back to the U.S., driven either by shifting production or by new foreign direct investment (FDI) by foreign companies into the U.S. in 2022. Electrical equipment (which includes the battery category) and computers and electronics (which includes semiconductors) accounted for over 65% of new jobs in the U.S. in 2022 driven by reshoring or FDI.

Catalysts in Europe are less clear, but a push for increasingly domestic supply chains in certain industries looks likely. In March 2023, the European Commission published its long-awaited Net-Zero Industry Act, a key pillar in Europe's ambition to drive green technology investment and secure domestic content. The Act proposes a 40% domestic content target for certain strategic net-zero technologies but is not yet signed into law. In the meantime, in September 2023, the European Commission announced a thirteen-month review into state subsidies of Chinese EVs imported into the EU, with the potential to impose additional tariffs.

We see the supply chain technology theme as more important than ever, with 2023 acting as a transition between the COVID-19-induced bottlenecks and the structural shifts we expect in the years ahead.

Figure 3. Manufacturing Job Announcements Per Year, Reshoring + FDI, 2010-2023E

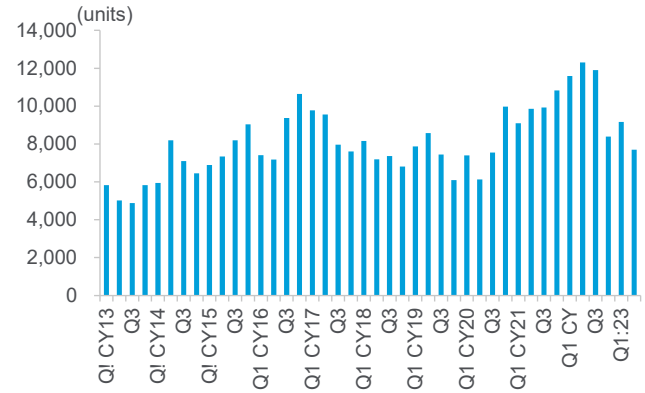


Source: Citi Research, Reshoring Initiative

Figure 4. U.S. Construction Expenditure Acceleration Driven by Government Policies Such as the IRA

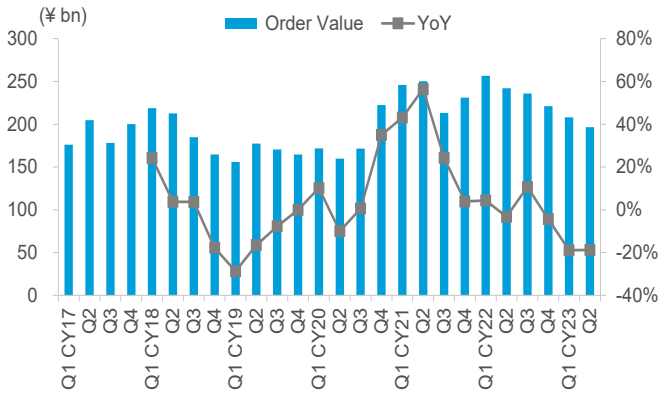
Source: Citi Research, DataStream

Figure 5. North American Robot Orders Started Decelerating from Q4 2022 as Backlogs Normalized from the 2021-22 Boom, But We See 2023 as a Transition Year



Source: Citi Research, Association for Advanced Automation

Figure 6. Japan Robot Orders Have Also Shown Cyclical Pressure



Source: Citi Research, Japan Robot Association (JARA)

Outline for This Report

Segment I of the report covers the production and storage parts of supply chains highlighted in Figure 2. While robots have been used in manufacturing for decades, their penetration continues to grow, aided by improvements in machine vision, end-of-arm tooling, and software. Growth in "cobots" (collaborative robots working alongside humans) is particularly noteworthy, as they contribute to a reduction in costs and an improvement in safety, while "lights-out" manufacturing (manufacturing without any human presence) is also growing. Additionally, we note in the section that RaaS (Robots-as-a-Service) is helping reduce upfront cost barriers, leading to a further acceleration of robot usage. 3D printing is also changing both manufacturing and supply chains by increasing speed to market and customization while reducing costs and waste. The COVID-19 pandemic accelerated the use of 3D printing, especially in medical supplies, and this trend could continue as supply chain reconfiguration includes more on-shoring or re-shoring.

With tight labor markets, many manufacturers are struggling to find workers. Automated Mobile Robots (AMRs) and Automated Guided Vehicles (AGVs) could help solve the labor issue by transporting products in factories. Payback periods for these technologies are already favorable, and costs continue to fall as they progress. Warehouse work is still largely manual, and automation, including Automation Storage and Retrieval Systems (AS/RS), can increase flexibility and resiliency.

As we highlight in Segment II, looking at changes taking place in supply chain distribution, automation in container terminals currently stands at just around 4%. As labor typically accounts for around 50% of costs for port operators, the use of robots, which has been shown to increase throughput and reliability, could reduce costs. The global freight market — where drivers make up around 50% of the cost per mile in trucking, and driver shortages are an increasing issue — could be helped by a shift to autonomous trucking for middle miles. Drone delivery, meanwhile, is a potential alternative for short-distance package deliveries or for inefficient rural routes. Hyperloop trials have also begun and could replace intracity air freight, providing speed to market, particularly in congested areas, with zero direct emissions.

Last-mile delivery is the most expensive part of the supply chain at around 41% of costs (versus warehousing, which makes up 13% of costs). While legged and wheeled robots are being trialed, we believe autonomous vehicles are more likely to be the long-term automated solution. Parcel sorters also play an important role in the last-mile segment, and automation is helping there, both by increasing speed to market and reducing the impact of seasonal human hiring.

In addition to automation helping from production to delivery, as entire supply chains need to move towards net-zero targets, robotic waste sorting will increasingly be part of the solution given the related technology is improving and costs are falling. It is estimated that half of waste management tasks can be automated, improving efficiency and recycling rates.

As discussed in Segment III, an important part of the digitization of supply chains is the Internet of Things (IoT): from monitoring machines and boosting production, to helping forecast stockouts, planning replenishments, and dynamically optimizing delivery transport routes based on traffic conditions. Falling sensor costs are helping to significantly increase the number of IoT-connected devices, and IoT is helped further by greater connectivity from 5G, which affords additional reliability, security, and private networks.

Digitization and automation solutions help generate data to feed machine learning and artificial intelligence (AI) decision-making tools, further optimizing supply chain processes from delivery to production. Over 70% of companies are still expected to use spreadsheets as the primary tool for supply chain decision-making, but data automation and AI can help reduce costs, increase speed, and lower risk. In the future, quantum computing will enable solutions beyond those classical computers are capable of, including solving “traveling salesman” logistics problems to better optimize supply chains.

Segment IV of the report covers the greater digitization happening in the documentation and payment segments of supply chains. A cross-border transaction currently requires an average of 36 documents and 240 copies, yet less than 10% of trade documents are fully digitized. Initiatives like the Digital Document Initiative seek to change this. Further change can also come from the growth of interoperable Digital ID ecosystems that help establish identities across supply chains, improving trade security and reducing risks from transactions such as fraud and legal breaches.

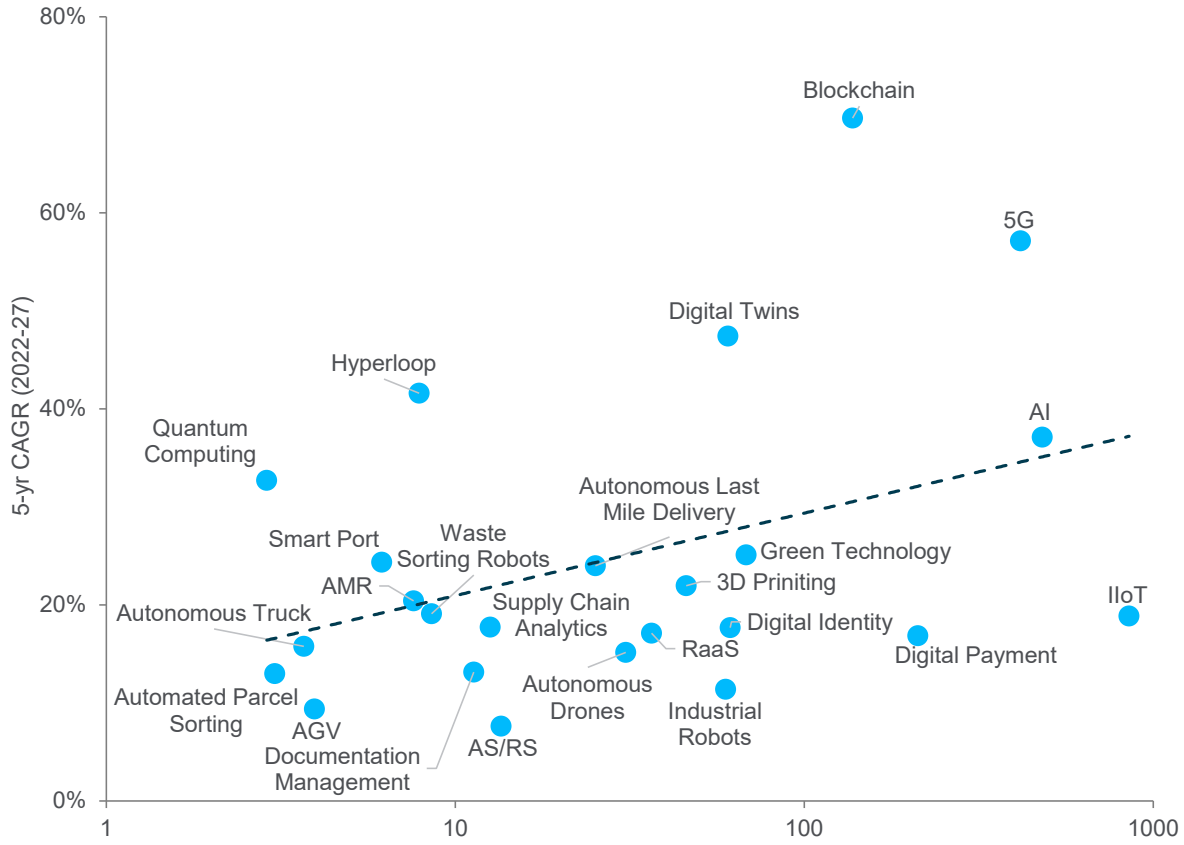
While most payment rails today are digital, the payment of customs, duty, and excise is still very paper-heavy, especially for small- and medium-sized enterprises (SMEs). Supply-chain participants often struggle with cash flow given that payments are usually made on delivery rather than on order. Digital Money 2.0, including blockchain and tokenization, could remove inefficiencies in the system by merging messaging and settlement into one. This would reduce errors, delays, and reconciliation issues; increase transparency and trust; and cut costs. Smart contracts can also automate payments provided certain conditions are met.

We next look at the importance and implications of ESG (environmental, social, and governance) considerations. A parallel megatrend is the drive towards net-zero emissions, not just within companies but throughout their supply chains. Technology, including clean tech, is not only part of the net-zero emissions solution, but it is also part of the policing mechanism. Companies need to ensure transparency around their supply chain emissions and to report this information to their stakeholders. That is a huge task, and data and technology have a big part to play in driving outcomes and efficiencies.

The report finishes with a discussion on how venture capital investment in supply chain technology has trended over time, as well as the significance of M&A in this area.

Given the complexity of supply chains and the diversity of the changes outlined in this report, we analyzed estimates for the total addressable market (TAM) size of 24 related themes using 125 sources. This data is presented in Figure 7, with the average 5-year compound annual growth rate (CAGR) for each theme from 2022-27 on the vertical axis and the 2027 forecast market size, in log scale, on the horizontal axis.

Figure 7. Analysis of Themes Related to Supply Chain Technology



Source: Citi Global Insights

Takeaways from our analysis include:

- As expected, AI is forecast to grow quickly and reach a significant TAM of $481 billion by 2027, but IoT is forecast to be almost double that size at $853 billion.
- While cryptocurrency may have faltered recently, other digital asset opportunities still appear promising, with blockchain forecast to have a 5-year CAGR of 70% between 2022 and 2027.
- While 5G is not small today, it is still at a relatively early stage in terms of commercial use, and forecasts are for a significant 57% 5-year CAGR between 2022 and 2027.
- Digital twins are forecast to have a 47% 5-year CAGR during the same period. Virtualization of everything might be on its way.

With parallels to the aftershocks of the global financial crisis (GFC), the effects of the COVID-19 pandemic will likely be felt for the next couple of decades as companies, nations, and policymakers reshape supply chains. This reshaping may include increasing domestic manufacturing via reshoring, relocating production facilities via onshoring, or encouraging the shift of manufacturing toward geopolitical allies via “friend-shoring.” It also may involve additional regulation, such as the CHIPS and Science Act or protectionism, as observed in the Inflation Reduction Act. What looks most certain is that technological progress, including automation and digitization, will play a big part in the reconfiguration of supply chains.

As noted throughout this report, relevant technologies are continuing to improve and get cheaper. In many cases, by working 24/7, they can substitute for areas where labor is in short supply or fluctuates seasonally. In other areas, such as AI, technology can augment decision-making. In most areas, digitization can improve speed, transparency, and outcomes. Technology will play a big part in post-pandemic aims to make supply chains more resilient. A chain is only as strong as its weakest link. Given the reconfiguration of many parts of the chain coming, we hope this report will help corporates, investors, and policymakers gain a holistic view of potential paths ahead.

Segment I: Production and Storage

Robot Penetration at New Highs

Martin Wilkie
Co-Head of Industrial, Technology & Mobility Super-Sector
Citi Research

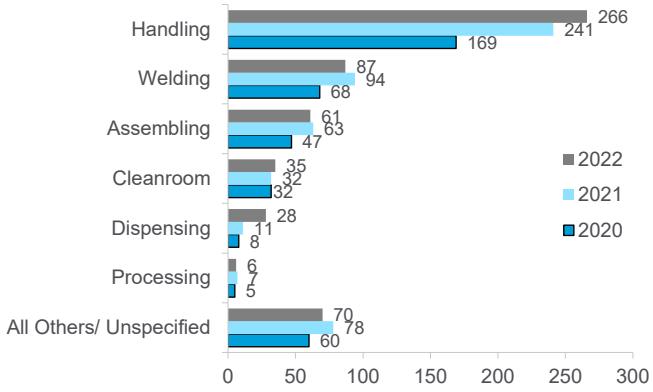
Graeme McDonald
Head of Pan-Asia Capital Goods Sector
Citi Research

The industrial robot market grew around 5% in 2022 following strong growth of 35% in 2021, despite issues like chip shortages. While final data for 2023 is not yet available as of the time of writing, the market in 2023 in terms of installations is supported by high backlogs and easing of bottlenecks, despite our expectation of negative order growth during 2023.

Demand for "cobots" (robots intended for interaction with humans) grew over 30% in 2022, outpacing the broader industrial robot market. However, cobots still remain a small part of the overall market in unit terms at less than 10%. In value terms, their penetration is even lower given their typically lower average selling price.

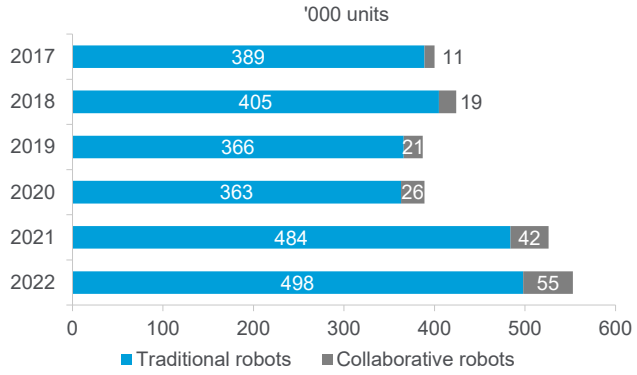
Since 2020, the electrical/electronic assembly market has overtaken automotive as the largest end-market. Handling — e.g., loading and unloading — remains the largest use case and was one of the fastest-growing uses for robots in 2022. Handling typically requires less dexterity than assembly, suggesting robots are still largely penetrating in repetitive and less complex tasks. We expect this to change over time as machine vision, complex end-of-arm tooling, and the software related to both continue to penetrate the robot market.

Figure 8. Global Annual Installations of Industrial Robots by Application ('000 units)



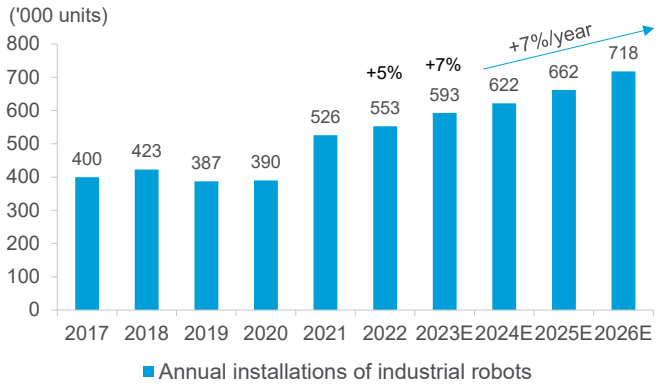
Source: Citi Research, IFR

Figure 9. Collaborative and Traditional Industrial Robots ('000 units)



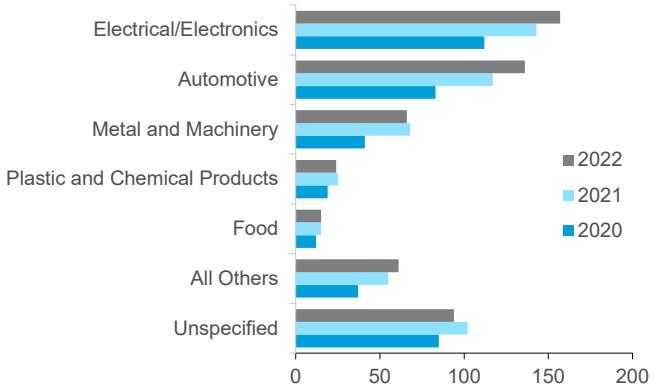
Source: Citi Research, IFR

Figure 10. IFR Expects Industrial Robot Growth to Increase ~7% Over 2022-26 After an Estimated 7% Increase in 2023



Source: Citi Research, IFR

Figure 11. Electrical/Electronics Has Maintained the Number-One Position in Installations Since 2020



Source: Citi Research, IFR

Lights-Out Manufacturing

Martin Wilkie
Co-Head of Industrial, Technology & Mobility Super-Sector
Citi Research

Graeme McDonald
Head of Pan-Asia Capital Goods Sector
Citi Research

As its name suggests, lights-out manufacturing requires little to no human intervention and is theoretically able to run on its own in the dark. The entire process — from raw materials delivery to finished goods — is automated. It is a more mature stage of the Fourth Industrial Revolution (Industry 4.0), although in practice, independence is not yet completely possible due to the continued need for human involvement in maintenance and inspection tasks.

Numerous factors, such as COVID-19, supply chain issues, and rising labor costs, have accelerated automation adoption. In order to become more resilient and less vulnerable to supply chain shocks, manufacturers, particularly in the West, want to move production closer to the point of consumption. This gives manufacturers an opportunity to rethink their manufacturing processes.

The lights-out concept makes most sense in process industries like pharmaceuticals or food and beverage, where human presence can contaminate products, or where the environment is dangerous. However, discrete manufacturing markets like automotive, electronics and electrical components, general manufacturing, and logistics and warehousing are also expected to accelerate their efforts to achieve completely automated lights-out manufacturing. A lack of human presence can have other benefits — some facilities with high penetration of fast-moving robots reduce oxygen levels to lessen the fire risk, making human occupation impossible during normal operating times.

Automotive manufacturing is already considered a highly automated industry, but lights-out approaches can take this further. The different technologies used to move towards lights-out manufacturing include AI, machine learning, IoT, sensors, machine vision, edge computing, cloud data, additive manufacturing, and digital twins.

The lights-out concept is not totally new, with some companies attempting the model in the 1980s and 1990s, but at that time, adoption was limited due to issues like constraints from fixed tooling and a lack of flexibility in production. The theme is gaining momentum again, however, with products ranging from industrial robots to electric shavers already made in such facilities.

Certain manufacturing operations, like picking parts from a box, are still largely performed by humans, even in highly automated factories and warehouses. A survey by Kearney and Drishti Technologies showed that humans still perform 72% of manufacturing tasks. And the specifics of some manufacturing operations and industries, such as short product life cycles, output variability, customization, and short production runs, may make lights-out technologies less feasible in those cases.

Robots-as-a-Service (RaaS)

Wenyan Fei
Analytical Insights Team
Citi Global Insights

Robots-as-a-Service (RaaS) is a subscription-based business model that enables manufacturers to rent robots to enhance the level of automation in their factories. Typically, manufacturers can also take advantage of integrated offerings such as robot algorithms, operating user interfaces (UIs), and periodic maintenance. The advantages are similar to those offered by other XaaS solutions like SaaS (Software-as-a-Service) and PaaS (Platform-as-a-Service). These advantages include:

1. Little upfront capital expenditure (no infrastructure required).
2. Flexibility and scalability in deployment.
3. Ready-to-deploy and up-to-date solutions (even customized for specific use cases).
4. Care-free hardware maintenance and system upgrades.

All XaaS solutions are cloud native. This enables the at-scale rental of these virtual services as if they were physical products, except that the marginal cost to onboard additional users is usually low. Providers of XaaS solutions also offer manufacturers the flexibility to opt out of the current service or switch to other platforms so that the trial-and-error cost is minimized.

RaaS robots can complete a variety of repetitive manufacturing tasks without fatigue 24/7/52. For example, they can assemble or weld parts together, load machines, package products, palletize products, and more.

In McKinsey's Global Robotics Survey, respondents indicated that the capital cost of purchasing robots (about $30,000 to $60,000) is the biggest concern hindering adoption.[1] RaaS solutions can solve this problem. Each robot in service is usually charged at an hourly rate, similar to how human factory workers are paid, but the robots are much cheaper (typically in the $2/hour to $8/hour range vs. $17.40/hour for the U.S. factory workers). Formic, a RaaS provider, claims their RaaS solution can be deployed 50% faster than standard approaches and can save manufacturers 42% on their operating expenses.[2]

Figure 12. Selected RaaS Robots' Hourly Rates

Company	Model	Hourly Rate ($/hour)
inVia Robotics	Picker	5.6
Mobile Industrial Robots (MiR)	AMR	4.4
OTTO Motors	AMR Model 100	2.3
Ronavi Robotics	AMR M500	1.9
Formic Technologies	Production Line Robots	8.0
U.S. Human Workers	$17.40	

Source: Company Reports, U.S. Bureau of Labor Statistics

[1] McKinsey & Company, *Industrial Robotics: Insights Into the Sector's Future Growth Dynamics*, July 2019.
[2] Manufacturing Automation, "New Robotics-as-a-Service Company Is Letting Manufacturers 'Hire' Robots," September 2021.

RaaS solutions are therefore quickly gaining ground on factory floors. According to ABI Research, the installed base for RaaS will grow to 1.3 million units in 2026 at a 10-year compound annual growth rate of 66%.[3] The corresponding revenue is expected to increase from $217 million to nearly $34 billion during the same period.[4]

Although the cloud market's oligopolistic nature and vulnerability to cyberattacks can cause concerns around adoption of XaaS solutions, RaaS is here to stay. According to Gartner, by 2025, cloud-native platforms will serve as the foundation for more than 95% of new digital initiatives — up from around 30% in 2021.[5]

[3] ABI Research, "Robotics-as-a-Service Is the Key to Unlocking the Next Phase of Market Development," May 8, 2019.
[4] Ibid.
[5] Gartner, "Gartner Says Cloud Will Be the Centerpiece of New Digital Experiences," November 10, 2021.

3D Printing: Technical and Economic Challenges to Mass Adoption

Wenyan Fei
Analytical Insights Team
Citi Global Insights

Amy Thompson
Social Economist
Citi Global Insights

3D printing offers four main benefits to supply chains:

- Increasing the customizability of products.
- Reducing the costs of production, including neutralizing the benefit of lower labor costs.
- Reducing waste.
- Simplifying supply chains and increasing speed to market. This can include re-shoring manufacturing closer to end-markets.

The companies deploying 3D printing beyond the prototyping phase are already reaping the benefits of reduced costs and increased customization. The medical and dental sectors have been early adopters of 3D printing. One example is clear aligners, a dental tool for straightening teeth, which SmarTech Analysis described as the "highest-volume application" of 3D printing.[6] The largest producer of this product is Align Technology, which produced 700,000 unique 3D-printed aligner parts per day in its manufacturing facilities across the globe in 2021.[7]

Aerospace and defense adoption accounts for over 15% of 3D-printing revenues.[8] In 2018, Airbus announced that it would install spacer panels manufactured by 3D printers on all its A320 aircraft. These panels are 15% lighter than those created with traditional manufacturing methods and can be produced at speed in low volumes.[9] Auto manufacturing has found similar uses for 3D printing in its supply chain, such as cradles and fixtures, which need the strength and durability provided by 3D-printed objects. For example, Ford won an award for its assembly lift assist, which cost less than 50% of the traditional counterpart while also reducing the lead time, and BMW has used 1 million 3D-printed parts in the last decade.[10] Future Bridge expects 3D printing in the auto market to reach $4.5 billion by 2025 and $7 billion by 2030, up from $1.5 billion in 2019.[11]

3D printing is also expected to expand into the consumer market. The 3D-printed footwear market is forecast to generate $5.9 billion in revenue by 2029, driven by customization for the mass market.[12] Additive manufacturing can also help reduce waste in the footwear market. Fitting into the circular economy, 3D-printed shoes can be biodegradable and made with recycled or recyclable materials.

---

[6] Davide Sher, "Latest SmarTech Analysis Report on AM in Dentistry Forecasts $9 Billion Market by 2028," April 4, 2019.
[7] Align, "Align Technology Expands Global Operations to Support Growth and Adoption of the Invisalign System in EMEA With Plans for Multi-Million Dollar Manufacturing Facility in Wroclaw, Poland," April 22, 2021.
[8] AMFG, "Industrial Applications of 3D Printing: The Ultimate Guide," accessed May 30, 2023.
[9] Ibid.
[10] Ibid.
[11] FutureBridge, "3D Printing – A Technology that Can Print Cars in Future on a Mass Scale?" June 11, 2020.
[12] SmarTech Analysis, "3D Printing in Footwear," PDF, accessed May 30, 2023.

Figure 13. 3D-Printed Shoes

Source: Shutterstock

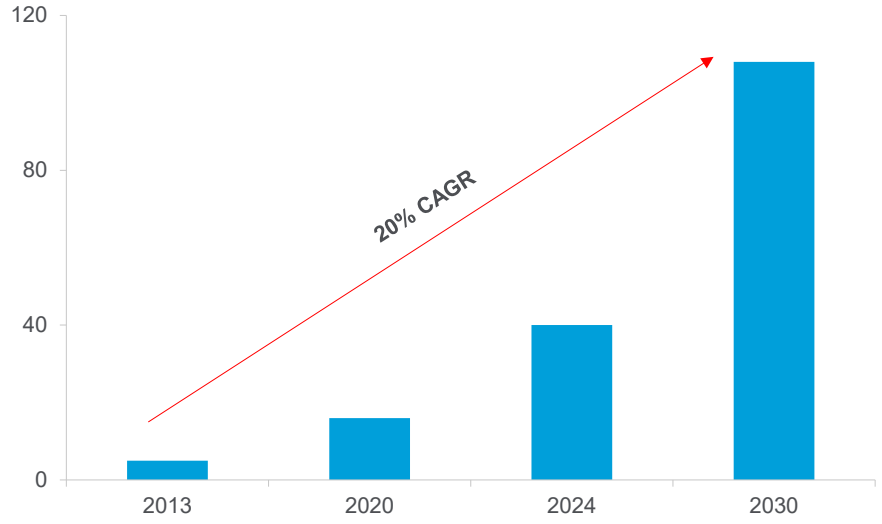
Several other consumer verticals could benefit from the use of 3D printing for customization. Customized helmets, for example, are already commercially available for cyclists. Helmet company HEXR claims to be able to build a 250,000-point model of a customer's head using a mobile phone app and then 3D print a helmet to fit perfectly.[13] This improves not only comfort, but also safety: HEXR statistics show that its custom helmets are 26% safer than traditional models.[14] The same products could also be used by motorcyclists, skiers, and American football players. Spectacles and even razor handles are also being incorporated into the customization trend.

Adoption Analysis

According to Statista, the 3D-printing market totaled $12.6 billion in 2020 and will reach nearly $60 billion by 2026.[15] Further estimates have the market surpassing $100 billion by 2030. By comparison, in 2013, the global 3D-printing market was worth less than $5 billion.[16] Uptake for 3D printing was accelerated by the COVID-19 pandemic. For example, the U.S. Department of Defense used additive manufacturing to shore up medical supply chains. The department used 3D-printing techniques to create N95 respirators, plus Continuous Positive Airway Pressure (CPAP) and Bilevel Positive Airway Pressure (BiPAP) masks for use during treatment.[17]

[13] HEXR, "Our Manufacturing Process," accessed May 30, 2023.
[14] HEXR, "Safety," accessed May 30, 2023.
[15] Statista, "Global 3D Printing Products and Services Market Size From 2020 to 2026," accessed May 30, 2023.
[16] Statista, "3D Printing Market Size Worldwide From 2013 to 2021," accessed May 30, 2023.
[17] Jeffrey Soares, "DOD Uses 3D-Printing to Create N95 Respirators," U.S. Department of Defense, January 25, 2021.

Figure 14. 3D-Printing Total Addressable Market ($ billions)



Source: Next Move Strategy Consulting

However, concerns around the availability of materials could hinder adoption. Ninety-four percent of additive manufacturing users claimed they sometimes chose traditional methods due to the lack of suitable 3D-printing materials, according a 2019 survey by Jabil.[18] This is a major challenge, especially in industries like aviation and healthcare, where parts require specific materials or certification before they can be used beyond prototyping.

For companies, embracing 3D printing requires a large initial capital expenditure in an entirely new production line. However, the trend towards reshoring supply chains could catalyze the adoption of 3D printing by providing a reset opportunity to make this initial expenditure. Although the price of 3D printers varies considerably across different intended use cases, the cost has come down in recent years — an entry-level 3D printer costs less than $300 today, compared to several thousand dollars a decade ago. As this cost is expected to continue to decrease, the capital investment will be more easily recouped by the much lower running costs of a 3D-printing-capable factory.

Manufacturers upgrading to additive methods must also develop new manufacturing ecosystems. For example, existing employees need to be reskilled to facilitate the transition. Forty-three percent of respondents to Jabil's survey noted that a lack of skilled staff and subject matter experts held them back from reaping the maximum benefits of additive manufacturing.[19] Currently, this leads to just under half of companies outsourcing their additive manufacturing work.[20]

[18] Jabil, "Top 3D Printing Challenges (And How to Overcome Them)," accessed May 30, 2023.
[19] Ibid.
[20] Jabil, "3D Printing Technology Trends," March 2021.

Automated Mobile Robots and Automated Guided Vehicles

Wenyan Fei
Analytical Insights Team
Citi Global Insights

In the future, fewer and fewer factory workers will be busy forklifting products and parts around — this can be done more efficiently and effortlessly by specialized robots called Automated Mobile Robots (AMRs). Unlike their predecessors Automated Guided Vehicles (AGVs), which can only follow predetermined routes and often require operator oversight, AMRs are more intelligent and can navigate the factory floor independently.

Hiring in the manufacturing industry was made increasingly challenging by the pandemic. The most recent manufacturing labor storage in the U.S. stood at 676,000 in April 2023, around 6% of overall employment in the sector.[21] Material handling used to account for 20%-50% of total operating costs in factories and remains a significant part of labor expenses.[22] Looking forward, a report from Deloitte suggests there will be 2.1 million unfilled manufacturing jobs in the U.S. by 2030.[23] Leaving this gap unfilled would cost the U.S. economy $1 trillion by 2030.[24] With the cost of robots dropping rapidly at the same time, AMR solutions are attracting attention from manufacturers struggling to find quality workers.

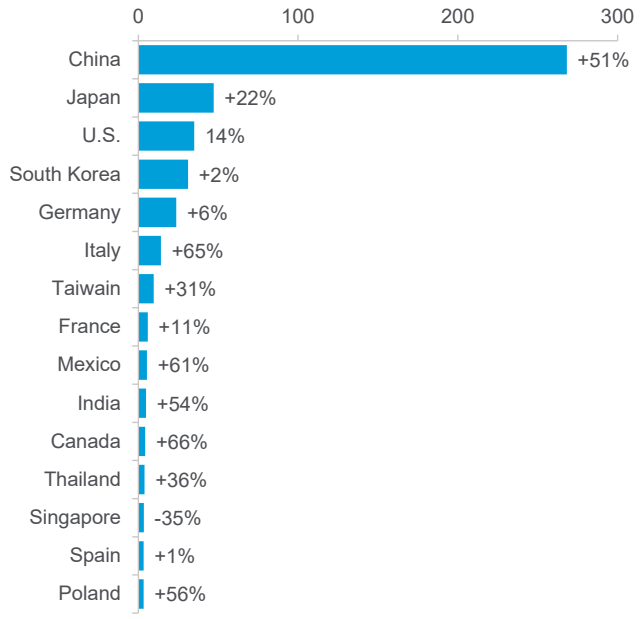
We are still in an early stage for AMR deployment in smart factories — commercial deliveries at-scale only started in 2021, when AMRs surpassed AGVs in revenues for the first time.[25] According to MiR, a mobile robot manufacturer, the International Federation of Robotics (IFR) said that global sales of AMRs and AGVs increased 45% from 2020 to 2021.[26] The growth rate further accelerated to 53% in 2022.[27] Interact Analysis projects the total number of material transport mobile robots installed will grow at a 41% CAGR and surpass 1 million units by 2027.

The secret behind AMR's intelligence is Simultaneous Localization and Mapping (SLAM). SLAM technology enables each robot to explore its unknown yet ever-changing environment by continuously mapping the area while keeping track of its own location via a real-time information feed. Current industrial solutions focus on visual SLAM, in which the robots are equipped with advanced cameras and AI processors to enable vision and automated decision-making (e.g., route planning and collision avoidance).

[21] U.S. Bureau of Labor Statistics, "Job Openings Levels and Rates by Industry and Region," Accessed June 27, 2023.
[22] James A. Tompkins et al., *Facilities Planning, 4th Edition*, (Wiley, 2010).
[23] Paul Wellener et al., "Creating Pathways for Tomorrow's Workforce Today," Deloitte Insights, May 4, 2021.
[24] Ibid.
[25] Ash Sharma, "100,000 Mobile Robots Shipped in 2021," Interact Analysis, March 22, 2022.
[26] Supply Chain Quarterly, "U.K. Lags in Global Adoption Rate of Warehouse Robots," accessed June 1, 2023.
[27] Ash Sharma, "Mobile Robot Shipments Grow by 53% in 2022," Interact Analysis, December 8, 2022.

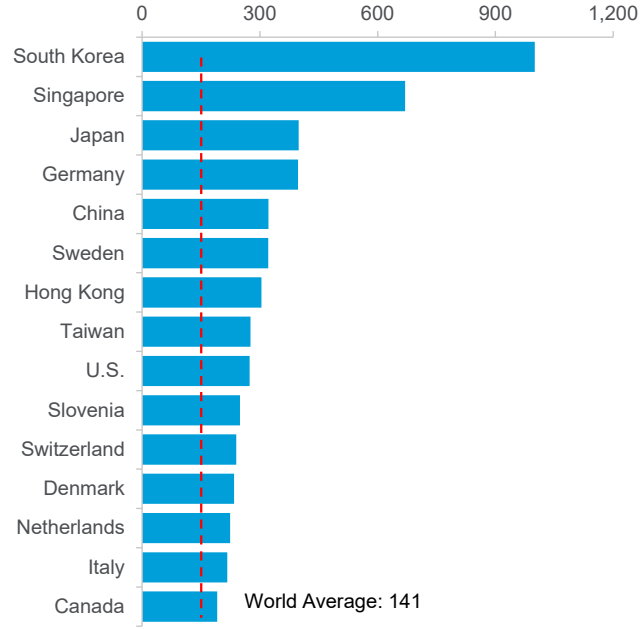
China has gained momentum in the robotic space in recent years. According to IFR, China surpassed the U.S. in robot density in 2021, ranking fifth in the world.[28] China also accounted for 40% of global mobile robot shipments in 2021. The country's share dominance is expected to continue for another five years.[29] The mobile robot market landscape is very different in China than in the U.S. and Europe. Chinese vendors currently focus more on lower-cost AGVs, whereas the U.S. and EMEA vendors favor AMRs.

Figure 15. Annual Industrial Robot Installations ('000 units)



Source: World Robotics 2022

Figure 16. 2021 Robot Density in Manufacturing (Robots Installed per 10,000 Employees)



Source: World Robotics 2022

Case Study: OTTO Motors

OTTO Motors provides "AMR-as-a-Service" solutions for factories. At the 2021 International Manufacturing Technology Show (IMTS) conference, OTTO claimed to be the world's first provider to commercially deploy an AMR solution at scale in the factory of a Fortune 500 company.[30] The AMR system is especially advantageous compared to other options like forklifts or human labor when a factory is large and the transport link is long. In one mega-factory occupying 1 million square feet where 100% of the transportation is done through an AMR fleet, 1,100 total miles are traveled with 5,200 tasks completed every day.[31]

[28] International Federation of Robotics, "World Robotics 2022," PDF, accessed June 1, 2023.
[29] Ash Sharma, "100,000 Mobile Robots Shipped in 2021," Interact Analysis, March 22, 2022.
[30] OTTO Motors, "IMTS Conference: The Business Case for Autonomous Mobile Robots in Manufacturing," video, accessed June 1, 2023.
[31] Ibid.

According to OTTO, the potential cost saving is huge when deployed at scale. The standard OTTO 100 model (1:1 human capacity) works 24/7/52 for an annual cost of $15,000-$25,000 per vehicle (around $2.30/hour), while the larger OTTO 1500 model (4:3 human capacity) costs $40,000-$50,000 per vehicle annually (around $3.90/hour). The cost of OTTO AMRs is 10% of that of a labor equivalent, 20% of that of a forklift driver equivalent, 50% of that of a conveyor system equivalent, and 66% of an AGV system equivalent. As a result, the payback period is quite favorable — less than 1 year for a system lease and 1-2 years for a vehicle-only lease.[32]

[32] Ibid.

Warehouse — AS/RS Market: Structural Growth From Mega-Trends

Martin Wilkie
Co-Head of Industrial, Technology & Mobility Super-Sector
Citi Research

During and immediately after the pandemic, most warehouse investment was focused on e-commerce fulfilment, driven by the surge in e-commerce sales precipitated by lockdowns. Following a surge in e-commerce sales growth rates to over 50%, e-commerce sales growth has reverted to trend levels of around 10% annually. This coincided with a surge in supply chain bottlenecks and a shift of focus of warehouse automation from e-commerce fulfilment to supply chain resiliency.

Warehouse Automation Still in Early Stages

Automation of warehouse operations can reduce order fulfilment lead times substantially through more efficient picking processes. It also enables a flexible supply chain that can handle fluctuations in demand without corresponding fluctuations in employment.

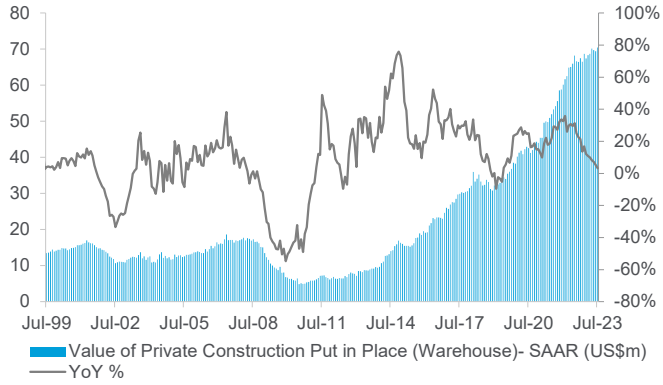
There are a number of stages involved in the warehousing process. After goods are transported to the site, the remaining stages are as follows:

- **Depalletization:** Unloading goods from large crates or pallets for storage.
- **Sorting:** Sorting the goods after the pallet is opened.
- **Storage and picking:** Retrieving the required goods from storage shelves.
- **Packaging:** Packaging the goods for fulfilment.
- **Transportation:** Transporting packaged goods away from the site.

Automated storage and retrieval systems (AS/RS) tackle the storage and picking part of this chain. Thus, to truly automate the warehouse fully, there are other elements required, such as depalletization.

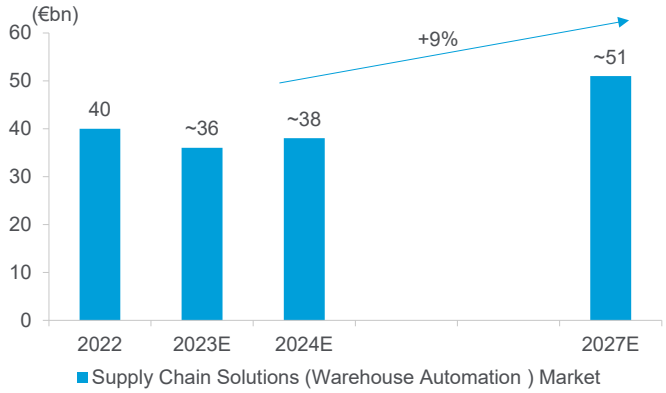
AS/RS is arguably the most complex part of automating the warehouse. As with other stages of warehouse management, it is still largely manual today. A 2020 report by LEK Consulting, *The Evolving Warehouse Automation Market and the Implications for Investors*, suggested that around 60% of existing warehouses use limited or no automation, with only 1%-2% of warehouses having become "lights-out," fully automated facilities. According to another consultant report, the AS/RS market penetration rate should grow from 15% in 2021 to 36% in the next 10 years, so most picking will still be still manual. Within the broader warehouse automation market, micro-fulfillment is one of the fastest structurally growing areas. Among the products, mobile automation is expected to grow at a CAGR of ~36% over 2022-27 (see Figure 20).

Figure 17. Though Growth Rates Have Come Down, U.S. Warehouse Spending Is Still Up Following Acceleration From COVID-19-Induced Lockdowns and e-Commerce Demand



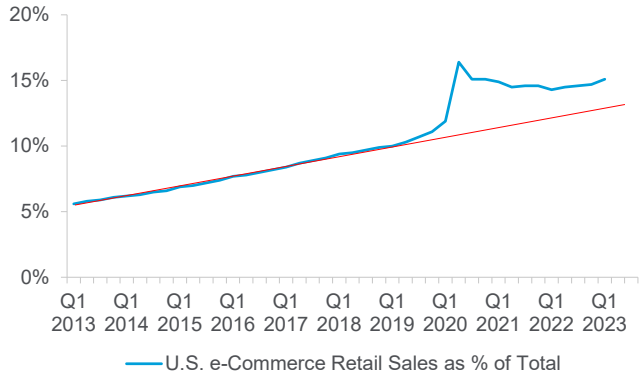
Source: Citi Research, DataStream

Figure 18. Overall Market Is Expected to Show High Single-Digit CAGR Over 2023-27



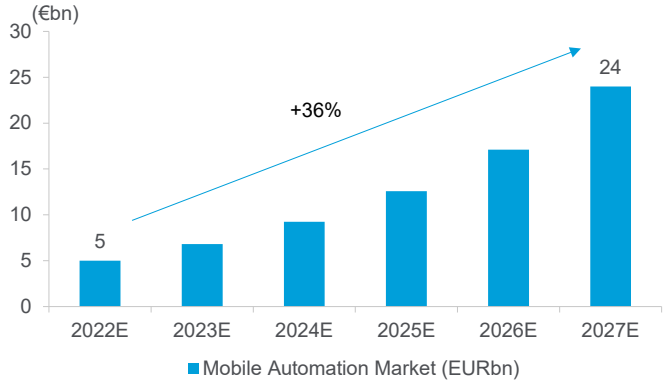
Source: Citi Research, KION, Interact Analysis

Figure 19. Though e-Commerce as a % of Total Retail Sales Came Down From Over 16% in Q2 2020, It Has Started Increasing Again, Resulting in the Step Change



Source: Citi Research, DataStream

Figure 20. Mobile Automation Market Is Expected to Show a ~36% CAGR Over 2022-27



Source: Citi Research, Interact Analysis Mobile Robot Market – Mid-Year Update May 2023, KION

Segment II: Delivery and Recycling

Loading/Unloading Robots

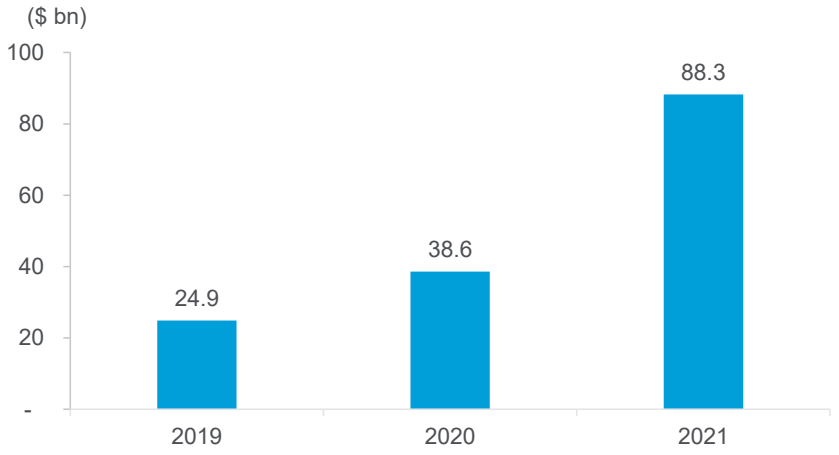
Ports:
Sathish B. Sivakumar
Head of EMEA Transportation Team
Citi Research

Factories:
Martin Wilkie
Co-Head of Industrial, Technology & Mobility Super-Sector
Citi Research

Port Automation

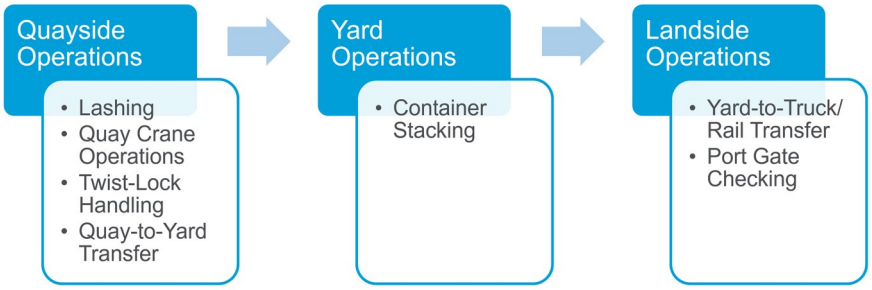
Sea freight rates increased by a factor of 4.5x between 2020 and 2022. This was mainly driven by the bottleneck at ports, both on the sea and land sides, during the pandemic. For example, when the U.S. economy opened up in the third quarter of 2020 following the first pandemic-related lockdown, imports surged. However, the social distancing protocols at ports resulted in a drop in throughput, especially at ports that were not automated. We estimate the capacity bottleneck at ports cascaded into different parts of the supply chain, resulting in a threefold increase in shipment time. This led to the 4.5x increase in freight rates between the third quarter of 2020 and the second quarter of 2022.

Figure 21. Cost of Container Freight Imports Into the U.S.



Source: Citi Research, SCFI

Figure 22. Movement of Cargo in Ports



Source: Citi Research

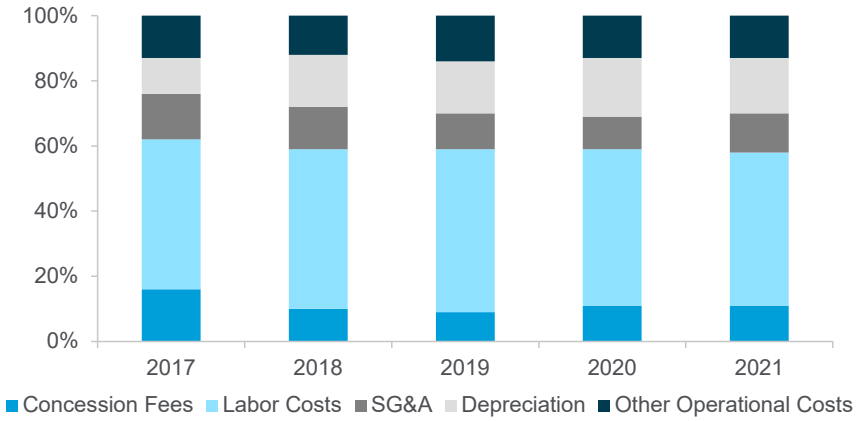
According to the OECD, only around 4% of container terminals in the world are automated. The percentage of automated terminals in the U.S. is only somewhat higher at around 11%, compared to Asia at around 32% and Europe at around 28%. The benefit of automation is not just lower handling costs (i.e., lower labor costs) but also increased reliability. The use of robots to unload containers from a ship to the yard, and from the yard to trucks and rail, will increase throughput and reduce the ship dwell time, i.e., the amount of time spent in port loading and unloading cargo.

In the quayside (see Figure 22), a crane can only handle one container at any given time. In the yard, however, an automated crane provides additional capacity during downtime by moving containers so that dwell time decreases when a truck comes in to load and unload the cargo boxes.

Productivity: Port Throughput

The automation of a port will help to reduce labor costs, which typically account for around 50% of costs for port operators. Automation also enables the port operator to better address seasonality by easily switching the port to operate more than one shift in the period of peak demand. To illustrate, in the fully automated Port of Rotterdam, productivity is twice that of the Port of Oakland.

Figure 23. APM Terminals Cost Evolution: 2017 to 2021

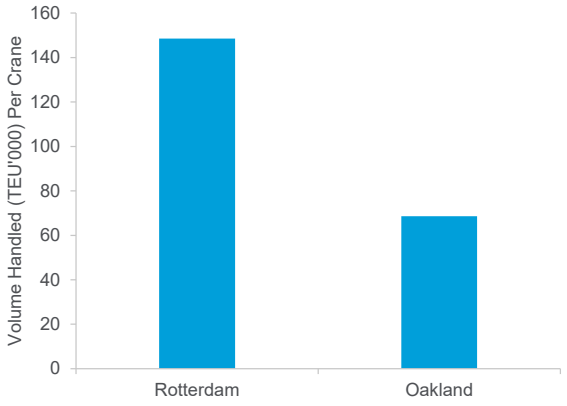


Source: Company Reports

Cost Benefit

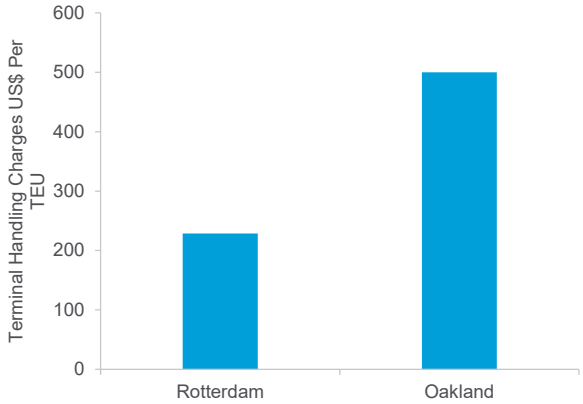
Based on the terminal handling charges disclosed by liners, we estimate that the Port of Rotterdam charges around 45% less per box of cargo handled than the Port of Oakland. When extrapolating from the fact that the Oakland port handles around 10% of total U.S. imports, we believe moving to full automation at the Port of Oakland could result in around $7 billion of cost savings per year.

Figure 24. Port Productivity: Rotterdam vs. Oakland



Source: Citi Research, Company Reports

Figure 25. Automation Lowers Cost for Shippers



Source: Citi Research, Company Reports

Autonomy Can Disrupt Traditional Trucking

Christian Wetherbee
Global Head of Transportation Sector
Citi Research

From a market size perspective, the global freight transportation industry is attractive for potential disruption. The total global freight market size is around $4 trillion, with China, the U.S., and Europe representing around $1.7 trillion, $800 billion, and $400 billion, respectively. A shift to autonomous trucking could help overcome the driver shortage constraining the market. Drivers make up around 40% of the cost per mile of trucking. TuSimple was the first autonomous vehicle (AV) trucking company to successfully complete a "driver out" run, and we believe that a ramp-up in autonomous truck production will occur in 2024-25 (depending on original equipment manufacturer issues) and will scale further over time.

The Middle Miles Are Up for Grabs

Autonomous trucks are disrupting a specific type of freight mile: on-highway middle-miles, performed by a specific type of vehicle — Class 8 tractors (i.e., tractor trailers). Additionally, autonomous trucking companies will be more focused on the U.S. market, at least initially. To calculate AV trucks' addressable freight miles, we estimate the active population of Class 8 sleeper and day cab tractors is around 1.9 million as of October 2021, and by 2024-25, the market is anticipated to grow to over 115 billion miles.

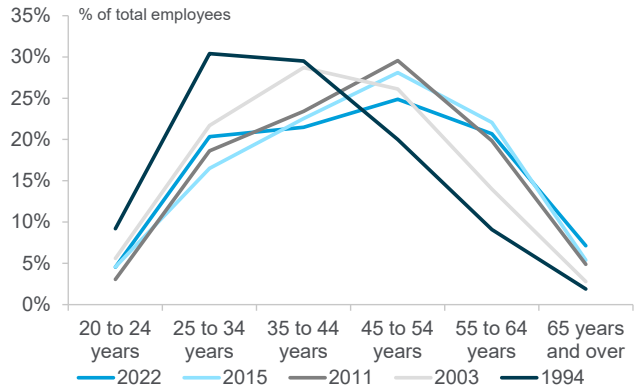
AV trucking companies intend to focus on the middle mile of freight transportation, which excludes the first and last mile of the load's trip from origination to destination. Looking at census data, around two-thirds of total miles represent what we would view as middle miles, which exclude very short-haul moves and the first and last miles within longer moves (essentially, this excludes the first and last 50 miles in moves above 100 miles). This places the annual addressable market for AV trucking companies in the range of 70 billion miles currently, and 80 billion by the time AV truck market penetration is accelerating — or an annual addressable market of $30 billion to $35 billion.

Addressing the Driver Shortage

Part of the appeal of Level 4 ("highly automated") autonomous tractors is that they address the qualified driver shortage.[33] Driver shortages have seemingly been a hindrance to the trucking industry for decades. The problem worsens during periods of strong economic activity, as driving is a difficult profession with many undesirable lifestyle characteristics such as extended time away from home, often for days or weeks at a time. As a result, driver turnover is extremely high in the Truckload industry, typically exceeding 100%. Moreover, the core driver population is aging, as illustrated in Figure 26 and Figure 27

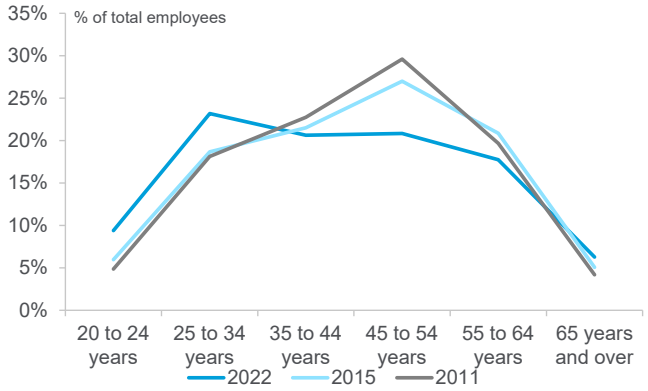
[33] Level 4 autonomy is "highly automated," meaning the vehicle does not require any human interaction in proper settings to operate. Drivers can override the automated system, which will disengage, but the system will not prompt the driver to take control. Level 5 autonomy is "fully automated," meaning the vehicle can operate on any road without human navigation — the vehicle will navigate all operations on its own.

Figure 26. The Truck Transportation Labor Force Has Aged



Source: Bureau of Labor Statistics, Citi Research

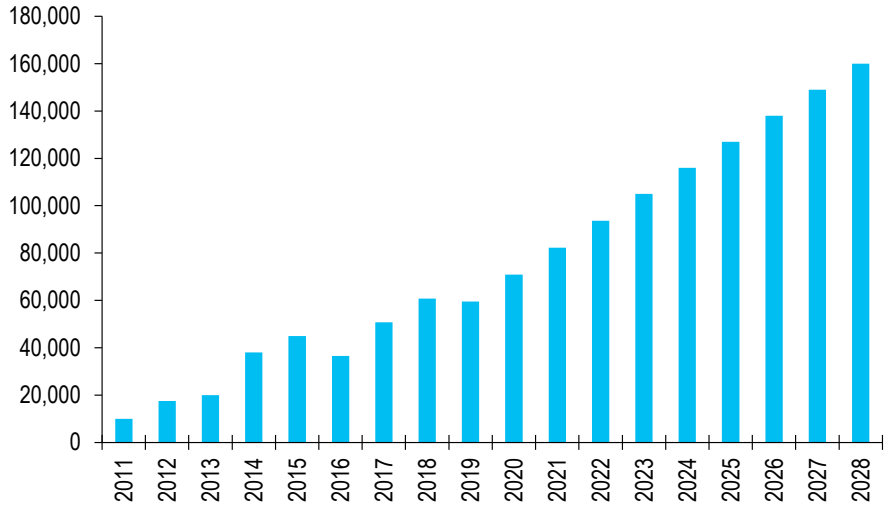
Figure 27. Transportation and Warehousing Labor's Age is More Static



Source: Bureau of Labor Statistics, Citi Research

The American Trucking Associations (ATA) estimated that 2019 would see a shortage of around 60,000 truck drivers. We estimate that shortage figure increased to slightly more than 70,000 by 2020, which equates to a low-double-digit percentage of the over-the-road (OTR) fleet, but a surplus of drivers emerged in 2H 2021 and 2022 as freight demand weakened. Looking forward, the ATA expects the driver shortage number to more than double to around 160,000 in 2028. This is likely predicated on a more robust freight market than we are currently in.

Figure 28. Driver Shortage Is Expected to More Than Double Over Next Decade



Source: Citi Research, ATA

Relative Simplicity of AV in Freight vs. RoboTaxi

Given differing technical and business considerations across the spectrum of AV operating domains (i.e., cities vs. highways), AV developers have increasingly focused their resources on achieving autonomy in one or two automation domains (Level 4) as opposed to attempting to achieve autonomy everywhere (Level 5).

Broadly speaking, the AV landscape can be broken down into the following applications: urban "RoboTaxis," commercial trucking, last-mile delivery and robotics, and consumer AV features and applications. Each has its own unique (and large) total addressable market (TAM), network effects, and risk-reward consideration, but all are effectively leveraging the same value-unlock that AVs enable — a substantially lower vehicle operating cost per mile and, in some cases, the potential for higher revenue per mile.

Below, we compare key aspects of the RoboTaxi end-market with that of autonomous commercial trucks. Key points are:

- Both appear to have significant addressable markets.
- RoboTaxis are a more complex domain than commercial trucks, which comes with both pluses (greater network effects) and minuses (greater risk of delays, more competition) compared to the commercial truck market.
- The AV development track differs across the two markets in some respects. RoboTaxis generally operate at lower speeds (up to 35 miles per hour), whereas commercial trucking requires high-speed performance and therefore greater range requirements.
- RoboTaxi development is arguably more transferrable to consumer AVs.

Figure 29. Urban RoboTaxi vs. Commercial Truck Considerations

	Urban RoboTaxi	Commercial Truck
U.S. TAM	~$350 billion	~$250 billion
@ Revenue/Mile	$1.00	$1.45
AV Complexity	Highest	High
Key Issues	City driving (turns, pedestrians) Rider experience (speed, assertiveness)	High speed (range) Handling detours
Purpose-Built Vehicle	Very important	Less critical initially
Network Effect	1. Deploy AVs (> human safety) 2. Purpose-built AV = higher load factor 3. Higher load factor = lower fares 4. Lower fares = more demand 5. More demand = more data 6. More data = improved performance 7. More data = expanded ODD 8. Improved performance + ODD = more demand 9. More demand = scale (cost savings)	1. Deploy AVs (> human safety) 2. More VMT = more data 3. More data = improved safety/performance 4. Improved safety/performance = more demand 5. Improved safety/performance = expanded ODD 6. Expanded ODD = more demand 7. More demand/VMT = more data
Competition	Highest	High
Migration to Consumer AV	Visible path	Less visible path

Source: Citi Research, Company reports

Future of Freight Could Include Airborne Delivery

Drone technology is a potential alternative for short-distance package deliveries. We believe the total addressable market for drone delivery in the U.S. includes not only launching drones from fixed locations (as Amazon has been developing since the late 2000s), but also launching them from mobile locations such as the roof of a delivery truck. This could be suitable for integration on UPS and FedEx routes, particularly inefficient rural routes. The investible opportunity here is more than science-fiction. We estimate the drone delivery market to consist of nearly 1.3 billion in total small packages per year, with 75% (965 million packages) driven by e-commerce sales, which would continue to scale along with more online sales.

While drone delivery still has many hoops to jump through — technological viability, operational infrastructure, and regulatory barriers, to name a few — the use cases are evident. We see a world where a rural delivery driver can deploy a drone at Stop 1 to deliver at Stop 2 and can then reconnect with the drone at Stop 3. Setting aside the capital intensity of setting up the network and purchasing the drones, we believe the economics could be made viable by one driver effectively becoming two, increasing the efficiency of each route by reducing fuel and labor costs.

Hyperloop: High-Speed Transportation System With an Initial Focus on Freight

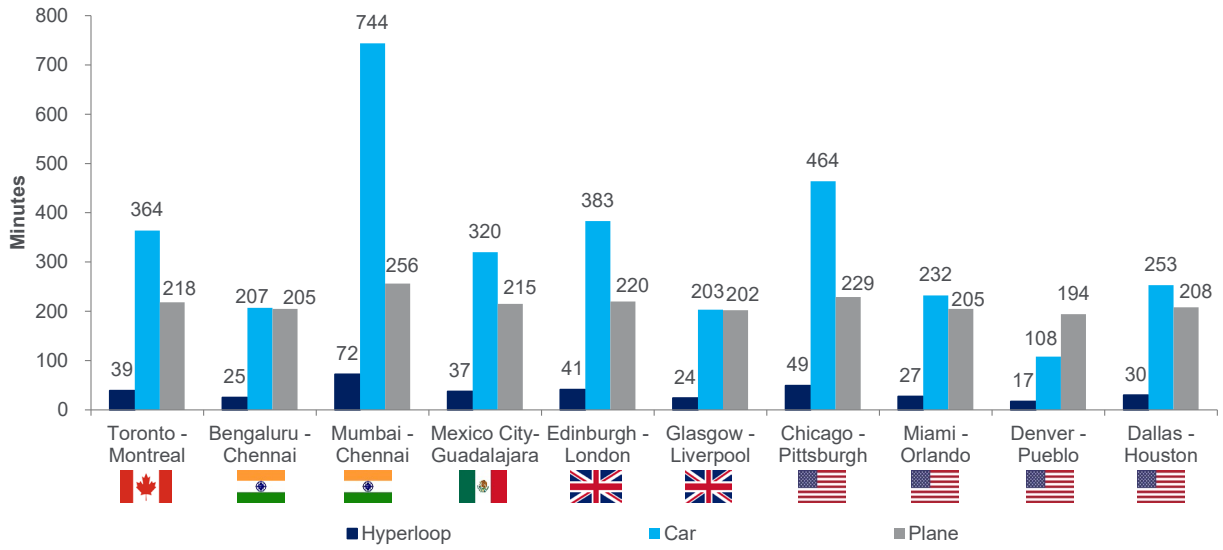
Sathish B. Sivakumar
Head of EMEA Transportation Team
Citi Research

During the pandemic, we saw cargo shipment time increase by two to three times for trips across the U.S. and to Europe from Asia. Delays in shipments were partly due to bottlenecks on the land side of the supply chain driven by truck driver shortages. Hyperloop infrastructure — which would enable passengers or freight in capsules to travel at high speeds (up to 760 miles per hour) through a network of vacuum-sealed, low-pressure tubes using a combination of induction motors, magnetic levitation, and air propulsion systems — could offer several solutions and advantages.

Faster Movement of Goods

The big advantage of hyperloop technology is around the speed of cargo transport. We believe that faster movement of goods will make supply chains more efficient by reducing the amount of inventory at warehouses, thereby freeing up capital. The rise of e-commerce has resulted in companies either building up inventory or nearshoring to respond to customer needs swiftly. However, we believe hyperloop technology will be able to address both the e-commerce industry's push for faster delivery times and the need to build regional fulfillment centers.

Figure 30. Hyperloop vs. Other Modes of Transport



Source: Eurosender, Citi GPS

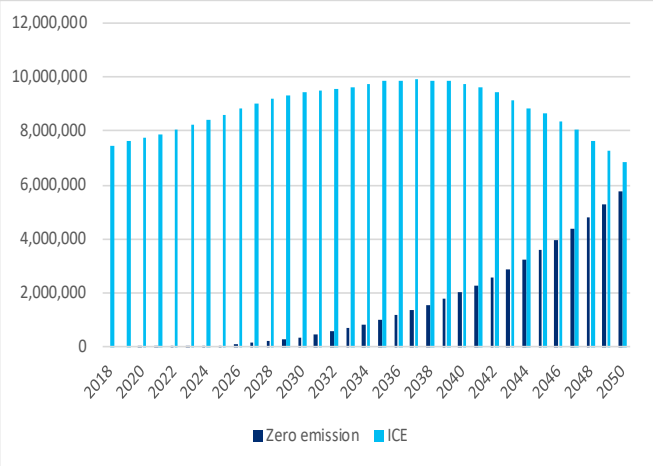
Scope to Replace Intracity Air Freight

Today, air freight constitutes about 4% of global freight. But the significance of air freight is around the speed of delivery. It takes around 20 to 30 days to move cargo from Asia to North America and Europe via shipping, and it takes about 10 hours to move the same cargo through air. Hence, products like perishables, as well as high-value but low-weight goods like pharmaceuticals and technology, have relied on air freight given the high cost. But we see scope for intra-continent movement of air freight via hyperloop technology. According to Eurosender, hyperloop could help reduce freight movement costs by a factor of eight compared to air freight. This modal shift would also come with zero direct emissions.

Environmental Benefits

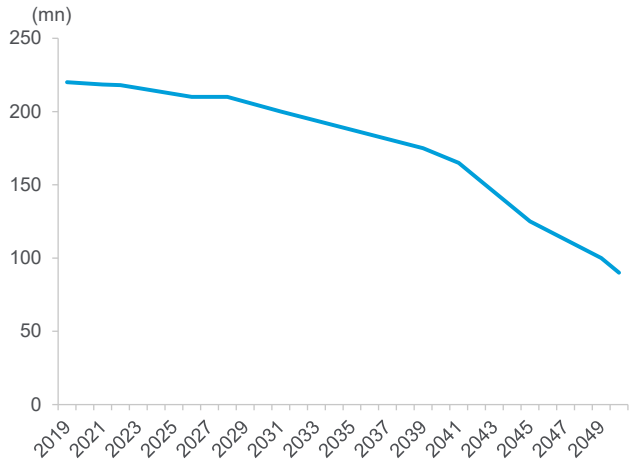
The lack of net-zero technology in transportation currently means that achieving carbon neutrality in 2050 would result in a prohibitively costly asset refresh cycle. If we assume around a 4%-5% underlying refresh rate for European trucks annually, the fleet will take 20-25 years to be fully converted to 2020 technology standards. This would imply only zero-carbon vehicles could be sold after 2030 to reach complete carbon neutrality by 2050. If we assume CO_2 emissions can be improved for the diesel fleet by 2.5% annually until 2050 and that all new truck purchases have zero-emission powertrains at that point, we still forecast the industry generating approximately 100 million metric tons of CO_2 annually. Crucially, over the period to 2050, we forecast that the industry generates 5,000 million metric tons of CO_2. While trucking may only be 6% of European CO_2 emissions today, we estimate it will consume roughly 10% of Europe's remaining carbon budget by 2050.

Figure 31. European Truck and Bus Fleet by Powertrain



Source: ACEA, Citi Research

Figure 32. Metric Tons of CO_2 Produced Annually by European Trucks and Buses



Source: European Federation for Transport and Environment, Citi Research

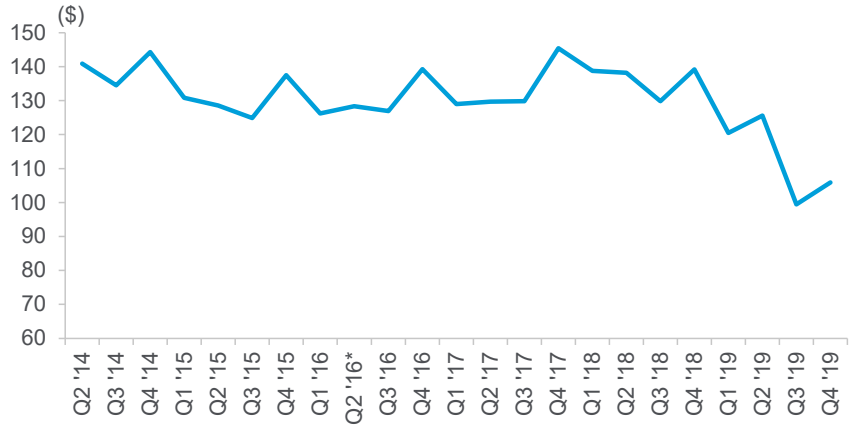
We estimate refreshing the entire truck fleet within a 10-year period (versus the normal 20 years) would cost about €1 trillion (around $1.05 trillion as of October 12, 2023) before any external costs like infrastructure investment or restructuring of manufacturing capabilities are considered. We see that, despite spending close to around €1 trillion to decarbonize the overland movement of freight, there will still be challenges such as increased congestion on roads, resulting in longer lead times. Hence, hyperloop technology could help us address the challenges of emissions and congestion to deliver clean and swift movement of freight.

Automated Parcel Sorting

Sathish B. Sivakumar
Head of EMEA Transportation Team
Citi Research

In the full supply chain, parcel operators play a vital role in the last-mile segment. We estimate that parcel logistics infrastructure operators typically capture around 10% of the e-commerce value chain. Parcel volumes have increased primarily due to the rise of e-commerce. They have also risen as networks of postal companies deliver the scale and configuration to allow relatively low delivery costs for small business-to-consumer (B2C) parcels, particularly to relatively infrequent shippers such as consumers and micro, small and medium-sized enterprises (MSMEs). Historically, integrators and parcel competitors have focused primarily on business-to-business (B2B) markets with higher drop density and less complex re-delivery requirements than B2C markets, albeit with far greater dependence on major customers. However, the boom in e-commerce has meant that parcel logistics operators have seen a mix shift toward B2C volumes. The increase in B2C mix comes with reduced basket size (i.e., more parcel volumes).

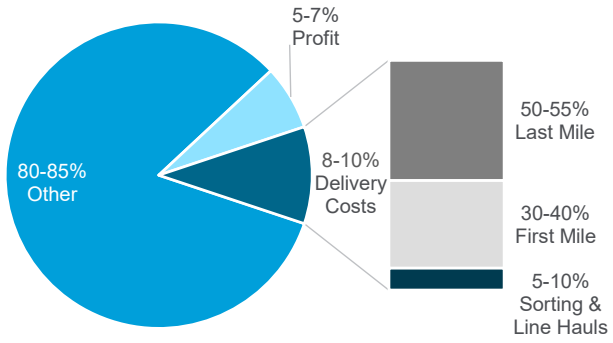
Figure 33. Average Basket Size: eBay



Source: Statista

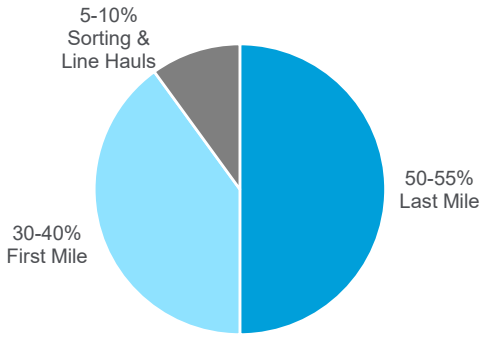
The decrease in basket size coupled with demand seasonality is likely to drive investment in end-to-end automation of sorting facilities. As in any network, utilization rates (i.e., the share of workers' hours spent on productive work for clients) are vital for last-mile logistics providers, with high utilization providing a virtuous cycle of rising volumes, supporting efficiency in drop density and lowering the marginal cost of delivery. When looking at a parcel delivery network, sorting and line hauls account for up to around 10% of the cost mix.

Figure 34. Traditional E-Tailer Cost and Profit Split



Source: Company Reports, Citi GPS

Figure 35. Breakdown of Parcel Network Costs

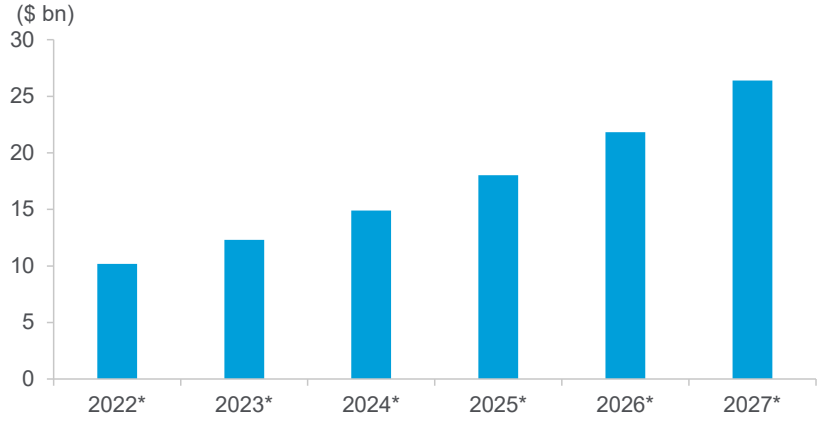


Source: Company Reports, Citi GPS

Benefits of Automation

- **Cost Benefits and Improved Efficiency:** We see automation of sorting hubs and fulfilment centers as important in driving down costs. For example, at around 50% e-commerce penetration, we estimate the parcel logistics (B2C) market in Europe is about $316 billion and the automation of hubs and fulfilment centers represents a $100 billion opportunity.
- **Reduced Impact of Seasonality:** Automation helps to address seasonality, as the industry hires around 25% more personnel during peak delivery season. The automation of sorting hubs will help meet peak-season demand without the need for additional temporary labor.
- **Service Improvement:** Automation also plays a crucial role in providing merchants with later cut-off times for next-day or same-day delivery. The global same-day delivery market is likely to more than double by 2027.

Figure 36. Global Same-Day Delivery Market Size (Estimates)



Source: Statista

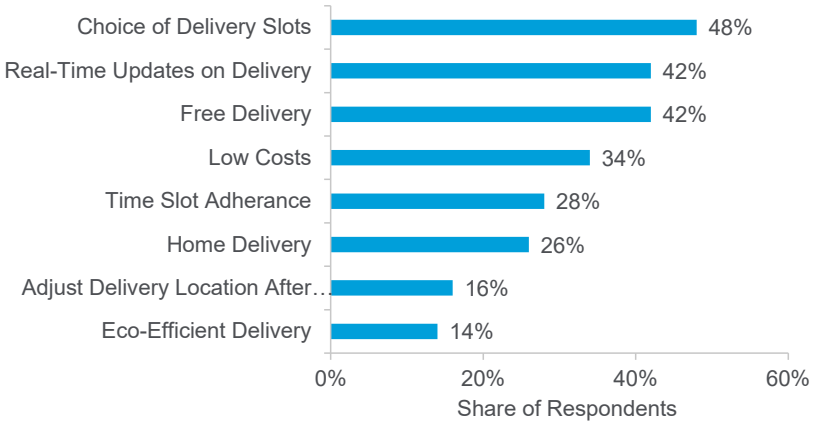
Last-Mile Delivery

Monique Pollard
Co-Head European Internet Team
Citi Research

Wenyan Fei
Analytical Insights Team
Citi Global Insights

Last-mile delivery in supply chains is the movement of goods from a transport hub to their final delivery destination (often a residential address in the case of B2C goods). Last-mile delivery is the most expensive part of the supply chain, and the ongoing online channel shift, e-commerce, and customer preferences for home delivery are fueling its expansion. Last-mile delivery costs are falling, but for a step change in costs (and emissions for bulky goods) to occur, automation is necessary. Food delivery and rapid grocery operators have created relatively efficient last-mile logistics networks, often with very few emissions, but they do rely on goods being under a certain weight/bulk and so are not a blanket solution. Public companies are scaling back their in-house testing and investment in automation given a focus on cash flow and profitability in the wake of rising rates, and so will increasingly look to outsource or partner instead.

Figure 37. Customers' Wishes on Last-Mile Services From Retailers, 2020

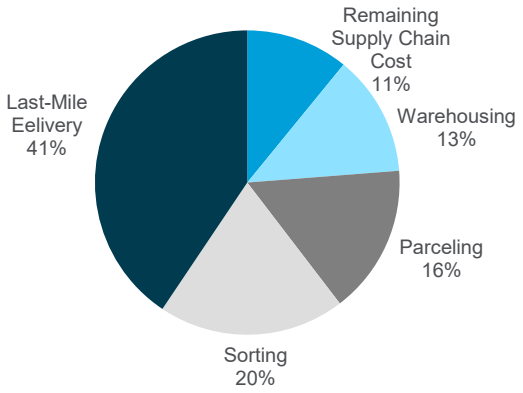


Source: Statista

According to Statista (see Figure 38), last-mile delivery represented about 41% of total global supply chain costs in 2018. It is a critical but incredibly costly part of most operators' supply chains (for context, warehousing represents just 13% of supply chain costs, according to Statista). As a result, there is rising scrutiny and focus on the best ways of optimizing last-mile delivery, with a lot of funding consequently being focused on this area (Figure 39).

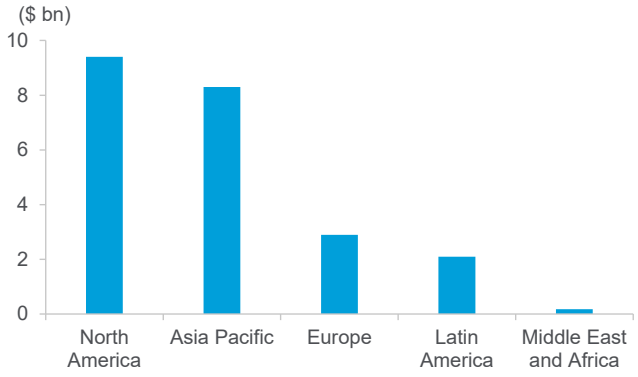
Importantly, last-mile logistics is an industry in its own right, addressing local commerce needs for customers who are increasingly making purchases online. Examples include the delivery of food, groceries, pharmaceutical products, and other essentials. In many ways, the global online food and grocery delivery players, through their buildout of local logistics networks, have created an infrastructure that is usable for a broader range of goods, as long as they are not too bulky or heavy. Indeed, it is these logistics networks and their ability to address local commerce needs that have likely led to Amazon's partnership and 12% equity investment in UK online food delivery operator Deliveroo, as well as its partnership with Grubhub in the U.S. (which includes up to a 15% equity stake via warrants).

Figure 38. Share of Supply Chain Costs by Type Worldwide, 2018



Source: Citi Research, Statista

Figure 39. Global Last-Mile Startup Funding by Region, 2020



Source: Citi Research, Statista

Given the materiality of last-mile delivery costs and the incentives to optimize them, we look at both the evolution and breakdown of these costs for food delivery operators over time. For an operator like Deliveroo, 92% of its costs of sales in 2020 were rider costs. The company's cost of sales per order (which is determined mostly by the rider cost per order) has shrunk at a 6.3% CAGR since 2018. Food delivery operators have made good progress in reducing last-mile logistics costs via better rider productivity (i.e., more drops per hour), enabled via more advanced routing and restaurant optimization technology. However, these operators can only address last-mile logistics needs that are based on small and relatively unbulky items, as they rely on human riders to carry the deliveries. For a step change to be made in last-mile logistics costs, automation will be required.

Automated last-mile delivery technologies fall into four key categories:

- **Drones:** These are unmanned aerial vehicles that can be used to deliver packages and goods in areas where road access is difficult. However, they face many regulatory issues and constraints (e.g., landing space, air traffic, security, and noise pollution), as well as range limitations, that lead us to believe they are unlikely to be a scalable solution in urban areas.
- **Legged Robots:** These robots are far more likely to be useful at other points within the supply chain, such as warehousing. Their limited speed and range mean they are largely unsuitable for last-mile delivery over any meaningful distance.
- **Wheeled Robots:** These are typically only used in pedestrianized or cycling-friendly environments like university campuses; they were also used effectively by Talabat, Delivery Hero's UAE brand, at the Dubai World Expo. Wheeled robots are small in size (the five most well-known wheeled robots measure an average of 2.4 feet height x 1.9 feet length x 2.4 feet width) and they operate at low speeds, with max speed typically less than 4 miles per hour — safe enough for them to be treated as "pedestrians." The average wheeled robot can load 30 kilograms of goods.

Wheeled robots adopt various technologies to enable autonomous navigation — for example, Starship Technologies' six-wheeled robot makes use of 12 cameras, ultrasonic sensors, radar, and AI learning algorithms.[34] Most product providers currently operate under a pay-per-use model. Kiwibot charges $3.99 per delivery, while Starship charges $2.[35] This cost is expected to continue to drop sharply. Investment management company ARK Invest has even estimated that autonomous delivery robots could lower the cost of last-mile delivery by over twentyfold, from $1.60 to $0.06.[36]

- **Autonomous Vehicles:** AVs, or self-driving vehicles, are the most likely automated solution for last-mile delivery. AVs are more cost-effective in any environment with roads. However, for dense urban areas, some combination of an AV with a drone or robot may be required to meet exact customer needs for home delivery.

Public companies have been investing in the automation of last-mile delivery solutions over the past three or so years. However, the increased focus on profitability and cash generation in the face of rising rates, among other factors, has reduced funding and focus on this area in the near-term. One such example is Amazon, which announced in October 2022 that it was shutting down tests of its home delivery robot, Scout, first launched four years ago.[37] Four hundred people were working on the project globally and have been offered new jobs within the organization, with a skeleton group continuing to look at autonomous robots. Scout was a small self-driving bot that could traverse pavements, stop at front doors, and open lids for customers to retrieve their packages.

Given an increasingly limited appetite for public companies to create their own automated solutions in-house, we believe that partnerships with private companies will become increasingly important. For instance, Uber Eats recently announced a 10-year multi-market partnership with Nuro, which begins with trial deliveries in Mountain View, California and Houston, Texas.[38] Nuro was the first AV company to have fully autonomous vehicle operations in three U.S. states (Arizona, California, and Texas) and the first to get an autonomous deployment permit from the California Department of Motor Vehicles.

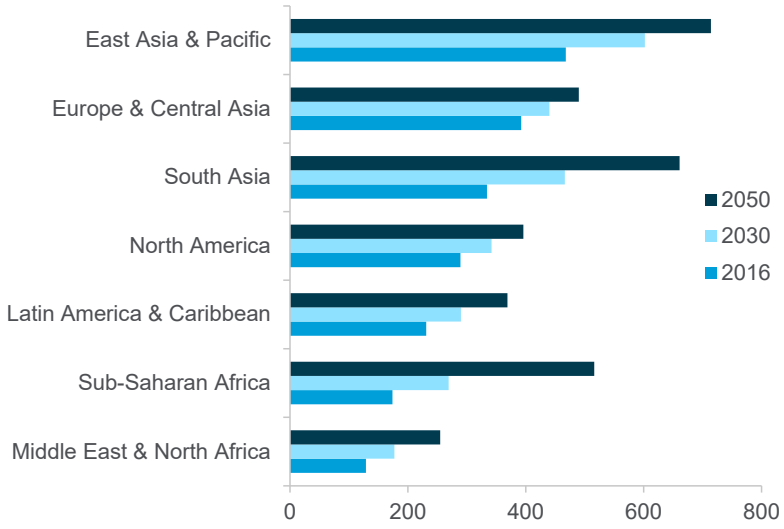
[34] AGV Network, "Starship Technologies Robots: FAQs All the Answers," accessed June 1, 2023.
[35] Michelle Lewis, "These Cute Electric Robots May Soon Deliver Your Dinner," elektrec, September 2, 2021; Ibid.
[36] Sam Korus, "Autonomous Delivery Robots Could Lower the Cost of Last Mile Delivery by 20-Fold," ARK Invest, September 12, 2018.
[37] Spencer Soper and Matt Day, "Amazon Abandons Home Delivery Robot Tests in Latest Cost Cuts," Bloomberg, October 6, 2022.
[38] Cision PR Newswire, "Uber and Nuro Announce 10-Year Partnership for Autonomous Food Deliveries Starting in California and Texas," September 8, 2022.

Robotic Waste Sorting

Wenyan Fei
Analytical Insights Team
Citi Global Insights

In addition to the digitization of production and distribution processes, the automation and recycling of waste is also important when looking at supply chains holistically. The world generates over 2 billion metric tons of municipal solid waste globally each year, and by conservative measure, at least 33% of that is not managed in an environmentally safe way, according to the World Bank.[39] Global waste generation is also growing fast and is expected to reach 2.6 billion metric tons by 2030 and 3.4 billion metric tons by 2050.[40]

Figure 40. Projected Waste Generation by Region (millions of metric tons per year)



Source: Statista

The global waste problem became even more acute in 2018 when China, which used to handle nearly half of the world's recyclable waste, enacted its "National Sword" policy, which effectively banned the import of most types of waste. Some of the waste is instead exported to Southeast Asian countries like Malaysia for recycling.[41] But that only solves part of the problem, as those countries do not have the processing capacity China does, and many waste-sorting facilities operate in substandard conditions that are bad for workers' health.[42] As the entire supply chain gradually moves towards a net-zero target, a more holistic strategy that includes recycling is important. One potential solution to this problem is robotic waste sorting — an integration of various supply chain technologies including robotics, IoT, cloud computing, AI, and blockchain.

[39] The World Bank, "WHAT A WASTE 2.0: A Global Snapshot of Solid Waste Management to 2050," accessed June 1, 2023.
[40] Ibid.
[41] Dominique Mosbergen, "Here's Why America Is Dumping Its Trash in Poorer Countries," Mother Jones, March 9, 2019.
[42] Ibid.

Waste-Sorting Opportunities

Sorting waste by hand can mean humans working in some of the worst possible workplace conditions. However, it is estimated that half of waste management tasks can be automated.[43] Robots could be used to replace human labor, freeing 19 million to 24 million waste-sorting workers from unpleasant working environments while reducing operational expenses (e.g., labor costs and training) for companies.[44]

These robots usually have end-of-arm tooling (EOAT) designed to sort the waste into different containers. Some robotic systems, such as AMP Robotics' Cortex high-speed sorting system, do this using suction cups, while others, including TOMRA's AUTOSORT sorter, use an air blaster.

High precision (over 99%) and high throughput (around 4,800 picks per hour) has already been achieved in some sorters thanks to computer vision enabled by sensor technology (i.e., camera and near-infrared) and deep learning algorithms.[45] The efficiency of these sorters can be six times higher than humans, who can only make 800 picks per hour.[46] A robot AI's continuous machine learning on the job could also improve its sorting purity. Higher sorting purity translates directly to better recyclate quality for reproduction process and can thus boost efficiency and lower costs.

Apart from item identification through machine vision, waste-sorting robots could also gather information on the waste stream and perform analysis on it. This analysis could help predict daily and seasonal effects and adjust the sorting lines accordingly, increasing agility and efficiency.[47]

Robotic waste sorters can have a significant positive impact on the environment. According to the U.S. Environmental Protection Agency (EPA), U.S. landfills emitted 122.6 million metric tons of carbon dioxide equivalent of methane through anaerobic decomposition process in 2020, 16.9% of total U.S. anthropogenic methane emissions across all sectors.[48] A more efficient recycling process enabled by sorting robots can contribute to net-zero targets through reducing the amount of waste going to the landfills and other methods. For instance, a higher recycling rate can help conserve energy and raw resources, which can also curb carbon emissions. A study from Project Drawdown concludes that if the average worldwide recycling rate increases to 62%-82%, recycling could prevent 10.36 gigatons of carbon dioxide equivalent ($GtCO_2e$) emissions to 11.29 $GtCO_2e$ emissions by 2050.[49]

---

[43] The Future of Things, "Robots in Waste Management: What Is There to Know?" accessed June 1, 2023.
[44] International Labour Office, *Sustainable Development, Decent Work and Green Jobs*, 2013.
[45] AMP Cortex, "Superhuman Sorting, Speed, and Precision," accessed June 1, 2023.
[46] BloombergNEF, "Robots Are Sorting Plastic Waste Better Than Humans," January 22, 2020.
[47] Holger Berg et al., *Digital Waste Management*, European Topic Centre on Waste and Materials in a Green Economy, September 2020.
[48] U.S. Environmental Protection Agency, "Frequent Questions About Landfill Gas," accessed June 27, 2023.
[49] Project Drawdown, "Recycling," accessed June 1, 2023.

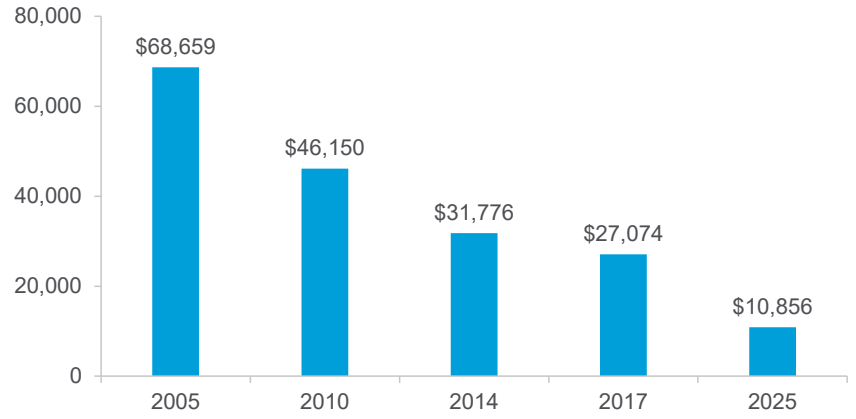
Adoption Analysis

As of late 2018, there were 633 material recycling facilities in the U.S. alone, but less than 14% of these facilities used robotic systems.[50] Despite current low adoption rates, in the International Solid Waste Association (ISWA) survey of around 1,000 experts in the waste management industry, half of the respondents think that the Fourth Industrial Revolution (or Industry 4.0) will have a great influence on the waste and recycling industry, while 45% think that it will have some influence.[51]

Five independent estimates indicate the TAM for global waste sorting stood at $824 billion in 2022 with a 5.2% CAGR over the next 5-10 years. Given the rapidly increasing waste generation rate and rising labor costs, wider adoption of waste sorting robots in recycling facilities over the next decade to automate this task and improve sorting efficiency looks likely. We examined four independent TAM estimates for robotic waste sorters and found the average market size estimate was $4.94 billion in 2022 with an 18.5% CAGR expected in the next 5-10 years.

Cost is also a factor in adoption. Recycling one ton of municipal solid waste (MSW) in New York City costs $686, whereas landfilling costs only $126.[52] The capital expenditure costs of robotic waste sorters can be high. However, robot costs continue to fall — ARK Invest expects industrial robot costs will drop by 50%-60% by 2025 — while labor costs increase and payback periods improve, driving rapid adoption rate increases.[53]

Figure 41. Average Cost of Industrial Robots in Selected Years ($)



Source: Statista

[50] RoboticsBiz, "Top Solutions in Robotic Waste Management in the U.S.," July 5, 2022.
[51] ISWA, "The Impact of the 4th Industrial Revolution on the Waste Management Sector," 2017.
[52] Savanna Stanfield, "Is Recycling Cheaper Than Landfill? (With Cost Comparison)," CitizenSustainable, accessed June 1, 2023.
[53] David Edwards, "Industrial Robot Costs to Drop by Half in the Next Three Years," Robotics & Automation News, May 12, 2022.

Segment III: Decision-Making

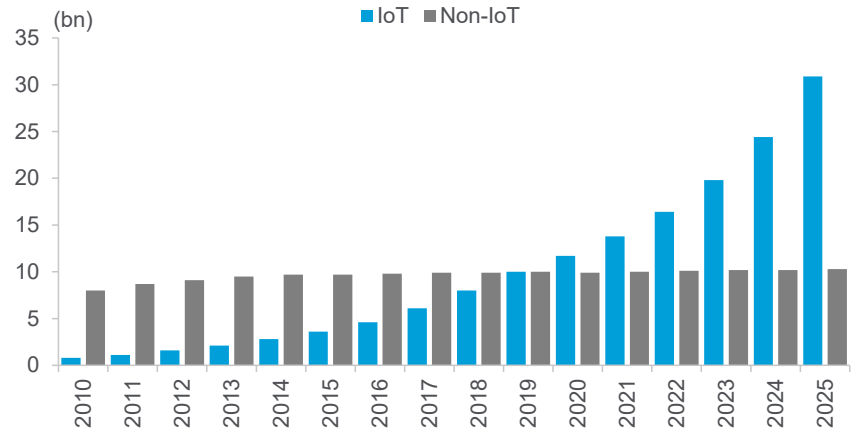
The Internet of Things

Wenyan Fei
Analytical Insights Team
Citi Global Insights

Rob Garlick
Head of Innovation, Technology, and the Future of Work
Citi Global Insights

The Internet of Things (IoT) is a key enabling technology for supply chain digitization because of its capacity to convert the physical world into data points and gather them together. This sort of visibility over the supply chain can enable better supply chain decisions. Industry estimates put the number of active IoT connections worldwide at 16.4 billion in 2022. According to Statista, this number is set to grow exponentially in the coming years while non-IoT active connections stay roughly constant. By 2025, we will have 30.9 billion active IoT connections.

Figure 42. Global IoT and Non-IoT Active Device Connections



Source: Statista

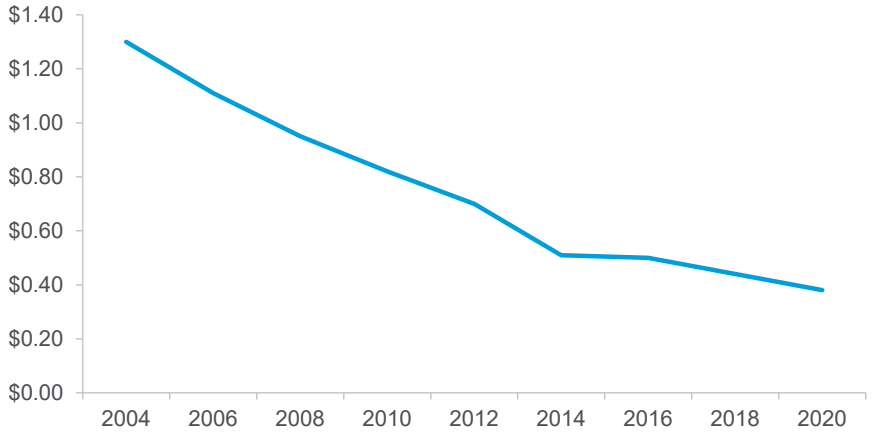
Collecting real-time location information for supply chains means more than simply knowing where things are. It is estimated that 107 billion parcel deliveries were made globally in 2019, equivalent to 293 million parcels per day.[54] Suboptimal routes calculated based on discrete location information obtained from manually scanning barcodes on the packages at each fulfilment center could significantly undermine delivery efficiency. With digital visibility on everything in the logistics process, IoT can offer real-time location updates and dynamically optimize transport routes based on traffic conditions. This can help reduce truck mileage and utilize trucks' loading capacity more efficiently, lowering both vehicle and driver costs.

Potential savings from large-scale IoT implementation could be significant. One distributor of fresh food products claimed a 20% potential reduction in truck mileage using a route and scheduler optimizer.[55] We calculate that a 1% cutback in mileage across the U.S. would translate to a total cost reduction of $10 billion.

The return on investment (ROI) for IoT projects has become even higher with the average cost of IoT sensors dropping dramatically over the years. Such improvement could also contribute to ESG goals. Based on the carbon footprint calculator from Commercial Fleet, a UK-based trucking consulting company, a 1% cutback in total mileage and 7 miles per gallon in fuel economy results in 6.4 million metric tons of carbon emission reductions.[56]

[54] Cision PR Newswire, "Lux Research Predicts Automated Deliveries Will Generate up to $48.4 Billion in Revenue by 2030," March 12, 2020.
[55] OptimoRoute, "Using OptimoRoute, Hardie's Fresh Foods Reduces Mileage by 20% While Increasing Delivery Capacity by 14%," May 9, 2022.
[56] Commercial Fleet, "Carbon Footprint Calculator," June 1, 2023.

Figure 43. Average Cost of IoT Sensors



Source: Statista

Real-time location information of goods could substantially benefit not only logistics, but also warehouse management. It is not always easy to locate goods in a warehouse, especially a large one occupying several hundred thousand square meters. IoT can help with this, as well as inventory management, by monitoring the flow of goods in the warehouse. One 2018 study of about 600 households and several retailers from IHL Group suggested that retailers missed out on $1 trillion in sales per year because of out-of-stock items globally.[57] IoT could help solve this issue by dynamically forecasting stockouts and planning replenishment in advance, recouping lost sales.

A "cold chain" — i.e., a low temperature-controlled supply chain — requires extra attention in logistics. For some food, chemicals, and pharmaceutical products, the temperature needs to be kept below a certain level or within a given range to ensure they do not spoil during the transportation process. For example, mRNA vaccines for COVID-19 need to be stored at -90 to -60 degrees Celsius during transportation and often have near-term expiry dates, resulting in many unadministered vaccines having to be thrown away.[58] According to the Biopharma Cold Chain Logistics Survey from IQVIA, the pharmaceutical industry alone loses around $35 billion every year due to failure to control the temperature in the cold chain.[59] IoT can help continuously monitor these transportation environments to reduce losses.

IoT can also help safeguard the delivery of valuables or breakables, as sensors can detect shock and intrusion. In addition, it can help monitor machines and boost factory productivity by spotting deviations in the production processes and enabling predictive maintenance, saving time and money.

[57] Daphne Howland, "Out-of-Stocks Could Be Costing Retailers $1T," Retail Dive, June 22, 2018.
[58] Centers for Disease Control and Prevention (CDC), "Pfizer-BioNTech COVID-10 Vaccine: Storage and Handling Summary," PDF, accessed June 1, 2023; Lise Barneoud, "The Huge Waste of Expired COVID-19 Vaccines," *Le Monde*, April 4, 2022.
[59] Air Cargo News, "Failures in Temperature-Controlled Logistics Cost Biopharma Industry Billions," July 26, 2019.

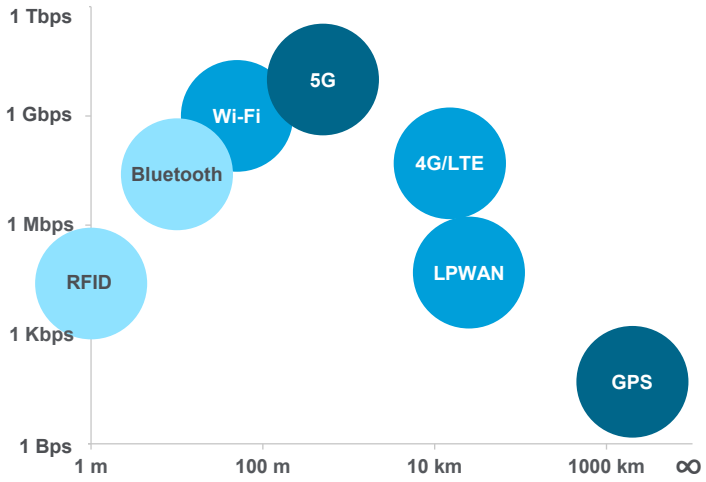
Adoption Analysis

Gartner's 2019 Digital Business Impact on the Supply Chain survey showed the IoT adoption rate in supply chains at 59%.[60] However, a more recent report from Inmarsat indicated the adoption rate had increased to 77% in 2021. The pandemic has had a clear accelerative effect on companies' adoption of IoT to better manage their supply chains.

We examined five independent total addressable market (TAM) estimates for the global logistics market. The average estimate for 2021 was $7 trillion, and the market is expected to grow at a 5.5% compound annual growth rate (CAGR) in the next 5-10 years. For global IoT in supply chains, three independent estimates averaged $42.9 billion in 2021 with a 14.3% CAGR in the next 5-10 years. The difference in CAGR between the two markets means that the penetration rate will continue to increase over the following decade.

Security is clearly a key concern when transferring information through a network. The EU Cyber-Resilience Act, which is expected to become law in 2024, requires IoT product makers to inform authorities and consumers about cyberattacks and to be able to implement quick fixes. Those that fail to comply will face a fine up to €15 million (approximately $15.8 million) or 2.5% of their previous year's global turnover, whichever is higher. In addition, the new rules will also give the European Commission powers to recall and ban non-compliant products.[61]

Figure 44. Different IoT Connectivity Solutions



Source: Citi GPS

[60] Gartner, "Gartner 2020 Hype Cycle for Supply Chain Strategy Shows Internet of Things is Two to Five Years Away from Transformational Impact," September 9, 2020.
[61] Javier Espinoza, "EU to Impose Tough Rules on 'Internet of Things' Product Makers," *Financial Times*, September 7, 2022.

A second issue for IoT deployment is connectivity. Signals can be weakened by obstacles like warehouse walls or containers on the back of the trucks, and the quality of communication can be degraded due to interference. Fortunately, several dozen wireless network protocols — with different combinations of connectivity features including coverage, bandwidth, and power consumption — are available for companies to get IoT gadgets connected, including a new option of Low Power Wide Area (LPWA), a wireless network protocol specially designed for IoT.

5G Connectivity

Michael Rollins, CFA
U.S. Communication Services & Communication Infrastructure Analyst
Citi Research

5G B2B Opportunities

Since launching in 2019, 5G, or "fifth-generation," networks have continued to expand in coverage and capability across the globe as the next generation of wireless. The primary use case during the initial deployment phase of 5G has been enhanced mobile broadband performance with faster speeds and lower latency (e.g., data delays) on smartphones over the current 4G/LTE network. For example, as of the third quarter of 2022, Verizon noted that 53% of its U.S. postpaid phone customers had 5G handsets, and T-Mobile noted that most of its devices and usage are already on 5G.

Beyond enhanced mobile services, 5G has applications for fixed wireless broadband service, which connects fixed locations like homes, businesses, and farms to the internet through airwaves. 5G services can enable turbo-charged 5G fixed wireless broadband services when combined with larger spectrum positions (including mid-band and millimeter wave spectrum) as well as a more robust set of services for B2B and IoT applications.

Fixed wireless is off to a strong start in the U.S., with major carriers tapping into extra capacity created by the expansion of spectrum usage for their 5G networks.

Future revenue and demand opportunities for B2B and IoT services are still emerging, but wireless management teams remain bullish on the future prospects of these areas. The U.S. national wireless carriers are likely to focus on selling customizable connectivity for a range of applications and use cases that can include private 5G networks, secure mobile connectivity to a broad range of connected devices and applications, mobile edge computing, machine-to-machine communications, and managed solutions for both consumers and business users. While TAM estimates vary widely, Verizon estimated its B2B 5G TAM at around $30 billion spanning private networks, edge computing, and enterprise solutions.

The advantages of leveraging 5G over Wi-Fi include opportunities to use licensed and managed spectrum resources, a reduction in latency, power management allowing more control over the connectivity and battery-life of a device, and much better throughput speeds when combined with larger allocations of spectrum. These benefits open up a world of opportunities and use cases, including virtual and augmented reality, remote robotics, drone control, and self-driving vehicles. For example, AI-enabled applications may need the related computing to be completed closer to the device, which could be conserved at the far-edge (with edge computing infrastructure closest to the user), in real time. We believe 5G networks can help to enable these emerging use cases. Also, in addition to connectivity, 5G carriers can offer prospective business customers applications to help them gather and analyze data from connected devices to help with decision-making.

One factor that may be slowing commercial 5G exploration and eventual adoption is the cost of the chipsets. The cost of a 5G chipset is still well above that of cheaper standard Wi-Fi solutions. A reduction in cost per chipset to enable 5G communications could provide a catalyst for broader enablement and adoption of 5G for business use cases and applications. While there is some chatter already around 6G technology, we find that the opportunities to leverage 5G technology remain front and center for carriers.

Below are some examples of how 5G networks can enable data collection and analysis in emerging use cases.

Smart Manufacturing

5G can provide connectivity for smart manufacturing (i.e., the digitization of manufacturing), through which entire supply chains can be interconnected to improve cost and efficiency. The German Federal Ministry of Education and Research published a white paper in 2017 with recommendations for implementing its “Industry 4.0” strategic initiative that included using IoT and related services in manufacturing. In the factory of the future, 5G enables devices on the factory floor to communicate with each other with security, latency, and reliable machine-to-machine communication. By collecting data from connected devices, smart manufacturing can leverage data analytics to optimize production and manage the inventory of raw inputs into the process. Manufacturers can use wireless connectivity to monitor environmental factors, automate changes, track inventory, and adjust accordingly. Connecting the entire supply chain enables end-to-end tracking and monitoring, from raw materials to finished goods. In essence, smart manufacturing represents the Fourth Industrial Revolution based on cyber-physical production systems that can autonomously perform end-to-end activities along the value chain.

Connected and Autonomous Vehicles

While fleet management solutions for containers, cargo, and in-cab monitoring have been successfully implemented with 3G and LTE, 5G is critical for autonomous vehicle connections to enable almost zero latency (no lag) situational awareness. Modern automobiles have dozens of sensors that can be used to foresee maintenance needs, predict track location, or ultimately affect autonomous driving. Embedding data connectivity into the car can make use of that data in ways that are not currently possible, including real-time traffic avoidance, better fleet management, and new ride-sharing business models. The low latency and large bandwidth available with 5G are necessary in automated vehicles, as milliseconds can matter in preventing collisions, and the amount of data created can be massive.

Smart Cities

Governments around the world are looking to IoT solutions to improve services, conserve natural resources, and generally improve citizens’ quality of life. 5G is critical in “smart city” applications where a lot of devices must share information — for example, the management of traffic, parking, energy consumption (smart meters), and noise. 5G could enable things ranging from coordinating traffic signals in real time to ease congestion, to tracking parking meter usage, to monitoring water and air quality and issuing timely emergency alerts. Sensors on critical infrastructure like bridges, roads, and utility networks could allow for predictive maintenance and avert poor conditions. Examples of smart city applications also include the monitoring of full street wastebaskets and mass-transit arrival information.

Private Networks and Network Slicing

In terms of 5G connectivity solutions, private 5G networks have been deployed to enable supply chain capabilities with better performance, reliability, and security. Privately managed networks that bypass the national macro networks, either in a single building or distributed across multiple locations, have long been the purview of wired access solutions augmented with limited wireless or Wi-Fi networks. With 5G, that could be reversed given the lower cost of installing, maintaining, and updating a wireless network. In a supply chain setting, this can enable every machine and device to be connected at all times and to be freely movable from room to room and floor to floor. Even for human employees, a private network will allow the environment to be more mobile and adaptable, with employees able to take devices anywhere in the building, or even outside the building, with a reliable, dedicated connection.

Private networks are seeing growing demand, with Verizon recently pointing to them as the area where the company has seen the most traction within 5G business opportunities and estimating the global TAM at $10 billion. AT&T is also seeing success, recently highlighting its work to transform Ford's Dearborn, Michigan factory by deploying a private 5G network along with edge computing powered by Microsoft Azure. The network enables machine vision and acoustic detection capabilities to enable real-time quality checks.

Network slicing is another 5G connectivity solution that allows the "production" of multiple virtual networks, which can be set up and "dismantled," thereby allowing "network as a service" to be delivered over a shared network domain. Network slicing allows for lower costs than current mobile networks, better security than Wi-Fi, and customization that tailors 5G offer to the application. While the opportunity remains nascent in deployment, we believe network slicing can be a powerful tool for supply chains to improve the dynamic optimization of their connectivity based on changing conditions. Verizon has highlighted a potential use case where forklifts in a factory could have a dedicated network slice to enhance their reliability, thereby providing additional safety for nearby factory workers in situations where other areas of the factory have surges in traffic.

AI/Machine Learning and Big Data

Wenyan Fei
Analytical Insights Team
Citi Global Insights

Rob Garlick
Head of Innovation, Technology, and the Future of Work
Citi Global Insights

Collecting data is just the first step in digitizing supply chains — the data must then be analyzed before it can help guide decision-making. While data volume is exploding, one recent report estimated that 99% of the data we generate is not analyzed.[62] Artificial intelligence (AI) and big data are two of the most important tools to unlock the full potential of supply chain data.

For a company, inventory is needed to meet demand, but over-production can impact working capital and cash flow. AI can help resolve this problem by forecasting demand and planning production in advance, including adjusting the size of raw material orders, thus enabling companies to be more agile. One example is German online retailer Otto Group, which was able to reduce its surplus stock by 20% and product returns by 2 million items per year after adopting a deep-learning algorithm to predict product sales.[63] The AI system they use can predict demand with 90% accuracy by analyzing around 3 billion historical transactions and 200 variables including the weather, advertising campaigns, and previous orders. Today, Otto Group purchases around 200,000 items a month from third-party brands with no need for human involvement or decision-making.[64]

Another part of supply chains that AI and big data could help optimize is logistics. The global logistics network is growing increasingly complex and vulnerable to disruptions. For example, the 2021 Suez Canal blockage held up an estimated $9.6 billion of trade each day.[65] AI can help re-optimize delivery routes continuously to contain the impact of adverse events over the entire supply chain. McKinsey claimed in a report that logistics costs could be improved by 15% for companies adopting AI in their supply chain management compared to slower-moving competitors.[66]

AI can also help with data automation. Supply chain managers historically relied primarily on cumbersome spreadsheets to deal with supply chain data, including integrating different data sources, cleaning up the data, and running basic analyses. Spreadsheets are still used by over 70% of companies as a primary tool for their supply chain decision-making.[67] AI could automate much of companies' data processing work to help them use data more efficiently and make better decisions. A 2021 PwC report on automating analytics found that even the most rudimentary AI-based extraction techniques can save businesses 30%-40% of the hours typically spent on such processes.[68]

---

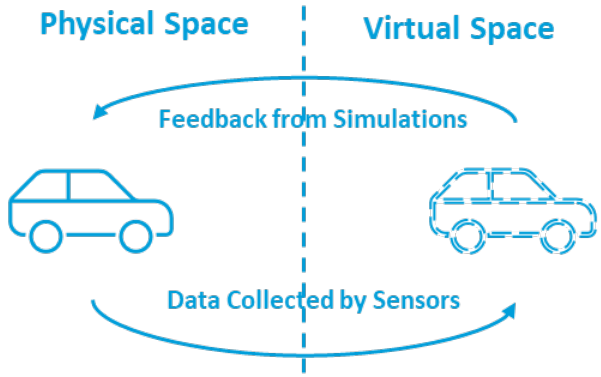
[62] Nicolaus Henke, Ari Libarikian, and Bill Wiseman, "Straight Talk About Big Data," *McKinsey Quarterly*, October 28, 2016.
[63] Telstra, "Otto: Using Predictive Analytics to Place Inventory in the Network," PDF, accessed June 1, 2023.
[64] Ibid.
[65] Mary-Ann Russon, "The Cost of the Suez Canal Blockage," BBC News, March 29, 2021.
[66] McKinsey & Company, "Succeeding in the AI Supply-Chain Revolution," April 30, 2021.
[67] Harkirat Ahluwalia, "Why Supply Chain Spreadsheets Can Cause Major Supply Chain Issues," The Owl Solutions, updated June 10, 2021.
[68] PwC, "Digital Intelligence: How to Make Your Analytics Functions More Efficient and Cost-Effective," accessed June 1, 2023.

Digital Twins

Enabled by AI, a "digital twin" is a virtual representation of a physical product and/or production process (automotive or electronic components, for example) that allows real-time transmission of data between the physical and virtual versions. Simulations can be run in the virtual version, with their results used to inspire product design or automate production decision-making, while the "big data" feedback from the physical side is fed to the simulation again so the digital twin can learn from the real world and continuously update its outcomes.

Before production begins, digital twin technology can help identify the best plan for allocating production resources and scheduling production lines while accounting for anomalies like machine breakdowns or raw material shortages.

Figure 45. How Digital Twins Work



Source: Citi Global Insights

During the manufacturing process, real-time data collected from machines and the environment will be fed to digital twins for analysis to make sure recalibrations on the physical side are carried out dynamically. This is particularly useful for ultra-precision manufacturing processes.

By collecting production-related data — including environmental information (e.g., temperature, pressure, and humidity) and operating parameters (e.g., energy use, productivity, and raw material use) — digital twins can not only keep manufacturers informed, but also forecast and schedule the maintenance and repair of machines and software systems. This assessment of the conditions of assets, processes, or systems, referred to as proactive asset lifecycle management, is crucial to increasing equipment and system lives.

Digital twins have brought commercial benefits to manufacturers. According to Boeing, digital twins have helped the company achieve up to a 40% improvement in first-time quality (a metric for estimating production efficiency) of the parts and systems it uses to manufacture commercial and military planes.[69] Challenge Advisory also demonstrated that digital twins were able to boost automobile manufacturing profit margins by 41%-54% and reduce the estimated average manufacturing time to 9-10 hours.[70]

[69] Woodrow Bellamy III, "Boeing CEO Talks 'Digital Twin' Era of Aviation," Avionics International, September 14, 2018.
[70] Carlos Miskinis, "Digital Twin Genie Case Study: 54% Reduction in Automotive Manufacturing Costs," Challenge Advisory, March 2018.

Adoption Analysis

We examined six independent TAM estimates for the supply chain AI market. The average estimate for 2022 was $3.9 billion with a 35% CAGR in the next 5-10 years, around 4% of the total AI market. In addition, six independent TAM estimates for supply chain analytics averaged $5.6 billion in 2022 with an 18% CAGR going forward. This means AI accounts for about 70% of the supply chain analytics market and will likely penetrate supply chains at a faster pace than other data analytical tools. In terms of adoption, a recent survey of 55 executives from logistics group Freightos indicated that up to 96% of supply chain professionals were planning to use AI technologies, although only 14% said they were already using them.[71]

Digital twinning is identified as one of the fastest growing AI-enabled opportunities. Five independent market sources estimated the TAM to be $8.6 billion in 2022 and further forecasted it to grow at an average CAGR of 46.4% and reach $67.6 billion in 2027. Although the concept of digital twins is not new, it has certainly captured more attention since AI made it more of a possibility. A recent report from Research and Markets indicated that almost 50% of IT decision-makers have not heard of digital twins.[72] Another recent survey from Capgemini covering over 1,000 organizations similarly pointed out that only 13% of surveyed organizations have developed full-scale digital twin strategies.[73]

Despite digital twins' early stage of industrial adoption, their capabilities are clear. The same Capgemini report found that organizations working on digital twins reported a 15% improvement in key sales and operational metrics and an improvement upwards of 25% in system performance. On the sustainability front, the average improvement in metrics owing to the use of digital twins is 16%.[74] Because of their ability to elevate entire industry chains from product design to production and finally to sustainability, digital twins are already seeing a huge surge in penetration rates. The Research and Markets report predicted that up to 94% of all IoT platforms will contain some form of digital twinning capability by 2028.[75] Organizations plan to increase the deployment of digital twins by 36% on average over the next five years, according to Capgemini.[76]

The power of data analytical tools like digital twins relies largely on data feeds. Data sharing, however, is not always a straightforward issue. Complete cost transparency on raw material data may undermine local suppliers' bargaining power during negotiations. Analysis of international supply chains would potentially require sensitive information to be shared across nation-states, something countries are generally hesitant to do, especially with their adversaries. One potential solution is "friend-shoring."

---

[71] Oliver Telling, "Multinationals Turn to Generative AI to Manage Supply Chains," *Financial Times*, August 13, 2023.
[72] Research and Markets, "Digital Twins Market by Technology, Twinning Type, Cyber-to-Physical Solutions, Use Cases and Applications in Industry Verticals 2023-2028," March 2023.
[73] Capgemini, "Digital Twins: Adding Intelligence to The Real World," accessed June 1, 2023.
[74] Ibid.
[75] Research and Markets, "Digital Twins Market by Technology, Twinning Type, Cyber-to-Physical Solutions, Use Cases and Applications in Industry Verticals 2023-2028," March 2023.
[76] Capgemini, "Digital Twins: Adding Intelligence to The Real World," accessed June 1, 2023.

By relocating manufacturing activities to allies who share similar ideological and strategic visions, countries might be more comfortable sharing their supply chain data.

Another problem is that data is not always interoperable across the different supply chain platforms that companies are using, as the data might not always be in the same format. Improvement in data interoperability may be possible through negotiations between suppliers and manufacturers within the supply chain, or governments could implement regulations to push for more data interoperability. The EU has been putting the European Interoperability Framework, a set of recommendations to enhance data portability, at the heart of their digital strategy in recent years. For example, in February 2023, the EU added a new mandatory cooperation framework on interoperability between member states and EU institutions to foster collaboration.[77]

Another area that might affect AI performance and hinder adoption is limited computing power availability. The application of AI algorithms, especially digital twins, to analyze big data is pushing the computing power of classical computers to the edge. One possible solution to this is that the next generation of computing — quantum computing — could potentially offer disruptive changes in four main areas: optimization, simulation, machine learning, and cryptography. We discuss this in more detail in the next section.

[77] European Parliament, "Briefing: Initial Appraisal of a European Commission Impact Assessment," PDF, accessed June 1, 2023.

Quantum Computing

Wenyan Fei
Analytical Insights Team
Citi Global Insights

Tahmid Quddus Islam
Analytical Insights Team
Citi Global Insights

With Moore's Law under pressure, even supercomputers are likely to be overwhelmed at some point by the amount of data being generated, and we are getting closer to this outcome.[78] However, the next generation of computing, quantum computing, could potentially provide a solution. Built on quantum mechanical principles including superposition and entanglement, quantum computers could in theory outperform classical computers in finding solutions to numerous commercially relevant areas, including: optimization, simulation, machine learning, and cryptography. Since these areas are all frequently used to support supply chain management in the Industry 4.0 era, quantum computing is expected to bring transformative changes to digitized supply chains in the future.

Production Processes

As production processes become more digitalized in the era of Industry 4.0, quantum computing could help in many aspects to enable more efficient decision-making processes. One such area is that of "digital twins," which are virtual simulations of products or system lifecycles that can be updated from real-time data; the results of these simulations are often used alongside machine learning and reasoning to help with decision-making.[79] Although digital twins have already proven to be an efficient tool, quantum computing is expected to enhance their ability to monitor and automate production processes.[80]

One potential application of quantum digital twins is in the production control process. There is a significant computational cost associated with running such simulations on classical computers. Quantum computers are expected to not only dramatically lower computational costs, but also to enable the visualization of real-time information on product quality in an intuitive form.[81]

Another area quantum digital twins might be good at is autonomous maintenance. Testing various simulations in each digital twin requires an extremely large amount of computing capability that today's classical computers might find difficult to provide. Quantum computing could offer significant performance gains and will potentially enable the completion of such simulation tasks in the least time via the most optimal strategy.[82]

---

[78] Agam Shah, "Keeping Up With Moore's Law Is Getting Harder," Computerworld, May 8, 2013; Avinash Chalumuri, Raghavendra Kune, and B.S. Manoj,"Training an Artificial Neural Network Using Qubits as Artificial Neurons: A Quantum Computing Approach," *Procedia Computer Science*, Vol. 171, 2020.
[79] IBM, "What Is a Digital Twin?," accessed October 3, 2023.
[80] C.K. Lo, C.H. Chen, and Ray Y. Zhong, "A Review of Digital Twin in Production Design and Development," Advanced Engineering Informatics, Vol. 48, April 2021; Malik Amir et al., "What Can We Expect From Quantum (Digital) Twins?" *Wirtschaftsinformatik 2022 Proceedings*, 2022.
[81] Javier Villalba-Diez et al., "Quantum JIDOKA. Integration of Quantum Simulation on a CNC Machine for In-Process Control Visualization," *Sensors*, Vol. 21, No. 15, 2021.
[82] Samir Khan et al., "On the Requirements of Digital Twin-Driven Autonomous Maintenance," *Annual Reviews in Control*, Vol. 50, No. 13-28, August 24, 2020.

Other areas that quantum computing has shown potential to streamline include:[83]

- Prediction of customer requirements and demands based on complex data-driven simulations.
- Real-time optimization of production targets.
- Management of Automated Guided Vehicle (AGV) and Autonomous Intelligent Vehicle (AIV) fleets in factories.

Figure 46. Automated Guided Vehicles in Factories

Source: Shutterstock

Logistics

Our supply chains are not as agile as we expected them to be. World events ranging from the Suez Canal blockage to the COVID-19 pandemic have shown how susceptible our supply chain management and logistics systems are to sudden changes in consumer and business demand, raw material availability, shipping, and distribution channels. Research from Ventana pointed out:[84]

- 79% of companies use spreadsheets for supply chain planning.
- Less than 25% say their supply chain plans are integrated with their company's manufacturing, procurement, or sales departments.
- 54% say they have limited or no ability to measure supply chain tradeoffs across departments when making decisions.

Most logistics systems are essentially optimization problems. In the real world, we find that such problems become exponentially more complex for every extra variable involved, for example when introducing additional vehicles, routes, or drivers in a logistics system.[85] Moreover, as we head further into Industry 4.0, supply chains have become more digitalized and interconnected. Increasing data visibility has driven supply chains to shift from a relatively static model (with infrequent data updates) to a more flexible model continuously updated by real-time market supply and demand data. (See our Citi GPS report *Global Supply Chains: The Complicated Road Back to "Normal"* for more details.) Fundamentally, modern supply chains are immensely complex.

[83] Tim van Erp and Bartlomiej Gladysz, "Quantum Technologies in Manufacturing Systems: Perspectives for Application and Sustainable Development," *Procedia CIRP*, Vol. 107, 2022.
[84] Robert Liscouski, How Quantum Computing Will Power the Future of Logistics," Supply Chain Brain, August 8, 2021.
[85] Ibid.

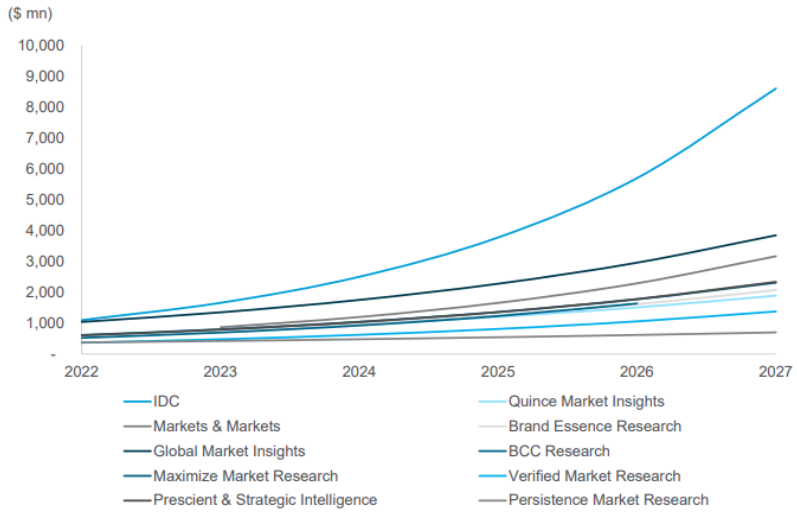
Quantum computers will likely be better at finding good approximate solutions to such "traveling salesman" optimization problems. In the future, quantum computers, with their anticipated advantage in solving optimization problems, could potentially enable better decision-making on delivery route and replenishment problems to lower costs and avoid lost sales on out-of-stock products.[86]

There are already a number of promising applications of quantum computing in logistics. The first pilot project for traffic optimization using a quantum computer was launched in late 2019 in Lisbon.[87] In it, automaker Volkswagen and public transport provider Carris were able to compute in near-real-time the fastest route for each of 9 buses over 26 stops.[88] Such a real-world application is key in demonstrating the practical advantages to quantum computing. Once quantum computers reach the point of quantum advantage in the area of optimization, it is thought that they could contribute to smoother traffic flows and ease congestion.

Adoption Analysis

One broad way of gauging the size of the quantum computing opportunity is to look at forecasts for its total addressable market (TAM). To do this, we identified 10 reports with perspectives on the market, and using these reports, pulled together a consensus estimate of the quantum computing TAM through to 2027. Based on the literature, the average market size estimate puts the quantum computing TAM at just under $650 million in 2022, growing at an average compound annual growth rate (CAGR) of around 30% to just under $3 billion in 2027. However, this is only part of the story.

Figure 47. Current TAM Forecasts (2022-27)



Source: Quince Market Insights, Markets & Markets, BCC Research, Maximize Market Research, Verified Market Research, Prescient & Strategic Intelligence, Global Market Insights, Fortune Business Insights

[86] Christopher Savoie, "How Quantum Computers Could Cut Millions of Miles From Supply Chains and Transform Logistics," Forbes, February 5, 2021.
[87] Volkswagen, "Volkswagen Optimizes Traffic Flow with Quantum Computers," October 31, 2019.
[88] DHL, "Quantum Computing Could Transform the Logistics Industry Within The Next Decade," September 24, 2020.

There does not seem to be any agreed-upon size for the current TAM for quantum computing, with 2022 estimates ranging by a factor of three, spanning anywhere from around $370 million to $1.1 billion. However, all the literature seems to agree the industry is poised for exponential growth over the current decade, with CAGR estimates ranging from around 15% on the lower end to more than 50% on the upper end. Given the large variations in both the current TAM and the growth rate, this understandably leads to increasingly diverging forecasts (by a factor of over 10) as we enter the latter part of the decade.

An EY survey found that, in the UK, almost all (97%) of 501 executives surveyed expected quantum computing to disrupt their sectors to a moderate or high extent. Furthermore, nearly half (48%) of the respondents reported thinking quantum computing would play an important role in their organizations by as early as 2025. To address this, most respondents said that their firms would be taking concrete steps within the next 1-2 years to prepare.[89]

Although quantum computing is still in its early stages in terms of commercialization, given that it could be transformative to supply chains, corporates should raise awareness internally and act in advance to secure a competitive position. There are two additional considerations around quantum computing.

First, quantum computing has the potential to break encryption. Proposed in 1994, Shor's algorithm laid out the theoretical foundation describing how a sufficiently advanced quantum computer could decrypt sophisticated public-key encryptions in just a few hours. While we are probably still years away from the point when quantum computers can break our current encryption, the threat is nonetheless imminent because of Harvest Now, Decrypt Later (HNDL) risk, which is the risk that bad actors are harvesting encrypted data now with the intent of using a quantum computer to decrypt it in the future. To offset this risk, corporates, especially those implementing Industry 4.0 solutions, should consider adopting the new Post Quantum Cryptography (PQC) standards once they are released by the National Institute of Standards and Technology (NIST) to protect their supply chain data.

Secondly, talent shortages could be a significant barrier to quantum computing adoption. To ensure they have sufficient talent to incorporate quantum computing in their business, corporates should consider:

- Reinforcing collaboration with academic institutions that supply most quantum talent to the industry.
- Offering meaningful internship programs to help upskill or re-skill workers with adjacent skills.
- Starting to build their own quantum computing candidate pools.

[89] Harvey Lewis, "How Can You Prepare Now for the Quantum Computing Future?" EY, June 27, 2022.

Segment IV: Digitization and Documentation

Digital Documentation (dDOC)

Gopinath Govindaraj
SVP, Partnerships and Innovation, Global Trade and Working Capital Solutions
Citi Trade and Treasury Solutions

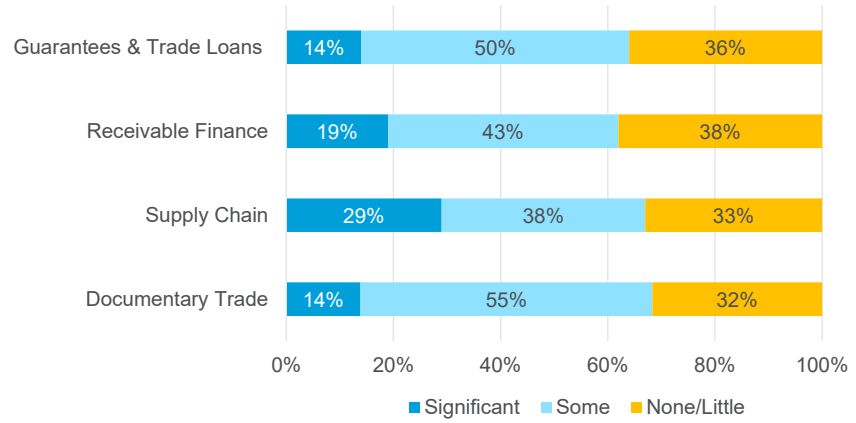
A cross-border transaction involves multiple actors and, on average, requires the exchange of 36 documents and 240 copies. Currently, fewer than 10% of trade documents are fully digitized. Lack of standardization of data is a key challenge that global trade faces today.

The Digital Documentation Initiative (dDOC) is a program initiated by the International Chamber of Commerce (ICC) Banking Commission to promote the digitization of trade finance documents. The goal of the initiative is to create a standardized framework for the exchange of digital trade finance documents, which can help reduce the time, cost, and risks associated with processing paper-based documents. The program includes the development of guidelines and standards for digital document exchange, as well as the creation of a platform for the exchange of electronic documents.

The dDOC is still in its early stages, but it has the potential to revolutionize the way that trade finance is conducted by making the process faster, more secure, and more efficient. The dDOC specifications cover several areas, including:

- **Document Format:** Defining the format of digital trade documents, including the structure, content, and metadata. This ensures digital documents are standardized and compatible with different digital systems.
- **Digital Signatures:** Defining the requirements for digital signatures, including the type of digital signature and the method of validation.
- **Data Security:** Defining the requirements for data security, including encryption and access controls. These ensure that digital documents are protected from unauthorized access, manipulation, and theft.
- **Interoperability:** Defining the requirements for interoperability between different digital platforms and systems. Few digitalization frameworks like Digital Negotiable Instruments (DNI), Distributed Ledger Payment Commitment (DLPC), Open Attestation, or Pan-European Public Procurement Online (PEPPOL) were built with interoperability in mind.

Figure 48. Usage of Digital Channels by Corporates with Global Banks



Source: 2020 ICC Global Trade Survey

Corporates considering the adoption of dDOCs should carefully consider the benefits and challenges of digitizing their trade processes by:

- **Identifying the Benefits:** The first step for corporates is to identify the benefits of dDOCs for their trade business. These may include increased efficiency, improved security, enhanced transparency, cost savings, improved compliance, and competitive advantage. Corporates should conduct a comprehensive analysis of their trade processes to identify the areas where dDOCs can provide the most significant results.
- **Assessing the Challenges:** Corporates should also assess the challenges of implementing dDOCs in their trade operations. These may include the cost of implementing digital solutions, the need for staff training, and the need to comply with regulatory requirements. Evaluation of these challenges and a plan to address them should be considered.
- **Developing a Strategy:** Once the benefits and challenges of dDOCs have been identified, corporates should develop a strategy around the right digital solution, operating procedures, and training, as well as develop a roadmap for implementation.
- **Evaluating Digital Solutions:** This includes determining what digital solutions are available that could provide seamless integration with existing systems, enhanced security features, and compliance with regulatory requirements.
- **Working With Partners:** Corporates should work closely with their partners, including banks, shipping companies, and logistics providers, to ensure that their digital solutions are compatible and meet the requirement of all parties involved in the trade transaction.

While dDOC is an important step towards digitization of trade, it is not a complete solution to the challenges of digitization. The adoption of digital trade documents requires significant investments in technology, infrastructure, and training. Businesses and organizations must also ensure the security and reliability of digital solutions they adopt and must comply with the regulation requirements of their respective jurisdictions.

Across multiple industries, the adoption of dDOC specifications for their digital solutions is gaining traction. Logistics providers like DHL and FedEx have implemented digital solutions based on dDOC standards such as customs declarations and shipping orders, and improving the tracking and monitoring of goods in transit. Shipping companies like Mediterranean Shipping Company (MSC) have implemented digital solutions based on dDOC standards to digitize bills of lading and customer declarations and improve the transparency and efficiency of their operations. Governments such as Singapore, the Netherlands, and the UK have implemented digital trade platforms based on dDOC standards, such as certificate of origin and custom declarations.

Digitization is a global challenge that requires patience and persistent cooperation. Industry participants are making consistent efforts toward unleashing the digital era for global supply chains in three main areas — modernizing outdated laws and regulations, supporting standards that enable interoperability of digital platforms, and changing industry behaviors and norms around the paper. dDOC is one of the key advocates of industry standards and aims to achieve harmonization between various actors in the trade ecosystem.

The adoption of dDOC standards data is steadily increasing as more businesses and organizations recognize the benefits of digital trade documents. While there is still room for growth, the trend toward digitization is expected to continue, driven by advances in technology, changing client and consumer preferences, and the need for increased efficiency and security in international trade.

With the global trade volume expected to reach $30 trillion by 2030, data is at the core of new and rapidly growing service supply models such as cloud computing, IoT, and additive manufacturing. dDOC lays the foundation for global trade data requirements.

The dDOC foundations can be extended to various applicable use cases in the Supply Chain Finance industry. Some of the interesting trends that could benefit players in the industry include:

- **Universal Commercial Code (UCC) Regulations Process Automation:** Traditionally, processes involved in UCC filings, including searching and managing collateral in secured transactions, are manually executed, which makes them susceptible to errors, delays, and inefficiencies. The amalgamation of various emerging technology forms the bedrock of UCC automation, ensuring that businesses can manage UCC filings and supply chain finance operations seamlessly, accurately, and compliantly. Banks are increasingly developing and utilizing Machine Learning algorithms to analyze patterns and trends within financial data to facilitate predictive analytics and robust decision making. AI can automate the decision-making process by assessing the creditworthiness of entities within the supply chain and making informed decisions on credit extensions. Combined with optical character recognition (OCR) and AI technologies, in-house digital solutions can be developed by banks to automate the UCC process.

- **eBill of Lading:** Digitization of the bill of lading has been slow and difficult to date, as various shareholders are involved in the process, all of whom have different interests, needs, and systems and therefore must be approached individually. Several factors indicate that the industry is ready to embark on digitalizing the bill of lading and there is no better time than now to do so. First, digital standards for the bill of lading have been established. Data and process standards for the submission of shipping instructions and the issuance of the bill of lading have already been established through the Digital Container Shipping Association (DCSA) and are accepted by nine container carriers representing 70% of containerized trade.

The dDoc initiative has ushered in a new era of digital documentation, melding technological advancements with sustainable practices to streamline, secure, and authenticate information management. Information technology has not only mitigated logistical impediments, but also reduced the carbon footprint associated with the physical documentation process.

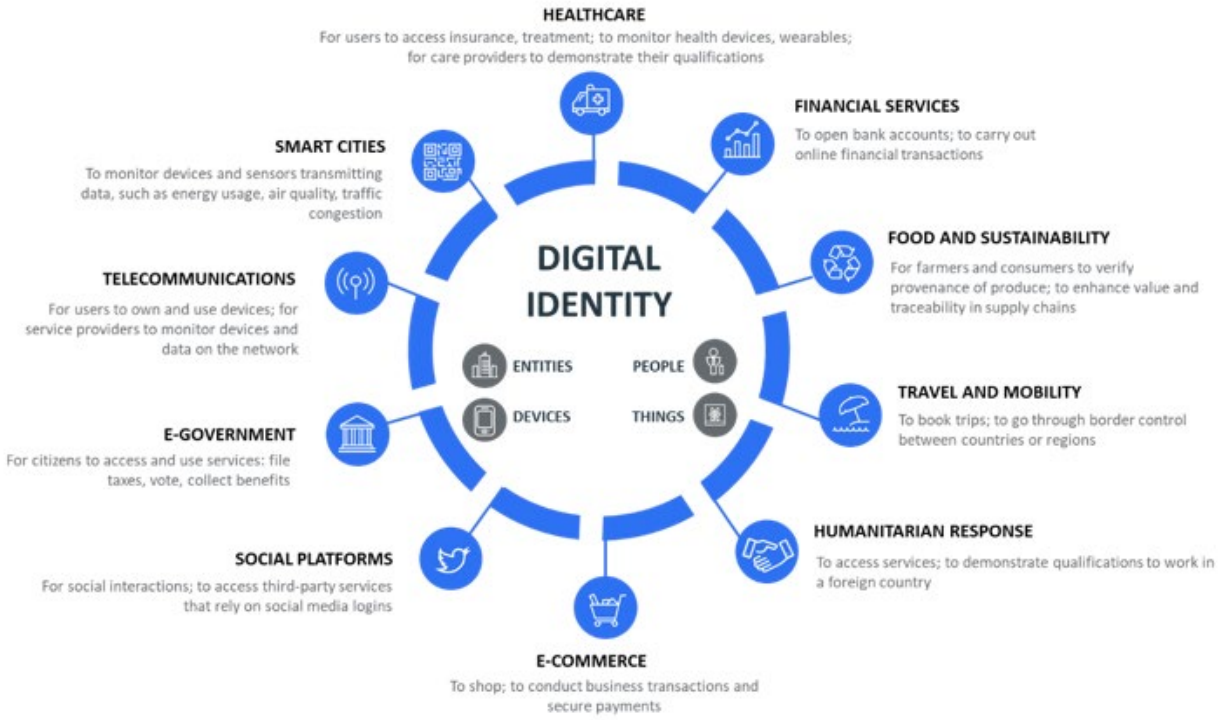
Digital ID

Anuj Gangahar
Analytical Insights Team
Citi Global Insights

Questions of identity are embedded along the length of global supply chains. For what are supply chains if they are not a series of points, each involving the identity of something? That thing could be a person. It could be a company. It could be an object. Whatever form they take, all those points need to have an identity that is recognized across the chain of supply if that chain is to remain intact and function as it should.

And that is not easy to do. Global trade features multiple parties including exporters, importers, banks for each party in a transaction, customs, freight forwarders, shippers, insurers, and more. That is a lot of different parties, and trust at all points along the chain is critical.

Figure 49. A WEF Depiction of the Centrality of Digital Identity



Source: World Economic Forum

As such, organizations need a comprehensive system for the verification and management of digital business identities that is both dynamic and trustworthy — a recent white paper from the World Economic Forum (WEF) pointed out that current digital identity management systems can often be costly and inefficient and may not be sustainable.

Making things better will be a difficult process by nature, given the sheer number of actors involved. Already there are several principles and recommendations being put forward for supply-chain organizations and governments in managing the growing complexity of the digital identities involved in global trade.

Establishing identities across the supply chain is critical in ensuring trade security and efficient access to finance throughout the life of a transaction. And the key looks to be interoperability — the idea that you do not need different identity credentials verified by a host of different agencies or governments or private companies to transact. This zeroes in on the Know Your Customer (KYC) aspect of global supply chains: How do you know that the person or organization that you are transacting with is who they say they are? Historically, this has been done through an elaborate and increasingly clunky process involving licenses and verification systems at every stage of a transaction. But as commerce becomes more digital, digital interoperability and identity credentials that can be used across a range of platforms and venues become more important.

Now that companies can operate 24 hours a day across times zones, they must be able to transact across borders and establish identities when time and geography make that impossible through physical or traditional methods. Digital identity is also becoming key to minimizing transaction risks like execution failure, fraud, money laundering, or other breaches of contracts and laws. Digital ID can bring about new commercial opportunities by simplifying transactions — the ability of counterparties to use it can speed up transactions while reducing their cost.

According to one research house, the market for digital identity is already big, with a $32.8 billion TAM in 2022, growing at an annual CAGR of almost 70% by 2027.

Historically, governments have been the keepers of identity. They remain a vital part of the digital identity development story, but the private sector is now exerting greater influence on the development of digital identity schemes. The three top verticals — or drivers of digital identity development — are financial services; digital commerce, in which supply chains are integral; and government.

As connected devices proliferate and digital transactions multiply, Boston Consulting Group expects the market for identity authentication and fraud solutions to boom, increasing from $12 billion in 2018 to $28 billion in 2023. Identity authentication will be an increasingly important component of that market. Robust front-end verification — ensuring that the person initiating a transaction is who they say they are — can help minimize fraud in the supply chain by keeping out bad actors. Many players want to lead the gatekeeping. Established identity solutions providers and startups alike are building capabilities as well as pursuing patents and acquisitions.

Traditionally, multinational companies had in-country operations and bank accounts to pay suppliers and collect from customers. But technological advances mean that many large companies now operate an asset-light model with a limited (or non-existent) physical presence. However, they still need to transact across borders. To do so, they must be able to establish their identities.

At the heart of this challenge are increasingly onerous KYC regulations, which are costly for banks and create potential delays for corporates. Corporate digital identity is widely seen as key to improving how KYC works.

As online interactions within supply chains grow, blockchain could be a potential tool to introduce trusted digital identity into the supply chain. A trusted digital identity effectively unlocks the potential of distributed ledger technology (DLT), bringing a greater level of confidence and safety into the digital world, and ultimately to supply chains.

Digital Payments in Supply Chain

Ronit Ghose, CFA
Head of Future of Finance
Citi Global Insights

Global trade can be cumbersome. Supply chains are heavily document-dependent, with settlement processes and the actual trade — two very distinct components — often separated. Notably, payments should be secondary or even unseen as compared to the underlying trade activity.

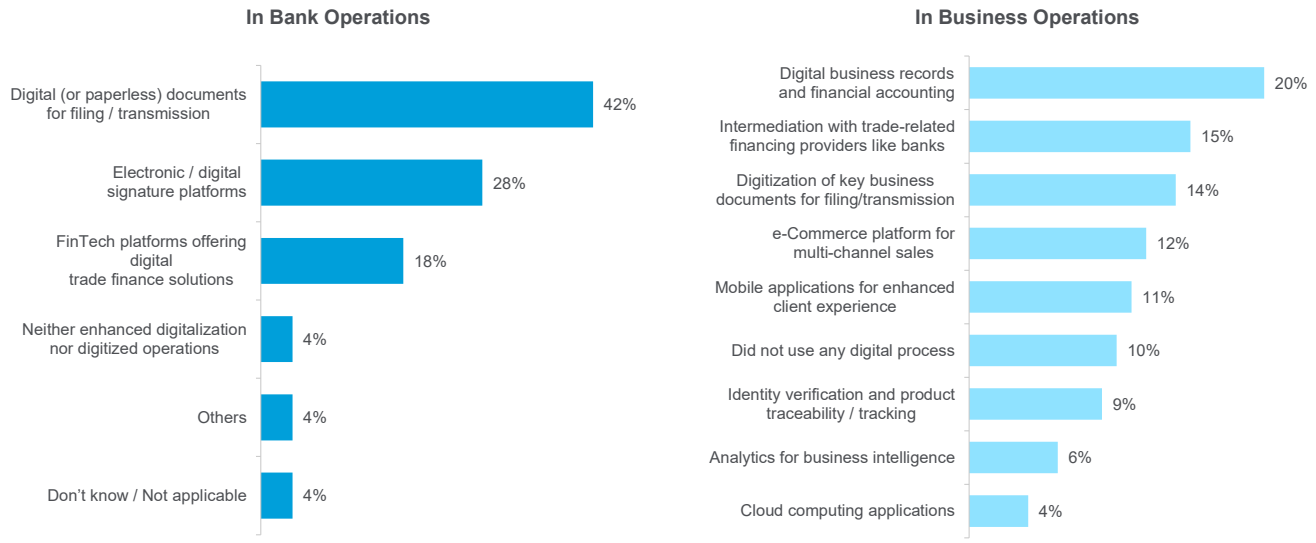
Most payment rails today are digitized using account-based money, but the infrastructure surrounding them for messaging, documentation, and payments is often siloed, requiring manual interventions with extensive paperwork. This results in low visibility of outstanding risk instruments. Most companies even today manage their financial flows manually, using paper-based invoicing and payment systems.

While we see a lot of payments innovation happening on the corporate-to-consumer side, corporate business payments such as the payment of customs, duty, and excise are still very paper-heavy (albeit evolving fast). Arguably, business payments have not kept pace with innovation and are underpinned by dated regulations.

The lack of a global invoicing standard — amid an array of tax laws, varying requirements on invoice receiving and archiving, and different invoice formats — results in inefficiencies, delays, and costs. Initiatives such as PEPPOL, an e-invoicing standard, aim to harmonize cross-border documentation.

According to a 2021 survey by the Asian Development Bank, the use of FinTech and digital solutions in the supply chain is limited and concentrated in a few areas.[90] In bank operations, only 42% of responding banks cited use of digital solutions for filing and transmission, and 28% for electronic signature platform purposes. Likewise, in business operations, just 20% of firms use digital solutions for business records and financial accounting, while just 15% cited use for intermediation with trade-related financing providers.

Figure 50. Areas of Digital Channel or Process Utilization in Trade Finance



Source: Asian Development Bank, "2021 Trade Finance Gaps, Growth, and Jobs Survey," October 2021

[90] Asian Development Bank, "ADB Briefs: 2021 Trade Finance Gaps, Growth, and Jobs Survey," PDF, No. 192, October 2021.

Technology impacts our lives on a daily basis. Internet-driven business models have disrupted consumer and industrial sectors and have been transforming money for more than a decade.[91] Similarly, technological advances could transform global supply chains, cut down on payment inefficiencies, reduce fraud, and help build trust. Admittedly, we already have electronic trade solutions (e.g., Tradeshift, Bolero) that aim to digitize global supply chains and simplify processes. However, adoption is often hindered by lack of resources from participants, especially SMEs.

Digitizing Global Trade Payments With SWIFT

Supply chain participants often struggle with cash flow problems as payments are typically made 30, 60, or 90 days from the day of order (i.e., when goods are actually delivered). Further, payment delays can result from factors like economic situations, politics, and banking relationships, leading to cash flow problems.

Cash flow problems are most pronounced for SMEs, who do not have the same access to trade finance as other large firms. This under-supply of trade finance also affects the opportunities for players to participate in global trade, as discussed in more detail in Citi's *Supply Chain Finance* GPS report.

SWIFT (Society for Worldwide Interbank Financial Telecommunications), the global provider of secure financial messaging services, is working to upgrade traditional correspondent banking. As part of the effort, SWIFT's Digital Trade Channel aims to digitize trade and promote financial inclusion by providing better trade finance access to SMEs. SWIFT is also working to develop trade-based application programming interfaces (APIs) that reduce friction from different standards in supply chains.[92]

Real-time payments in global trade could bring atomic settlement (i.e., immediate payment on delivery of goods) by eliminating the problem of trust among intermediaries. Corporates are also investing in technology to support "Always-On" treasuries — given that various treasury systems such as enterprise resource planning (ERP) systems and treasury management systems (TMSs) deployed at most corporates are not ready for real-time infrastructure yet — as an upgrade from the current batch-based SWIFT confirmations.

Digital Money 2.0 in Supply Chains

Real-time payments using SWIFT are undergoing ongoing improvements, but we also see scope for Digital Money 2.0 to streamline supply chain payments. Digital Money 2.0 is a tokenized version of money, offering features such as: (1) 24x365 operability, (2) atomic settlement, (3) programmability, and (4) a shared global ledger. Digital Money 2.0 can exist in the form of bank deposits, stablecoins, and central bank digital currencies (CBDCs).

When payments are made with tokens, the functions of messaging and settlement are merged into one. The token acts as a digital bearer instrument, so when the token moves to the recipient's wallet, the transaction is complete. Tokenized value exchange removes inefficiencies inherent to the account-based system, including errors, delays, and reconciliation issues. Notably, different industries are embracing Digital Money 2.0 at varying speeds, with gaming and retail among the first movers.

---

[91] Citi GPS, *Future of Money: Crypto, CBDCs and 21st Century Cash*, April 2021; Citi GPS, *Metaverse and Money: Decrypting the Future*, March 2022.
[92] SWIFT, "Major Trade Banks and Ecosystem Players Highlight Key Enablers for Trade Digitization," August 12, 2021.

Figure 51. Tokenized Form of Money (Digital Money 2.0) Can Help Overcome Challenges of Account-Based Money (Electronic Money)

Cryptocurrencies	Stablecoins	Central Bank Digital Currency (CBDCs)	Tokenized Deposits (Bank Issued Stablecoins)
▪ Original bitcoin & hundreds of derivative instruments are intangible assets traded on exchanges and peer-to-peer. ▪ Have not been commonly used for payments due to high price volatility. ▪ Examples: BTC, ETH, SOL, AVAX, etc.	▪ Seek to deliver benefits of tokenization while removing risk of price volatility. ▪ May or may not represent liabilities of an institution. The institution may or may not be regulated. ▪ Examples: USDT, USDC, Dai, BUSD, etc.	▪ Issued by governments or central banks as a digital form of fiat money and is controlled centrally, like fiat money. ▪ Retail CBDCs are under consideration by various central banks. ▪ Examples: Project Jasper, Project Ubin, Project Khokha	▪ Minted by commercial banks using a credit line or a cash deposit, enabling intraday liquidity. Offers interoperable with other banking products. ▪ Relevant for large transactions, where CBDC supply may be inadequate or stablecoin issuer balance sheet size is not sufficient.

Source: Citi Global Insights

The benefits of tokenized digital payments include:

- **Overcoming Suboptimal Traditional Cross-Border Payments:** SWIFT, the money system used to communicate money transfers between banks, is often critiqued for being slow and inflexible in the age of real-time atomic settlements. Tokenized digital payments can help revolutionize supply chain transactions. SWIFT, together with other partners, is exploring the development of tokenized assets using central bank digital currencies (CBDCs) and fiat currencies.[93]
- **Enabling and Improving Trust Among Intermediaries:** Lack of trust among different supply chain intermediaries often leads to excess documentation, making processes slow, costly, and inefficient. Tokenized money combined with digital identity solutions could enable greater trust among counterparties.
- **Increasing Security, Reducing Fraud:** Paper-based processes are inherently prone to data loss and misappropriation. According to an annual B2B payments survey by Bottomline, 49% of firms reported serious payment fraud attempts, with 15% of all firms suffering financial losses.[94] Modern payment solutions like tokenized digital payments can help mask sensitive information and reduce theft and fraud.
- **Eliminating Slow Paper Processes:** Banks have issued letters of credit for years, helping supply chain participants secure financing. However, these paper processes are slow and often lead to fraud, errors, and high compliance costs. Digital payment using tokenized assets can eliminate manual intervention.
- **Improving Transparency, Lowering Costs:** Cross-border money movement via traditional rails can take days before funds appear on the other side. Tokenized payments can ensure payment-versus-payment atomic settlements, making the experience transparent and eliminating the need for reconciliation. Automation and speed brought by tokenization payments could help reduce bank fees and foreign exchange charges.

[93] Nick Kerigan, "Exploring Tokenized Assets: Collaborative Innovation in Action," Finovate Blog, March 22, 2022.
[94] Bottomline, "B2B Payments Results 2021," accessed June 2, 2023.

- **Enabling Automation With Smart Contracts and APIs:** The manual and error-prone task of procurement payments can be automated using smart contracts (i.e., programs stored on a blockchain that run when predetermined conditions are met) and banking application programming interfaces (APIs). Smart contracts can communicate across existing ERPs and automate payments to entities, based on certain set conditions. Banking APIs can also help set standard instructions to release payments. Experiments to leverage smart contracts and payment APIs are underway, although mass adoption is likely further away.

Digital Money 2.0 Experimentation and Challenges

Digital payment integration is crucial for the smooth operation of supply chains. While people often cite crypto assets as perfect for cross-border payments, it is important to note that public crypto assets (e.g., Bitcoin) operate as bearer instruments on an anonymous basis. Unleashing these instruments for cross-border payments does not help guard against financial crime. By contrast, CBDCs and stablecoins may be better suited for cross-border payments. A number of real-world experiments in using digital money are currently taking place, including:

- **USDC and USDT (Stablecoins):** USD Coin (USDC) and Tether (USDT) are stablecoins, that promise 24x7 availability, instant cash flow, and low transaction costs.

- **Project Dunbar (Multi-CBDCs):** This project is led by the Bank of International Settlements (BIS) Innovation Hub in partnership with the Reserve Bank of Australia, Central Bank of Malaysia, Monetary Authority of Singapore, and South African Reserve Bank. The project aims to facilitate direct cross-border transactions, using a common shared platform for settlements, between financial institutions in different currencies.[95] Other cross-border CBDC collaborations under experimentation include the m-CBDC Bridge between the central banks of China, UAE, Hong Kong, and Thailand, along with the BIS Innovation Hub, and Project Aber between the Central Bank of UAE and the Saudi Central Bank.

- **Interlinking Multiple Tokenized Assets With SWIFT:** Experiments in late 2021 explored the feasibility and benefits of using SWIFT as a "single access point," linking multiple tokenization platforms and various cash leg payment types such as the SWIFT Global Payments Innovation (GPI) standard, Real-Time Gross Settlement (RTGS) systems, and CBDCs.

However, Digital Money 2.0 is still relatively new and has not seen mass adoption. Frequent hacks and scams in the smart contract codes could leave digital payment rails vulnerable to large losses. Data privacy and security is a growing concern in the age of increased cyberattacks and cyberwarfare.[96]

[95] BIS Innovation Hub, *Project Dunbar: International Settlements Using Multi-CBDCs*, March 2022.
[96] Chuck Brooks, "Alarming Cyber Statistics for Mid-Year 2022 That You Need to Know," *Forbes*, June 3, 2022.

Digital Money 2.0 is itself fragmented across many protocols and use cases. Digital payment networks built on top of the fragmented fabric of money would move the global supply chain away from standardized payment methods and rails in order to decrease both time and cost to settle payments. Adopting “Digital Payments 2.0” would require technical upgrades and interoperable systems for ecosystem participants.

In addition, adopting new payment technology can be expensive, especially if existing systems are based on legacy technologies. Small importers and exporters and logistics partners may not be able to afford these upgrades, leading to fragmentation. A lack of available skilled talent to handle these new technologies could also hinder adoption.

Blockchain Transforming Supply Chains

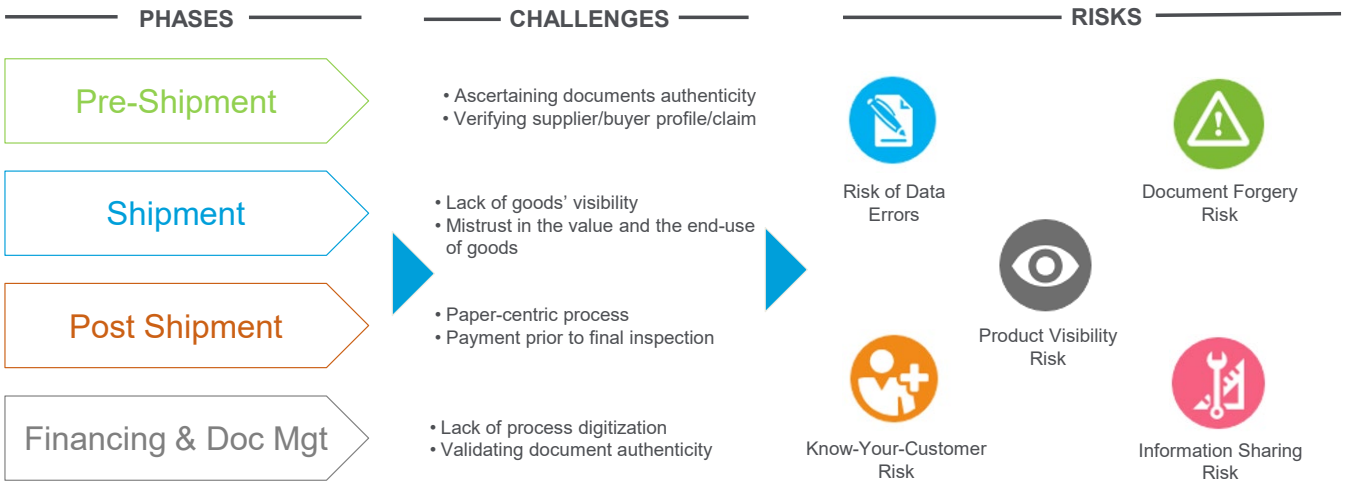
Ronit Ghose, CFA
Head of Future of Finance
Citi Global Insights

Tahmid Quddus Islam
Analytical Insights Team
Citi Global Insights

A blockchain is a digital database that enables the flow of information between a distributed network of computers, which could consist of individuals, businesses, banks, and central banks. Blockchain, by design, enables real-time updating and information access for all participants, making it the single version of "truth."

The decoupling of goods and finance flows remains a major overall challenge in supply chains, but other challenges and risks are present at various stages, including pre-shipment, shipment, post-shipment, and finance and document management. Blockchain can help by delivering value in complex supply chains that involve multiple parties dealing at arm's length. It can also help reduce the cost of interdependent transactions, prove product and document provenance, and increase transparency.

Figure 52. Challenges and Risks in Global Supply Chain



Source: Citi Treasury and Trade Solutions

Blockchain can help transform supply chains in the following ways:

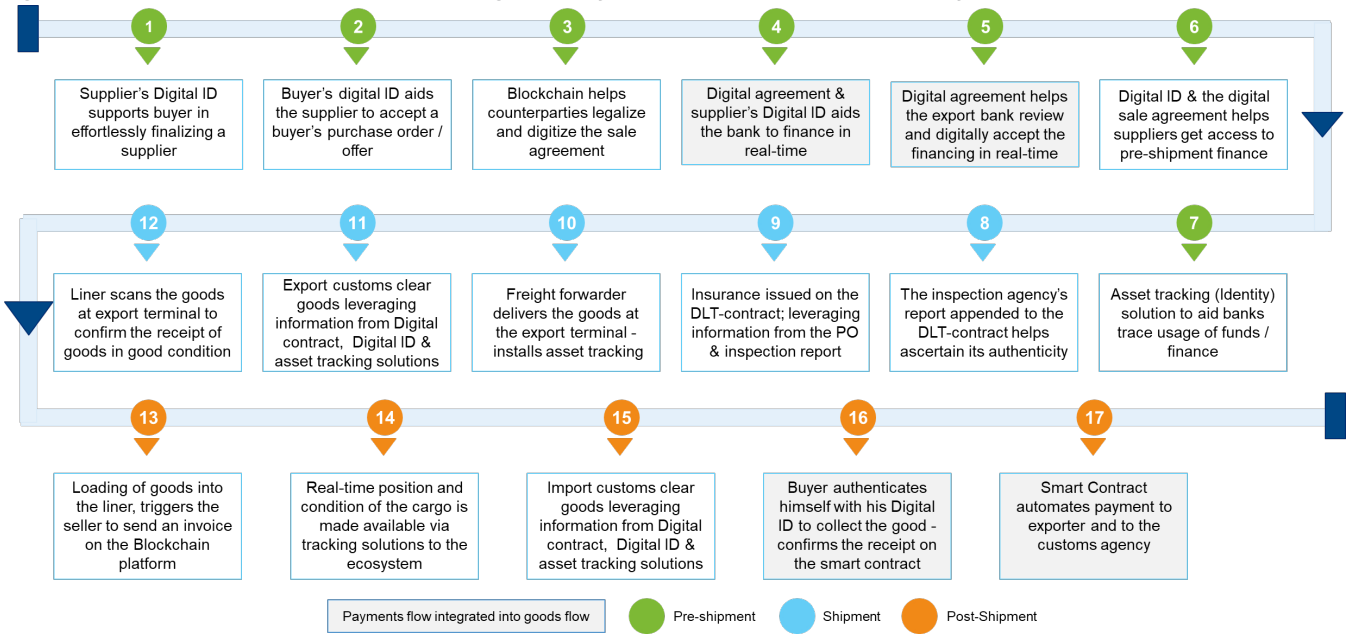
- **Ensuring Authenticity and Access to Documentation:** Typical shipments can involve up to 20 different documents printed out at different stages. The process also entails significant manual input of the same data by different parties, leaving room for errors and fraud due to fragmented and non-interoperable interfaces or technology systems.[97] According to Bain & Company, 50% of a bank's cost for a letter of credit arises from manual handling and checking, potentially leading to delays, errors, and/or fraud.[98] By contrast, blockchain creates and upholds a single version of documentation that each party can access and edit in real time, eliminating the need for duplicative manual processes and the potential for forgery, saving both time and money.

[97] Kati Suominen, *Revolutionizing World Trade: How Disruptive Technologies Open Opportunities for All* (Redwood City: Stanford University Press, 2019); IMDA Singapore "International Trade and Logistics," last updated April 4, 2023.
[98] Glen Williams et al., "Distributed Ledgers in Payments: Beyond the Bitcoin Hype," Bain & Company, June 12, 2016.

- **Tracking Product Provenance:** The global counterfeit and pirated goods market was estimated at $509 billion in 2019, or 3.3% of world trade.[99] Unsuspecting consumers may buy counterfeit products unknowingly, often online, through replicas of retailer or manufacturer websites or dishonest sellers or resellers. Blockchain technology can facilitate the traceability of products to their origin and help manufacturers, retailers, and consumers validate authenticity across the product lifecycle.

- **Improving Transparency and Visibility of Shipments:** A shipment goes through various bottlenecks as it moves through ports, customs areas, or international borders, largely due to the lack of transparency and visibility of the shipment and its contents. A ship coming to port might interact separately with the port operator, customs agents, exporter, and freight forwarder. This leads to low visibility in offloading goods from ships, clearing them through customs, and loading them on trucks. These challenges often get more pronounced for small exporters in developing countries, as their shipment and cross-border processes are not fully digitized.

Figure 53. Illustration of How Blockchain-Enabled Digital Identity and Smart Contracts Optimize Supply Chains



Source: Citi Treasury and Trade Solutions

Real-World Use Cases of Blockchain in Supply Chains

A few prominent trade networks comprised of banks, corporates, traders, and others are leveraging blockchain technology in supply chains:

- **Trusple:** Trusple is a blockchain-based international trade platform for SMEs, launched in 2020. The platform includes trade marketplaces, domestic and international banks, and logistics and supply chain service providers. The platform aims to make it easier and less costly for SMEs to sell their products and services to customers. It also aims to lower SME servicing costs for financial institutions.

[99] OECD, "Trade in Fake Goods Is Now 3.3% of World Trade and Rising," March 18, 2019.

- **Contour:** Formed by a group of trade banks, Contour is a Singapore-based digital trade network that entered live production in 2020. Contour uses technology to help streamline complex trade finance processes, starting with digitized letters of credit, enabling everyone to collaborate seamlessly and securely in real-time.

Barriers and Challenges to Adoption

- **Technology Infancy, Limited Adoption:** Blockchain development is in its early days, and its implementation in supply chains faces several challenges, including lack of trust and accountability, inability to integrate with existing infrastructure, and potential for security risks from code errors or exploits. Just 1 in 10 distributed ledger technology (DLT) solutions have been successfully rolled out.[100] Blockchain's limited adoption thus far hinders its effectiveness — for example, supply chain blockchains need adoption not just at the distributor/producer level but across the entire chain, including suppliers, logistics partners, financers, and retailers.

- **Evolving Regulatory Landscape:** Limited regulations around blockchain have led to a lack of common process standards and information disclosure. Data localization laws confining the collection, processing, and storage of data to particular countries also pose constraints for blockchain networks across multiple nations.

- **Interoperability and Lack of Standards:** As supply chains become more data-driven and interact with multiple business ecosystems, interoperability between all systems interacting with the blockchain will be crucial for mass adoption. A lack of standards often prevents the seamless flow of data throughout the supply chain. This is most evident in the challenges banks face in addressing trade finance in a regulatorily-compliant manner, as standards often vary across geographies.

- **Sustainability and Scalability:** Blockchain transactions are immutable, so the chain continues to grow as more transactions are added, resulting in large chain sizes that are unsustainable to maintain on each node. This could hinder mainstream adoption of blockchain in supply chains, especially given the large number of participants involved. Further, most pilots have only been tested at small scale, and scaling them up for real-world uses could pose challenges.

- **Cost of Technology:** While blockchains can improve process efficiency, adopting blockchain to support a large industry network would require significant computing resources and an additional overhead over traditional databases.

[100] Fujitsu, "Digitally-enabled and Governed Consortia Ecosystems: How to Transform, Digitally Accelerate and Disrupt the Foundations of Economic Fabric," May 2020.

What Is Next for Digital Supply Chains?

Digital IDs and full digitization of documents using blockchain can help increase supply chain visibility, build mutual trust, and improve authentication of ownership and title. Digital IDs can be used for both individual identification (of buyers, suppliers, or inspection agencies) and identification of assets for inventory and shipment tracking.

As digitization and blockchain gain momentum, we could see an uptick in embedded trade (i.e., the integration of logistics, ordering, and financing on one platform), which could help streamline supply chains further. While efforts have been made to enhance transportation logistics with the help of marketplace platforms, aligning financing with the flow of goods has been complex, and blockchain could help. As discussed in the next chapter, it could also improve supply chain transparency into “green” metrics.

Green Metrics

Anita McBain
Head of ESG Research, EMEA
Citi Research

A reconfiguration of supply chains is underway to meet the demands of an increasingly sophisticated investor base. This is the result of changing regulation that demands greater transparency and traceability in supply chains, including the potential risk of a full supply-chain audit. The progress on transparency and traceability made in the last decade has allowed for a greater understanding of how global supply chains interconnect and has delivered enormous advances for emerging economies, reducing inequality and improving social outcomes.

Increased Investor Scrutiny

Given investors' increased scrutiny of corporate disclosures and their degree of alignment with an emission reduction strategy, it is no surprise that the integration of environmental disclosures is moving from the realm of non-traditional investor data into a more traditional data set. The questions many investors ask of their portfolio companies stem from a desire to understand how well the investee company has understood future risks and is preparing to mitigate them. This applies firmly to understanding where hotspots or blind spots in supply chains may exist, and this could be linked to emissions, biodiversity, or modern slavery.

During the early months of the pandemic in 2020, companies that had fully tracked and traced their supply chains were better able to pivot towards alternative suppliers, away from bottlenecks and supply chain dislocation. These mapping exercises had been conducted as part of an emission scoping activity to understand risks related to energy security, energy disruption, and price fluctuations. Conducting such a thorough mapping not only allowed companies to reduce costs when and where needed, but also delivered agility and resilience as a buffer against future disruption.

An Era of Data Superabundance

The COVID-19 pandemic raised important questions about supply chain risk and resilience. In the face of supply chain disruption from pandemics, climate change and conflict, the operational strength of companies to deliver essential goods and services in a challenging supply and demand environment has been stress-tested in recent years.

In the post-pandemic world, often described as an era of "data superabundance," the sheer quantity of data generated can at times appear overwhelming. Data collected from handheld devices, daily shopping, commuting, and purchasing activities is expertly collected and tracked. Earth observation satellites monitor extreme weather events such as floods and droughts, arctic ice melts, population displacement activity, fugitive methane emissions, and even illegal deforestation activity.

This data, with the application of artificial intelligence and machine learning, has transformed the way the world evaluates the success and efficiency of global supply chains. Extreme weather events linked to a changing climate bring sharply into focus the immediate impact and ensuing havoc acute weather events such as the heat stress experienced in the UK in 2022, or the -20 degree freeze witnessed in the U.S. in 2023, can unleash. These events are more intense than manufacturing and transportation assets such as trucks, rail, and vans can withstand.

Extreme Weather Events Wreak Havoc on Supply Chains

If we continue to examine supply chain impact through an environmental lens, an analysis of water stress and biodiversity loss will become increasingly important in the face of new European regulation. In times of water stress or high flood risk, supply chains once again face massive disturbances. Several events this century highlight the major disruption to global supply chains from meteorological and climatological events.

The 2011 floods in Thailand not only devastated the city of Bangkok but also changed the global perception of flooding as a risk factor, resulting in an exodus of manufacturers to neighboring countries deemed to possess a low flood risk status. In 2022, an auto factory in Durban, South Africa was flooded after heavy rain, resulting in extensive damage to the plant, suspended production, and halted exports, not to mention the deleterious impact on worker health and safety.

Earth Observation

Earth observation satellites and hyperspectral imaging can reveal information important in the detection, identification, and tracking of floods and droughts. This is often critical for local, on-the-ground disaster relief and can guide governments and company executives with accurate data, advice, and management.

Measuring biodiversity loss and its direct linkage to ecosystem services is more complex. One example of a critical ecosystem service is pollination, estimated to be responsible for every one out of three bites of food.[101] Pollinator decline is directly linked to a class of chemicals, knowns as neonicotinoids, used to control insects and pests found in common crops.[102] The arrival of bio-sensors, precision agriculture, and smart sensors now equips farmers with more accurate data on crop health and insect prevalence and can be used to deploy chemicals more effectively in agricultural processes.

These new technologies do not negate the impact of harmful chemicals but may marginally lessen the amount deployed, reducing negative outcomes. If anything, they represent a step toward closer monitoring and management of agricultural supply chains and will hopefully lead to a gradual phasing out of chemicals, or at least toward a situation where they are used less often.

Illegal Supply Chain Deforestation

Another area where we are seeing data and technology improve supply chain transparency is in the monitoring of illegal deforestation. With the arrival of European regulation that seeks to impose a financial penalty on companies found to have sourced key forest risk commodities linked to deforestation, the onus is upon the company and its supply chain to demonstrate ownership, transparency, and traceability.

Almost in near-time, satellites can now monitor changes to landscapes, which can then be mapped to protected areas and cross-referenced using drones. This information can be used to alert local authorities and companies that are linked to these supply chains.

---

[101] U.S. Department of Agriculture, "The Importance of Pollinators," accessed June 2, 2023.

[102] Demian Nunez and Madeline Potter, "Neonicotinoids: The Good, The Bad, The Ugly," University of Maryland Department of Entomology, December 21, 2020.

Fugitive Methane Emissions

One of the interesting outcomes from the 2021 Glasgow COP26 climate talks was the Global Methane Pledge to reduce emissions by 30% by 2030. Events of 2022 saw methane fall away from the headlines, but the topic has been given prominence once again as part of the U.S. Inflation Reduction Act.[103] The U.S. aims to impose a fee on excess methane emissions within certain oil and gas facilities, expected to come into effect on January 1, 2024.

Satellites are being designed to monitor fugitive methane emissions, and they can measure methane pollution from oil and gas facilities and pipelines with impressive scope and precision.[104] This will be a vital information source to companies and governments as they seek to reduce emissions in supply chains.

Surveillance Data to Monitor Chemical Pollution and Infectious Disease Outbreaks

New technologies are also arriving to monitor chemical pollution in rivers and waterways more accurately and measure the infectious disease burden in wastewater treatment plants. The impacts to society from polluted water and poor sanitation are well documented, and the recent 2023 UN Water Conference shone a spotlight on the lack of access to safe drinking water experienced by 26% of the world's population.[105] The use of diagnostics to monitor water health, as well as soil health, has generated vast repositories of data that allow governments, regulators, and investors to monitor the burden on human health from disease outbreak or inadequate pollution controls.

[103] Congressional Research Service, "Inflation Reduction Act Methane Emissions Charge: In Brief," PDF, updated August 29, 2022.
[104] Environmental Defense Fund, "How MethaneSAT Is Different From Other Satellites," accessed June 2, 2023.
[105] UNESCO, *The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water*, 2023.

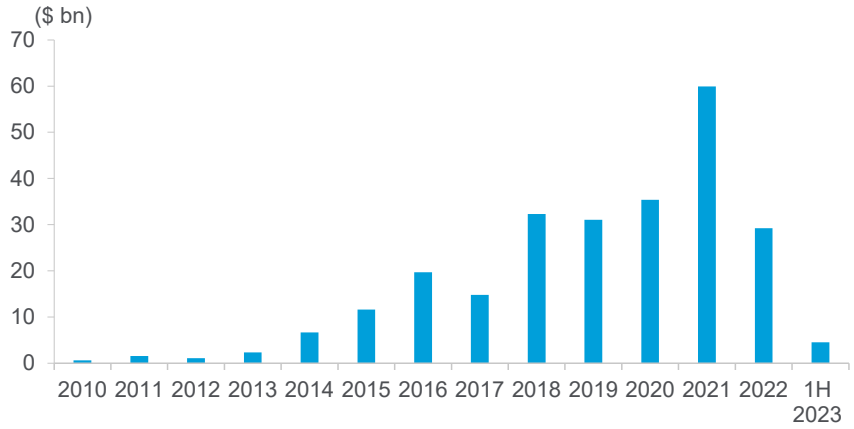
Venture Capital Growth in Supply Chain Technologies

Tahmid Quddus Islam
Analytical Insights Team
Citi Global Insights

When looking at the total venture capital (VC) investment across all deal types in the Supply Chain Tech space, we have seen a substantial increase over the past decade. Supply Chain Tech grew from an embryonic category with less than $1 billion in VC investment in 2010 to around $35 billion in 2020.

2021 seems to have been a breakout year, with an almost 70% increase in Supply Chain Tech VC investment to just under $60 billion, most likely a reflection of the start of the COVID-19 pandemic in 2020. 2022, however, saw a decline in year-over-year investment of over 50% to a little over $29 billion as interest levels rose, valuations fell, and the market's risk appetite cooled on low- or no-profit early-stage technology companies. This decline continued in 2023 with only $4.5 billion raised in the first six months of the year.

Figure 54. Overall VC Investment in Supply Chain Tech

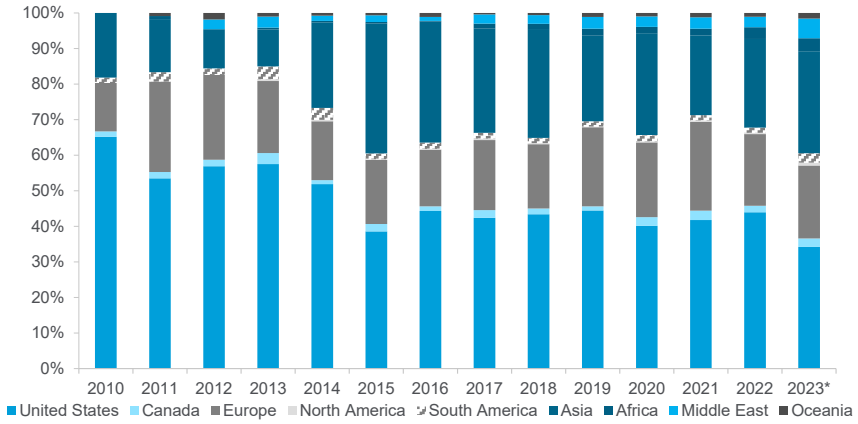


Source: Pitchbook Inc., Citi GPS

Global VC Investment and Deal Activity Landscape by Geography

In terms of geographies, the U.S. alone accounted for 44% of the Supply Chain Tech VC deal activity in 2022, whereas Europe and Asia combined contributed a 45% share.

Figure 55. Breakdown of Supply Chain Tech Deal Activity by Geography

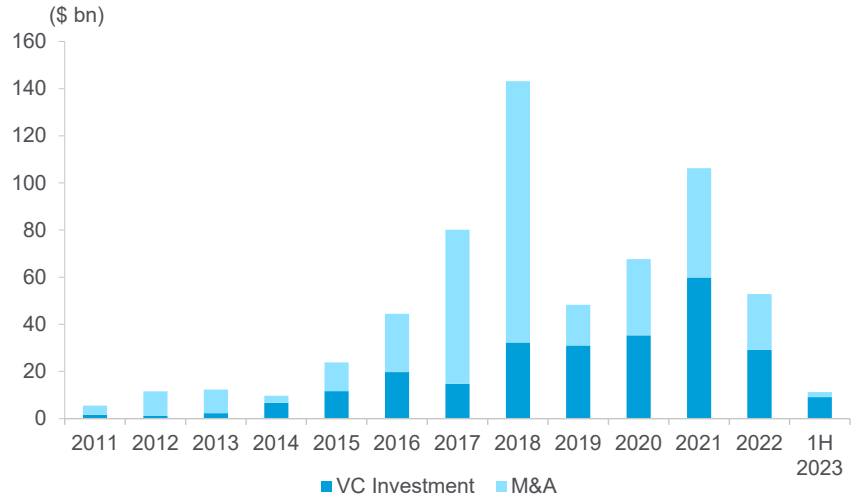


Note: 2023 data is as of end-June.
Source: Pitchbook Inc., Citi GPS

M&A Deal Size and Deal Activity

There is a healthy secondary market within the Supply Chain Tech space. Looking back over the past decade, we see that deal sizes in the primary markets (for which we take venture capital as a proxy) are similar to the secondary market's deal sizes (see Figure 56). Given the growth demand outlined in this report and the need to finance supply chain technology, continued M&A is likely to remain a theme ahead.

Figure 56. Supply Chain Tech VC/M&A Deal Size



Source: Pitchbook Inc., Citi GPS

As our premier thought leadership product, **Citi Global Perspectives & Solutions (Citi GPS)** is designed to help readers navigate the most demanding challenges and greatest opportunities of the 21st century. We access the best elements of our global conversation with senior Citi professionals, academics, and corporate leaders to anticipate themes and trends in today's fast-changing and interconnected world.

All Citi GPS reports are available on our website www.citi.com/citigps

Technology at Work v7.0
The Third Phase of Globalization
October 2023

Africa
A New Growth Model
October 2023

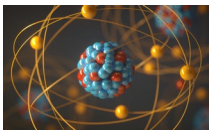
Skills That Pay
The Returns from Specific Skills
October 2023

Future of Cross-Border Payments
Who Will Be Moving $250 Trillion in Next Five Years?
September 2023

Unleashing AI
The AI Arms Race
September 2023

Hydrogen
A Reality Check on the Hydrogen Craze
August 2023

Quantum Computing
Moving Quickly From Theory to Reality
July 2023



Future of Nuclear Energy in a Low-Carbon Environment
Fission and Fusion Advanced Reactors to Prevail
July 2023

Voluntary Carbon Market
A Critical Piece of the Net Zero Puzzle
July 2023

Economic and Social Mobility
The Role of Business in Improving Outcomes
June 2023

Sustainable Ocean Economy
Charting a Prosperous Blue Future: Risk to Resilience
June 2023

Asia as a Time Machine to the Future
Seven Areas Where Asia Gives Insights Into the Future
May 2023

Money, Tokens, and Games
Blockchain's Next Billion Users and Trillions in Value
March 2023

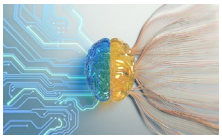
The Cyber Problem
Causes and Consequences of the Rise in Cyber Skill Demand
March 2023

The Creator Economy
Getting Creative and Growing
March 2023

Generative AI
ChatGPT and Search
February 2023

Supply Chain Finance
Uncertainty in Global Supply Chains Is Going to Stay
January 2023

State of Global Electric Vehicle Adoption
A Trip Around the World
January 2023



Disruptive Innovations IX
Ten More Things to Stop and Think About
December 2022

Antimicrobial Resistance
The Silent Pandemic
December 2022

Climate Finance
Mobilizing the Public and Private Sector to Ensure a Just Energy Transition
November 2022

Food Security
Tackling the Current Crisis and Building Future Resilience
November 2022

Energy Transition: Vol 1
Mixed Momentum on the Path to Net Zero
November 2022

Energy Transition: Vol 2
Building Bridges to Renew Momentum
November 2022

China's Inward Tilt
The Pursuit of Economic Self-Reliance
October 2022

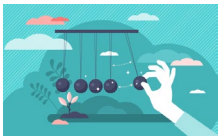
Philanthropy v2.0
Reinventing Giving in Challenging Times
October 2022

Food and Climate Change
Sustainable Foods Systems for a Net-Zero Future
July 2022

Home of the Future 2
PropTech – Towards a Frictionless Housing Market?
June 2022

Global Supply Chains
The Complexities Multiply
June 2022

Space
The Dawn of a New Age
May 2022

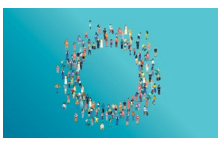


Investing for Outcomes
Why Impact Is Relevant Beyond Impact Investing
April 2022

Metaverse and Money
Decrypting the Future
March 2022

Global Art Market Disruptions
Pushing Boundaries
March 2022

Women Entrepreneurs
Catalyzing Growth, Innovation, and Equity
March 2022



Eliminating Poverty
The Importance of a Multidimensional Approach
February 2022

Global Supply Chains
The Complicated Road Back to "Normal"
December 2021

If you are visually impaired and would like to speak to a Citi representative regarding the details of the graphics in this document, please call USA 1-888-800-5008 (TTY: 711), from outside the US +1-210-677-3788

IMPORTANT DISCLOSURES

NOW / NEXT

Key Insights Regarding the Future of Supply Chain Technology

INNOVATION

Global events of the last few years —and policy reactions to them —are reshaping supply chains and driving adoption in new technologies that not only lower costs, but also increase flexibility, transparency, and resilience. / Automation and digitization will play a big part in the reconfiguration of supply chains, especially as relevant technologies continue improving and getting cheaper.

SUSTAINABILITY

In an era of "Tier 3" carbon measures, where companies must report on CO_2 embedded in their supply chain, digital supply chains become key. / Satellites are being designed to monitor fugitive methane emissions and pollution with impressive scope and precision. This will be a vital information source as companies and governments seek to reduce emissions in supply chains.

TECHNOLOGY

The industrial robot market grew around 35% in 2021 following weaker years in 2019 and 2020. Growth in "cobots" (collaborative robots working alongside humans) is particularly noteworthy as costs come down and safety improves, while fully-automated manufacturing is also growing. / Handling remained the largest use case of robots in 2021, suggesting robots are still largely used for repetitive and less complex tasks. This may change, however, as machine vision, complex end-of-arm tooling, and related software continue to penetrate the robot market.