# The Evolution of the Warehouse: Trends in Technology, Design, Development and Delivery

**Steve Weikal** and **James Robert Scott**

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## About NAIOP

NAIOP, the Commercial Real Estate Development Association, is the leading organization for developers, owners and related professionals in office, industrial, retail and mixed-use real estate. NAIOP comprises some 20,000 members in North America. NAIOP advances responsible commercial real estate development and advocates for effective public policy. For more information, visit naiop.org.

The NAIOP Research Foundation was established in 2000 as a 501(c)(3) organization to support the work of individuals and organizations engaged in real estate development, investment and operations. The Foundation's core purpose is to provide information about how real properties, especially office, industrial and mixed-use properties, impact and benefit communities throughout North America. The initial funding for the Research Foundation was underwritten by NAIOP and its Founding Governors with an endowment established to support future research. For more information, visit naiop.org/research.

## About the Authors

**Steve Weikal** is a lecturer, researcher and the CRE Tech lead in the MIT Real Estate Innovation Lab, which focuses on innovative new technology and business models that disrupt the traditional ways of developing, transacting and managing real estate. He is also head of industry relations at the MIT Center for Real Estate, where he is responsible for managing relationships between the center and its global network of industry partners. Weikal holds a Master's of Science in Real Estate Development (MSRED) and Master's in City Planning (MCP) from the Massachusetts Institute of Technology, and a law degree from Suffolk University Law School.

**James Robert Scott** is a lead researcher in the MIT Real Estate Innovation Lab. He speaks regularly at industry conferences about how technology and automation are fundamentally changing real estate, with a focus on new real estate products, processes and data technologies. Prior to attending MIT, Scott was a successful real estate transaction attorney, practicing in Ireland. He holds a Master's of Science in Real Estate Development (MSRED) from the Massachusetts Institute of Technology, a Master's of Business Studies from University College Dublin, and is a licensed attorney.

## Disclaimer

This project is intended to provide information and insights to industry practitioners and does not constitute advice or recommendations. NAIOP disclaims any liability for actions taken as a result of this project and its findings.

**A note about the cover image:** This architectural rendering is for an industrial-anchored mixed-use building designed by Heitman Architects for a site near Chicago's central business district. The bottom floor has a clear height of 40 feet and houses a mix of industrial uses, including additive manufacturing and distribution facilitated by automated storage and retrieval systems (ASRS) and very-narrow-aisle racking systems. Multifamily units on the top floors can receive packages from a dedicated ASRS system linked to the bottom floor.

*Source: Heitman Architects*


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# Executive Summary

For several years, the industrial real estate sector has benefited from technological disruption as rapid growth in e-commerce has driven demand for logistics real estate. Online retailers and third-party logistics firms have invested in logistics facilities ranging in size from large distribution centers to small fulfillment centers to meet growing consumer demand.

Relatively new technologies that increase the productivity of logistics facilities, such as automated storage and retrieval systems (ASRS), have also attracted substantial investment. The continued evolution of these technologies and the emergence of new ones—from drones to autonomous vehicles—will likely contribute to more efficient and responsive supply chains and greater productivity for industrial assets. Consumer demand for rapid delivery will continue to spur innovative approaches to distribution, such as multistory warehouses and micro-distribution centers. The coronavirus pandemic has accelerated demand for e-commerce and for technologies that can improve the efficiency, responsiveness and flexibility of logistics facilities.

The NAIOP Research Foundation commissioned this report to provide the real estate development community with insight into current and future trends in building and logistics technologies and their implications for industrial real estate. The authors' analyses of secondary sources and interviews with professionals specializing in industrial building design and automated systems integration provide insights into emerging trends that will be of interest to industrial developers, building owners and tenants:

- **The trend toward automation of distribution center operations will deepen**. Automated storage and retrieval systems, autonomous guided vehicles and robots can substantially increase a distribution facility's throughput. Further advances will make these technologies more adaptive, productive and cost-effective.
- **Data analytics and artificial intelligence (AI) will increase the efficiency of supply chains and industrial real estate**. Data collected along the supply chain and from operations within logistics buildings will help developers make better locational decisions and will improve facilities' operational performance.
- **Despite increasing automation, industrial properties will continue to employ human workers.** Robots, sensor networks and AI will make the workplace safer and more efficient, and will allow human workers to focus on creative problem solving.
- **New technologies are facilitating the expansion of logistics operations into new spaces and blurring the line between retail and industrial real estate**. Increased throughput from new technologies can make multistory warehouses and micro-distribution centers more cost-efficient, and relatively compact automated storage and retrieval systems can allow retail property owners and their tenants to add logistics uses to existing buildings.

# Introduction

The real estate industry is experiencing an unparalleled transformation across all asset classes. Advancements in technology and the adoption of new applications for real estate mean that the built environment is undergoing an automation evolution. Data analytics, ubiquitous sensors, AI and autonomous vehicles promise to create higher levels of productivity and allow for more efficient use of space. Warehouse and distribution properties will benefit considerably from these changes.

Industrial real estate will continue to be reconfigured as a new wave of innovation responds to growing consumer demand for fast product delivery, rising land and labor costs, and the increasing complexity of logistics systems. Supply chains and the buildings on which they rely are becoming increasingly interwoven within the everyday life of cities. Technological innovation is contributing to and accelerating each of these trends.

Over the course of three months in early 2020, the authors interviewed three forward-thinking industry practitioners, along with three academic researchers engaged in numerous areas of the real estate industry.

These interviews—covering topics such as design, technology and project development for both new and existing assets—provide unique insights into current trends and future developments within the industry. This report also draws from extensive secondary research with a focus on media sources and industry reports that address emerging trends in logistics real estate.

This report:

- Explores new and emerging trends in logistics and building technologies and examines how these are affecting the design and use of industrial buildings.
- Identifies the limitations and risks of individual technologies and barriers to their adoption.
- Considers how new supply chain patterns that are emerging from the growth of e-commerce are creating demand for industrial space in new building formats and blurring boundaries between industrial and retail uses.
- Evaluates how new technologies can affect the productivity and efficiency of logistics facilities and create new opportunities in the design of industrial and mixed-use buildings.

# Demand Drives Innovation

Much of the media attention on industrial real estate in recent years has focused on the rise of mega-warehouses developed for household names like Amazon, Walmart and Target to satisfy the explosive growth of e-commerce. These massive buildings, often reaching millions of square feet, are usually highly automated yet employ thousands of workers to store, package and ship goods directly to consumers.[1] However, demand is also soaring for smaller light-industrial warehouses of less than 120,000 square feet as e-commerce accelerates competition for industrial space close to major population centers.[2] Supply chain disruptions and increasing e-commerce sales due to the coronavirus pandemic appear to be increasing demand for both types of assets.

E-commerce supply chains require more than three times the distribution space required by traditional retail supply chains centered on brick-and-mortar distribution.[3] In the traditional model, warehouses are used principally for longer-term storage, especially for bulk, palletized inventory that is later distributed to retail outlets, or for commodities supporting manufacturing operations. With the rise of e-commerce, warehouses have expanded beyond storing bulk inventory to become full-service fulfillment centers. Fulfillment centers still hold inventory, but for shorter periods; individual items are stored in smaller quantities, with the expectation that inventory will be turned over quickly as orders are consistently shipped. Fulfillment centers provide additional services for customers, such as handling incoming online orders, picking products, packing and shipping. They may also handle returns as well as kitting and assembly projects.[4] These functions require significantly more warehouse space than traditional bulk storage.

This shift in warehouse utilization has renewed demand for older, smaller warehouses located close to dense urban areas and primary transportation routes. These warehouses may not have the clear heights, dock-to-square-footage ratios or yard space needed for modern large-scale logistics uses, but they can accommodate fast-moving, quick-turning and frequently ordered e-commerce inventory,[5] and they are well positioned to serve as micro-distribution or micro-fulfillment centers (MDCs/MFCs). Venture-capital-funded Darkstore is an example of an on-demand, last-mile distribution provider that aims to use these older spaces and is currently working from 43 urban warehouses across the U.S.[6]

An underground Fabric storage and retrieval system in Tel Aviv. ■ *Source: Fabric.*

MDCs in older warehouses can also be automated. Automation is perfectly suited to fit into existing structures—and at lower space-utilization rates than industries that previously occupied a building may have required.[7] "Automated storage and retrieval systems are really very flexible in the way they can be designed and put together," notes **Byron Pinckert**, director at HPA Architecture.[8] Calgary, Alberta-based Attabotics, for example, makes automated fulfillment systems that are small enough to fit inside an average-size retail store. They are currently deployed in the U.S. in spaces that range from 350 square feet up to 61,000 square feet.[9] Fabric (formerly CommonSense Robotics), which also provides storage and retrieval systems, promises to "deploy to any parameter."[10] One of its sites in Tel Aviv is located in an underutilized underground parking garage with 11-foot ceilings.[11]

Strategically located older urban warehouses that cannot be effectively retrofitted can be replaced with new vertical, multistory automated warehouses that double or triple the usable square footage on the same footprint. Real estate advisory firm CBRE is tracking at least 13 multistory warehouse projects completed or in the pipeline in New York City, San Francisco and Seattle,[12] including Prologis's Bronx 1 in the Bronx and Georgetown Crossroads in Seattle, and Innovo's 2505 Bruckner project, also in the Bronx.

Architectural rendering of Georgetown Crossroads, Seattle, WA. ■
*Source: ProLogis.*

However, according to NAIOP Research Foundation Governor **Jeff Milanaik**, principal of Bridge Development Partners, getting goods into and out of a multistory facility can be difficult, particularly in dense urban environments with streets too narrow to handle multiple large trucks. Bridge is currently facing this challenge as it develops a 1.3-million-square-foot distribution center in Brooklyn. When complete, this speculative project will be the largest multistory warehouse in the U.S.[13] Going vertical to create a multistory warehouse, while more common in Europe and Asia, is a relatively new concept in the U.S. and can be a financially viable—and often necessary—design strategy in land-constrained markets.

Shrinking retail footprints also provide new opportunities for distribution. "We're starting to see a lot more traction with the idea of retail space mixed with automation, for micro-fulfillment[…] that's forward-deployed in a retail environment," according to **Blake Bearden**, regional director at systems integrator Bastian Solutions.[14] Target and Walmart, for example, are experimenting with using space in their existing retail stores for warehouse and distribution, blurring the line between retail and industrial uses.[15] Robotic systems provider Dematic is focused on building micro-distribution hubs that use between 10,000 and 12,000 square feet inside existing store spaces; it is currently in trials with Grand Rapids-based Meijer, Inc.[16] Likewise, Takeoff Technologies in Waltham, Massachusetts, has installed micro-fulfillment facilities for grocery retailers Albertsons and Ahold Delhaize,[17] and it is partnering with Knapp warehouse logistics and automation solutions to open 50 micro-fulfillment centers across North America.[18]

Walmart has even filed a patent for an automated system for storing inventory above the drop ceilings in its superstores, with a fleet of robotic vehicles to ferry inventory between this "attic" space and the retail floor.[19]

Walmart is also integrating further up the supply chain. It recently rolled out its ship-from-store service to 2,400 sites using AI to manage every purchase across its thousands of stores. Walmart's software produces a millisecond-by-millisecond record of stock and can analyze millions of variables (including availability, speed of delivery and cost to Walmart) to identify which store is the best choice to fulfill a local online order, thus further integrating warehouse and retail activity.[20] And for locations that no longer support human foot traffic, Walmart and Stop & Shop are testing fully automated "dark stores" for curbside pick-up and delivery fulfillment.[21] In fact, it is possible that many of today's traditional grocery stores, already equipped with cold and frozen storage capabilities, will evolve into these single-purpose, dark distribution and delivery centers.[22]

Video still of a worker interacting with a Takeoff Technologies micro-fulfillment system. ■
*Source: Takeoff Technologies*

Technology is even enabling Warehouse as a Service (WaaS), with algorithms that match buyers, sellers and renters of warehouse space. These services allow clients to rent a portion of a warehouse's space and logistics capacity on flexible terms and help warehouse owners quickly monetize their underutilized space.[23] New companies like Warehouse Exchange, Flexe and FlowSpace offer on-demand general warehousing and fulfillment, while companies like ShipFusion and ShipBob act as tech-enabled 3PLs (third-party logistics) to fulfill e-commerce orders at scale for direct-to-consumer brands.

# Uses Are Blurring

Demand for warehouse and fulfillment space is leading developers, owners and operators to rethink other real estate product types and blur traditional uses. Millennium Parking Garage in Chicago, one of the largest underground parking systems in the U.S. with 3.8 million square feet over two floors, was recently transformed into an urban fulfillment center.[24] Repurposed underground parking garages can process orders just blocks from where customers live, reducing congestion from delivery trucks and making neighborhoods more walkable, livable and people-friendly.[25] Colliers International reports that owners are also exploring repurposing Class-B office buildings as industrial space in response to falling office occupancy rates.[26]

An emerging network of nano-distribution sites—even smaller than MDCs—is filling unconventional space in a relentless push to be closer to consumers. Instead of displaying items for passing customers, vacant storefronts are becoming storerooms and delivery depots for businesses that have moved entirely online.[27] New York City-based startup Bond recently raised an additional $15 million to expand its network of "mini warehouses" for last-mile delivery. Typically between 600 and 1,000 square feet, these spaces are most often at street level, with a storefront accessible by bikes, scooters and local delivery crews.[28] Similarly, Colibri is a pilot system that has established hubs in New York City to receive packages and distribute them using special electric cargo bikes.[29] Some nano-distribution sites are even smaller. Warehousing startup Ohi operates "last-touch" warehouses in former office or retail spaces that range in size from a few hundred square feet to a few thousand. Ohi is currently in 80 U.S. cities.[30]

Even empty fast-food restaurants and bank branches are being repurposed. Online grocery operator Peapod is reconfiguring these spaces into remote grocery pick-up locations. The company is also exploring nano-distribution strategies that do not require buildings. Peapod recently launched "warerooms," small, urban parking lots of 5,000 to 8,000 square feet where the company cross-docks vehicles to move products manually from one to the other.[31] In this way, delivery fleets act as a substitute for warehouses. This is also evident at Fabric's new Brooklyn micro-fulfillment centers, where vans pick up orders and then convey them to gig-economy delivery workers within walking distance of the orders' final destinations.[32] Elastic Path Software has pushed this concept further and envisions a future of autonomous semi-trucks that not only transport products but also create an interlinked network of moving warehouses that redefine last-mile delivery.[33]

### New Warehouse Types

- **Multistory Warehouses:** Designed to overcome the limitations of smaller lots, these warehouses are built vertically, with truck ramps and docks located on multiple floors.
- **Darkstore Distribution Centers:** These distribution centers are designed to replace retail distribution with last-mile delivery and frequently employ partially automated fulfillment systems. Although they are not open to the public, many appear similar to conventional stores, with aisles and shelves.
- **Grocery Conversion:** Micro-fulfillment systems installed in existing grocery stores.
- **Flexible Micro-Distribution Centers (MDC):** Smaller spaces that have been repurposed for distribution using automated systems, such as turning an empty underground parking garage into a grocery fulfillment center.
- **Nano-Distribution:** "Last-touch" fulfillment from former office or retail space.

## Suburban Transformation

As traditional retail continues to struggle, suburban mall owners and developers are exploring new and innovative ways to reconfigure and monetize their assets. New York-based startup Fillogic is a Logistics as a Service (LaaS) platform that converts underutilized space within retail centers into tech-enabled micro-distribution hubs for fulfillment of online purchases. Five major retail properties owned by Brookfield, Taubman and Macerich in New Jersey and Connecticut will be the first locations for Fillogic's ship-from-store service hubs.[34]

Fully vacant mall anchors provide a different kind of opportunity. According to Green Street Advisors, more than 50% of the roughly 600 suburban U.S.

shopping malls anchored by department stores are expected to close permanently by the end of 2021.[35] These sites are often located close to major suburban markets, with large surface parking lots and proximity to freeways.[36] Most already have high-capacity loading docks with sufficient clear heights to load and unload trucks and plenty of floor space.[37] With mechanized and automated micro-fulfillment systems like those from Dematic and Takeoff Technologies, developers can repurpose these empty anchor stores into strategically located, automated distribution centers. This strategy appears to be gaining traction. Simon Property Group, the largest mall owner in the U.S., is exploring the possibility of turning some anchor department stores at Simon properties into Amazon distribution hubs.[38]

Video still of a Dematic micro-fulfillment system. ■
*Source: Dematic*

In some cases, former shopping malls will be replaced by large distribution centers. According to CBRE, there are 24 former retail properties in the U.S. that have been or are currently being redeveloped into warehouses or distribution facilities.[39] Notable examples include:

- A 650,000-square-foot Amazon distribution center at the former Euclid Square Mall, Ohio.[40]
- An 855,000-square-foot Amazon distribution center at the former Randall Park Mall, Ohio.[41]
- A 351,000-square-foot FedEx distribution center at the former Big Town Mall, Texas.[42]

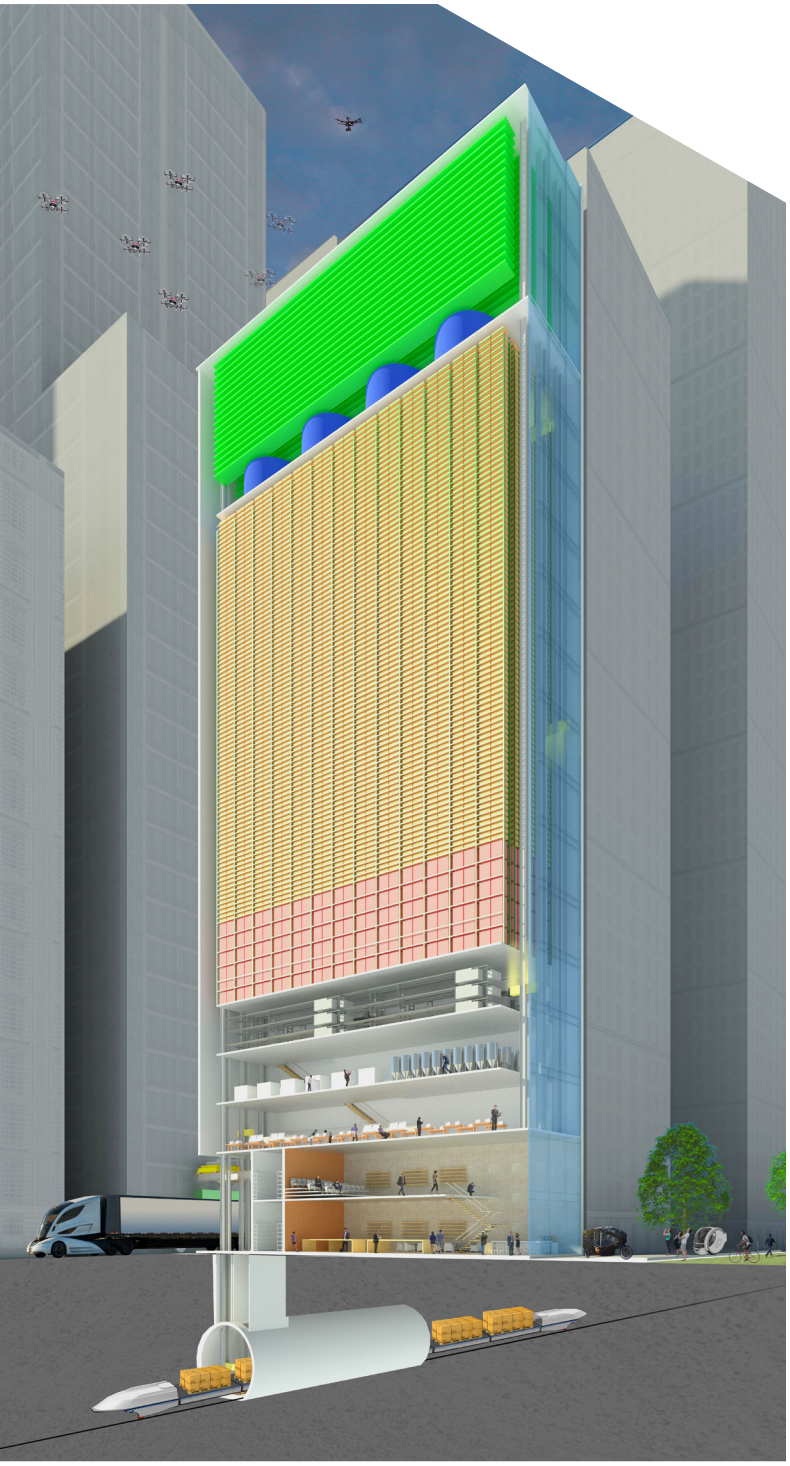
## New Models for Development

Warehouse or production-anchored mixed-use developments represent an intriguing new kind of blended real estate product. These multifunctional locations of the future promise to be places where ideas are generated, companies collaborate and innovative products are created, produced and distributed at a rapid pace to an increasingly localized market.[43] To maximize an industrial-anchored property's value, developers may add uses such as residential, live-work and shared office space, and possibly rooftop farming or renewable power generation.

Real estate technology startups SaltBox and ReadySpaces, for example, provide industrial Space as a Service that combines flexible warehouse, coworking and fulfillment space as a turnkey solution for small companies. On a larger scale, Brooklyn-based Case Equity Partners envisions a new type of shopping fulfillment center, with a highly curated, experiential retail environment at the front and a high-tech, automated fulfillment center in the back.[44] Such a configuration could combine the foot-traffic functionality and showroom frontage of retail with warehouse space that accommodates production, assembly and repair, inventory, fulfillment and drive-in loading docks.[45]

A distinct, food-focused model is also gaining popularity: "ghost kitchens." These enable restaurants to outsource all aspects of food delivery to large centralized locations, where numerous restaurant brands can benefit from economies of scale through shared inventory, production and delivery services. It is estimated that there are more than 1,280 ghost kitchen facilities globally, primarily located in large, dense cities such as New York, Los Angeles and Chicago.[46] Deal activity in ghost kitchen facilities was $1.9 billion in 2019 and is growing,[47] with hospitality operator SBE, for instance, partnering with retail owner Simon Properties and hotel operator Accor to open 140 locations by the end of 2020 and another 250 by 2022.[48]

**Michael Bennett**, principal at design firm Ware Malcomb, thinks that productive urban logistics clusters could be multilevel and mixed-use, with direct freight rail or truck access below grade, clean manufacturing and production like 3-D printing and



An architectural rendering of a 40-story mixed-use urban resource hub designed by Heitman Architects. Products and raw materials are transported to the building by rail via an underground freight tunnel. Middle floors are dedicated to additive manufacturing and customization of products offered for sale in the building's ground-floor shops. Upper floors are occupied by an ASRS system with a throughput capacity comparable to a large traditional distribution center, with top floors dedicated to a vertical farm. ■

*Source: Heitman Architects*

aero/hydroponic farms on the first two floors at street level, rising up to a park or entertainment level, with office and housing above that.[49] Karl Heitman, founder and president of Heitman Architects, has advanced a similar argument about the benefits of multistory warehouses: "The warehouse of today is really long and really thin. […] If you tip the whole thing on its side, you could fit one million square feet of horizontal warehouse into a really tall but really narrow vertical space, as the perfect urban configuration."[50]

Another emerging trend in industrial design is the integration of rapid logistics and high value-added production into airport-anchored transportation "super hubs." Examples include the FedEx World Hub in Memphis and the proposed Dubai World Central at Al Maktoum International Airport. These hubs aim to reduce the logistical friction of moving goods from warehouses or factories to national or international distribution by directly integrating each of these functions. "This has powerful urban land use and economic implications," says **Dennis Frenchman**, a professor of urban design and planning at MIT.

For example, Frenchman's firm, Tekuma Frenchman, has partnered with Milan-based transportation planner Mobility-in-Chain to design an autonomous logistics corridor in Jinan, China. There, robotic vehicles collect goods from "productive warehouses" and deliver them directly to waiting planes at an adjacent airport logistics center for fast shipment to U.S. or Asian markets. These productive warehouses are located to maximize efficiency and integrate fully automated value-added assembly with testing, packaging and branding. This is ideal for higher-value perishable and specialty items like food and pharmaceuticals or electronic parts.[51]

These examples, both urban and suburban, suggest that uses will continue to converge in the future, creating familiar yet entirely new real estate product types. KSS Architects Partner **Ed Klimek** has observed that in the future, industrial real estate will be more agile and frictionless; not just mixed-use but "integrated-use": the fluid blend of where we make things, where we produce things and where we distribute things, combined with where we live.[52]

# Implications of Robotics for Logistics, Labor and Real Estate

## Material Handling

More than 4 million commercial robots will be installed in 50,000 warehouses by 2025, up from about 4,000 robotic warehouses in 2018, according to a report by ABI Research.[53] Many robots are designed to collaborate with workers to make work environments safer and more productive.

According to MIT Technology Review, there are two categories of tasks in warehouses: those that require legs, like moving boxes from the front to the back of the space, and others that require hands, like picking items up and putting them in the right place.[54] The former can be accomplished with the aid of Autonomous Guided Vehicles, which use lasers, embedded floor sensors and machine vision to navigate warehouses and move inventory. Unlike conveyor belts or other fixed equipment, these autonomous mobile units can be added quickly to existing distribution operations to help cope with swings in volume.[55] Robotic carts like those from Fetch, Otto, Canvas (recently acquired by Amazon) and 6 River Systems (acquired by Shopify) can carry goods for long and short runs across a warehouse. They also enable social distancing to protect against the spread of COVID-19 by allowing workers to reduce direct contact with one another.[56] Boston Dynamics' Handle robots do more than just shuttle goods; they use machine vision to identify and locate boxes, unload trucks, and palletize and de-palletize goods. They can execute all of these functions autonomously. Handle's sibling, Atlas, is an eerily human-like "bipedal humanoid robot" developed for search and rescue. In the future, it could be adapted to warehouse applications to work alongside and assist human workers.

Compared with transporting objects from one location to another, picking items up and putting them in the right place is a much harder task for robots. Researchers at MIT's Computer Science and Artificial Intelligence Laboratory have developed robots that inspect objects with machine vision before using a unique gripper called the Magic Ball to pick up items ranging from wine bottles to broccoli, grapes and eggs.[57] Similarly, San Francisco-based Covariant has successfully integrated AI and machine vision to allow commercially deployed robots to nimbly adapt to a wide variety of product shapes and sizes in ever-changing orientations.[58]

Even forklifts, which were invented in the early part of the 20th century and are ubiquitous in most warehouses today, are increasingly robotic. Not only can automated forklifts now work both vertically and horizontally, they also incorporate autonomous guidance technologies that rely on lasers, image recognition and locational sensors to measure distances, map facilities, store data and navigate based on their position relative to the contours of walls, racks and other machinery. And soon, robotic forklifts will have the ability to recognize the state of a loading dock, such as the presence of a trailer and the dock's position, as well as the trailer's destination or origin. 4Front Engineered Solutions/Entrematic maintains that this ability will allow the forklifts to connect goods with specific inbound and outbound vehicles.[59]

Despite the integration of these leading-edge technologies, robotic forklifts still have some limitations. They are often too slow and regimented for the fast pace and frequent pivots required in modern warehouses. They can also be less compact in scale,

requiring a larger envelope of operating clearance than human-operated forklifts. But these challenges will likely be resolved as young, well-funded companies like autonomous forklift developer Third Wave, which recently emerged from stealth mode with $15 million in venture capital funding,[60] design and manufacture smaller, more flexible and more powerful autonomous products.

Independent robots and ASRS are expected to become increasingly integrated, alongside a variety of other innovative industrial technologies. Dematic's ASRS, for example, manages an inventory of full pallets alongside independent robots that pick products.[61] The roughly 3,000 robots in Ocado Technology's larger warehouses rely on integration of the cloud, robotics and a central AI processing system.[62] Berkshire Grey, which recently raised $263 million in series B funding, combines the use of AI, computer vision, machine learning and advanced sensing to manage its "pick, pack and sort" systems. Even Google is interested in warehouse operations. The tech behemoth recently filed a patent for a robotic pallet storage optimization system that detects if one or more pallets of an item can be consolidated and sends robots in to re-stack them. This frees up floor space.[63]

Do increasingly intelligent robots and flexible ASRS mean that future warehouses will be "dark boxes," operating with little, if any, human intervention? Bennett thinks it is possible. "Input from the receiving dock is fairly normal, but then the pallets are automatically unloaded, unbundled, sorted and racked until such time as goods go out as part of an order—kind of like a giant vending machine."[64]

It may take time to reach this level of automation, however. Scott Anderson, director of Amazon Robotics Fulfillment, told reporters earlier this year that given existing technological limitations, the company was at least a decade away from running fully automated warehouses.[65]

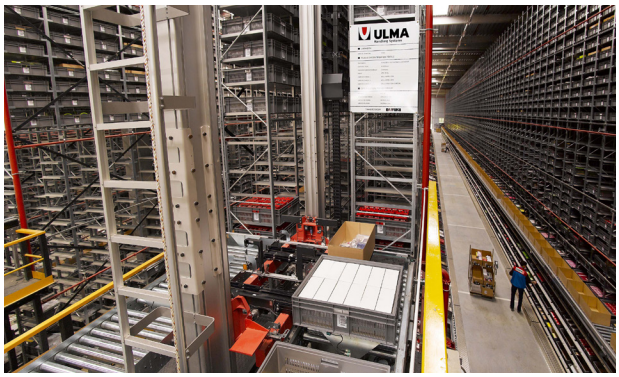
## Human Labor

The warehousing and storage sector of the U.S. economy employed 785,000 workers in 2015, according to the U.S. Bureau of Labor Statistics (BLS); however, as of August 2020, that number has grown to 1.22 million—a 55.6% increase—driven primarily by the rise in e-commerce sales across the U.S.[66] Moreover, despite increasing adoption of robotics and automation, the growth of human jobs in the industry shows no signs of slowing down, with many companies finding it increasingly difficult to fill positions in warehouses, even during the COVID-19 economic slowdown. Notably, Amazon announced in September that it plans to hire an additional 100,000 employees in the U.S. in Canada, building on the firm's large-scale hiring in the spring.[67] Peter Schnorbach, product manager for supply chain solutions provider Manhattan Associates, argues that automation cannot fully solve the logistics industry's labor shortage.[68] As distribution and fulfillment demands continue to increase, so does the variability in order profiles and picking types. While investments in automation and software systems will continue to increase worker productivity, the increased variability and unstructured environment mean that significantly more workers will be required in the short to medium term.

## TYPES OF ROBOTIC AUTOMATION

### Automated Storage and Retrieval Systems (ASRS)

- Can include shuttles, conveyors, cranes, carousels, vertical lifts (VLMs)
- Human engagement: *low*




*Source: Ingenieria-Logistica, image licensed under CC BY-SA 4.0*

### Collaborative Mobile Robots (CoBots)

- Smart, mobile, scalable; assist with human functions
- Human engagement: *medium*

Video still of Locus cobots
*Source: Locus Robotics*

### Humanoid Robots

- Mimic human motions, such as grabbing, moving, lifting and carrying
- Human engagement: *low*

Video still of Handle Robot
*Source: Boston Dynamics*

### Augmenting Robots

- Enhance current human capabilities
- Human engagement: *high*


CLOi SuitBot
*Source: LG Electronics*

## Real Estate Development

Prologis projects a 5%-10% increase in the size of inventories in the U.S. when the economy emerges post-COVID, as well as an increase in manufacturing across the Americas. Both trends would require more warehouse development.[69] Real estate services firm JLL estimates that the U.S. alone may need another one billion square feet of warehouse space by 2025 to meet expanding demand from e-commerce.[70] At the same time, robotics can decrease the need for real estate. If a robot can do a task 1,000 times an hour and a human can do it only 250 times an hour, installing robotics in an existing facility can be a more time- and cost-effective alternative to deploying capital to build another facility.[71]

Warehouse design itself, for both existing structures and new builds, is also impacted by robotics. Because robots shrink a building's operational footprint, distribution can now be squeezed into underutilized and unusually shaped real estate, in spaces previously considered too constrained for warehouse activity.

While advancements such as early suppression fast response (ESFR) sprinkler systems to control fires have allowed greater clear heights, narrow-aisle (NA) and very-narrow-aisle (VNA) reach trucks and robotic systems use vertical space more effectively, helping push ceilings higher. According to Cushman & Wakefield, clear heights of 36 feet are common in large distribution facilities, with some exceeding 40 feet.[72] Some developers are even pushing ahead with heights of almost 50 feet, according to NAIOP's *Rules of Thumb for Distribution/Warehouse Facilities Design*.[73]

Robots can also help with warehouse property management. Research teams at Amazon Robotics and the MIT Computer Science and Artificial Intelligence Lab, for example, have both built UV-light-emitting robots designed to cruise the warehouse floor and kill viruses such as the one that causes COVID-19,[74] while Avidbot's Neo robot is an autonomous floor scrubber for large commercial spaces, including warehouses.

## The Demise of Inventory?

Warehouse and distribution technology is enabling a shift "to more fragmented and dynamic inventories, as a consequence of on-demand consumerism and the corresponding need for faster and more flexible delivery services," according to **Matthias Winkenbach**, Ph.D., director of the MIT Megacity Logistics Lab & CAVE Lab. Production facilities are also being impacted by technology. As industries embrace industrial 3-D printing and additive manufacturing technologies, for example, the lines between factory and warehouse will blur.[75]

3-D printing has been a tool over the past decade for higher-cost limited-run prototypes, but it is now gaining adoption as a "bridge manufacturing technique"—a means of making moderate quantities of parts at lower cost to go into real working products.[76] In a recent market research study by Ernst & Young, 65% of 900 surveyed firms are already using additive manufacturing, with 18% of respondents using it for serial, end-use production.[77] As additive manufacturing becomes more cost-effective, its adoption is expected to grow, and with it, the technology's potential to disrupt traditional manufacturing operations.

Notably, the continued growth of on-demand production and customization may reduce the need for bulk inventory storage.[78] In the future, industrial 3-D printers may transform factories into printing and distribution facilities, filled with printers on one side and outbound inventory racked and stacked on the other side. Manufacturers in any part of the world could use computer-assisted technologies to design a product and then instruct remote 3-D printing machines to build it from raw materials—in some cases, removing international shipping and stocking from the equation entirely.[79] While the raw materials for 3-D printing require storage, they do not need as much space as traditional inventory. According to Winkenbach, "inventory is no longer a fixed concept," which could have long-term implications for warehouse demand.[80]

## Autonomous Transport

While much of the media's attention is on driverless passenger cars, progress is being made in applying autonomous technology to vehicles and systems throughout the logistics chain. Rolls-Royce and ABB Marine, for example, are experimenting with crewless container ships, while the Association of American Railroads is running trials of driverless freight trains.[81]

One emergent opportunity for applying driverless technology is line hauling. In 2016, the first autonomous truck platoon, with a single driver in the lead vehicle, traversed Europe as part of the European Truck Platooning Challenge, with teams from manufacturers including Daimler, Scania, DAF, Iveco, MAN and Volvo competing.[82] While these early trials were confined to the highway, progress has been made toward systems that will allow autonomous trucks to navigate safely hub-to-hub and even dock-to-dock.

Once these long-haul vehicles arrive at a warehouse, new autonomous technologies in the docking yard can take over. Outrider, a startup focused exclusively on autonomous yard operations for logistics hubs, recently raised $104 million to further develop its system of autonomous electric yard trucks to efficiently and safely manage yard traffic.[83] Whether yard truck, delivery van or long-haul tractor trailer, these autonomous vehicles could optimize a warehouse's operational footprint by reducing space required for onsite navigation and maneuvering. They could also increase a warehouse's throughput by allowing it to operate 24 hours a day.[84] In the future, when it is time for goods to leave the warehouse, they may be delivered by autonomous vehicles and drones.

Before COVID-19, reducing the cost of delivery was a primary reason for the adoption of automation technologies. Since the pandemic, automation is increasingly being adopted to expand capacity.[85] For example, narrow urban streets can hinder the efficient movement of goods by truck. Companies like UPS in conjunction with Waymo, California-based UDelv and China-based Neolix are developing smaller, often electric multimodal autonomous vans that can efficiently navigate densely populated and traffic-congested areas.

Firms may also deploy fleets of airborne delivery drones in the near future. In August 2018, Iceland-based Flytex became the first company in the world to drone-deliver directly to customers' backyards and was an early participant in U.S. Federal Aviation Administration (FAA) trials of drone delivery. Google X Development has already created Wing, a drone delivery service that was approved by the FAA for a pilot program to deliver Walgreens packages for FedEx.[86] Recent research from the MIT Center for Transportation Logistics suggests that as much as 35% of end-consumer deliveries could be effectively accomplished by drones,[87] and synchronized truck-drone delivery systems could improve last-mile performance by as much as 80%.[88]

Even the "last block" can be serviced autonomously. Delivery robots like Amazon's Scout and TeleRetail's Pulse One deliver packages to the doorstep,[89] while Mercedes-Benz has partnered with Starship Technologies to develop Robovan, an integrated delivery van (likely autonomous in the future) that acts as a mothership for a swarm of Starship delivery bots that make individual doorstep deliveries.[90] An alternative concept to these delivery bots involves autonomous mobile stores that bring retail inventory to neighborhoods, allowing consumers to shop locally and avoid traveling to strip centers and malls. Nuro's R2 delivery vehicle and RoboMart are both driverless, electric mobile markets that deliver groceries and other goods on demand.

Design requirements for industrial buildings will undoubtedly change as the supply chain becomes more autonomous. Drones may require landing pads, as well as new package pickup and drop-off stations. Optimized delivery networks of autonomous long-haul vehicles, multimodal vans and delivery bots will carry more goods, requiring fewer visits to the warehouse. Greater precision from autonomous technology will allow driveways and loading docks to be smaller, and overhead door spacing will be tighter. These changes will make land use more efficient, allowing larger warehouse footprints on smaller sites. Conversely, as automation improves warehouse throughput, vehicle traffic may increase, requiring more space for onsite vehicle traffic. This would lower the site coverage for structures and shrink the buildable area on a given site.

## MOBILE WAREHOUSES

Starship Technologies' automated package handling and delivery robots are dropped off near customer locations by Robovan delivery vans for autonomous "last block" deliveries. ■

*Source: Starship*

Video Still of a Robomart mobile mini-mart. This self-driving store carries its own inventory. Consumers can hail it via an app on their phone. When it arrives in their neighborhood, they can shop, check out and carry goods home. ■

*Source: Robomart*

# Data-Driven Real Estate Decisions

Data analytics are becoming increasingly important in locational decisions for industrial real estate. Analytics can help identify optimal placement of smaller distribution facilities for timely delivery to dense urban and suburban populations, as well as the best locations for multistate or multimarket distribution facilities. For example, Prologis refers to data on access to major ports, proximity to transportation routes, drive times and proximity to consumers in addition to site-specific variables that affect throughput and operational efficiency when identifying new locations for logistics facilities. It weights these variables differently depending on whether it is planning a new multimarket distribution center or a last-mile facility.[91] Optimizing trucking and rail routes can require analyzing additional data on energy markets, labor markets, climate and local economic trends.

Researchers in the CAVE Lab at the MIT Center for Transportation and Logistics are applying machine learning and network science to these kinds of large and diverse datasets to improve the efficiency and performance of logistics networks. MIT's Sustainable Logistics Initiative has even designed a routing tool that accounts for topography in its decisions.[92] While ESRI and ArcGIS remain the industry standard for modeling distribution and transit networks, a handful of technology startups are also providing innovative new tools for making better locational decisions. Companies like Carto, SiteSeer, eSite Analytics and StateBook offer easy-to-use spatial data science and visualization tools for real estate professionals.

Efficiency of the supply chain itself also impacts locational decisions. Digitized supply chain management systems that are automated and predictive can provide firms with a deeper and timelier view of the total value chain all the way down to raw material providers.[93] Machine learning can then help optimize inventory levels at the various distribution centers in an individual company's network[94] and more closely match need with available space.

Along with these new and powerful tools for identifying optimal locations, the process of valuing assets will evolve. For example, given the increasingly vertical nature of the buildings and the automated systems inside, old valuation models may no longer apply. Bearden wonders if leases in the future should be priced on a dollar per cubic foot, instead of the traditional dollar per square foot, given the increased heights of buildings and usable clear space. "Most people are looking at it in terms of the throughput numbers," he says.[95] Pinckert identifies alternative measures applied by some industry players: "Pallet per square foot or case per square foot…are things that are talked about, but the key metrics are more throughput-driven than they are space-driven," with less focus on specific infrastructure costs.

### Why Use an Urban Solution in a Rural Location?

Along Interstate 40 on the western outskirts of Albuquerque, New Mexico, Amazon has broken ground on a 465,000-square-foot distribution center.[96] Its location on a remote but easily accessible, undeveloped parcel of land makes sense. What may come as a surprise, however, is that the relatively large building will be a five-story, multilevel warehouse similar to those designed for site-constrained urban environments. Why choose such a significantly more expensive and complex building design where land is inexpensive? Sometimes, opting for a multistory design increases a facility's throughput to the point that the higher construction and equipment costs are outweighed by the building's ability to generate higher operating income. Pinckert explains that sometimes with multistory warehouses, "it's not about construction expense or land prices, for sure; it's about throughput numbers."[97]

# Challenges to Warehouse Innovation

While robots and automation may offer significant operating efficiencies and cost savings for warehousing and distribution, the current costs and limitations of these technologies can be a barrier to their adoption.

## Cost of Automation

Berkshire Grey claims its robotics systems can reduce an industrial warehouse's operating costs by up to 70%. Warehouse automation and robots, however, can require significant upfront capital costs. At this point, only the best-capitalized operations can afford highly automated systems. "It would be unusual for a warehouse to have a single fully automated storage/automatic retrieval matrix in it," Pinckert says, noting that "they're very expensive [to buy] and they're expensive to operate. And they're very expensive to modify. So it's not typical of the majority of distribution operations."

To reduce the upfront costs of adopting new technologies, some systems providers offer RaaS: Robotics as a Service. Several firms, such as Ocado, Fabric and InVia, will install equipment in exchange for a cut of a retailer's revenue or offer the equipment on a subscription basis.

## Technological Limitations

It will take time to realize the potential advantages of many emerging warehouse technologies. According to Joe Dunlap, head of supply chain advisory at CBRE, the COVID-19 crisis has shown that robots are often not nimble enough to respond to throughput volatility and will require frequent human intervention in those situations. AI-driven automation currently works best with steady, predictable volumes.[98] Nonetheless, new automation technologies will continue to reduce repetitive tasks and heavy labor for warehouse workers.[99]

Many obstacles also stand in the way of the development of fully autonomous vehicle systems. These include latency in vehicle response, high hardware costs, and challenges in developing systems that can adapt to the effects of weather and respond to external factors like pedestrians and other vehicles. Some of these issues will be resolved by better light detection and ranging sensors (LIDAR) and the deployment of 5G communications, but this will take time. In the meantime, the current capabilities of

autonomous mobility are best suited for low-speed travel within limited and controlled environments, such as within buildings or geofenced areas like a warehouse yard.

## Data Infrastructure

It is important to recognize that traditional warehouse operations practices can sometimes be an impediment to deploying new technology. For example, the most potentially transformative technologies require access to large amounts of high-quality data, but older procedures and systems often do not collect or digitize data. In some ways, a digital divide is emerging between companies that invest in systems to have the best and most consistent data and those that end up operating with practical, but more basic, operating systems.

Gathering the data necessary to take full advantage of AI-driven automation technology also requires the most current digital infrastructure, which can be difficult and costly to install in existing buildings. Increasingly complex automation and robotic systems will require ever-more-robust communications that rely on a mix of new and old communications technologies—Wi-Fi, 4G LTE, 5G, CAT 5-7 Ethernet and fiber. Costs will drop over time, however, allowing owners to partially futureproof their buildings by installing excess data capacity. In the meantime, companies such as San Francisco-based Unmanned Life are emerging to provide Autonomy as a Service (AaaS),

a single management interface for autonomous robotic fleets that operates using a building's existing communications networks and integrates with a firm's current business-intelligence systems.[100]

## Zoning and Building Codes

One advantage of fully automated warehouse and distribution facilities is the ability to run nearly 24 hours a day, seven days a week. While this optimizes operations and helps speed goods to their destinations, it does mean a steady stream of logistics vehicles and worker traffic from multiple shifts. Freight trucks generate air pollutants, noise, pavement damage and traffic safety issues—in the future, drone traffic will likely join the mix—so "cities are generally very firm on their permitting requirements," Bearden says. He also notes that the number of workers necessary to support some facilities can dramatically increase the need for parking. "Some multistory urban structures are considering adding employee parking structures on the upper levels, while the solution for other distribution centers is off-site parking with shuttle buses to handle the volumes of workers that go in and out of these warehouses every day," Bearden notes.[101] It is no surprise, then, that some neighborhoods push back against adjacent development projects, such as when residents of Enfield, Connecticut, protested a planned half-million-square-foot distribution center in 2020.[102]

Another challenge to larger and more automated facilities is building codes concerning ESFR systems for fire protection. Most distribution buildings can meet the requirements for most commodities by positioning fire sprinkler protection in the roof area, and in-rack sprinklers are rarely required. But ESFR systems face height limitations. According to Pinckert, for a time "the maximum you could do for factory-neutral underwriting for an ESFR system was a 45-foot deck height." But as warehouses grow taller to accommodate even more complex automated storage and retrieval systems, he is encouraged that "every year there's a little different ESFR configuration, and now we can go to 55 feet."[103]

## Energy

The trend for warehouse operations and equipment to require more electrical power will continue. New equipment, the implementation of fiber-optic networks to connect all aspects of warehouse operations, and electric vehicle charging stations (potentially for warehouse vehicles, trucks and/or employees) will consume significant amounts of power.[104] Warehouse developers, owners and operators will need to find solutions that are both cost-effective and energy-efficient, especially in those markets where electrical power is expensive and challenging to secure.[105] Technology can, however, reduce or offset energy-related operating costs. Prologis, for example, is intensely focused on energy efficiency across its global portfolio, deploying motion-activated LED lighting, rooftop solar and wind turbines in its primary operations. Prologis is also committed to expanding LED lighting to 100% of its portfolio by 2025, noting that energy costs are 45% lower in its LEED-certified buildings.[106] The industry will likely follow suit, as further breakthroughs in energy technology reduce equipment costs and increase efficiency.

# On the Horizon

Due to rapid advancements in technology, it is difficult to predict what lies ahead for the industry; however, flexibility, integrated operations and advanced applications such as digital twin technology will be important going forward. Building Design + Construction predicts that buildings will be increasingly intelligent and responsive, and they will "tune themselves to changes in conditions."[107]

## Flexibility

In the near term, business-to-consumer distribution activity is only expected to grow alongside increasing demand from e-commerce and consumer expectations for next-day—and even next-hour—delivery. However, "all these distribution centers have peak seasons," Bennett notes. "They gear up in terms of products, in terms of staff, when they hit peak optimization of floor space, and then for the remainder of the year it goes back to being underutilized."[108]

This seasonal variation could decrease going forward, though, given the substantial increase in e-commerce brought on by the COVID-19 pandemic. Amazon, for example, reported a 25% increase in dollar volume in the first quarter of 2020 with its fulfillment centers experiencing unusually high volumes, and it instituted stricter quantity limits for third-party merchants that store goods in its U.S. warehouses.[109] Nonetheless, variability in demand will persist, requiring tools that can analyze throughput and anticipate demand to provide insight on how to best use space. New business models like Warehouse as a Service can also help to better optimize and monetize space.

Likewise, domestic production and business-to-business distribution will continue to expand in response to growth in re-shoring, a trend that has accelerated due to the pandemic. If buildings are developed specifically for e-fulfillment now, but the longer-term trend is toward clean manufacturing and 3-D printing of products from plastics, metals or organic materials, the buildings will likely need to be reconfigured. According to Pinckert, "nobody really knows, three years from now, what people are going to want to do. It's changing so fast, so flexibility is critical."[110] Dynamic automation and robots will play key roles in making buildings more flexible and adaptable to future demands.

## Integrated Operations

In the future, automated storage and retrieval systems, autonomous guided warehouse vehicles, robots, humans and the logistics network will be part of an integrated and dynamic operating system. Sensors, RFID tags, barcodes and lasers will not only direct autonomous carts, forklifts and robots; they will also track the arrival of goods and materials, where they are stored and how they leave. Each piece of interconnected hardware will generate immense amounts of data that AI and machine learning will continuously analyze and evaluate to make adjustments in real time and optimize operations. This dynamic operating system will encompass logistics networks as well. Bennett foresees an autonomous delivery fleet that is not only responsive to fulfillment activity, but also communicates with the yard and the building itself.[111]

But is there a role for humans in a future of digitally enabled, automated warehouses? Recent trends in warehouse technology suggest that workers will continue to play an important part in logistics facilities. Technologies like machine vision, cameras and wearable sensors promise to improve worker safety and efficiency. Cambridge, Massachusetts-based SmartVid.io, for instance, uses high-resolution cameras, AI and sophisticated image recognition to analyze real-time video and automatically detect positions of machinery, materials and workers to identify imminent hazards. Even workers' clothing is becoming smarter. Wearables can help make workers more productive and keep them safer. Smartcap makes safety helmets that use sensors to track brain waves to monitor worker fatigue and distraction. Triax

makes Spot-r wearable clips to alert workers and their team members of possible health issues or proximity dangers. Similarly, Reflex's KINETIC wearables automatically detect high-risk postures to prevent injuries. Researchers at Australia's Royal Melbourne Institute of Technology have developed smart vests and smart boots that use sensors to provide heat and body temperature warnings, proximity alerts and GPS locational data.[112] Such technologies can also help manage and enforce social-distancing protocols necessary to protect workers against COVID-19.

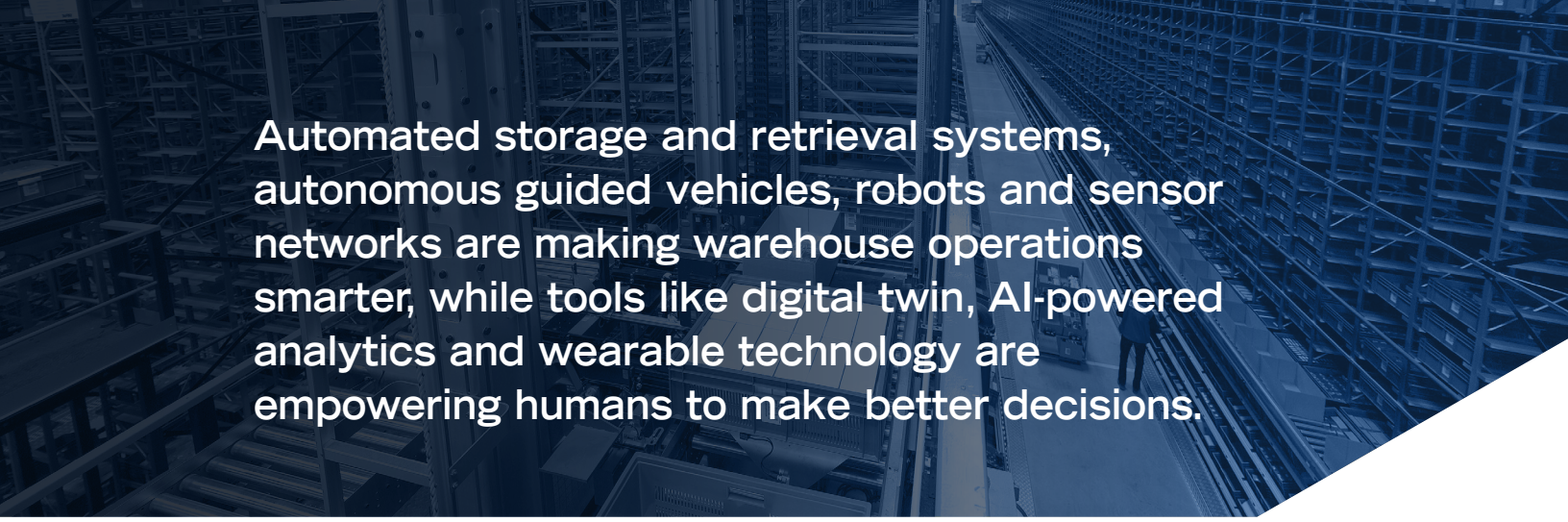
## Digital Twin Technology

The built environment is becoming increasingly digital, allowing new and unusual ways of interacting with real estate. One is digital twin technology, which is a digital, virtual, spatial model that replicates the physical world. It represents the physical state of an object as well as its behavior, making it a powerful tool for understanding the interaction between systems and their environment. For example, companies like Dassault Systems use digital twin to design jet engines and test them in real-life conditions. PTC uses digital twin to design complex manufacturing systems and test their performance. Likewise, digital twin can represent the design and layout of new and existing buildings, allowing companies to optimize space utilization and simulate the movement of products, personnel and material-handling equipment.[113]

Typically starting with building information modeling (BIM), a digital twin brings disparate building systems into one platform to become the single source of information for a structure. Importantly, it is continuously updated over time with data collected from the internet of things (IoT) within the building—automated storage and retrieval systems, autonomous warehouse vehicles, robots, building sensors and worker wearables—to model the relationships between machines, people and places. These data allow firms to analyze and further optimize their operations and the building itself. Startups such as Willow and Invicara support the creation of digital twins by providing robust platforms to collect, organize and analyze data and construct a dynamic, intuitive spatial model.

Digital twin technology can also improve worker productivity and engagement. The twin can monitor systems and components for needed repair and maintenance, and it can be used to test and evaluate the potential impact of layout modifications or the introduction of new equipment before committing to changes on the warehouse floor. The twin can also be linked to "mixed-reality" smart eyeglasses like Microsoft Hololens, which superimpose virtual images onto the physical world (through augmented reality, or AR) and also provide virtual reality capabilities. Through the Hololens, workers gain X-ray-like vision that allows them to identify breakdowns in building mechanicals, walk through repairs and maintenance, or see where a part is located in a rack.

In the near future, data will also be analyzed to create digital twins of supply chains. Manufacturers, suppliers, warehouse and distribution centers, and retail partners will be able to see consumer-level demand in real time, allowing them to accurately forecast and plan production and replenishment. This ability to accurately forecast demand will become a powerful new tool for anticipating short- and long-term space needs and locational requirements for warehouses.



**Automated storage and retrieval systems, autonomous guided vehicles, robots and sensor networks are making warehouse operations smarter, while tools like digital twin, AI-powered analytics and wearable technology are empowering humans to make better decisions.**

# Conclusion

Organizations are adopting and adapting to technologies that are fundamentally changing how the industry operates. Old business models are being challenged, and the built space that supported them is evolving into new and exciting uses. In the future, real estate will be increasingly digital and autonomous, and the boundaries between traditionally separate uses will blur. In response to persistent demand for faster delivery times, rising land and labor costs, and increasingly digital logistics networks, warehouse and distribution real estate is on the leading edge of technological change. Automated storage and retrieval systems, autonomous guided vehicles, robots and sensor networks are making warehouse operations smarter, while tools like digital twin, AI-powered analytics and wearable technology are empowering humans to make better decisions. According to JP Morgan Asset Management, automation could increase global GDP by more than $1.1 trillion in the next 10 years.[114] Ultimately, every industry will undergo some degree of transformation, including real estate.

Logistics technologies and their applications are creating new opportunities for developers, building owners and other commercial real estate professionals. Technologies that increase throughput and make more efficient use of vertical space can increase the value of existing or planned logistics facilities. These and related transportation technologies can also make smaller buildings in urban locations attractive redevelopment opportunities, and they can increase the profitability of new multistory warehouses. Space within malls, shopping centers or individual retail locations can be devoted to distribution, helping the viability of properties that have experienced a decline in foot traffic and creating advantages for retailers that embrace hybrid distribution models. As technology disrupts traditional ideas about the role and location of industrial space, it will be important for commercial real estate professionals to develop creative approaches to integrating industrial spaces into previously unexpected places.

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