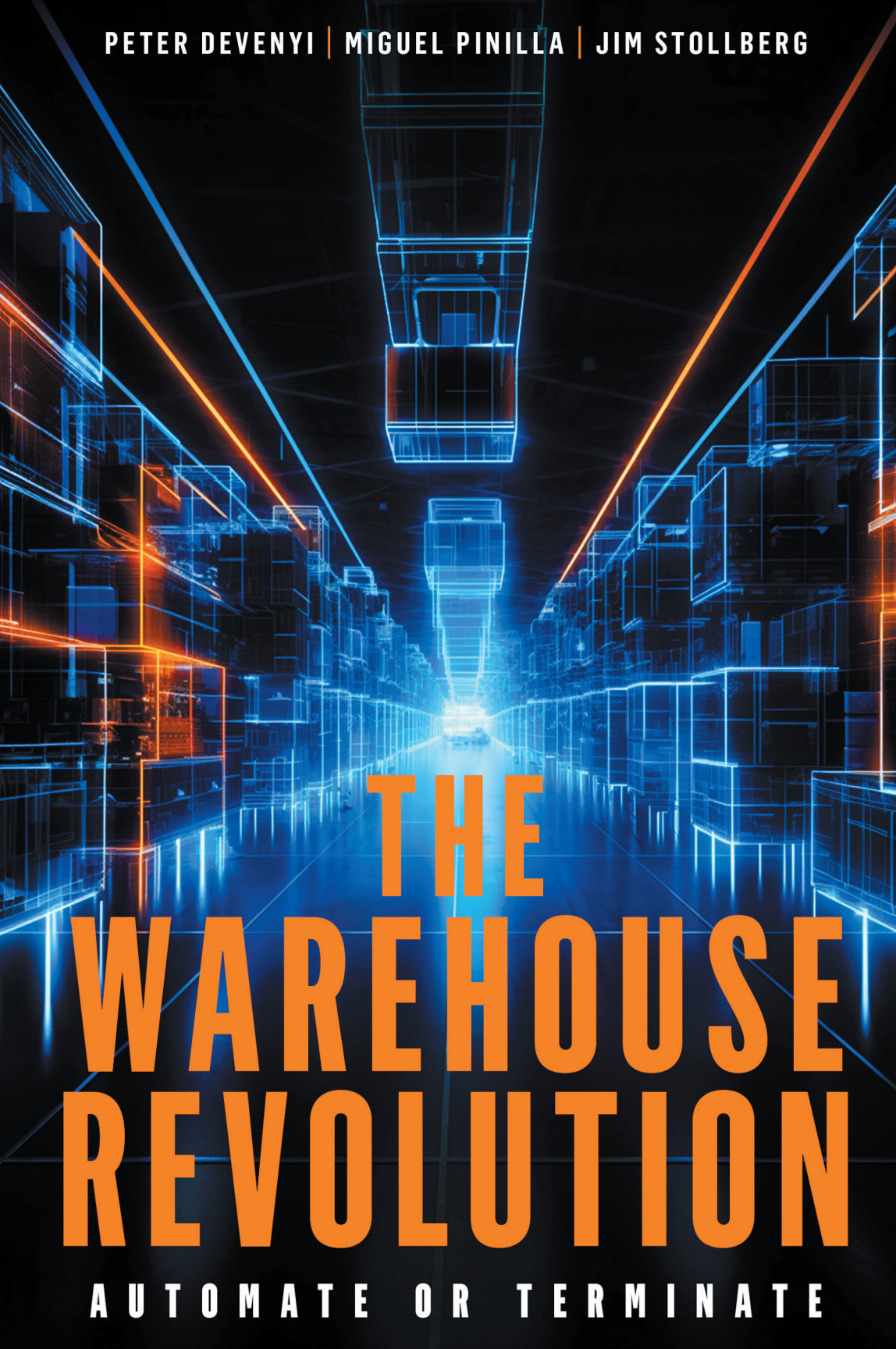


PETER DEVENYI | MIGUEL PINILLA | JIM STOLLBERG



THE WAREHOUSE REVOLUTION

A U T O M A T E O R T E R M I N A T E

The Warehouse Revolution

Automate or Terminate

Peter Devenyi, Miguel Pinilla, and Jim Stollberg

The Warehouse Revolution: Automate or Terminate

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*To my wife Sue, and my kids, Brittany, Josh, and Cassie, for
all the love, support, and encouragement you have provided
me throughout my career.*

Peter Devenyi

*To my wife Pam, daughter Marta, and son Pablo for a full life
that made pursuing my career rewarding and fun. I would not
be the person I am without you.*

Miguel Pinilla

*To my wife Leslie, son Justin, and daughter Lauren, for thriving
through my absence while I globe trotted through my career.*

You are a blessing to me.

Jim Stollberg

Description

The *Warehouse Revolution* is a must-read for technologists, retailers, and investors who seek to understand the warehouse automation industry and the associated technologies. It walks through an array of automation options using understandable terms. It describes the history of the industry and how e-commerce catapulted warehouse automation to the forefront of supply chain operations. The book describes all associated processes including receiving, storage, picking, packing, sortation, and shipping. It compares manual, automated, and robotic alternatives in each case, highlighting the pros and cons. It will also be interesting to those who are simply curious and seek to understand what's happening behind the curtain: the highly choreographed movement of people and machines that enable packages to show up at our respective doorsteps in less than a day.

Keywords

warehouse automation; distribution center; fulfillment center; e-commerce fulfillment; robotics; articulated arm robot; automated storage and retrieval system; ASRS; shuttle system; cubic storage system; autonomous mobile robot; AMR; warehouse execution system; WES; warehouse control system; WCS; automated guided vehicle; AGV; industrial automation; microfulfillment center; storage system; picking; packing; shipping; receiving; sortation; linear sorter; crossbelt sorter; circular sorter; conveyor; warehouse management system; WMS; artificial intelligence; goods-to-person; person-to-goods; supply chain management

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Testimonials

“The Warehouse Revolution is a must read for anyone who has an interest in the rapidly evolving warehouse automation industry. The authors, all veteran industry experts, have written a comprehensive, easy to read, and very interesting history of this industry, which has evolved from being a mere cost center to being a critical element of competitiveness in many industries.”

—Rick Wagoner, Retired CEO, General Motors

“The Warehouse Revolution offers a comprehensive and easy-to-read account of the past, present, and future of the warehousing industry and all associated technologies. It should serve as a launch pad for anyone who is new to the industry or for those who are facing automation investment decisions in the coming years. With unprecedented market growth levels anticipated over the course of the next decade, this book couldn't have come at a better time!”

—Jeff Moss, CEO, Ascential Technologies

“I would highly recommend this book to anyone interested in warehouse automation. It provides a comprehensive overview of the topic, including the latest technologies and trends. The authors draw from their extensive experience and deep knowledge of both the industry and the science to provide an excellent explanation of the benefits of warehouse automation and how it can help businesses improve efficiency and competitiveness. I particularly enjoyed the sections on software and the future evolution of the industry, with artificial intelligence and robotics being two of the most promising technologies for warehouse automation. Overall, this is an essential read for anyone who wants to stay ahead of the curve in the ever-changing world of logistics.”

—Dr. Eike Boehm, Retired CTO, KION Group

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—Pete Devenyi, Miguel Pinilla, Jim Stollberg

Introduction

A good friend of ours, a self-proclaimed coffee aficionado, recently purchased an espresso machine on Amazon. It was one of those high-end models that grinds the beans, adjusts the strength, and warms the milk, all with the touch of a button. He clicked the order button at 8 am and by 4 pm, much to his delight, the 40-pound wonder-machine was sitting on his doorstep.

While most of us could not imagine such possibilities a decade ago, it hasn't taken us long to recalibrate our expectations. Our psyche of consumption has changed considerably. What was acceptable a decade ago, no longer is. For younger generations, this has become normal commerce. Future generations will expect even more. Order fulfillment will be measured in hours, not days, and the delivery location will be the one that works best for us. It might be your front porch or you may prefer to pick up the order at a kiosk on your way home from work. Alternatively, you might have it placed in the trunk of your car, all while attending to your busy day at the office. Speed of delivery, high inventory availability, and maximum consumer convenience will be the name of the game. You will expect to buy whatever you want, whenever you want it, delivered to the most convenient location, almost instantly.

Most people don't worry about the operational and technological gymnastics that take place in the background to make this all possible. What happens in those few hours after the order button is pressed and before the item shows up at your door? The highly complex, synchronized movement of machines and workers that is launched within seconds is as fascinating as it is astonishing. Understanding the associated processes, capabilities, costs, and limitations will define the difference between success and failure for a growing number of companies.

This book walks through the myriad of technological options in detail, in plain language, using understandable terms. It is not a deeply technical book containing a sea of scientific jargon. It will be valuable to

technologists who are new to the space and are motivated to understand the industry quickly, and also to experienced logistics professionals who are seeking to plug some knowledge gaps. It will also be useful to retailers, wholesalers, and third-party logistics providers who face a multitude of automation choices but don't know which way to turn. Those who are considering investing in the space will benefit by understanding what the future is likely to hold. Finally, it will be educational for day-to-day consumers, those who are simply curious and seek to understand what's happening behind the curtain: the highly choreographed movement of machines that continues to turn this modern-day miracle into daily reality.

The Four Industrial Revolutions

When we look back at recent history and the evolution of the four industrial revolutions, we learn about the progress made in manufacturing process automation, steam power, electric power, and a wide range of other technologies. We are now approaching the tail end of the 4th revolution and arguably entering the start of the 5th. This is a world in which we will see greater synchronization of artificial intelligence (AI), smart technologies, robots, and humans. Warehousing and distribution become critical areas of focus, enabling a new set of consumer experiences across a breadth of shopping and service verticals.

The U.S. Federal Reserve's Production Index, which measures the output of all facilities located in the United States for manufacturing, mining, and electric and gas utilities, has increased by 20 times over the past 100 years. According to Statista, a leading data statistics company based in Germany, global trade has increased by 300 times over that same period. Taken together, it is inescapable that we are producing, importing, and exporting orders of magnitude more products today than we did in prior generations, and all this product needs to reach consumers.

Until recently, relatively modest attention was placed on post-manufacturing activities. The manner in which finished goods were stored, transported, and distributed to consumers was treated as necessary evil, a required cost of doing business. The migration of manufacturing to lower-cost countries, including offshoring to the likes of Mexico and

China, has stretched supply chains and turned warehousing and distribution into a critical element of the end-to-end ecosystem. These days, global supply chains break down if warehouses don't operate efficiently or if transportation routes are impeded in any way. Recent pandemic disruptions have made these requirements impossible to ignore.

According to Statista, there were approximately 160,000 large, commercial warehouses in operation globally in 2022, expected to reach 180,000 by 2025. The vast majority of these continue to rely solely on manual processes and manual labor. With ever-increasing consumer expectations, there is a requirement to increase the efficiency of these warehouses. AI, robotics, and cloud systems are being deployed to satisfy this need. It is no longer reasonable to expect human beings, armed with clipboards and manual pick lists, to walk up and down aisles retrieving items from storage racks, transporting them to consolidation and packing locations, or physically wheeling them to shipping docks for manual sortation and truck loading. Simply put, the majority of warehouses in operation today are not fit to handle rapidly evolving consumer demands and expectations.

The Warehousing and Distribution Revolution

The first known warehouses were used to store yields and crops and to better align supply and demand. Since those early days, the rise in commerce has driven an evolution in the supply chain industry. While warehousing was once the supply chain component that received the least focus, it has since been elevated to its core. For some companies, the efficiency of their warehouse processes has become their primary competitive advantage. According to the U.S. Bureau of Labor and Statistics, the rise of warehouse workers has doubled in the past 10 years and tripled in the past 30. It has been fueled by a combined growth of global trade and e-commerce. The turnover in jobs has been notoriously high due to low pay, low job satisfaction, and high numbers of work-related injuries. Attracting people to work in warehouses has become difficult. Maintaining the same labor growth rate as seen in prior decades is unrealistic. The most unpleasant jobs are slowly but surely being replaced by automated alternatives. The good news is that the operation and maintenance needs

of the equipment are giving rise to new jobs that offer higher levels of employee satisfaction and better pay.

Warehouses have become increasingly specialized within supply chains. The term warehouse may refer to either a distribution center or a fulfillment center. *Distribution Centers* are essentially merchandise hubs. The products they ship are sent to retail stores, to other distribution centers, or to fulfillment centers. *Fulfillment centers*, on the other hand, primarily support e-commerce or other direct to consumer shipments. Some warehouses do combine distribution and fulfillment activities under one roof.

Warehouse Automation 1.0

In the 1970s and early 1980s, producers (manufacturers) wielded most of the power. Large companies like Procter and Gamble with their multiple brands, addressing a wide variety of consumer needs and with strong marketing, were able to negotiate lucrative deals with retailers. They wielded a position of strength. To purchase the products they wanted, consumers had little option but to drive to their nearest retailer. The retailers, in order to be able to offer those products, were forced to purchase in bulk and to sell off any inventory that wasn't moving, often at large discounts. Manufacturers typically shipped pallet loads of goods to retailers as it was in their best interests to do so. It allowed them to sell more goods and to minimize the overall complexity of their warehouses, effectively "pushing" their products through the supply chain to the consumer. Warehouses were considered cost centers with limited impact on top line revenue. As a result, relatively low levels of investment were being made in them.

Warehouse Automation 2.0

From the mid-1980s through the early 2000s, the power shifted toward retailers. Companies like Walmart grew in strength and they began to wield considerable power over their suppliers. If a manufacturer wanted Walmart to carry their products, they would have to operate by Walmart's rules and agree to their discounts. Manufacturers' warehouses had to

change to fit the model. They could no longer force pallet loads of goods on retailers. They often had to break up their pallets and manage the distribution of individual cases as the retailer had much more control over the amount of product they were willing to accept on any given day. Supply chains were forced to become leaner and more responsive and manufacturers had to handle many of the product variability complexities that were previously handled at the retail level.

Warehouse Automation 3.0

By 2010, Amazon's annual revenues grew to over \$30B. The bulk of this revenue was generated through e-commerce, of which approximately \$12B was in the United States. Statista reported total retail sales in the United States of over \$2T in that year, with e-commerce sales accounting for about \$170B, or 4.5 percent. At that time, e-commerce sales hit an inflection point, and power began to shift more toward consumers. For the first time, consumers felt less restricted by physical proximity to their favorite stores. Instead, they voted with their wallets, placing a premium on price, product availability, and rapid delivery, forcing retailers to adapt.

Fast forward to 2022. Statista reported total retail sales in the United States of \$7.2T, with over 15 percent of it attributed to e-commerce. Analysts estimate that the e-commerce share of the global retail market is even greater, exceeding 20 percent in 2022.

Amazon's sales grew the fastest, surpassing \$500B globally in 2022, with over \$350B in the United States. Consumers were making new decisions on what they would consume, how much they needed, and where they were going to buy it. Warehouses needed to rethink their operations once again, continuing to fulfill orders from retail outlets in pallets and cases, but also fulfilling them directly to consumers as individual items. Amazon had to figure out how to get that espresso machine to our friend's house in a day or less, which meant dispatching robots into action the moment he clicked the order button. Consumer convenience became paramount and non-Amazon warehouses across the world struggled to compete using processes, systems, and equipment that were quickly becoming obsolete. Retailers found themselves thrust into an omnichannel world with a requirement to fulfill orders through

a multitude of channels while adhering to challenging time constraints. Warehouses designed to optimize the storage and movement of goods during the Warehouse Automaton 1.0 and 2.0 eras proved inadequate to satisfy the new agility and flexibility requirements. Investing in automation was required for retailers to keep pace. Warehouse automation companies like Kiva, Swisslog, Dematic, Intelligrated, and Vanderlande became hot commodities and were scooped up by the likes of Amazon, Kuka, KION, Honeywell, and Toyota.

With an annual warehouse automation growth rate already at double-digit levels, COVID served to push that number further into the teens, pouring fuel onto an already well-lit fire. Automate or terminate became the new reality facing many retailers. They witnessed their in-store revenues plummet, snatched up by competitors better positioned to serve consumers' rapidly changing expectations. No retailer benefited from this shift more than Amazon. Many iconic businesses that were unable to react to the changing times began to struggle, and some like Toys R Us, K-Mart, and Sears either liquidated the lion's share of their stores or shut down altogether.

Warehouse Automation 4.0

While we don't yet know exactly how warehouse automation will evolve as we proceed through the second half of the 2020s, we do know it will have a lot to do with advanced robotics, dark-stores, 24×7 operations, networked warehouses, AI, big data, and the ability to better predict the demand for specific goods at specific locations. Realistically, the only way to get goods to consumers faster is to store them closer to the point of demand. With consumers concentrated in urban areas, there is a need to make more efficient use of smaller spaces in those areas. The winners will be those who are able to combine the latest technologies into standardized, small-footprint modules that can be deployed quickly and inexpensively. We explore the various options in this book.

Summarizing the Four Automation Phases

While warehousing activities date back to ancient times, warehouse automation has seen a revolution over the past few decades. Still, the most significant transformations are likely to be the ones that are still in front of us. The timelines and characteristics of the four stages of this revolution are summarized in Table I.1.

Table I.1 Key characteristics and timeframes of the four warehouse automation phases

	Warehouse Automation 1.0	Warehouse Automation 2.0	Warehouse Automation 3.0	Warehouse Automation 4.0
Timeframe	1980s	1990s to early 2000s	Mid-2000s to 2010s	2020s
Power broker	Manufacturer	Retailer	Consumer	Consumer
Automation focus	Pallets	Cases	e-commerce (eaches)	Small urban warehouses (Microfulfillment)
Storage technology	Pallet Cranes	Mini Load cranes	Shuttle systems	Mobile robots
Automation software	Warehouse management system	Warehouse control system	Warehouse execution system	Warehouse Execution system with AI

CHAPTER 1

Warehouse Automation Through the Years

The first Automated Storage and Retrieval System (ASRS), often considered the heart of modern automated warehouses, was developed by Dematic (Demag, at the time) in Germany in the 1960s. Large, sprawling warehouses were difficult to construct in Europe, given the relative scarcity of land. The introduction of ASRSs changed the game. They enabled the full height of the warehouse to be used for the storage and retrieval of goods. They also helped companies manage the impact of rapidly increasing labor costs.

These early ASRSs and their associated rails were initially secured upside down, with racks and masts hanging from the ceiling to help reduce sway. The first production system, which was installed at the Bertelsmann Publishing House in Gütersloh, Germany, is shown in Figure 1.1. It was 20 meters high and had the capacity to store up to 7 million books. It was a pioneering achievement at the time, and it took full advantage of the massive technological investment being made across Europe, most notably in Germany. It set the stage for a new era in warehouse automation.

Warehouse storage was previously stuck at ground level with heavy, palletized goods moved by forklift trucks and conveyors. At times, low-level racking was used to store and retrieve lighter products accessible with Reach Trucks, but heavier products were always stored on the ground. As technological advancements progressed, heavy goods moved upwards and racking, rails and masts were resecured to the ground.

J.C. Penny introduced the Warehouse Management System (WMS) as a game-changing technology in 1975, the first retailer to update stock inventory in real time. Daifuku, a leading provider of automated material handling solutions since the 1960s, deployed its first ASRS at Fujimura



Figure 1.1 The first automated high-bay warehouse installed by Demag at the Bertelsmann publishing house in Wetter, Germany in 1962

Iron Works in Japan in 1972. Despite the relative abundance of warehousing space available in rural areas of North America, by the 1980s, ASRSs began to infiltrate that region as well. Today, 1,000 kg pallet loads can be retrieved by a single crane at rates of approximately 1 pallet per minute, from storage locations as high as 45 meters in the air.

According to Fact.mr, the global ASRS market is not showing any signs of slowing down and is expected to reach \$24 billion by 2032, up from approximately \$10 billion in 2022. This contributes to the broader warehouse automation market, estimated by Industry Research to be at

\$19 billion in 2022, with a Compound Annual Growth Rate (CAGR) of 13.7 percent through 2028. Soaring land and labor costs are driving much of the investment. As in Europe, companies in North America are prioritizing height over footprint when building new warehouses. While Asia Pacific has lagged both Europe and North America in terms of monetary spend in the past, its anticipated CAGR is the highest in the world today. Despite access to relatively low-cost labor, government-led investment in industrialization, the region's population density, and its early embrace of e-commerce have fueled its growth in recent years. Large global warehouse automation providers have also recognized the breadth of opportunities in Asia. Many have elected to open regional headquarters there, declaring it to be one of their strategic growth engines. According to Research Nestor, the size of the warehouse automation market in Asia is expected to reach European and North American levels by 2030. Additionally, there has been a significant increase in the number of Asian companies serving that market, making it difficult for global players to compete effectively on price. Larger Asian manufacturers have also recognized the importance of entering the North American and European markets and are pursuing global growth initiatives of their own.

Warehouse Automation 1.0 Technologies

The 1980s focused on the automation of pallet movement, which was at the core of most manufacturers' operations. Pallets had to be retrieved from storage, conveyed to consolidation areas, and optionally reconfigured before being dispatched to shipping docks via pallet conveyors. The planning cycles that were built into the associated WMS systems were typically measured in days or weeks, rather than hours or minutes. Plans were committed as soon as they were determined, without revalidating them prior to execution.

In some cases, pallets received by warehouses only needed to be cross-docked. These pallets were processed by coordinating the timing of inbound product receipts with outbound shipments, enabling them to be moved directly from one dock door to another. Walmart was the first to popularize automated cross-docking. They had the ability to track the movement of goods throughout their distribution centers and retail stores.

An ASRS that handles pallets, known as a Unit Load system, includes one or more aisles of dual-sided racking, each containing multiple levels. To further increase storage density, double-deep racking may be installed, enabling two pallets to be stored on each side of the aisle. Unit Load cranes move fast, reach the highest levels of tall facilities, and deliver high throughput. The alternative to an ASRS is a fleet of manually operated forklift trucks, which remain popular to this day. Forklift trucks are more restricted in their maximum reach and speed, require more labor, and yield significantly lower throughput rates. They do offer greater flexibility, however, making them the preferred choice for lower throughput, high inventory operations. While the cost of a single high-reach fork truck is considerably less than a crane, the throughput rates, storage density, and labor cost savings associated with an ASRS can result in a return on investment (ROI) in three years or less.

Pallet conveyors, which are used to transport pallets at ground level, are composed of both straight and specialized segments such as inclines, declines, and right-angle transfers (RATs). RATs enable pallets to divert and weave their way around a warehouse.

WMSs control the operation of most modern warehouses. They manage orders and maintain inventory locations and counts in real time. Programmable Logic Controllers (PLCs) and the software that runs on them manage the detailed movement of the machines themselves. Dedicated control software executes the directives received from higher-level software systems (e.g., a WMS). During the Warehouse Automation 1.0 timeframe, there was no strong requirement for sophisticated automation control software, as the primary role of machines was to manage the bulk movement of heavy pallets.

While these warehouses were not overly complicated by today's standards, they did occupy significant square footage. They were erected primarily in rural locations and serviced large regional areas, receiving pallet loads of product from manufacturers and shipping them to retail stores.

Warehouse Automation 2.0 Technologies

As the world entered the Warehouse Automation 2.0 era of the 1990s and 2000s, cases, rather than pallets, became the dominant package size

shipped by most warehouses. This change had a significant impact on the operation and complexity of warehouses, including those that invested heavily in pallet-based automation. WMSs became more sophisticated as well, as it became typical for planning cycles to be measured in hours rather than days. Warehouse Control Systems (WCS), the precursor to Warehouse Executions Systems (WES), managed the movement of goods through automation equipment, helping to further increase throughput and reduce cost. Real-time events would trigger replanning cycles to reoptimize prior plans as new data became available.

It was no longer sufficient to store and retrieve palletized products in racks as high as the eye could see. It became increasingly important to store individual cases packed to the ceiling as well, retrieving them when needed, and consolidating them into orders before loading them onto trucks. Unit Load ASRSs didn't disappear as they were still needed for bulk storage of inventory but pallets often had to be broken down into individual cases and re-stored before orders could be processed. A new kind of ASRS dedicated to case handling, Mini Load machines, was created for this purpose. They work much like Unit Load ASRSs, but they move faster, their load capacities are less, and their load-handling devices are telescopic arms, rather than forks.

Two-stage logistics systems comprising a Unit Load ASRS for pallet storage and conveyors for transport evolved into more complicated multistage systems. Unit Load ASRSs and pallet conveyors were still used for bulk storage, retrieval, and transport. In addition, depalletizing stations were used to break pallets into individual cases, Mini Load ASRSs stored and retrieved the cases, case conveyors transported them in and out of the Mini Load system, and high-speed linear sorters, equipped with barcode readers, routed them to their designated shipping areas. Retailers' ability to pressure manufacturers to ship smaller caseloads of product to their stores, impacted the structure of warehouses. The new multistage operations and processes forced many manufacturers to establish partnerships with distributors, leading to the creation of hub-and-spoke networks. Many manufacturers and importers elected to bulk-ship pallet loads of product to their distributors so they could process incoming orders on their behalf. Sophisticated software systems, including WMSs, became vital to manage batch inventory movements in and out of the facility.

Warehouse Automation 3.0 Technologies

As e-commerce grew, the demands facing warehouse operators elevated to new heights. The Warehouse Automation 3.0 era of the 2010s spawned the arrival of many new technologies designed to address the increasingly complex requirements. These technologies extended the ones already in place for pallet and case automation requirements. Now, manufacturers and distributors need to automate the fulfillment of individual items, or “eaches,” ordered by an increasing number of consumers through the Internet. Cases had to be broken down so that individual items were ready and waiting to fulfill this new stream of inbound consumer orders. Demands on software systems correspondingly grew. Sophisticated optimization algorithms had to be added to WCSs which gave rise to WESs, enabling planning cycles to be reduced from hours to seconds, and in some cases, subseconds. The practices of “plan and print” that were associated with the warehouse automation 1.0 timeframe, or “plan and replan,” associated with the 2.0 timeframe, were changed to “continuous planning” to enable ongoing optimization.

Retailers and distributors who invested in e-commerce-driven automation were facing a choice between two primary alternatives:

- Person-to-Goods (PTG) Picking: Decant individual items into accessible containers for storage on static shelving units, using lights or voice commands to direct the movement of human pickers assigned to different picking zones.
- Goods-to-Person (GTP) Picking: Decant cases into totes stored in ASRS machines such as shuttle systems which retrieve the totes in a required sequence and send them to workstations where associates pick the items and deposit them into order totes.

By automating the storage and retrieval process of totes, they can be delivered rapidly to ergonomic workstations. Workers simply follow the instructions displayed on a computer screen, picking items from donor totes and placing them into adjacent order totes. When an order is complete, the associated tote is dispatched on a conveyor belt to the

packing area while the donor totes are returned to storage. A similar process, executed in reverse, is used to replenish goods in the storage system. Improved performance and lower error rates are possible as unproductive walk time is eliminated.

Pallet, Case, and Eaches Picking in the Same Warehouse

For many warehouses, it became necessary to automate a wider array of order processing systems. Pallets needed to be stored, retrieved, or cross-docked to support the requirements of bulk-order customers; cases needed to be stored to support the requirements of a growing number of retail customers; and individual items needed to be stored to support the requirements of e-commerce customers. Inventory availability and rapid delivery expectations increased across all customer segments. Warehouse managers needed to determine how many pallets to break into cases and how many cases to break into eases. Systems connected Unit Load ASRSs to pallet conveyors, depalletizing machines, case singulators, inbound case conveyors, tote handling ASRS machines, outbound case conveyors, pick workstations, packing stations, labeling and manifest stations, high-speed sorters, and so on. The permutations and combinations, and the number of possible material flow paths, grew exponentially. Each item in the warehouse needed to be tracked with sophisticated software, and processes had to be designed to recover from a variety of failure conditions and unforeseen events.

Warehouse Automation 4.0 Technologies (and Beyond)

Autonomous mobile robots (AMRs), which often use Light Detection and Ranging (LiDAR) technology to gain spatial awareness of their surroundings, are gaining popularity. Enabled with adaptive AI, they can navigate from one location to another without following a predetermined path and can avoid dynamic obstacles (e.g., people, other AMRs) in order to reach their destination. They are manufactured in various shapes and sizes and can support a variety of attachments, each designed to perform a unique task. For example, some AMRs are lighter weight and may

be equipped with tilt trays to sort smaller packages. Others have larger weight capacities and are dedicated to pallet transportation. They may move shelving units around to enable GTP picking or may be dispatched to assist pickers in a PTG operation. Regardless of the size or function of an AMR, the units operate as a swarm, controlled by the WES or an associated orchestration engine. The engine dispatches software commands to individual AMRs over the air, instructing them to perform specific tasks. When an AMR completes a task or encounters difficulties, it communicates back and awaits its next command.

Robotic picking is also becoming increasingly popular. Articulated arm robots with integrated grippers, 2D and 3D cameras, and machine-learning software, will eventually replace human pickers. They are able to robotically pick items from donor totes and place them into order totes or onto conveyors. The speed, accuracy, and cost of these robots make them difficult to cost-justify in some environments but improvements are happening rapidly. The level of investment in robotic picking technologies is expected to increase significantly over the next several years.

As we proceed through the early part of the 2020s, e-commerce is expected to drive a transition toward micro-fulfillment. Micro-fulfillment centers (MFCs), sometimes located in the back of large box stores, are configured with standardized automation equipment, enabling orders to be fulfilled in a location that's just around the corner from the consumer. The MFC model offers a number of advantages (e.g., rapid delivery, simplified returns, and flexible pickup options) but also introduces several challenges. Ensuring inventory availability in the right quantity and location requires sophisticated demand planning software. It also requires a new level of software functionality that looks beyond the four walls of the warehouse, enabling multiple MFCs to operate in a network as a virtual fulfillment center. Orders may be fulfilled from multiple MFCs and each MFC may replenish depleted inventory levels of neighboring ones. Inventory must be updated in real-time with network-level visibility. Additionally, orders should be able to reserve inventory in any networked warehouse. These micro-warehouses, which are changing the very definition of a warehouse, require increased levels of reliability due to the lack of knowledgeable, permanent service personnel. Despite the challenges, micro-fulfillment is expected to increase

in adoption as we proceed through the decade and as new technology companies enter the fold. The grocery industry is leading the way but other verticals are watching closely and are expected to follow suit as the technology matures.

Key Takeaways

- Warehouse Automation first gained attention in the early 1980s when Unit Load ASRSs, pallet conveyors, and WMSs were used more widely to automate the transport of heavy pallets.
- In the 1990s and 2000s, warehouse automation expanded to support case loads as retailers were less likely to accept full pallets of goods from manufacturers. Automated equipment and software increased in complexity as a result.
- In the early 2010s, e-commerce gained traction and end-consumers began to wield more power. Vendors were forced to offer retailers more sophisticated, automated each-picking solutions.
- In the 2020s, more flexible automated warehouses using AMRs, robotic picking, and AI-based software became popular. A shift toward smaller warehouses in urban areas began to surface in parallel. These trends are expected to continue through the balance of the decade and likely beyond.

About the Authors

Peter Devenyi spent his 40-year engineering career working in software and technology development in the fields of networking, telecommunications, and logistics. He held senior executive positions at large global companies like RIM (BlackBerry) and Dematic. He earned bachelor's and master's degrees in Electrical Engineering from the University of Toronto. Currently, he consults in the field of Warehouse Automation and Logistics and teaches engineering leadership at the University of Toronto.

Dr. Miguel Pinilla has over 30 years' experience in the supply chain information systems industry. He held leadership positions at Dematic, RedPrairie (now Blue Yonder), SmartTurn, and Navis. Originally from Spain, he obtained a Senior Engineer Degree in Industrial Engineering from ICAI and came to the United States as a Fulbright scholar, obtaining a Masters in Engineering degree from Carnegie Mellon and a PhD from Stanford in Manufacturing Information Systems. Currently, he is principal of Salduba Technologies, advising clients in the field of Supply Chain Automation.

Jim Stollberg has business experience spanning over 35 years. He held senior executive roles in the automation and management consulting industries, including leadership positions with Dematic, HK Systems, and Accenture. He has participated in several successful equity transactions and continues to advise market-leading companies and thought leaders in the field of supply chain technology. He earned his bachelor's degree in Mechanical Engineering from Marquette University, where he also serves as Executive in Residence and as a member of the Supply Chain & Operations Management Advisory Board.

THE WAREHOUSE REVOLUTION

AUTOMATE OR TERMINATE

PETER DEVENYI, MIGUEL PINILLA, AND JIM STOLLBERG

"A must read for anyone who has an interest in the rapidly evolving warehouse automation industry"—Rick Wagoner, Retired CEO, General Motors

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The Warehouse Revolution will also be of interest to those who are just curious and seek to understand what's happening behind the curtain—the **highly choreographed movement of people and machines that enable packages to show up at our respective doorsteps in less than a day.**



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