The Warehouse of the Future

Toward Highly Automated, Interconnected, Sustainable Warehouses

MIT Center for Transportation & Logistics

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Executive Summary

The **warehouse of the future** represents a paradigm shift in warehouse design and operation. It is the industry's response to the burgeoning growth of e-commerce, worldwide supply chain disruptions including warehouse labor shortages in developed markets, and increasing awareness of the significant volume of greenhouse gas (GHG) emissions emitted by warehouses.

In this white paper, we detail the concept and fundamental characteristics of the warehouse of the future: a shift toward a highly automated, interconnected system that leverages automation and digitalization to enhance precision, flexibility, and efficiency to adapt to changing market and supply chain trends, while integrating environmental sustainability alongside technological innovation. This concept signifies a forward-thinking model that aligns operational efficiency with a sustainable approach to warehousing, that is pivotal to the evolution of contemporary supply chains.

Strategic innovations in three key areas define the warehouse of the future:

1. **Automation:** With advancements in technology and the growing need for greater efficiency and productivity, warehouses are increasingly adopting automation solutions across all processes. Speed remains a paramount concern, especially in the context of e-commerce, while flexibility has emerged as another critical factor, differentiating modern automation solutions from their predecessors. In addition, the challenge of integrating multiple automation technologies forces companies to ensure interoperability, to manage complexity, and to make better decisions about capital expenditure and long-term benefits.
2. **Digitalization:** While automation brings efficiency and precision to warehouse operations, it is the integration of digital technologies that can unlock the true potential of highly automated warehouses. Key elements include high-speed connectivity for real-time adjustments and AI systems for enhancing the precision of robotic operations. However, the transformation journey faces two key challenges: the need for data accuracy and the acquisition of the right talent.
3. **Sustainability:** The implementation of automation technologies in warehouses forces companies to reassess their sustainability strategies. This reassessment encompasses both the embodied carbon emissions from the materials used in warehouse automation and the energy consumption of new automation systems, like electric forklifts and automated storage systems (AS/RS). Sustainable practices, including the integration of renewable energy sources, like solar and wind power, and employing more energy-efficient technologies, are pivotal in reducing the environmental impact of warehousing activities.

About the Report

Many of the insights detailed in this report originated from an MIT Center for Transportation & Logistics roundtable hosted by Maersk in February 2023 at the latter's warehousing facility in California, attended by more than 30 supply chain experts from 20 different companies. The insights in this report are based on the roundtable discussions and extensive research conducted by the authors at their respective organizations.

MIT Center for Transportation & Logistics roundtables are open to member companies of the Center's Supply Chain Exchange, an industry partnership program that offers companies a variety of exclusive opportunities to engage with Center research, insights, and guidance. For more information on how to join the Supply Chain Exchange, please contact us.

About the MIT Center for Transportation & Logistics

Founded in 1973, the MIT Center for Transportation & Logistics (MIT CTL) is a dynamic, solutions-oriented research center where students, faculty, and industry leaders pool their knowledge and experience to advance supply chain education and research. Through its Global Supply Chain and Logistics Excellence (SCALE) Network, MIT CTL sits at the heart of an international network of six centers of excellence, with over 80 researchers and faculty members from multiple disciplines, and more than 150 corporate partnerships.

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Foreword

The transformative power of e-commerce in recent years has led to a retail landscape almost unrecognizable from that of a decade or so ago. The introduction of fast shipping in one or two days and omnichannel retail and fulfillment are among the many changes that have become standard.

Nowhere is this transformation more striking than in the warehouse. These hubs of activity are now driven by groundbreaking innovations in automation, including robotics and artificial intelligence, and the need to meet the challenges of building sustainable supply chains.

Today, companies need to optimize their warehousing operations for agility, flexibility, precision, and perhaps most importantly, adaptability as change in retail accelerates further. This white paper is a must-read for companies who wish to stay ahead of the curve and ensure that their warehouse networks remain competitive in a fast-changing world.

The MIT Center for Transportation & Logistics is pleased to have such a longstanding, productive partnership with Maersk, whose insights direct from industry have proved an invaluable resource to the Center's research and to advancing supply chain innovation.

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Miguel Rodríguez García is a Postdoctoral Associate in the Omnichannel Supply Chain Lab at the MIT Center for Transportation & Logistics. He has knowledge on all aspects of SCM including Procurement, Warehousing, Manufacturing, and Transportation, with a focus on e-commerce and omnichannel logistics. He has collaborated with industry leaders through applied research projects with direct, positive economic impact throughout his career.

In the MIT Omnichannel Supply Chain Lab, Miguel is undertaking state-of-the-art research on the future of supply chains and warehousing due to the growth of e-commerce and technology developments.

Miguel earned his PhD in E-Grocery Supply Chain Management from the Industrial Engineering School at the University of Vigo, Spain, in 2021. His PhD work aimed to serve as a guide for omnichannel retailers in the e-grocery industry to choose the most suitable, cost-effective e-fulfillment strategies.

Miguel also works in digital learning, supporting the development, research, and management of the MITx MicroMasters® Program in Supply Chain Management.

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Dr. Erez Agmoni serves as the Global Head of Innovation at Maersk, spearheading the Maersk Innovation Center with its three pillars: R&D, Digital Innovation, and Product Innovation. His role extends to fostering ecosystems encompassing internal stakeholders, customers, academia, government entities, and venture capital partners. With over 25 years of extensive experience in supply chain management, freight forwarding, logistics, engineering, and digital innovation, Erez excels in creating sophisticated solutions for comprehensive supply chain improvements.

His academic background is as diverse and impressive as his professional journey. Erez holds a bachelor's degree in Computer Engineering, a master's degree in Telecommunication Science, and a PhD in Organizational Development. His global career path has taken him from Israel to various parts of Asia and Latin America, and he is currently based in New Jersey, USA.

Erez's personal life is as fulfilling as his professional one. He is a family man, married with three children, and finds joy in traveling, hiking, and mountain biking. His passion for learning and experiencing new cultures is evident in his language skills; he is fluent in Hebrew, English, and Thai, and at a beginner level in Japanese.

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The Warehouse of the Future

Warehouses have always been important nodes in supply chains, but until a few years ago, these storage facilities largely operated in the background, sometimes taken for granted and garnering little public attention. That is quickly changing. Today, warehouses are increasingly being recognized not only as core to a company's ability to deliver outstanding customer service, but also as hotbeds of technical innovation and leaders in mitigating supply chains' environmental impacts—key attributes of the warehouse of the future. In this white paper, we explore how companies can leverage the power of transformative forces such as automation, digitalization, and sustainability in the warehouse so they can stay ahead of the competition and play a crucial role in shaping a greener, more responsible future for supply chains.

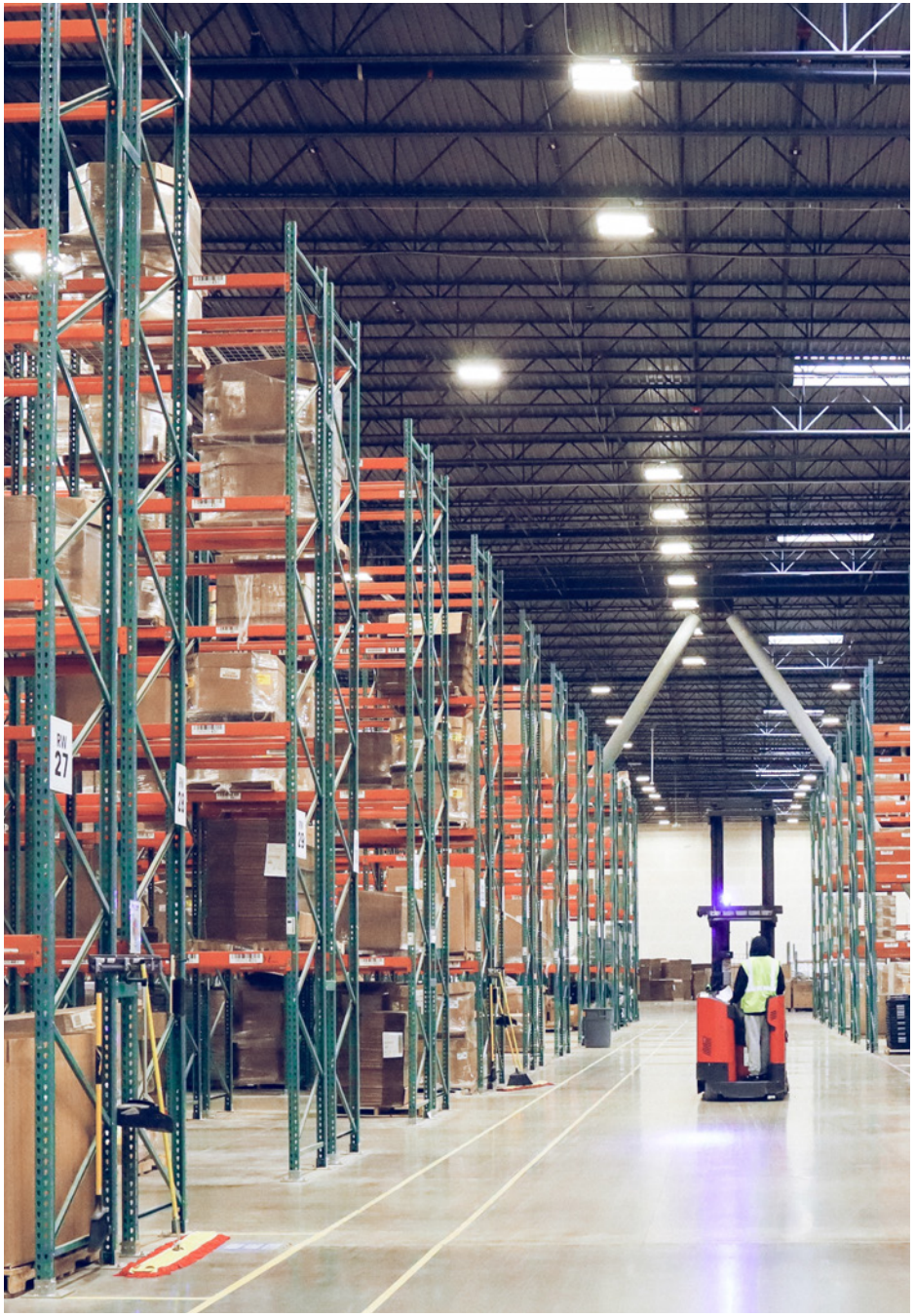
Opportunities to make strides in warehouse automation, digitalization, and sustainability are growing—and are even becoming a business imperative. One reason is that the warehousing industry has witnessed a significant expansion in recent years.[1] E-commerce has been one of the main drivers of a surge in warehousing space. This is because e-commerce has fueled an increase in the number of stock-keeping units (SKUs) while simultaneously elevating customer expectations of delivery speed. As a result, the previous strategy of preparing online orders at retail stores became infeasible due to rising picking costs, and companies shifted their attention toward warehouse e-fulfillment strategies.[2]

Furthermore, companies were compelled to add storage space to accommodate the unpredictable manufacturing and shipping delays experienced since 2020, when schedule reliability hit all-time lows because of the Covid-19 pandemic.[3] In addition, demand patterns were shifting faster than before because of changing restrictions on travel, social interaction, and commercial activity; in response to this instability, more companies adopted buffer inventory strategies, which, in turn, required more storage space.[4] Lastly, labor shortages in developed markets put a lot of strain on supply chains. Companies in many industries continue to face a lack of skilled workers across all processes. The shortages are driven by the high number of Baby Boomer workers retiring and a generational shift in workplace priorities and expectations, particularly among Millennial and Generation Z workers, characterized by an increasing emphasis on work-life balance, purposeful work, and a strong company culture. These labor issues affect manual tasks, such as order picking or truck unloading, that strongly impact warehouse operations.[5]

To address the challenges posed by these trends, many companies there are focusing on warehouse automation. While the concept of automation is not new in the warehouse environment, it has undergone a remarkable evolution. Early on, automation primarily involved technologies that improved pallet handling, like stacker cranes, forklifts, automated guided vehicles (AGVs), and palletizers and depalletizers. For many years, these technologies made warehouse operations more efficient and productive. However, the digitalization of warehouses, or the use of digital technologies to improve warehouse operations, are revolutionizing warehouse automation.[6]

Today's warehouses deploy cutting-edge advancements such as artificial intelligence (AI)-powered robotic arms that use machine vision, deep-reinforcement learning, and advanced sensing to pick items of any kind with the precision of surgeons.[7] These capabilities were once limited to the realm of highly standardized manufacturing processes. Gone are the days when almost every warehouse followed a standard design and process flow. Moreover, to compete in the current logistics environment, companies need to tailor automation to their unique operational needs, which has led them to pursue more efficient and customized solutions.[8] The warehouse of the future embodies this shift, representing a highly automated, interconnected system that leverages automation and digitalization, enhancing precision, flexibility, and efficiency to adapt to changing market and supply chain trends.

However, despite the potential for meaningful productivity benefits it may offer, the increasing adoption of automation and digilization also brings new challenges surrounding energy usage.[9] For years, have been significant contributors to greenhouse gas (GHG) emissions, accounting for up to 3% of global GHG emissions.[10] Consequently, integrating environmental



Many of the insights for this research originated from a 2023 MIT CTL roundtable hosted by Maersk.

sustainability alongside technological innovation is becoming an indispensable part of the journey toward the warehouse of the future.

In early 2023, the MIT Center for Transportation & Logistics (MIT CTL) and Maersk, the Danish shipping and logistics giant, convened a roundtable titled "The Warehouse of the Future" for two days at Maersk's warehousing facility in California. This roundtable brought together over 30 supply chain executives from 20 different companies to discuss some of the challenges mentioned above, which most companies consider when they are designing the warehouse of the future. The event's lively discussions revealed several questions that were topmost on executives' minds:

- What are the main challenges companies face when implementing innovative automation solutions in an ever-expanding global warehouse network?
- How can digitalization drive automation as a transformative force, enabling greater precision, flexibility, and efficiency in warehouse operations?
- In the pursuit of a sustainable warehouse of the future, how can companies strike a balance between technological advancements and environmental responsibility?

In the following sections, we present a comprehensive overview of the technological and environmental transformations that are now underway and will be essential for warehouses in the future.

Automation in the Warehouse

The New Frontier

Automation has emerged as a transformative force in the warehousing industry, revolutionizing operations and redefining the way goods are handled, stored, and distributed. With advancements in technology and the growing need for greater efficiency and productivity, warehouses are increasingly adopting automation solutions across all processes. One of the key reasons is that automation can relieve human workers from performing warehouse tasks that, historically, were physically demanding and monotonous. Examples include the use of advanced robots, like those from Amazon[11] or Locus Robotics,[12] that automate product movement across the warehouse, or the new technology for truck unloading developed by Boston Dynamics.[13] Both solutions minimize physically demanding

Boston Dynamics's Stretch robot can automate warehousing tasks.

manual tasks, reducing the risk of workplace injuries and enabling warehouse workers to focus on higher-value activities such as process improvement and equipment maintenance and management. This means the human factor is one that companies need to evaluate carefully when adopting automation in warehouses, but it is only one of many considerations.

The roundtable participants mentioned the growing importance of considering flexibility when evaluating new automation. Flexibility can be viewed in different ways, such as a solution's ability to scale operations up or down based on fluctuating demand; the capacity to handle different loads, including various SKU sizes and packaging types; and the adaptability of the technology to different facilities, as companies move warehouse resources in response to changing business needs. For those reasons, companies can gain a significant advantage by integrating new automation solutions into their existing facilities, as they can adapt to different locations and changing business demands.

In recent years, Maersk has adopted this approach to retrofit its legacy warehouses. Notable examples include the use of inventory drones from Zürich-based Verity, which improve inventory management in traditional facilities, allowing more efficient and accurate checks.[14] BionicHive's solution, a robot installed in traditional racking systems to lift and transport goods across the warehouse without using additional floor space, is another example.[15] Additionally, Maersk has partnered with Fabric, a provider of fulfillment automation technology to install a flexible, high-density-storage Micro-Fulfillment Center (MFC) that can automate some or all of an existing warehouse's operations, and it can be scaled up later as demand increases.[16]

Fulfillment speed was another factor that roundtable participants considered critical, as e-commerce requires short lead times. Warehouses are under immense pressure to deliver orders quickly and efficiently, and automation is a pivotal tool to help expedite the order fulfillment process and thus enhance customer satisfaction. Order fulfillment automation is nothing new; what is new

Maersk has retrofitted its legacy warehouses with new technologies like Verity inventory drones to minimize manual, physically taxing tasks, reducing the risk of worker injury.

Ocado Group's cube storage system for e-grocery fulfillment

is the previously unheard-of speed at which some orders are now being picked and packed. Ocado's grid solution, for instance, is a state-of-the-art cube storage system for online grocery fulfillment that can put together an order of 50 items in just five minutes,[17] something that would take a human worker over 10 times longer.[18] The solution uses thousands of robots that travel over a grid system, picking and packing grocery orders, and is being implemented by multiple grocery chains across the globe, including US-based Kroger and Morrisons in the UK.

Many companies face a related challenge of effectively integrating new automation technologies into their warehouse operations. Roundtable participants highlighted the increasing importance of interoperability: the ability of new automation to work with existing warehouse systems. As more companies look to tailor warehouse automation to their particular needs, the number of startups developing unique technologies that can solve specific warehousing challenges has grown exponentially.[19] While that may be a welcome development, there is a drawback: Different automation solutions are being designed based on diverse platforms, standards, or protocols. Warehouse systems have become more complex, and with so many interconnected elements, the potential for errors increases. A failure or bug in one part of the system can have a cascading effect, leading to widespread operational issues. Additionally, multiple solutions make it harder to maintain, upgrade, and adapt the integrated system over time. Companies must deal with various vendors with differing support, maintenance, and upgrade policies. Also, multiple automation solutions require different skill sets to operate and maintain, increasing the system's complexity and requiring "layers of support."[20] To address this, companies will need to find and train staff to manage a multi-solution environment, which can be both time-consuming and costly.

Under these circumstances, warehouse managers face the challenge of selecting the right automation technologies that align with their warehouse's specific requirements. Supply chain executives at the roundtable emphasized that the

proliferation of solutions and technology suppliers is making it much harder for them to keep pace with technological developments. Moreover, this diversity increases the time required to analyze each type of automation, as many factors like facility layout, order profiles, demand patterns, and time to implement need to be considered whenever a new solution is evaluated. Also, while automation usually offers long-term benefits, the initial capital expenditure (CAPEX) required can be substantial. Companies that are considering automation solutions need to assess the return on investment (ROI) and long-term cost savings that each automation initiative can provide and carefully decide which is the best option.

Overall, there is a clear trend among warehouse operators toward developing a comprehensive automation strategy, assessing each process's potential for improvement, and then creating a tailored approach to incorporating automation into their operations. Three key insights are crucial for firms to consider when planning to implement these solutions. First, speed remains a paramount concern, especially in e-commerce operations, where rapid order fulfillment is essential. Second, flexibility has emerged as a critical factor, differentiating modern automation solutions from their predecessors. Third, the challenge of integrating multiple, complex automation technologies highlights the need for careful planning and robust support systems. Companies must navigate a growing array of solutions while ensuring interoperability, managing complexity, and making informed decisions about capital expenditure and long-term benefits.

How to Select the Right Automation for Your Warehouse

Maersk's Approach to Technology Evaluation

As a global company with numerous facilities and thousands of customers around the world, Maersk follows a structured and comprehensive approach to evaluate and implement new warehouse technologies. Through this methodical and thorough approach, Maersk ensures that the selection and implementation of automation technologies are not only strategic but also are tailored to deliver maximum operational efficiency and customer satisfaction. Here are the four main stages of this proven process:

1. **Assess the business impact of the solution:** The technologies need to resolve a major customer pain point as well as an internal pain point. A *gemba* walk follows this initial assessment to observe firsthand the issue in the warehouse that the technology could solve.
2. **Use multi-criteria analysis (MCA) to compare potential solutions:** MCA assesses the value of solving the issue with a particular solution. The main criteria are safety, throughput improvement (mainly during peak times), and cost efficiency. Technologies scoring highest on these criteria are advanced to the proof of concept (PoC) stage.
3. **Develop a proof of concept (PoC):** This stage encompasses studying, designing, testing, and then physically executing the solution. The length of time can differ, ranging from a few weeks to several years, depending on whether the technology is new or already established. The process favors scenario analysis based on success probabilities rather than running simulations, which are often complex and laden with assumptions.
4. **Pilot the solution:** Finally, upon achieving a successful PoC, Maersk chooses a warehouse to carry out the pilot based on several factors:
    a. Having a capable local team in the warehouse, with the right mindset for piloting and improving the technology
    b. A location conducive to significant scaling, which allows for the observation of full deployment and immediate results
    c. Strong support from vendors and customers in that warehouse, which is vital for effective implementation and feedback

Digitalization

A Key Enabler for Automation Takeoff

In the dynamic landscape of modern warehousing, digitalization is a key enabler of warehouse automation technology adoption.[21] Everyone attending the California roundtable agreed that data accuracy and visibility make up the essential foundation of this connection between digitalization and automation in warehouses.

Automated systems rely more and more on accurate and up-to-date data to make the right decisions. This means that a small discrepancy in data can lead to significant operational errors. In addition, warehousing operations need to adjust in real time to changing conditions such as unexpected orders or shipping delays. Real-time visibility enables swift responses to changes like these. Moreover, as warehouses incorporate more robotics into their operations, precise data and high-speed connectivity are required for these systems to function effectively.[22] Ocado's

Verve Motion's SafeLift exosuit

grid solution is a perfect example of this, with thousands of collaborative robots ("cobots") generating around 5,000 data points 1,000 times per second in a single warehouse.[23] The cobots, which are controlled by an advanced artificial intelligence (AI) system running in the cloud, communicate 10 times a second with this AI system to coordinate their movements.

Advanced AI systems are among several digital technologies that can support warehouse automation. One promising development enabled by AI is state-of-the-art exosuits for warehouse operators. Exosuits are wearable robotic devices designed to work in harmony with the human body, offering support, augmenting strength, and reducing physical strain. Verve Motion is a startup based in the Boston area whose solution focuses on aiding warehouse workers in lifting and repetitive tasks to create a healthier work environment.[24] These new exosuits leverage AI to make dynamic adjustments and tailor the support they provide to the specific task at hand. Using sensors and machine learning algorithms, the exosuit can recognize the type of task a worker is performing and adjust its support level based on the activity, making it a much more flexible solution than earlier rigid models.

Computer vision is another digital tool that plays a vital role in various aspects of warehouse automation. It provides the capability to recognize visual images and convert them to data, enhancing the precision of certain kinds of operations. For instance, computer vision enables robotic arm solutions to pick items with the utmost accuracy—even delicate and irregularly shaped products like groceries. Another application of this technology, which Maersk shared at the roundtable, is a solution that tracks cartons on conveyor

belts. Based on video analytics, the tool can predict whether a particular carton will become stuck. By alerting Maersk to this risk before it actually happens, equipment operators can prevent conveyor jams.[25]

Digital twins, another groundbreaking application of digitalization in warehousing,[26] virtually represent the physical warehouse, encompassing all its physical infrastructure elements and logistics processes. This virtual system operates in real-time and can be embedded with advanced perception, reasoning, and recommendation capabilities that can engage directly with the automation in the warehouse to make recommendations and even autonomous decisions. Participants at the roundtable agreed that creating a virtual "mirror" of a facility will aid in simulating future scenarios and evaluatingthe impact of different types of warehouse automation, refining their strategies before implementing changes in the real world. Incorporating reinforcement learning in digital twins could enable future automation solutions to learn from their past behavior and autonomously improve task performance.[27]

While digitalization is very promising and potentially offers transformational benefits, it also presents certain challenges that warehouses will need to overcome. Finding the right talent to manage the digital transformation of warehouses was the most difficult task mentioned by executives during the roundtable. The challenge, as one attendee put it, lies in "finding talent that combines a strong operations and supply chain background with enough knowledge about data analytics and automation." As an example, most attendees agreed that digital twins are a solution with great potential, not only for the warehouse of the future, but also for the entire supply chain. However, only a few participants said their companies are deploying digital twins—a situation they attributed to the challenge of creating teams to oversee the technology's adoption. Digitalization in highly automated warehouses requires skilled professionals who can develop, implement, and manage sophisticated technology solutions. As the example above suggests, companies will need to invest in talent acquisition and development to attract and retain individuals with expertise in data analytics, AI, and other digital domains—skills necessary for a successful warehouse digital transformation.

The ever-evolving technology landscape requires flexible and replicable solutions that can adapt to future advancements in both software and automation. While automation brings efficiency and precision to warehouse operations, it is the integration of digital technologies that can unlock the true potential of highly automated warehouses. Key elements include high-speed connectivity for real-time adjustments and AI systems for enhancing the precision of robotic operations. However, the transformation journey faces challenges: the need for data accuracy and the acquisition of the right talent. These factors are essential for realizing the synergies between automation and digitalization.

How to Prepare Your Workforce for the Warehouse of the Future

The Maersk–MIT CTL Partnership

One of the most pressing challenges facing warehouse operators today is ensuring that they have the talent needed to deploy and manage new automation and digitalization technologies. Maersk's Innovation Center develops innovations and advanced data analytics for warehousing and distribution—but a crucial part of its function is to develop talent, helping the company identify and nurture teams with the right knowledge and skills.

A significant part of this talent-development endeavor is Maersk's partnership with MIT CTL. This collaboration has led to a tailored educational program designed to train individuals from various departments within Maersk, particularly in areas crucial to supply chain innovation. The curriculum, provided by MIT CTL, covers a wide range of topics, including the latest technologies in warehousing operations as well as supply chain sustainability and AI applications in logistics.

This comprehensive program extends beyond the classroom, offering participants opportunities to visit leading robotics companies and gain firsthand insights into the industry's cutting-edge advancements. Modeled after the "Shark Tank" concept, the culmination of the program is a unique competitive event where participants present their innovative ideas to Maersk executives in a five-minute pitch. The most promising proposals not only receive recognition but are also given the opportunity to be developed into actual proof of concept projects.

The Maersk–MIT CTL initiative has proved to be a resounding success. In just two years, the program has trained over 75 innovation leaders. These individuals have become ambassadors of innovation within Maersk, demonstrating the company's commitment to fostering talent and driving forward-thinking solutions in the logistics sector.

Sustainability

A Multifaceted Challenge for the Future of Warehouse Operations

Sustainability in the warehouse encompasses a wide range of practices aimed at reducing the environmental impact of warehouse operations. These include reducing the facility's carbon footprint by implementing energy-efficient practices, using renewable energy sources, and the efficient use of supplies. This multifaceted endeavor makes the definition of a "sustainable warehouse" more intricate than it might initially appear. From the materials used in construction to the energy sources that power the facility, every component plays a role in the overall sustainability of this key supply chain node. The roundtable participants admitted that improving warehouse sustainability requires a holistic approach that neither research nor practice has yet addressed.

In their pursuit of sustainability, decision-makers involved in warehouse development must first weigh the benefits of retrofitting existing facilities with innovative solutions against constructing entirely new warehouses. Retrofitting involves additional costs, of course, but it can be more sustainable than constructing new facilities. That's because retrofitting requires fewer materials and resources than building a new warehouse and adding new automation, which would contribute to embodied carbon emissions. Embodied carbon emissions are the total carbon emissions released during the complete lifecycle of building materials, including extraction, manufacturing, transportation, construction, and disposal.[28]

Practitioners may also reduce carbon emissions by applying technologies and making certain design choices for warehouse automation. This approach is becoming a higher priority, as implementing automation technologies in warehouses has led to an increase in the demand for energy, primarily electricity.[29] Material handling equipment (MHE) is one area that offers opportunities to reduce energy usage. For example, electric forklifts and electrified yard tractors present several advantages over traditional diesel-powered vehicles, including potentially lower operating costs and lower emissions. A graduate capstone project recently conducted at MIT CTL by Osama Alhasan '23 and Kirill Lobanov '23 and sponsored by Maersk showed that while the initial cost of purchasing electric MHE may be higher than that of traditional MHE, the long-term cost savings in fuel and maintenance expenses may offset this difference over time, which could lead to payback periods as short as three years.[30] Researchers have also studied hydrogen-powered forklifts, but they found that these forklifts have higher storage-infrastructure and maintenance costs. From a cost perspective, then, the advantage leans toward electric solutions, particularly newer ones powered by lithium-ion batteries.

Another recent capstone at MIT CTL, conducted by Taylor Peterson '22 and Miguel García González '22, also sponsored by Maersk, showed that incorporating *automated storage and retrieval systems* (AS/RS) can reduce both the carbon emissions and the physical footprint of warehouses, due to those systems' high-density storage and the efficiency gains they provide. However, the energy used to manufacture, ship, and install

Rhenus Logistics wareohuse in Tilburg, Netherlands, fitted with its own renewable power generator

AS/RS systems, which contributes to embodied carbon emissions, as well as the computing power required to run these highly automated solutions, could offset the potential sustainability benefits. Peterson and González also pointed to labor reductions as another potential opportunity to reduce carbon dioxide (CO_2) emissions when automating a warehouse. Because automation can reduce headcount, fewer workers will commute to and from the facility.[31] However, the expected reduction in worker numbers is tricky to measure, as highly automated facilities require more highly skilled workers to control and maintain the technology being used.[32]

With the electrification of MHE, the increased electricity consumption by AS/RS systems, and increases in the number of technological solutions in warehouses, it becomes crucial to harness green energy sources to enhance warehouse sustainability. Both new construction and older warehouses can integrate solar panels and small wind turbines on their roofs or install them in nearby areas, which can generate energy sufficient to meet all the energy requirements of the facility.[33] While these solutions offer significant long-term savings in energy expenses, they may require a substantial upfront investment. However, companies can bypass this initial barrier by opting for *power purchase agreements* (PPAs). Under this type of agreement, energy providers develop, fund, and operate the green energy project. The company then purchases all the power produced from the system at a predetermined rate per kilowatt-hour for an agreed-upon term. Depending on utility rates, this option could immediately reduce energy costs with no up-front capital investment, making it an attractive "low-hanging fruit" option for some companies.

This shift toward alternative energy sources like solar and wind power underscores the necessity of an integrated approach when evaluating multiple solutions within the warehouse of the future. The interdependence of these solutions becomes particularly evident when considering the operational economics of sustainable MHE, such as electric forklifts. The cost-effectiveness of electric forklifts, for instance, depends highly on the cost of electricity—a factor directly influenced by the choice of green energy sources. As Alhasan and Lobanov highlight, adopting solar and wind power can significantly lower electricity costs, thereby affecting the payback period of sustainable MHE investments. This interconnectedness of decisions around energy sources and warehouse equipment underscores the importance of a holistic approach in assessing and implementing sustainability measures in warehouse operations.

Finally, the research conducted at MIT CTL by Alhasan and Lobanov evaluated all major sustainable solutions for retrofitting a warehouse, including heat, ventilation, and air conditioning (HVAC) systems; lighting; and rainwater harvesting to reduce water consumption. This research showed that HVAC systems, which are among the highest contributors to energy consumption in warehouses,[34] can be made more efficient with the use of smart windows (windows with specialized glass that keeps heat in during winter and lets it out during summer), high-volume low-speed (HVLS) fans, infrared heaters, and white roofs, which reflect sunlight. The study also found that rainwater harvesting, a solution that can channel collected water for non-drinking purposes such as landscaping or internal plumbing, will incur lower costs and bring greater sustainability benefits when incorporated into the initial construction of the warehouse layout. LED lighting is another basic solution that has proved very

effective in reducing energy consumption, with some case studies showing up to a 90% reduction compared to that of incandescent lighting.[35]

The implementation of automation technologies in warehouses is forcing companies to reassess their sustainability strategies. This reassessment encompasses both the embodied carbon emissions from the materials used in warehouse automation and the energy consumption of new automation systems, like electric MHE and AS/RS. To mitigate those impacts, warehouse operators are considering solutions such as retrofitting existing facilities with more sustainable materials and employing more energy-efficient technologies. A shift toward the generation of green energy generation, like solar and wind power, complements these efforts, which can significantly reduce long-term energy costs and reliance on traditional power sources. The transition to more sustainable warehouse design and operation, however, requires an integrated approach to assessing sustainability that considers the interdependence of various factors, such as the cost of electricity, the choice of energy sources, and the overall operational economics of the warehouse.

Tips for a Successful Journey to Sustainable Warehouses

Insights from the Warehouse of the Future Roundtable

Participants in the MIT CTL roundtable hosted by Maersk considered multiple paths to attaining warehouse sustainability. They shared some recommendations for how to make this transformation happen:

1. **Identify "low-hanging fruit."** To kick off a sustainability initiative effectively, consider beginning with quick wins: initiatives that will demonstrate a positive economic impact and significant sustainability gains in a short period. A successful start can lead to greater organizational support for the broader and more complex sustainability transformations.
2. **Know the implications of ownership versus leasing.** The ownership of the warehouse facility highly influences the success in achieving sustainability goals. Companies that lease warehouses may face challenges in implementing sustainability initiatives that require the installation of fixed assets, such as solar panels, if they do not have full control over the property.[36] Companies that cannot or choose not to own their warehouses can establish contract terms with property owners that include provisions that allow for the development of sustainability initiatives.
3. **Beware the challenges in harnessing green energy sources.** Sources like solar and wind often have peak production times, so energy-storage solutions may be required for off-peak periods. Additionally, participants raised concerns that many US cities do not have utility grids that are ready for the demands of widespread electrification across warehouses and other facilities.
4. **Improve data access for sustainable decision-making.** Warehouse managers often lack essential data for sustainability-focused decisions. Companies should install systems that can track and monitor key sustainability metrics, such as the energy usage of MHE equipment, and employ data analytics tools to process and analyze the collected data. This will help in identifying patterns, inefficiencies, and areas for improvement.
5. **Create a culture of sustainability in the warehouse.** Once the right data is available, training across all settings (both inside and outside of the warehouse) is required to highlight the importance of sustainability-focused decision-making. Incentives based on sustainability goals can drive innovation in the warehouse, rewarding sustainability trailblazers.
6. **Extend the approach to warehouse sustainability beyond the four walls.** Besides their own internal activities, warehouses motivate external supply chain activities that also contribute to emissions and energy consumption. Thinking of the warehouse as part of a supply chain ecosystem creates opportunities to further enhance sustainability. For instance, warehouses could support the sustainability of transportation to and from the facility by providing EV charging stations for electric-powered trucks. This would be consistent with the anticipated adoption of electric trucks for goods transportation,[37] positioning warehouses as hubs of sustainable change.

Toward Sustainable, Interconnected, Highly Automated Warehouse Systems

AUTOMATION is transforming the warehousing landscape, enabling facilities to operate with unprecedented levels of precision, speed, and efficiency. From drones for inventory control to collaborative robots and automated guided vehicles (AGVs), automation technologies are driving the industry forward. At the same time, companies are grappling with the challenge of integrating diverse automation technologies in warehousing. The surge in startups offering unique automation solutions has not only made it harder for companies to keep up with technological development, but it has also increased warehouse systems complexity, which demands specialized staff to manage multi-solution environments. Moreover, the future of warehousing is dynamic, and warehouse operators must be prepared to respond rapidly to new, unforeseen cargo types and operational needs. For that reason, designers should create automation solutions with adaptability in mind.

Integrating digitalization is further enhancing the capabilities of automated systems in that respect, creating warehouses that leverage data and analytics for optimal performance and allow for more flexible automation thanks to the development of AI. Digital technologies can enable seamless integration of automated systems, where data-driven decision-making and real-time analytics drive operational excellence. However, to harness the power of digital solutions, warehouses need to first achieve higher levels of data visibility and accuracy, and build teams with the right skills and knowledge that can understand and make the right decisions based on that data. Looking forward, we expect warehouse systems to be more interconnected — making joint decisions with other elements of the supply chain, such as other warehouses, factories, and autonomous vehicles, about smart inventory allocation, transportation scheduling, and so on. Ultimately, such capabilities will enhance overall supply chain efficiency.

Finally, to ensure a greener and more environmentally responsible warehouse of the future, we must complement the adoption of automation with sustainable practices. The growing energy requirements of automated systems necessitate the adoption of green energy solutions, such as electric forklifts, and other eco-friendly technologies to minimize greenhouse gas emissions. Research has showed that there is enough "low-hanging fruit" in today's warehouses for companies to move toward a sustainable future. Also, digital solutions will facilitate sustainability initiatives by providing real-time data on energy consumption, emissions, and resource utilization. As warehouses become smarter and more efficient through digitalization and automation, their sustainability efforts will gain additional momentum. And as the world of warehousing continues to evolve, the fusion of automation, digitalization, and sustainability will shape the warehouses of tomorrow, creating a more agile, efficient, and environmentally friendly supply chain ecosystem.

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