Robotics for Smarter Material Handling in the Era of Industry 5.0:
Insights from the Intralogistics Robotics Survey

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Introduction

Robotics and Automation topped distributive technologies that would provide companies with competitive advantages in the next ten years since MHI started publishing its Industry Annual Reports, and the year 2024 was no different. We are on the verge of a significant increase in robotics adoption due to the increasing sophistication of robotic systems that can autonomously perform tasks such as picking, packing, and data-driven decision-making. Key technologies like sensors, vision systems, machine learning, Artificial Intelligence (AI), and edge/cloud computing are converging to enable more autonomous robotics. While such technological advances accelerate the adaptation of robotics in manufacturing and material handling systems, the recent social trends shape how and where robotics are used. By examining these dimensions, we aim to provide actionable insights into the transformative potential of robotics in the era of Industry 4.0 and Industry 5.0.

Bridging Industry 4.0 and 5.0: Transforming Robotics in Material Handling

Industry 4.0 technologies, including the Internet of Things (IoT), Cloud Computing, Big Data Analytics, Cybersecurity, RFID, Machine-to-Machine Communications, and 3D Printing, etc., are leading the way for “smart” factories with advanced features [1]. The common characteristics of these technologies, such as flexible automation, adaptivity, data-driven processes, real-time decision-making, and connectivity, have been instrumental in achieving and maintaining higher levels of productivity and operational efficiency in the ever-changing market dynamics of the modern economy. These technologies work together in an integrated way, enabling seamless communication and coordination across various systems and processes within the factory. Likewise, integrating robotics into material handling systems has significantly transformed manufacturing operations. In a typical setup, robots equipped with advanced sensors and AI algorithms can autonomously handle tasks such as sorting, picking, and transporting materials. These technologies not only increase throughput and quality but also reduce the risk of human error and workplace injuries and allow human workers to focus on more complex and strategic tasks [2]. This integration allows for predictive maintenance, where potential issues can be identified and addressed before they cause significant downtime, thereby reducing costs and improving reliability. Additionally, the use of advanced analytics and machine learning enables continuous process optimization, ensuring that operations are always running at peak efficiency. The connectivity provided by IoT and other technologies also facilitates better supply chain management, allowing for real-time tracking of materials and products, which enhances transparency and reduces lead times. Overall, implementing Industry 4.0 technologies transforms traditional manufacturing into a more agile, efficient, and responsive system capable of adapting to new challenges and opportunities in the global market.

As many companies are still adopting Industry 4.0 technologies and concepts, new trends are also emerging in manufacturing and supply chain systems by shifting the focus from purely technological to a human-centric approach, pure cost/value-based decision-making, to well-being and social impact. Collectively called Industry 5.0, these new emerging trends complement and extend Industry 4.0 by considering environmental, social, and fundamental rights factors in technology adaptation. While Industry 4.0 emphasizes automation and efficiency, Industry 5.0 aims to bring humans back into the loop. This enhanced collaboration between humans and machines is expected to improve operational resilience and adaptability to disruption. The transition from Industry 4.0 to Industry 5.0 represents an evolution to create a more balanced, sustainable, and human-centric industrial ecosystem. Xu et al. [3] emphasize that Industry 4.0 is technology-driven, focused on improving productivity, efficiency, and automation. Meanwhile, Industry 5.0 is value-driven, centering on societal goals, sustainability, and human-centric production. It highlights technologies like collaborative robots and augmented reality to support this collaboration. Furthermore, Industry 5.0 places sustainability at the forefront, addressing planetary boundaries through resource efficiency, circular economies, and resilience, compared to Industry 4.0's more indirect approach to these goals. Industry 4.0 focuses on technical upskilling (e.g., data analysis, cybersecurity), while Industry 5.0 highlights the need for human-centric skills like creativity, adaptability, and critical thinking. As illustrated in Figure 1, Industry 4.0 and Industry 5.0 share core technologies such as AI, IoT, Big Data, and robotics. These technologies evolve in Industry 5.0, prioritizing sustainability and human-machine collaboration. This evolution reflects a shift towards more human-centric and environmentally friendly manufacturing practices.

The focus of Industry 4.0 is on creating smart factories that achieve higher levels of efficiency, automation, and data-driven decision-making, enhancing productivity and reducing costs. In contrast, Industry 5.0 shifts the focus toward human-centric innovation, where collaboration between humans and machines becomes central. While Industry 4.0 prioritized technology-driven optimization, Industry 5.0 emphasizes the harmonious integration of human creativity and advanced technologies to foster sustainability, personalization, and societal well-being. The transition to Industry 5.0 does not negate the achievements of Industry 4.0 but builds upon them by reintroducing human values into manufacturing systems. Where Industry 4.0 sought to replace human involvement with automation, Industry 5.0 repositions humans as co-creators alongside smart technologies, ensuring more inclusive and resilient production processes.

Robot companions play a pivotal role in the evolution of Industry 5.0, as both concepts address shared challenges across multiple sectors, such as automotive manufacturing, agriculture, healthcare, and process digitization. Additionally, their impact extends into everyday life, enhancing areas like logistics, transportation, high-quality services, accessible healthcare, and public safety within interconnected and dynamic ecosystems. The idea of robot companions first emerged in 2011 through the Future and Emerging Technologies (FET) initiative under the CA-RoboCom coordination action. It was later expanded through the 2012 FET Flagship RoboCom proposal and further refined in the FlagEra RoboCom++ Project [4]. In recent years, the global spotlight on robot companions has intensified, particularly in Japan's Society 5.0 initiative, which envisions a human-centered society integrating cyberspace and physical space to drive economic growth while solving societal issues [5].

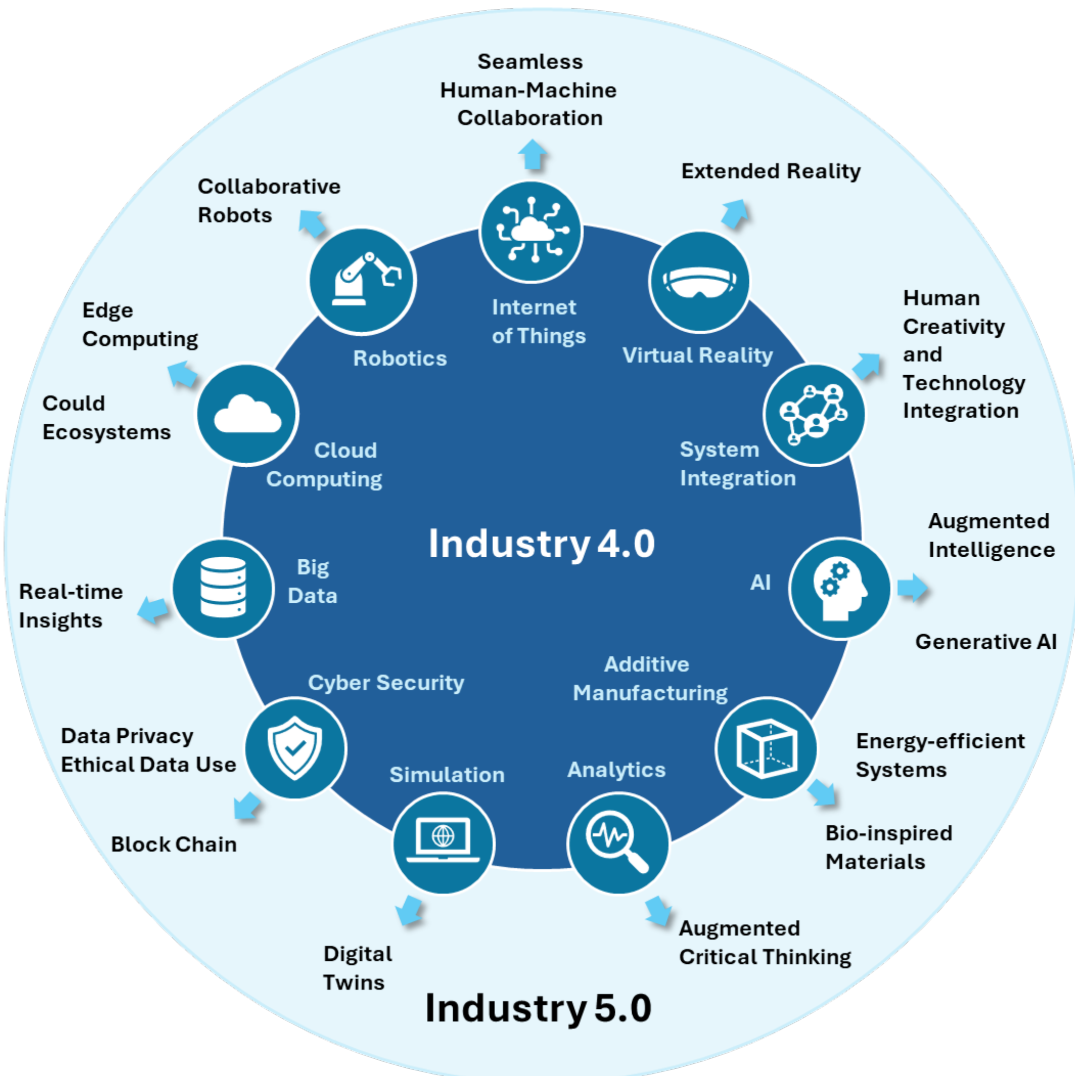

Figure 1 The evolution of Industry 4.0 core technologies to achieve enhanced efficiency, sustainability, and human-machine collaboration goals in Industry 5.0.

Emerging Technologies for Robotics Applications in Material Handling

All technologies that have enabled Industry 4.0 by interconnecting isolated automation systems through intelligent and data-driven environments are still relevant for Industry 5.0. However, those technologies should be realigned for more human-centric and collaborative approaches to make automated systems more responsive and adaptable. This section reviews key emerging technologies that lay the groundwork for this transition from Industry 4.0 to Industry 5.0, focusing on the use of robotics in material handling systems. While Industry 5.0 introduces new technologies like bio-inspired materials and energy-efficient systems, many foundational technologies from Industry 4.0 (e.g., IoT, AI, digital twins) are still central to achieving Industry 5.0 goals. Hence, Industry 5.0 is not a replacement for Industry 4.0. Instead, they coexist, with Industry 5.0 complementing and extending Industry 4.0 to incorporate societal and environmental priorities into technological innovation [3].

Generative AI: Generative AI (Gen AI) is one of the fastest-adopted technologies by industry and society in recent years. With an annual growth rate [6] of 46.47%, the global market size is expected to reach US$356.10bn by 2030. The use of Gen AI is expected to significantly boost efficiency and productivity in fields ranging from customer service to healthcare and education through improved communication, customization, and problem-solving abilities. Likewise, the integration of GenAI and advanced robotics promises significant advancements in material handling systems.

- *Training Autonomous Robots:* Typically, reinforcement learning algorithms are used to train robots that require advanced locomotion skills and navigate complex terrains. However, reinforcement learning can be resource-intensive, time-consuming, and slow, as it requires extensive data from both simulated and real-life environments to learn effective policies to guide robot movements. GenAI is increasingly used to generate synthetic data and scenarios or augment existing scenarios to address this bottleneck, thereby accelerating and improving the training process [7]. Integrating GenAI into robot training simulators such as Nvidia Isaac Sim [8] enhances the robustness and adaptability of autonomous robots [9].
- *Enhanced human-robot interaction*: One of the main challenges in human-computer interaction (HCI) through verbal communication has been the vagueness and incompleteness of human instructions and the lack of understanding context by natural language processing [10]. Advances in Large Language Models address this gap and open new possibilities for seamless HCI [11]. For example, KnowNo robotic framework asks for human help when the robot is unsure or has incomplete data, rather than making potentially incorrect decisions [12]. Chatting with the environment, robots can also augment vision-based sensory information by object latent properties such as weights, hardness, and texture [13].
- Meanwhile, it is possible to use pre-trained models without any fine-tuning to complete tasks, as demonstrated by ProgPrompt [14] and CaP [15], which directly generate code of control policies for robots by putting instructions and planning samples into GPT models.

- *Route Generation:* GenAI improves transportation efficiency in supply chains by analyzing real-time data to optimize and adjust routes. For example, UPS' On-Road Integrated Optimization and Navigation (ORION) system processes vast amounts of real-time data to adjust delivery routes dynamically.

Augmented Intelligence: Augmented intelligence enhances human decision-making in material handling systems by integrating cognitive adaptability and autonomous responses. Unlike static and dynamic adaptability, augmented intelligence enables systems to autonomously trigger and execute adaptive responses, integrating context awareness, self-optimization, and self-planning powered by AI technologies. Through the use of sensors, IoT, IT, IoP, and CPPS, augmented intelligence is expected to support agile and scalable production capacity. Reconfigurable material handling systems is an emerging concept that utilizes augmented intelligence concepts to adapt product flows, adjust machine configurations, and manage production changes [16].

Collaborative Robots: Collaborative robots, or cobots, represent a significant evolution in industrial automation, designed to work alongside humans in shared spaces. Unlike traditional industrial robots operating in isolation, cobots are equipped with advanced sensors and software that enable safe interaction with human workers without protective barriers [17]. This shift towards Human-Robot Collaboration (HRC) necessitates the development of sophisticated robotic systems capable of intention recognition, cooperative task execution, and maintaining robust safety protocols throughout joint operations [18].

The implementation of HRC involves integrating various technologies, including artificial intelligence (AI), human-computer interaction (HCI), human–robot/machine interaction (HRMI), natural language processing, and gesture recognition. These complex systems create a synergistic relationship between humans and robots within a shared workspace to improve the efficiency and flexibility of industrial operations.

In addition, HRC offers numerous benefits to the industrial sector. By allowing robots to handle repetitive or hazardous tasks, human workers can focus on complex, high-value work that requires uniquely human skills, such as critical thinking and problem-solving [18]. This partnership not only enhances productivity but also significantly reduces the risk of workplace injuries. Moreover, the combination of human creativity with robotic precision drives innovation, fostering the development of new products and processes. As HRC systems continue to evolve, they are expected to transform the industrial landscape further towards creating more productive and safer work environments. This collaborative approach promises to enhance competitiveness in material handling operations by leveraging the strengths of both human workers and robotic systems. Application areas for Cobots are expanding from inventory management and shelf stocking in retail to picking, packing, and sorting in warehouses.

Extended Reality: Extended Reality (XR), which encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), offers real-and-virtual combined environments for human users to interact more effectively with machines and robots [19]. AR has already been effectively used in areas such as training workers in complex material handling processes [20] and displaying optimal picking routers and item locations [21]. The XR applications can dynamically adjust their behavior and visualization based on the specific machine being used by loading the machine's DT data with minimum customization [19]. This allows greater scalability and flexibility of XR models.

Digital Twins: A digital twin is a virtual representation of a physical system interconnected through sensors and various data collection devices. Digital twins facilitate real-time study, analysis, and monitoring of the robotic system's behavior, as well as simulation and optimization of robotic systems before actual deployment. This allows for operational and strategic decision-making through in-depth scenario experimentation. For example, different configurations and strategies for robot pallet loading and pick-and-place operations can be tested to identify the most efficient strategy [2]. Digital twins play a crucial role as a virtual platform for model-based training or programming of robots [22] and training the workforce to operate robot-based production lines [23].

Trends and Changes in Industry Perspectives

As organizations navigate the complexities of modern supply chain challenges, robotics has emerged as a critical solution for enhancing operational resilience and efficiency. The emerging technologies discussed above are expected to accelerate adoption rates and evolve implementation strategies of industrial robotics across diverse business sectors. This section examines the trajectory of robotic automation adoption, highlighting significant trends in deployment models, use cases, and technological integration going from 2022 to 2024 based on the data collected by the "Intralogistics Robotics Survey" developed with input from the Robotics Group at MHI, WERC and editors at Peerless Media. This examination of industry data reveals the growing acceptance of robotic systems and the evolution from task-specific automation to integrated solutions. Particularly noteworthy is the transition from traditional capital-intensive deployment models to more flexible approaches like Robot-as-a-Service (RaaS), enabling broader accessibility across different organizational scales. This shift, coupled with advancements in AI and collaborative robotics, signals a fundamental transformation in how businesses approach automation and operational optimization.

The trend chart for adoption (Figure 2) depicts a continuous rise from 2022 to 2024, with a growing number of companies either actively using or planning to use robotics. A significant 40% had yet to make plans for 2022, highlighting that many companies were still in the exploratory phase. Forty-three percent of organizations in 2023 are either currently using or planning to use robotics within the next three years, which indicates that companies began moving beyond exploration into more concrete planning and early-stage implementations. The data for 2024 shows further progress, with more organizations transitioning from planning into full-scale deployment or piloting multiple robotic systems. In other words, the percentage of companies without plans for robotics steadily decreases, while those implementing and piloting robotics are steadily increasing, reflecting broader industry acceptance and technological improvements.

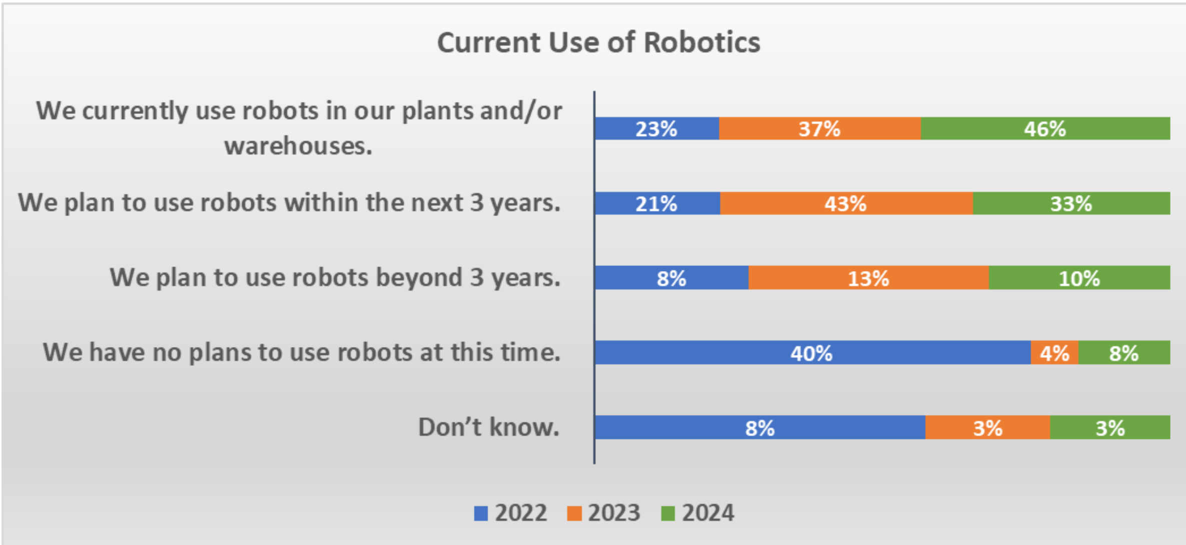

Figure 2 Usage of robotic automation systems and/or autonomous mobile robots in warehouses, distribution centers and/or manufacturing operations.

The use case chart (Figure 3) shows continued dominance in core tasks like picking and sorting but with a notable increase in more comprehensive automation functions like receiving/unloading and mobile systems. This reflects an evolution from task-specific automation to more integrated solutions. In 2022, the dominant use cases focused on labor-intensive and repetitive warehouse tasks. In 2023, companies began automating broader processes within their logistics and warehousing operations, moving beyond specific tasks. In 2024, we see growing technology sophistication and a shift toward automating entire workflows rather than individual tasks. Over the three-year period from 2022 to 2024, there has been a clear and consistent trend toward increased adoption of robotic automation across industries. The use cases for robotics have expanded from basic picking and sorting tasks to more complex systems like mobile goods-to-person solutions and autonomous data collection (listed in the other category). Organizations are now motivated not just by labor savings but also by safety, predictive maintenance, and operational analytics. The readiness of both companies and the robotics industry to scale deployments has improved significantly, with many organizations moving into full-scale deployments by 2024.

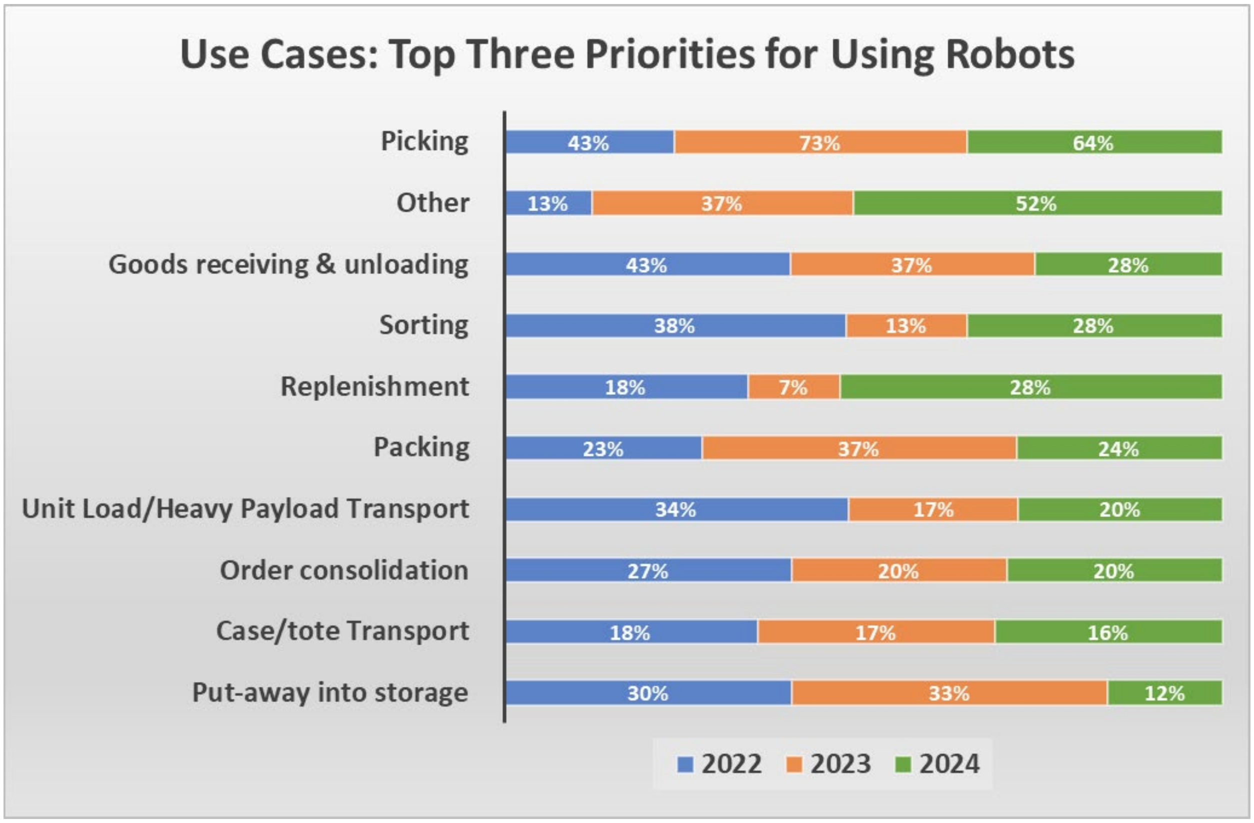

Figure 3 Top three priority use cases for robots.

Figure 4 indicates a growing interest in exploring robotic solutions, with the percentage of companies piloting robotic systems rising from 17% in both 2022 and 2023 to 23% in 2024. The proportion of companies deploying robots across multiple locations increased, with the highest level in 2024 at 31%. Implementation in a first live production environment also increased to 17% and 15%, respectively, in 2023 and 2024 from 6% in 2022.

Financial models (as seen in Figure 5) show a decline in the percentage of organizations opting for pure CAPEX solutions, while hybrid models and Robot-as-a-Service (RaaS) show increasing adoption. This trend reflects the growing need for financial flexibility in scaling robotic solutions. The 2024 data reflect a further move toward flexible models like RaaS, especially among small to mid-sized companies, which value the lower upfront costs and scalability offered by subscription-based models.

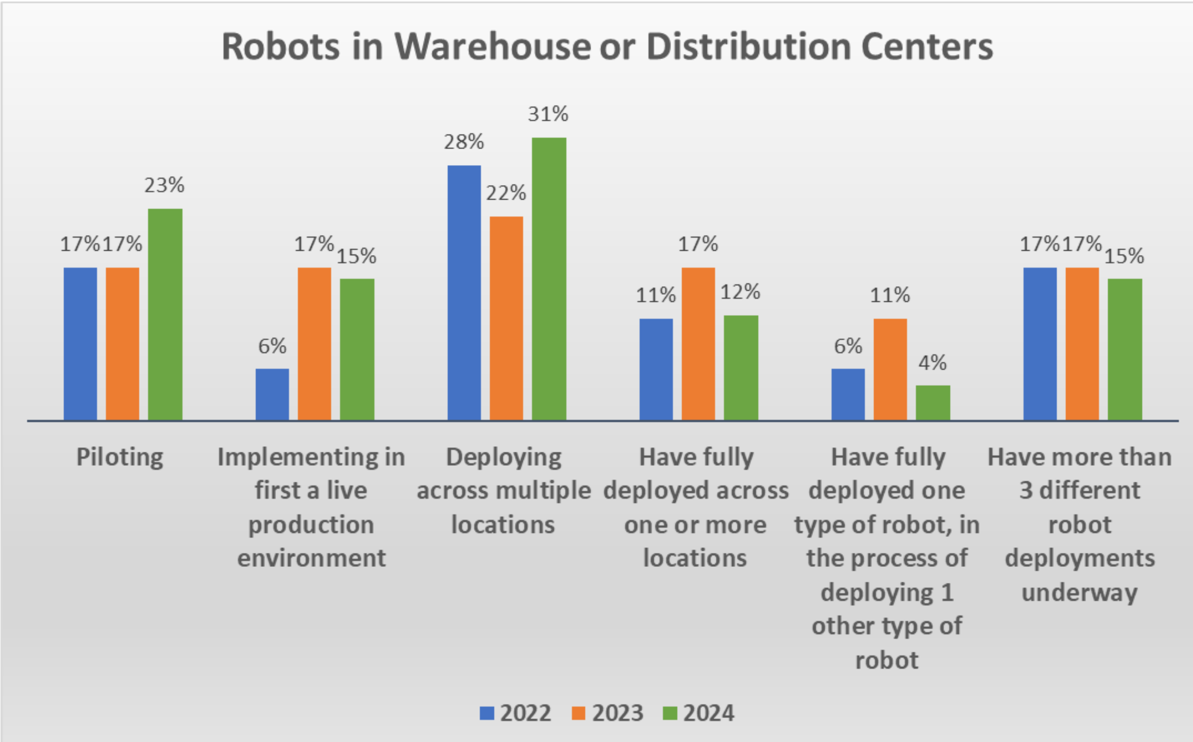

Figure 4 The current state of the organizational pursuit of robots in warehouses or distribution centers.

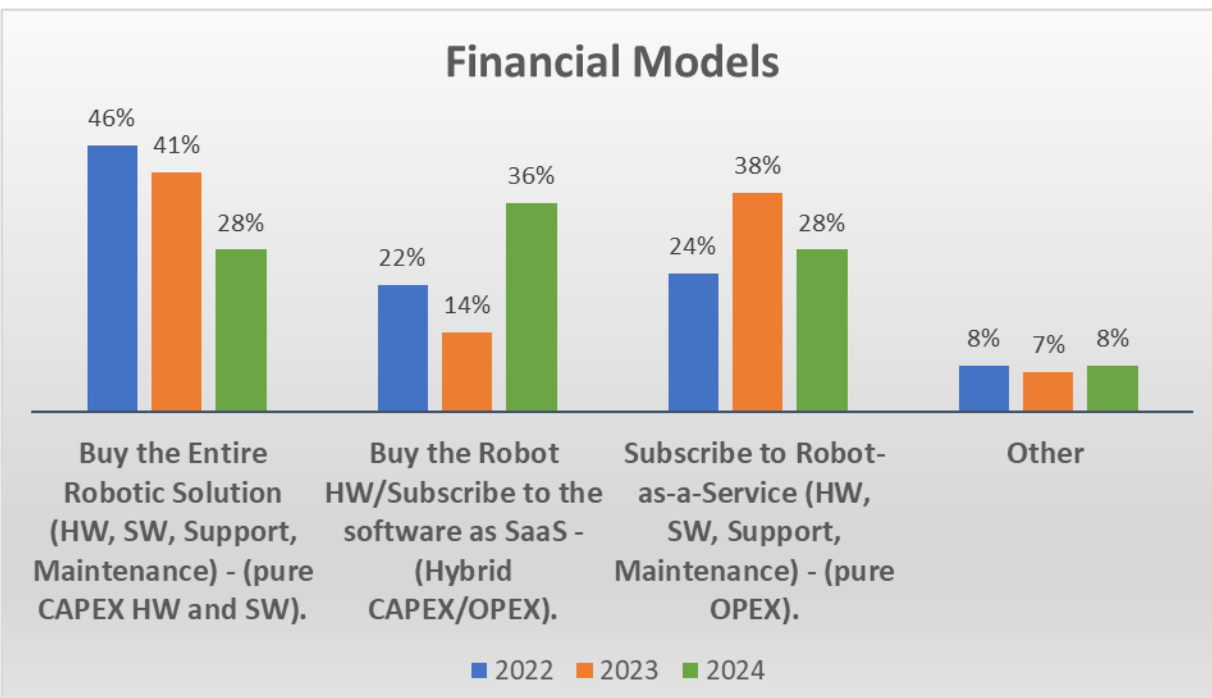

Figure 5 Preferred financial model for planned robotics initiatives.

Barriers to Companies Adopting Robotics:

Figure 6 illustrates the rank of specific obstacles/barriers to overcome when considering advanced robotic automation systems based on the top three selections by industry experts. 'Identifying and Achieving Return on Investment (ROI)' remained the highest-ranked challenge in 2022 and 2024, while 'Lack of Internal Robotics Experience and Expertise' was ranked lower in 2023 and 2024. 'Lack of Internal Robotics Experience and Expertise' ranked second in 2022 and dropped to sixth in 2023 and 2024. This decline suggests that, over time, organizations may be building or gaining the necessary experience and knowledge to implement robotics, implying increased familiarity with these systems. Other notable challenges, such as 'Concerns with Robotics Technology Maturity' and 'Difficulty Finding Partners,' reveal evolving barriers as the industry adapts. As internal expertise becomes less of a primary concern, other challenges (like project lead times, ROI, and technology maturity) are taking precedence. This shift could indicate that organizations are moving beyond fundamental familiarity issues and are encountering more advanced challenges with the growing complexity of systems.

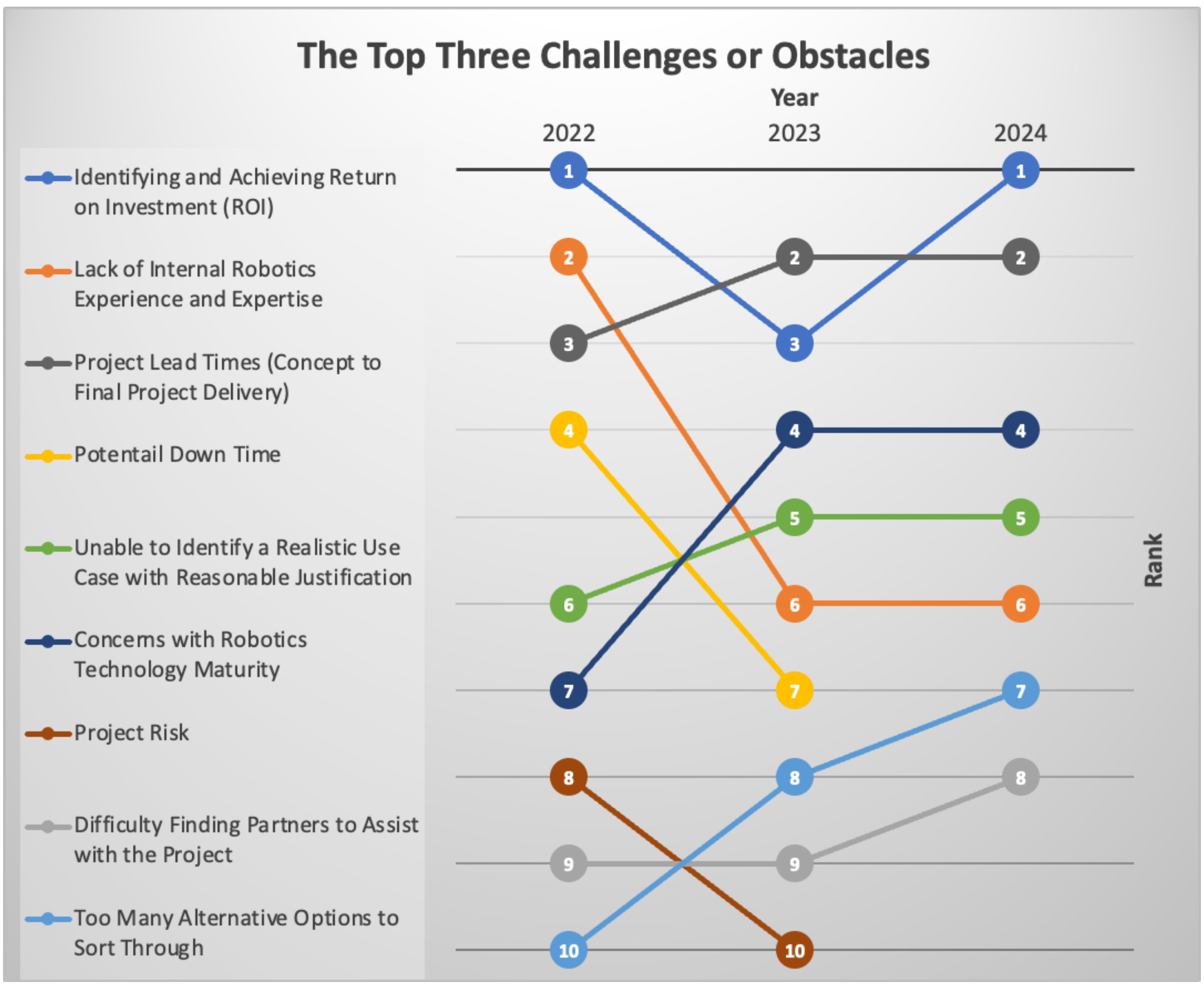

Figure 6 Relative rank of specific obstacles/barriers to overcome to consider advanced robotic automation systems.

Figure 7 summarizes an analysis of open-ended responses to the question, “What specific obstacles/barriers would have to be overcome for you to consider advanced robotic automation systems in your operations?” in the 2022 survey. Respondents highlighted several key barriers, expressed as percentages of total responses. Cost-related barriers were the most frequently mentioned, representing 25% of responses, with concerns centered around budget limitations and the perceived cost-effectiveness of automation. Similarly, Operational Complexity or Customization Needs also accounted for 25%, reflecting challenges with product variability and custom orders that complicate automation processes. Lack of Need or Applicability was cited in 20% of responses, indicating that many businesses feel robotics may not be relevant to their industry or business model. Scale of Business/Feasibility was mentioned in 12.5% of responses, mainly from smaller or early-stage businesses for which robotics is not feasible. Technical and Equipment Limitations appeared in 7.5% of responses, where respondents noted that necessary technology is either unavailable or impractical for their specific operations. Finally, Process Standardization and Reorganization Needs were identified by 10% of respondents, highlighting that significant organizational changes would be required for automation adoption.

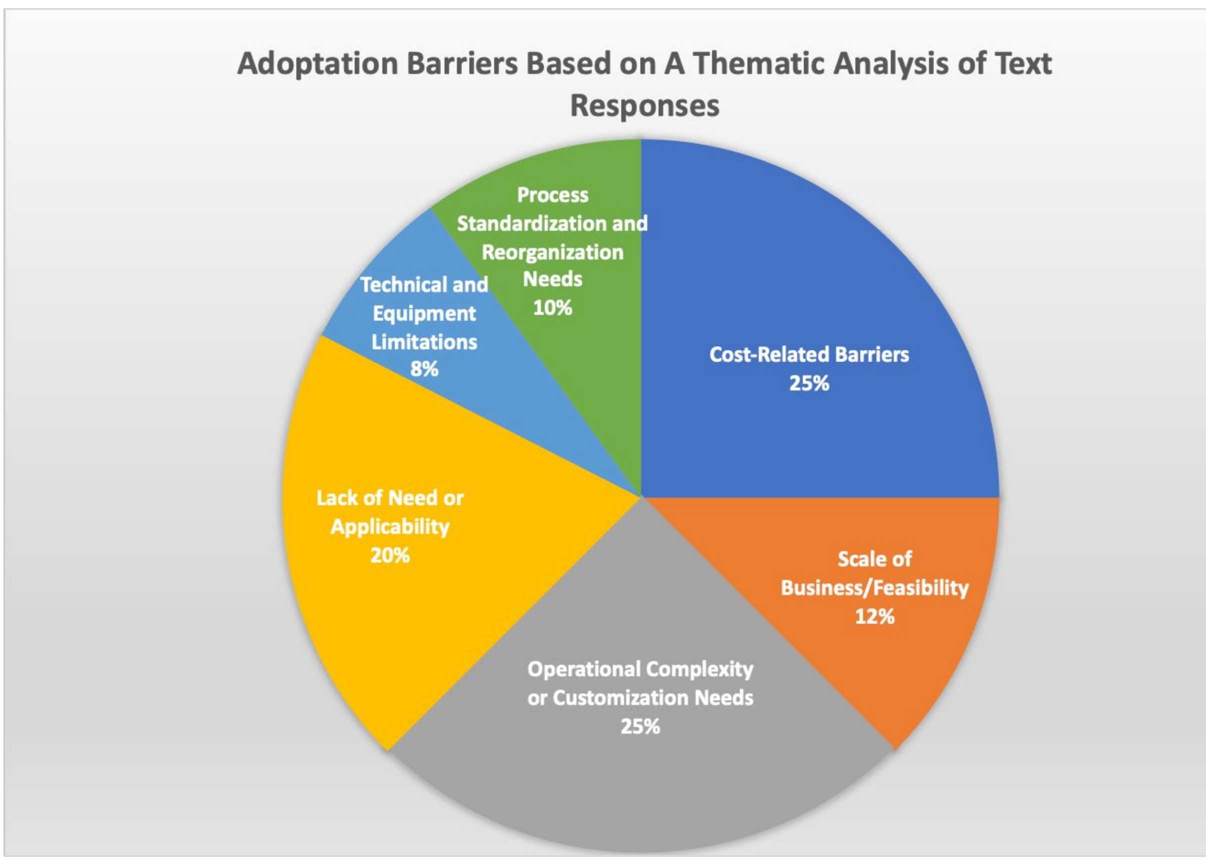

Figure 7 Summary of barriers to robotic automation adoption in warehouse operations, based on open-ended responses in the 2022 survey.

The Primary Types of Robotic Automation Systems to Be Considered:

Over the three years, there has been a marked evolution in the types of robotic systems organizations use (See Figure 8). Over the three-year period (2022, 2023, and 2024), the primary types of robotic automation systems used by companies evolved to reflect advancements in technology and broader adoption across industries. The data highlights both the types of robots that were popular early on and the more advanced systems that gained traction as adoption increased. The initial focus on basic material handling robots in 2022 shifted toward more advanced autonomous systems by 2024. Companies moved from using robots for isolated tasks like sorting and picking to integrating more complex systems like mobile goods-to-person robots and autonomous retrieval-to-person robots that can perform a broader range of functions autonomously. This reflects the growing sophistication of robotics technology and the increasing demand for full-scale automation in warehousing, logistics, and manufacturing industries.

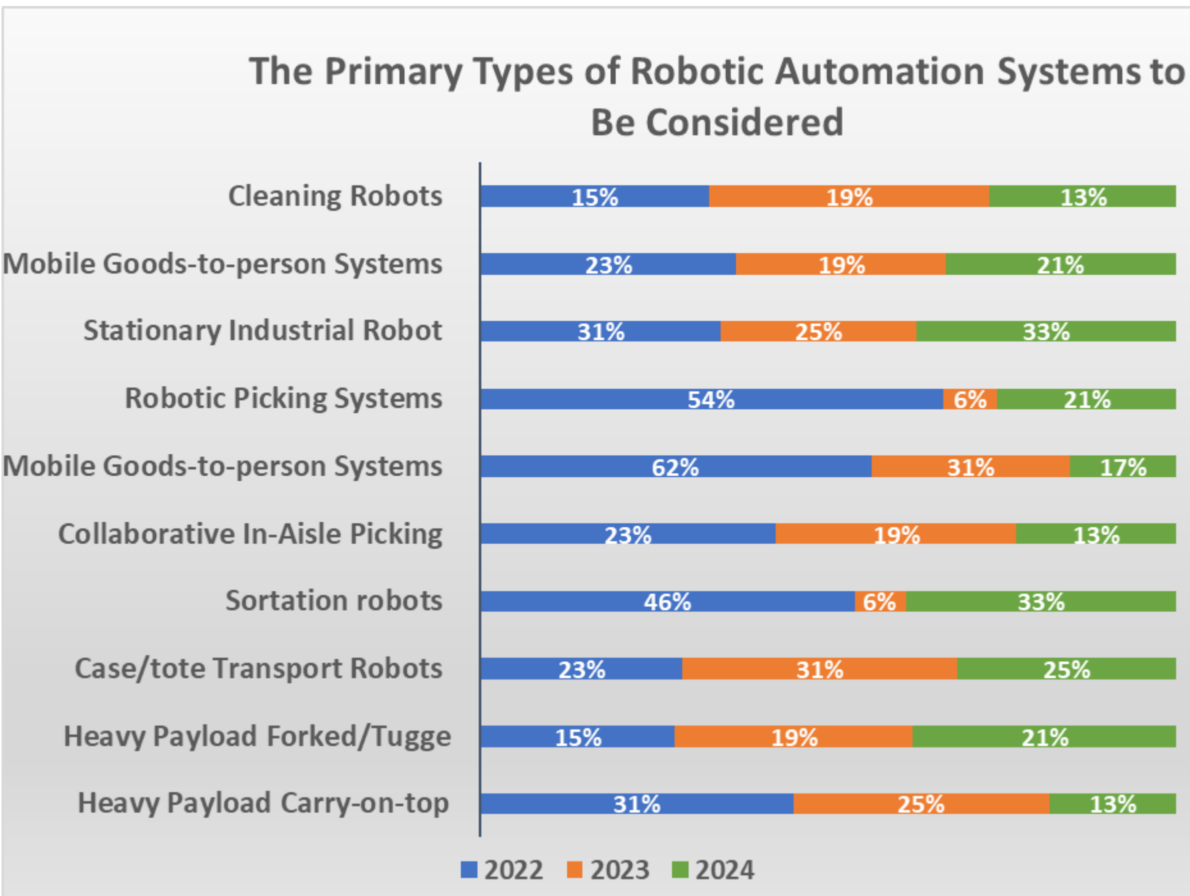

Figure 8 The primary types of robotic automation systems to be considered in the next two to five years.

Important Factors While Choosing Robotics Solutions:

As captured through a radar chart, Figure 9 illustrates the evolving priorities in choosing robotics solutions for 2022, 2023, and 2024. Key factors include time to value, integration costs, investment risk, cybersecurity risk, data/insight, total cost of ownership, payback time, safety, and return on investment (ROI). Over the three years, factors like time to value and integration costs consistently rank higher, indicating a growing emphasis on quick deployment and seamless integration. Conversely, cybersecurity and investment risks show a slight decline, reflecting improved trust and risk mitigation strategies in the robotics industry. Notably, the total cost of ownership and payback time appear to maintain steady importance, highlighting cost-effectiveness as a persistent consideration. This trend reflects a shift toward practical, efficient, and reliable robotics solutions aligned with industry advancements.

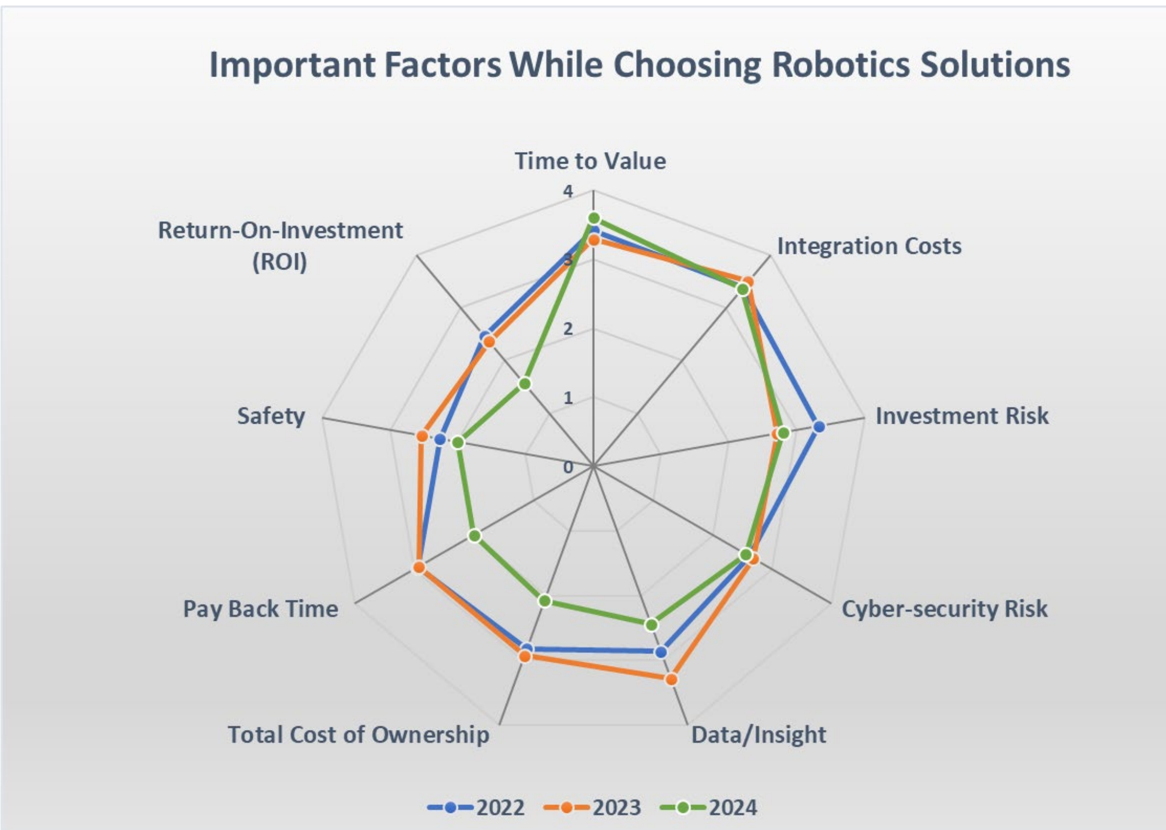

Figure 9 The importance of business case while choosing your robotics solutions (0-Not at All, 7-Extremely).

Conclusion

Companies increasingly adopt robotic systems for core logistics processes, supported by real-time data sharing, AI, and machine learning technologies. Thanks to innovations like RaaS and low-code systems, the cost of adoption is decreasing, allowing more companies to benefit from automation. Ultimately, the convergence of technology and automation leads to greater efficiency, reduced labor reliance, and a shift toward end-to-end robotic solutions.

As industries embrace these advancements, the focus shifts beyond operational efficiency to fostering sustainability and resilience in supply chains. The integration of robotics with smart sensors and IoT not only optimizes resource utilization but also aligns with global sustainability goals by reducing waste and energy consumption. Furthermore, as Industry 5.0 emphasizes human-centric innovation, the coexistence of humans and robots within collaborative environments will redefine workplace dynamics, emphasizing adaptability and upskilling.

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