International Journal of Basic and Applied Sciences
INFORMATICS JOURNALS

We'Ken- International Journal of Basic and Applied Sciences
DOI: 10.18311/weken/2026/v11/i1/51814
Volume 11, Issue 1, June 2026, pp. 9-18

AI Based Warehouse Management Systems, Autonomous Mobile Robots, Robotic Picking Systems and Automated Guided Vehicles in Consumer Retail Stores

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Abstract

The rapid evolution of Artificial Intelligence (AI) has revolutionised multiple domains, including warehouse management in consumer electronics retail stores. AI-driven solutions enhance operational efficiency, inventory accuracy, and customer satisfaction by streamlining processes such as inventory control, demand forecasting, and order fulfilment. This paper examines the integration of AI in Warehouse Management Systems (WMS) for consumer electronics retail, highlighting key technologies, processes, and their impacts. Case studies and insights into challenges and future trends are also discussed to provide a comprehensive understanding of the subject. Warehouse management is a cornerstone of supply chain efficiency, and AI has emerged as a transformative force in this domain. This paper examines the key technologies underpinning AI-based Warehouse Management Systems (WMS), including Machine Learning (ML), computer vision, robotics, the Internet of Things (IoT), and Natural Language Processing (NLP). By analysing their applications, benefits, and challenges, this research aims to provide a comprehensive understanding of how these technologies drive innovation and operational excellence in warehouse environments. The integration of advanced robotics in warehouse operations is revolutionising logistics and supply chain management. This paper explores three key technologies: Autonomous Mobile Robots (AMRs), Robotic Picking Systems, and Automated Guided Vehicles (AGVs). AMRs utilize AI to navigate dynamically and optimise real-time path planning for transporting goods. Robotic Picking Systems employ AI-driven robotic arms for efficient picking, sorting, and packing. AGVs, designed for transporting pallets, ensure systematic material flow within warehouses. This research provides an in-depth analysis of these technologies, highlighting their functionalities, applications, and impact on operational efficiency.

Keywords: *Artificial Intelligence, Autonomous Mobile Robots (AMRs), Automated Guided Vehicles (AGVs), AI-Driven Path Optimization, Data Collection, Machine Learning, Robotic Picking Systems, Robotics and Automation, Vision System, Warehouse Management Systems (WMS)*

Received: 27-02-2026; **Revised:** 22-03-2026; **Accepted:** 25-03-2026

1. Introduction

Warehouse management in consumer electronics retail is a complex endeavour due to the high value, rapid obsolescence, and diverse range of products. Traditional practices often struggle with inefficiencies in inventory tracking, stock replenishment, and order processing. The introduction of AI in warehouse operations addresses these challenges by leveraging advanced algorithms, machine learning, and robotics to optimize processes[1].

This paper explores the current state of AI-driven warehouse management systems in consumer electronics retail, their benefits, and potential areas of improvement. The global surge in e-commerce, coupled with rising customer expectations for fast and accurate deliveries, has placed unprecedented demands on warehouse operations. Traditional systems often struggle with the complexity and scale of modern supply chains, necessitating the adoption of AI-powered solutions. This paper explores the technological pillars that enable AI-based WMS to revolutionize inventory management, order fulfilment, and overall operational efficiency. Warehousing and logistics are undergoing transformative changes with the adoption of robotics and AI technologies[2]. Traditional manual operations are increasingly being replaced by automation solutions that enhance productivity, accuracy, and scalability. Among these solutions, AMRs, Robotic Picking Systems, and AGVs have emerged as critical components for modernizing warehouse operations. This paper examines their roles, benefits, and the challenges associated with their implementation[3].

2. Key Technologies in AI-based Warehouse Management

2.1 Machine Learning (ML)

Machine learning models enable predictive analytics for inventory management[4]. These algorithms analyse historical sales data, seasonal trends, and market dynamics to optimize stock levels and reduce overstocking or understocking issues. ML is a core component of AI-based warehouse management, enabling predictive analytics, demand forecasting, and optimization of resource allocation[5].

2.1.1 Applications

- **Inventory Optimization:** ML algorithms analyse historical sales data, seasonal trends, and market conditions to predict demand and optimize stock levels[6].
- **Order Picking:** Reinforcement learning and clustering algorithms streamline picking routes to minimize travel time[7].
- **Anomaly Detection:** ML models identify irregularities in inventory counts or order patterns, reducing shrinkage and fraud.

2.1.2 Benefits

- Enhanced accuracy in forecasting[8].
- Reduction in stock outs and overstock situations[9].
- Faster response to market changes[10].

2.1.3 Challenges

- High computational resource requirements[11].
- Dependence on quality and volume of training data.

2.2 Computer Vision

Computer vision technology enables real-time monitoring and analysis of warehouse operations through image and video processing. Computer vision technologies facilitate real-time inventory tracking and quality control. Cameras integrated with AI algorithms identify and count items, detect damages, and ensure proper labelling[12].

2.3 Robotics and Automation

AI-driven robotics are transforming warehouses by automating repetitive and labour-intensive tasks.

2.3.1 Applications

- **Autonomous Mobile Robots (AMRs):** These robots navigate dynamically to transport goods, leveraging AI for real-time path optimisation[13,14,15].
- **Robotic Picking Systems:** AI-powered robotic arms perform picking, sorting, and packing tasks[16].
- **Automated Guided Vehicles (AGVs):** Used for transporting pallets within warehouses[17,18].

2.3.2 Benefits

- Increased throughput and productivity.
- Lower labour costs.
- Scalability in operations[19].

2.3.2 Benefits

- Integration with human workers[20].
- Maintenance and scalability concerns[21].

2.4 Internet of Things (IoT)

IoT connects devices and sensors within the warehouse to collect and transmit data, enabling real-time decision-making[22].

2.4.1 Applications

- **Smart Shelves:** IoT-enabled shelves track inventory levels and trigger automatic reorders.
- **Environmental Monitoring:** Sensors monitor conditions such as temperature and humidity, critical for perishable goods.
- **Asset Tracking:** RFID tags and IoT devices provide real-time location data for goods and equipment[23].

2.4.2 Benefits

- Enhanced inventory visibility[24].
- Reduced manual interventions.
- Real-time insights for proactive decision-making[25].

2.4.3 Challenges

- Data security and privacy concerns[26].
- Interoperability of devices.

2.5 Natural Language Processing (NLP)

NLP enables human-like interaction with WMS, enhancing user experience and operational efficiency.

2.5.1 Applications

- **Voice Picking:** NLP-driven voice assistants guide workers through picking tasks, improving speed and accuracy[27].
- **Chat-bots:** Virtual assistants handle routine inquiries and training for warehouse staff.
- **Document Processing:** NLP automates the extraction of information from invoices and shipping documents.

2.5.2 Benefits

- Streamlined communication and workflows[28].
- Reduced training time for staff[29].
- Higher accuracy in data processing[30].

2.5.3 Challenges

- Language and accent variability[31].
- Limited understanding of complex queries[32].

2.6 Autonomous Mobile Robots (AMRs)

AMRs are autonomous systems equipped with sensors, cameras, and AI algorithms that enable them to navigate dynamically within warehouse environments. Unlike fixed-path robots, AMRs adapt to changing layouts, obstacles, and traffic in real time[33].

2.6.1 Functionalities and Features[34]

- **Dynamic Navigation:** AMRs use simultaneous localization and mapping (SLAM) techniques to build and update maps of their surroundings[35].
- **AI-Driven Path Optimization:** Algorithms analyse traffic patterns and obstacles to determine the most efficient routes[36].
- **Collaboration:** AMRs can work alongside human operators and other robots, ensuring seamless integration into existing workflows.

2.6.2 Applications

AMRs are widely used for transporting goods between storage areas and workstations, inventory management, and order fulfilment. Companies like Amazon and DHL have successfully deployed AMRs to streamline operations[37].

2.6.3 Benefits and Challenges[38]

- **Benefits:** Increased flexibility, reduced labour costs, and improved safety.

- **Challenges:** Initial investment costs, integration complexity, and Cybersecurity concerns.

2.7. Robotic Picking Systems

Robotic Picking Systems utilize AI-powered robotic arms to handle repetitive and labour-intensive tasks such as picking, sorting, and packing items[39].

2.7.1 Functionalities and Features[40]

- **AI and Machine Vision:** Robotic arms use cameras and sensors to identify and manipulate objects accurately[41].
- **Multi-Tasking:** These systems can handle various shapes, sizes, and weights of items[42].
- **Speed and Precision:** Advanced algorithms ensure high-speed operations with minimal errors[43].

2.7.2 Applications Robotic Picking Systems

Applications Robotic Picking Systems are commonly used in e-commerce warehouses, where they manage high volumes of diverse products. They are also employed in food and pharmaceutical industries for sorting and packaging[44].

2.7.3 Benefits and Challenges[45]

- **Benefits:** Enhanced accuracy, reduced operational time, and scalability.
- **Challenges:** High dependency on data quality, significant setup costs, and limited adaptability to new or unfamiliar objects[46].

2.8 Automated Guided Vehicles (AGVs)

AGVs are automated vehicles designed to transport pallets and other heavy loads within warehouses. These vehicles follow pre-defined paths, often guided by magnetic strips, laser navigation, or GPS[47].

2.8.1 Functionalities and Features[48]

- **Guided Navigation:** AGVs rely on fixed paths for predictable and reliable transportation[49].
- **Load Handling:** Equipped with specialized tools such as forklifts or conveyors to handle pallets efficiently[50].
- **Safety Features:** Sensors and collision avoidance systems ensure safe operations[51].

2.8.2 Applications AGVs

Applications AGVs are extensively used in large-scale warehouses and manufacturing facilities for transporting raw materials, finished goods, and waste materials[52].

2.8.3 Benefits and Challenges[53]

- **Benefits:** Consistent performance, reduced manual labour, and integration with warehouse management systems.
- **Challenges:** Limited flexibility, high maintenance requirements, and dependency on infrastructure modifications[54,55].

2.9 Comparative Analysis

While AMRs and AGVs both address material transport, AMRs offer greater flexibility, making them suitable for dynamic and high-variability environments[56]. Robotic Picking Systems, on the other hand, focus on tasks requiring precision and dexterity. The choice of technology depends on warehouse requirements, operational complexity, and budget considerations[57,58,59].

2.10 Applications

2.10.1 Inventory Management

AI-powered systems provide real-time inventory visibility, ensuring accurate stock levels. Predictive analytics prevent stock outs and overstock scenarios by forecasting demand with high accuracy[60].

2.10.2 Order Fulfilment

AI optimizes picking routes and reduces processing times through intelligent task allocation. This ensures faster order fulfilment, meeting customer expectations for quick delivery.

2.10.3 Demand Forecasting

AI algorithms analyse market trends, customer preferences, and historical sales data to predict demand patterns. This minimizes excess inventory and aligns procurement with actual demand.

2.10.4 Quality Control

Computer vision and AI sensors automate quality checks, identifying defects or discrepancies during receiving, storage, and dispatch.

2.10.5 Space Optimization

AI tools analyse warehouse layouts to optimize space utilization. Simulations help redesign layouts to accommodate changing product volumes and categories efficiently.

2.10.6 Case Studies

Case Study 1: Amazon's AI-Driven Fulfilment Centres: Amazon leverages AI-powered robotics and machine learning algorithms to streamline operations across its warehouses. Computer vision systems track inventory in real-time, while predictive models optimize order processing and reduce delivery times.

Case Study 2: Best Buy's Smart Inventory Management: Best Buy utilizes AI for demand forecasting and inventory replenishment, ensuring high-demand electronics are always in stock. The integration of IoT sensors improves inventory accuracy and minimizes shrinkage.

3. The Technical in Outs

3.1. Autonomous Mobile Robots (AMRs)

AMRs are flexible and intelligent robots equipped with advanced sensors and software that enable them to navigate dynamic environments without fixed paths.

3.1.1 Applications

- Order fulfilment and picking assistance.
- Inventory transportation.
- Real-time inventory tracking.

3.1.2 Technical Specifications

- **Navigation:** LiDAR, cameras, and SLAM (Simultaneous Localization and Mapping).
- **Load Capacity:** Typically ranges from 50 kg to 1,500 kg.
- **Speed:** Up to 2 m/s.
- **Power Source:** Rechargeable lithium-ion batteries with 6-12 hours of operation per charge.
- **Integration:** Compatible with Warehouse Management Systems (WMS).

3.1.3 Examples

- **MIR (Mobile Industrial Robots):** Known for adaptability and ease of integration.
- **Fetch Robotics:** Offers robots specialized for material handling and data collection.

3.1.4 Advantages

- High flexibility for dynamic environments.
- Quick deployment without major infrastructure changes.

3.1.5 Limitations

- Higher initial investment compared to simpler solutions.

3.1.6 Working Principle Flow Chart

1. **Start**
2. **Initialize System**: Load map/environment and assign tasks.
3. **Navigation**: AMRs use sensors (e.g., LiDAR, cameras) to perceive the environment.
4. **Path Planning**: Use AI algorithms to calculate the optimal path.
5. **Object Detection**: Identify obstacles and dynamically reroute.
6. **Task Execution**: Deliver items to designated locations.
7. **End Task**

3.2 Robotic Picking Systems

These systems leverage robotic arms, AI, and machine vision to automate picking and placing items in warehouse operations.

3.2.1 Applications

- Order picking in e-commerce fulfilment.
- Sorting goods on conveyors.
- Palletizing and de-palletizing.

3.2.2 Technical Specifications

- **Vision System:** Cameras and AI algorithms for object recognition.
- **Payload Capacity:** Varies from 2 kg to 20 kg.
- **Speed:** Up to 1,000 picks per hour depending on item complexity.
- **Power Source:** Electrical grid or battery backup.
- **Accuracy:** Picking accuracy up to 99.9%.

3.2.3 Examples

- **RightHand Robotics:** Known for advanced AI-driven picking solutions.
- **ABB FlexPicker:** High-speed robotic arm designed for lightweight item sorting.

3.2.4 Advantages

- High precision and speed.
- Reduces human labour in repetitive tasks.

3.2.5 Limitations

- Limited to predefined item types and sizes.
- Requires integration with existing workflows.

3.2.6 Working Principle Flow Chart

1. **Start**
2. **Initialize System**: Configure inventory layout.
3. **Scan Orders**: Retrieve order data.
4. **Identify Location**: Pinpoint item position using vision or barcodes.
5. **Pick Item**: Use robotic arms or suction to grasp items.
6. **Place Item**: Transfer to a conveyor or packing station.
7. **End Task**

3.3 Automated Guided Vehicles (AGVs)

AGVs are pre-programmed robots that follow fixed paths using magnetic strips, tracks, or sensors to move materials.

3.3.1 Applications

- Material transportation in manufacturing plants.
- Moving pallets in warehouses.
- Loading and unloading at docks.

3.3.2 Technical Specifications

- **Navigation:** Fixed paths (magnetic tapes or QR codes).
- **Load Capacity:** Up to 10,000 kg.
- **Speed:** Up to 1.5 m/s.
- **Power Source:** Lead-acid or lithium-ion batteries with 8-16 hours of operation.
- **Integration:** Limited integration with WMS compared to AMRs.

3.3.3 Examples

- **Toyota Material Handling:** Offers AGVs for heavy-duty applications.
- **JBT Corporation:** Specializes in automated material handling systems.

3.3.4 Advantages

- Reliable for repetitive tasks.
- Cost-effective for structured environments.

3.3.5 Limitations

- Lack of adaptability to dynamic changes.
- Requires significant infrastructure setup.

3.3.6 Working Principle Flow Chart

1. **Start**
2. **Initialize System**: Set guide paths and load task queue.
3. **Follow Path**: Navigate pre-defined routes using magnetic strips, QR codes, or lasers.
4. **Obstacle Management**: Stop or reroute upon detection.
5. **Load/Unload**: Transfer goods autonomously or semi-autonomously.
6. **End Task**

3.3.7 Key Comparisons

Table 1. Key Comparisons of AMR, RPS and AGV

Feature	AMRs	Robotic Picking Systems	AGVs
Navigation	Dynamic (SLAM)	Fixed workstation	Fixed paths
Flexibility	High	Medium	Low
Load Capacity	50-1,500 kg	2-20 kg	Up to 10,000 kg
Speed	Up to 2 m/s	Up to 1,000 picks/hour	Up to 1.5 m/s
Power Source	Lithium-ion batteries	Electrical grid/battery	Lead-acid/Lithium-ion
Applications	Dynamic material handling	Item picking/sorting	Structured material transport
Cost	Higher initial investment	Moderate to high	Lower compared to AMRs

3.3.8 Comparison of Robotic Picking Systems

Feature/Robot Type	Articulated Robot	Delta Robot	SCARA Robot	Cobot	AGV with Robot Arm	3D Vision Robot	Conveyor + Robot
Speed	Medium	Very High	High	Medium	Medium	Medium	High
Payload Capacity	High	Low	Medium	Low	Medium	Medium	Medium
Precision	High	Medium	High	High	Medium	Very High	Medium
Flexibility in Task	High	Low	Medium	High	Medium	High	Medium
Ease of Setup	Medium	High	Medium	High	Low	Medium	Low
Cost	High	Medium	Medium	Low	Very High	High	Medium
Best for	Heavy-duty tasks	Fast picking	Precision	Collaborative	Mobility + Picking	Precision tasks	Sorting & Picking

Each robotic picking system has its advantages and ideal applications depending on factors like speed, flexibility, precision, and cost. When selecting a robotic system, businesses need to evaluate the type of items they handle, the scale of operations, and the specific needs of their workflows.

4. Conclusion

AI-based warehouse management systems have transformed operations in consumer electronics retail stores by improving efficiency, accuracy, and customer satisfaction. While challenges remain, ongoing advancements in AI technologies promise to further enhance warehouse processes. Retailers must navigate these challenges strategically to harness the full potential of AI, ensuring long-term competitiveness in the rapidly evolving market. AMRs, Robotic Picking Systems, and AGVs are transforming the landscape of warehouse automation. By leveraging AI and robotics, these technologies offer significant improvements in efficiency, accuracy, and scalability. However, their adoption requires careful planning and investment to address challenges such as integration, costs, and adaptability.

As technology continues to evolve, these systems will play an increasingly critical role in shaping the future of logistics and supply chain management. The choice between AMRs, Robotic Picking Systems, and AGVs depends on specific warehouse needs. AMRs are ideal for dynamic and complex environments, Robotic Picking Systems excel in precision picking tasks, and AGVs are best suited for repetitive, structured workflows. Investing in the right technology can significantly enhance productivity and operational efficiency in modern warehouses.

The selection of an AGV depends on the specific needs of the facility. Laser-guided AGVs are great for flexible environments, while magnetic and inductive AGVs are ideal for well-defined, stable paths. Vision-guided AGVs are useful in complex, dynamic environments. Towed AGVs and automated forklifts excel in handling heavy loads over long distances, but they may have limitations in flexibility. Each type has its own advantages and disadvantages depending on cost, installation complexity, and operational needs.

Robotic picking systems are designed to automate the process of selecting, handling, and sorting items from bins or shelves. These systems combine robotics, machine vision, artificial intelligence (AI), and other technologies to increase speed, accuracy, and efficiency in fulfilment centres, warehouses, and manufacturing environments. Here's a technical breakdown of the various types of robotic picking systems and their comparisons:

AI-based warehouse management is reshaping the logistics industry by enabling smarter, faster, and more efficient operations. By leveraging ML, computer vision, robotics, IoT, and NLP, businesses can achieve unprecedented levels of accuracy, productivity, and customer satisfaction. As these technologies continue to evolve, they will play a pivotal role in defining the future of supply chain management.

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