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INVESTIGATION OF THE LOGISTICS INTEGRATION AND EFFICIENCY OF AUTONOMOUS MOBILE ROBOTS (AMRS) AND AGV SYSTEMS IN AN INDUSTRY 4.0 ENVIRONMENT

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Abstract: *In the environment of Industry 4.0 in the 21st century, manufacturing companies require flexible internal logistics solutions. The article presents a technical and economic comparison of AGV and AMR technologies. It analyses navigation principles, infrastructure needs, and the role of WMS and FMS systems. Parameterized model calculation examines the performance of systems in two industrial scenarios. The results show that in a dynamic environment, SLAM-based routing of AMRs provides a capacity increase of about 10% compared to AGVs. Based on a 5-year TCO analysis, higher investment costs are offset by lower operating costs, so AMR technology provides better ROI and greater flexibility in a rapidly changing manufacturing environment.*

Keywords: *Industry 4.0; AGV; AMR; internal logistics; TCO*

1. INTRODUCTION

The Fourth Industrial Revolution (Industry 4.0) is fundamentally transforming manufacturing and intralogistics. Shorter product life cycles, increasing customer customization, and labour shortages require flexible, automated logistics solutions instead of traditional manual material handling processes [1]. In this context, Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs) have become key technologies. While AGVs have been widely used in industry for decades, AMRs represent the latest generation of intelligent material handling systems, enabled by advances in LiDAR sensors and SLAM-based autonomous navigation [2]. Their integration into cyber-physical systems provides the flexibility required by modern production environments [3].

Choosing between AGV and AMR technologies has become an important decision for industrial companies because the two solutions differ significantly in navigation, flexibility, integration costs, and operational efficiency. In accordance with the principles of Industry 4.0, intelligent logistics systems should operate as coordinated networks rather than isolated machines, requiring system-level optimization during their implementation [4-5].

The main objective of this article is to compare the logistics integration and industrial performance of AGV and AMR systems in an Industry 4.0 environment. The research is based on the synthesis of recent international literature and is complemented by logistics model calculations. The study evaluates the impact of both technologies on productivity, lead time reduction, error minimization, and economic performance using key performance indicators such as OEE and ROI. A comparative case study is used to demonstrate the performance differences between AGV and AMR systems in dynamic industrial environments, followed by conclusions and future development trends.

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2. TECHNOLOGY OVERVIEW OF AGV AND AMR SYSTEMS

During automating modern material handling, companies mostly think for the implementation of Automated Guided Vehicles (AGVs) or newer generation Autonomous Mobile Robots (AMRs). Although the two concepts are often used synonymously in professional language, their technological foundations, navigation methodology and logistical flexibility are sharply separated from each other [6]. Understanding this technological difference is essential for proper logistics decision-making.

2.1. Operating principle and limitations of the Automated Guided Vehicle (AGV)

The industrial application of AGV (Automated Guided Vehicle) systems has a history of several decades. The basic principle of their operation is fixed-track navigation, which means that vehicles can only travel along a predetermined, fixed physical or optical infrastructure [7].

The navigation of traditional AGV systems is typically based on one of the following technologies:

- **Inductive or magnetic line tracing**: Powered cables recessed into the floor or magnetic tapes glued to the floor provide the trail. Sensors mounted on the bottom of the vehicle follow these signals to keep the machine on track. An example of this type is shown in Fig. 1.

Figure 1. *Automated Guided Vehicle (AGV) using line tracing [8]*

- **Optical line tracing**: The application of contrasting strips on the floor, which is tracked by the machine with optical sensors (photocells).
- **LIDAR sensor-based (LGV - Laser Guided Vehicle)**: This is a more advanced AGV technology, where fixed reflective prisms (reflectors) are installed on the walls and columns of the warehouse. The rotating laser scanner on the vehicle calculates its position based on the angle of the reflected rays by triangulation [2, 9]. The biggest advantage of AGVs is their extreme reliability and high load capacity. At the same time, in the dynamic environment of Industry 4.0, the disadvantages of

technology are becoming more and more significant. The "intelligence" of AGV systems is minimal: the machine blindly follows the designated trajectory. If an unexpected obstacle appears on the route, for example, an incorrectly stacked pallet or a worker, the AGV's safety scanner, for example, SICK or Pilz lasers, detects it and the vehicle immediately applies the emergency brake [10]. The machine will stand until the obstacle is physically removed from its path. It is not able to avoid the obstacle or plan an alternative route, which can cause a serious bottleneck in a fast-paced intralogistics process. In addition, modifying the track network involves physical reconstruction, which is time-consuming and costly.

The above-mentioned methods are illustrated in Fig. 2.

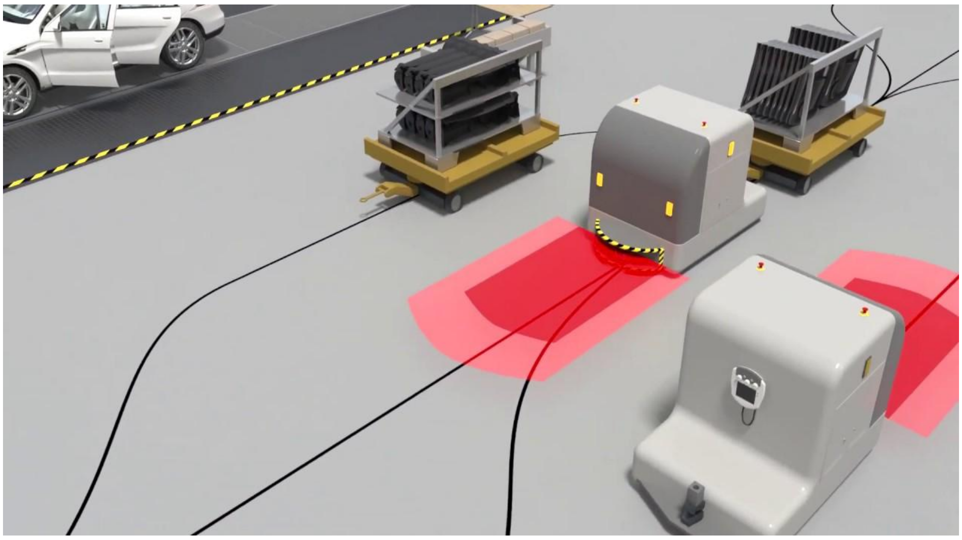

Figure 2. *Sensors and sensor solutions for automated guided vehicles (AGVs) [11]*

2.2. Software navigation for Autonomous Mobile Robots (AMR)

AMR (Autonomous Mobile Robot) technology is a direct result of the development of Industry 4.0 and artificial intelligence. Unlike AGVs, AMR does not require external navigation infrastructure (magnetic tape or prisms). The operation of the machine is based on map-based software navigation and dynamic route planning. [3].

The "soul" of AMRs is the SLAM (Simultaneous Localization and Mapping) algorithm. When the system is commissioned, the robot is manually guided through the facility while the machine uses the principle of built-in sensor fusion to process data from different sensors to create a high-resolution digital map [12]. Precise mapping of the environment and real-time navigation are ensured by the following primary sensors:

- **LiDAR (Light Detection and Ranging):** A laser rangefinder that scans the horizontal plane to draw a 2D floor plan of the warehouse and static obstacles. This method is illustrated in Fig. 3.

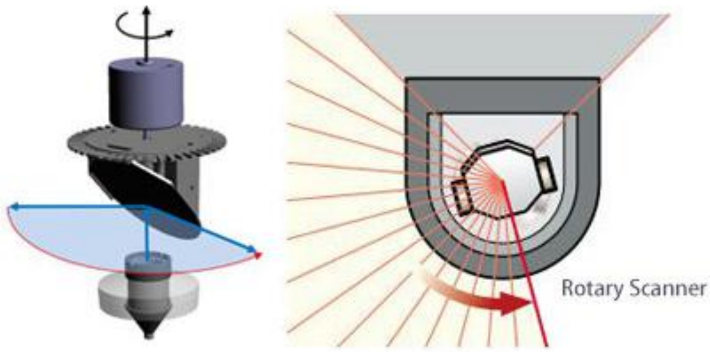

Figure 3. *LiDAR (Light Detection and Ranging) [13]*

- **3D ToF (Time-of-Flight) cameras:** These optical devices emit infrared light pulses and use the reflection time to calculate the exact distance to objects in the environment. This method creates real-time depth perception and a 3D point cloud, which is essential for detecting obstacles above or out of the plane of LiDAR (such as a box hanging from a shelf or a forklift fork). This is illustrated in Fig. 4.

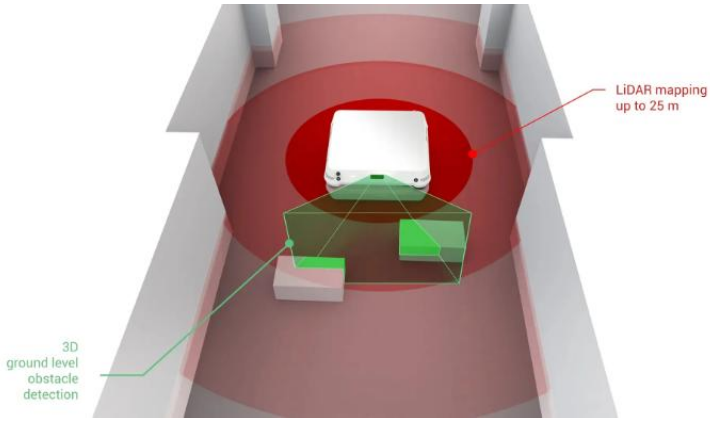

Figure 4. *3D ToF (Time-of-Flight) camera [14]*

- **Inertial Measurement Unit (IMU):** An electromechanical sensor with built-in accelerometers and gyroscopes that measure the robot's tilt, angular velocity, and acceleration. It plays a key role in compensating for backlash and wheel slip (udometry): with its help, the robot can calculate exactly how much and where it has moved, even if the wheels slip on an oil spill or the optical sensors are momentarily blind spotted.

The main logistical advantage of AMR technology is autonomous decision-making. If the Fleet Management System (FMS) issues a transport task from "A" to "B", the AMR software calculates the optimal route. If it encounters a dynamic obstacle, for instance, a forklift truck or a pedestrian, while driving, the robot does not stop and block the aisle, but replans the route in real time and avoids the obstacle using the SLAM algorithm and artificial intelligence. [1]. This flexibility makes AMRs the perfect service tool for flexible manufacturing systems.

2.3 Interoperability between infrastructure requirements and systems

In addition to the choice of technology, software integration is also a critical point when designing logistics systems. Seamless data connectivity with the enterprise resource planning (ERP), warehouse management system (WMS) and production management system (MES) is essential for the efficient operation of both AGV and AMR systems [15]. In the past, it was a serious industry challenge that robots from different manufacturers, for instance KUKA, MiR, KION, Omron, used their own, closed protocols, so different fleets could not communicate with each other in the same warehouse. To solve this logistical and IT-level problem, the VDA 5050 (Verband der Automobilindustrie) standard was created, which provides a universal interface [16]. The introduction of the VDA 5050 protocol is a milestone in Industry 4.0, as it enables a single, cloud-based master control software to manage a heterogeneous fleet of a mix of AGVs and AMRs, optimizing intersection traffic and the use of charging stations.

While the initial cost of ownership (CAPEX) of AGV systems is generally lower, the hidden operating costs (OPEX - operating cost) due to infrastructure constraints can increase significantly later on. On the other hand, the higher sensor and computational hardware costs of AMRs are quickly compensated for by plug-and-play integration and the software, i.e., no physical cost, adaptability of layout changes [4].

2.4. Safety standards and regulations (ISO 3691-4)

One of the most critical issues in the industrial application of autonomous mobile robots (AMRs) and automated guided vehicles (AGVs) is occupational safety and security. As machines and humans increasingly share a common workspace (Human-Robot Interaction - HRI) in the Industry 4.0 concept, traditional physical separation, for example, safety fences, is no longer a viable option [17]. This paradigm shift has also been followed by international standardization bodies.

The most important and comprehensive current standard for driverless industrial forklifts and their systems is ISO 3691-4, which has replaced the previous (now obsolete) EN 1525 standard. This document sets strict requirements for manufacturers and operators in terms of design, risk assessment and integration of systems [18]. The standard defines different safety zones within the facility based on the interactions between the infrastructure and the robot:

- **Operating zone:** Where vehicles are allowed to travel at normal speeds and pedestrians are allowed. In this zone, safety systems must be able to detect any obstacle in time and stop the vehicle.
- **Danger zone:** Areas where an adequate escape distance (usually 0.5 metres) cannot be maintained between the vehicle and fixed obstacles (walls, shelves) and therefore require increased safety measures (e.g. mandatory speed limits or extra visual and acoustic warnings).
- **Restricted zone**: This is where staff are not allowed to enter at all while the system is in operation; this includes dedicated robot cells and closed transfer lanes.

2.5. Sensor technology and laser protection

Physical safety is guaranteed in modern AGV/AMR systems by safety laser scanners (Safety LiDAR) and the associated PLd (Performance Level d) or PLe safety level controllers (Safety PLC). Ullrich also points out that vehicles must be equipped with redundant non-contact obstacle detection systems in addition to mechanical bumpers [6].

The scanners create software-configurable, virtual safety fields in the direction of travel and blind spots in the vehicle's blind spots:

1. **Warning field:** This is the outer zone, usually marked in yellow. When a person or forklift enters this area, AMR emits an acoustic beep, visually indexes, and reduces its speed to a safe manoeuvring level (often 30-50% of the rated speed).
2. **Protective Field:** This is the inner, red zone that is dimensioned directly to the robot's braking distance. In the event of a violation of this field, the system immediately performs a hardware safety emergency stop: it releases the torque of the drive motors and activates the mechanical brakes, avoiding physical contact [18]. Fig. 5 outlines the visualization of this.

Figure 5. *Dynamic safety zones for autonomous vehicles: warning (yellow) and protective field (red) [19]*

One of the biggest innovations of modern intelligent systems is dynamic zone switching. The size of the protective fields is not static: it changes in real time depending on the vehicle's driving speed, steering angle and the inertia of the transported load. At higher speeds, the braking distance increases, so the scanner "sees" farther ahead, while when manoeuvring or docking slowly, the protective field shrinks quite tightly around the vehicle. This allows precise navigation in confined spaces without the machine making an unnecessary emergency stop due to false obstacle detection [6, 17].

3. Logistics efficiency and management of automated systems

The physical implementation of automated material handling technologies alone does not guarantee the optimization of company processes. To demonstrate the increase in logistics efficiency, the software integration of the systems and the numerical indicators describing performance, i.e. Key Performance Indicators (KPIs), must be examined. In an Industry 4.0 environment, the success of the integration of AGV and AMR systems depends on the clarity of the software hierarchy, productivity indicators (OEE) and financial return on investment (ROI).

3.1. Software Integration: The Hierarchy of WMS and FMS

In modern intralogistics systems, the physical hardware is inoperable without the appropriate software background When developing fleet management strategies, the mathematical modelling of machine-to-machine communication and task assignment plays a key role [20]. In the strict logistics hierarchy, the functions of the Warehouse Management System (WMS) and the Fleet Management System (FMS) must be clearly separated, which work closely together to ensure automation.

- **The Warehouse Management System (WMS):** This software is the "brain" of logistics processes. The WMS keeps track of inventory, items, and storage locations. When the production needs material, the WMS generates the logical transport job. However, WMS does not know and does not have the job of knowing which robot will physically perform this.
- **The Fleet Management System (FMS):** This software is called "Traffic Controller". The FMS receives the logical task from the WMS and optimizes the execution. You can see the real-time position, battery charge and occupancy of all AGVs and AMRs in the warehouse. The FMS selects the free robot closest to the task, gives it the order, plans the route and manages traffic situations at intersections, preventing collisions and deadlocks.

The seamless communication of these two systems (also facilitated by the VDA 5050 interface mentioned earlier) is the basis for ensuring that the machines not only move autonomously, but also serve enterprise resource planning (ERP) purposes.

3.2. Productivity, Cycle Time and Availability (OEE)

One of the most important indicators of the performance of logistics systems is the material handling cycle time and the number of loads moved per unit time. In conventional forklift handling, cycle times vary greatly due to operator cognitive fatigue, shift changes, and subjective routing. In the case of automated machines (AGV/AMR), this standard deviation is minimized, and the process becomes predictable and plannable.

When examining the Overall Equipment Effectiveness (OEE), the following factors should be taken into account:

- **Availability:** While forklift drivers need a rest period, AGVs and AMRs can operate 24 hours a day (24/7). The only downtime is the charging period, which can be scheduled into off-hours with intelligent fleet management.
- **Performance:** Although an experienced forklift driver may work at a higher maximum speed in the short term, the constant, steady pace of automated machines and the lack of rest times over a full shift result in a higher overall output.
- **Quality:** In logistics, the quality indicator means the rate of flawless performance. Barcode, RFID and sensor-controlled identification of automated systems almost completely eliminates mistakes and scrap from falling or hitting a shelf.

3.3. Investment and return models (CAPEX and OPEX)

For management, the most critical decision point in technology change is the financial return on investment. The cost structure of the two technologies is significantly different, which requires a thorough TCO (Total Cost of Ownership) analysis.

In the case of AGV systems, a significant part of the cost of capital (CAPEX) is made up of the construction of the infrastructure itself. The installation of magnetic tapes, reflectors, and the preparation of the floor all require a serious initial investment. In addition, if the production layout is changed at a later date, the entire infrastructure will have to be redeployed, which entails hidden, high operational costs (OPEX). In contrast, the initial hardware cost of AMR systems is typically higher due to advanced LiDAR sensors. At the same time, the cost of building infrastructure is zero. From a financial point of view, AMR systems therefore provide faster returns on investment in rapidly changing plants, while AGVs are rational for systems that have remained unchanged for many years and move massive volumes.

3.4. Power supply and battery technologies in autonomous fleets

One of the main technological and operational constraints of uninterrupted (24/7) intralogistics processes has traditionally been energy storage. An essential condition for efficient fleet management (FMS) is the selection of the appropriate battery technology and the associated charging strategy.

Lithium-ion vs. Lead-Acid Technology: While previous generations of AGVs typically used lead-acid or gel batteries, modern AMR systems are almost exclusively based on lithium-ion (Li-ion) or lithium-iron phosphate (LiFePO4) technology. The critical disadvantages of lead-acid energy storage are their high dead weight, low energy density, and long charging times (up to 8-10 hours). In the case of these systems, continuous operation can only be achieved through physical battery replacement, which requires a dedicated, well-ventilated charging room and human (or complex robotic arm) intervention. On the other hand, modern Li-ion batteries have a fraction of the charging time of lead-acid types (a full charging cycle takes only 1-2 hours), their energy density is several times higher than that of traditional types, their weight is significantly lower, they have no memory effect, and they practically do not require maintenance (e.g. hydration) [6].

Fast Charging and Opportunity Charging: The paradigm shift in energy storage technology has enabled completely new fleet management strategies. With the spread of advanced Battery Management Systems (BMS), the so-called Opportunity Charging has come to the fore. Kostromitinova's research shows that lithium-based systems are able to absorb high-current (fast) charges in a short period of time without damage or a decrease in lifespan.

As a result, AMRs perform short docking cycles of 5-10 minutes during off-hours between workflows (such as waiting for loading or during shift changes). With this strategy, the average state of charge (SoC) of the fleet can be kept in the optimal range of 40-80% at all times, eliminating downtime of several hours per shift and maximizing overall equipment efficiency (OEE). The software also monitors battery degradation (SoH – State of Health) indicators in real time and optimizes the charging current to extend the service life.

Wireless inductive charging systems The technological pinnacle of the automation of the charging process is wireless inductive charging technologies (WPT – Wireless Power Transfer). There are no wearing mechanical connectors, copper slips, or open contacts in this design. The transmitter coil of the charging station is recessed into the floor or integrated into a wall-mounted panel, while the receiver coil is located on the robot's chassis. When the AMR navigates over the charging point, energy transfer is initiated through the principle of electromagnetic induction.

This solution not only reduces operating costs (OPEX) due to the absence of consumables, but is essential in clean space environments (e.g. pharmaceuticals, electronics) or environments with high dust and humidity where open electrical contacts could cause a risk of sparks, short circuits or oxidation problems. Inductive technology allows charging points to be located at logically optimal nodes in the warehouse, even in the middle of the work area, further reducing downtime on the journey to the charging station.

3.5. Cybersecurity Challenges and IT Integration in AMR Fleets

The logistical integration of Industry 4.0 technologies and cyber-physical systems (CPS) is not only a hardware and software issue, but also a serious IT security (cybersecurity) challenge. Thramboulidis' research highlights that the number of connected devices in smart factories is growing exponentially, which drastically increases the attack surface of systems [21].

While a traditional AGV with a guide bar functioned as a closed, dumb system (which had to be physically accessible for manipulation), modern AMRs are essentially moving computers. These robots provide continuous, real-time, bi-directional data connectivity to cloud-based fleet management (FMS) and enterprise resource planning (ERP/WMS) systems via the factory's local Wi-Fi or private 5G network [22]. The transmission of visual and map data (SLAM) collected by LIDAR and camera sensors, as well as information on production volumes, generates a continuous flow of data.

The biggest risk of this connectivity is data leakage and the assumption of external, unauthorized control over the systems. A potential cyberattack, such as ransomware or a distributed denial-of-service (DDoS) attack, can paralyze the central server, resulting in an immediate shutdown of the entire logistics fleet and a critical disruption to production (and supply chain). Osterrieder et al. point out that in modern intralogistics, data protection is at least as important an availability indicator (KPI) as the physical reliability of machines [22].

In order to protect yourself, modern logistics systems must be designed according to the principle of "Defense-in-Depth". This includes end-to-end encryption between devices and servers, network segmentation (where the guest network is physically and logically separated from the network of machines), and the use of a zero-trust architecture when authenticating devices. Furthermore, with the use of edge computing, critical navigation and safety calculations are carried out on the robot itself, so that in the event of a network outage, the safe, local stopping of the vehicle remains guaranteed [21, 23].

4. Fictitious Case Study and Model Calculation

To verify the theoretical and technological differences presented in the previous chapters, we perform a simple parameterized, estimation-based model calculation. The aim of this phase of the research is to quantitatively prove the hypothesis that in an Industry 4.0 intralogistics environment with dynamic barriers, the flexibility of AMR systems (SLAM navigation) compensates for the lower top speed and higher cost of ownership of machines compared to AGV systems.

4.1. Parameterization of the examined logistics system

For the model calculation, we model a typical, modern manufacturing company environment, where unit loads (pallets) have to be transported from the raw material warehouse to the production lines. Material handling takes place in a dedicated main corridor, which is also used by other logistics vehicles (human-driven forklifts, pedestrians).

For a realistic and objective comparison, the model calculation was performed based on two different simplified scenarios (scenarios):

1. scenario (Ideal case): An accessible environment that assumes continuous progress.
2. scenario (Dynamic case): A real-world industrial environment where unexpected obstacles (e.g. pedestrians, forklifts) appear in the main aisle.

In order to make the performance of the two technologies (AGV and AMR) clearly comparable, the following environmental parameters and boundary conditions are considered constant for both scenarios:

- Environment: Indoor, enclosed industrial hall with a constant temperature of around +20 °C.
- **Floor:** Completely flat, free of expansion defects, industrial resin-coated flooring, which provides optimal grip for the drive wheels.
- **Light conditions**: Uniform, artificial industrial lighting that does not cause variable light and shadow effects (this is critical due to the operation of the sensors).
- **Communication network**: Stable, industrial Wi-Fi/5G coverage along the entire route studied."

The tested unit load is a material placed on a standard EUR pallet (800 x 1200 mm) with an average weight of 500 kg and a maximum height of 1.5 meters.

The following industrial average values and boundary conditions were recorded for the mathematical model based on the literature recommendations [3]:

- **Transport Distance(s)**: 120 meters (round trip one cycle: 240 meters)
- AGV Average Driving Speed (AGV): 1.5 m/s
- AMR Mean Speed of Travel: 1.2 m/s
- Recording and Delivery Time ($\boldsymbol{t_{loading}}$):30 – 30 seconds per cycle
- **Shift length**: 8 hours (28,800 seconds), of which 85% is Actual Availability (OEE) due to loading times and operator breaks (24,480 seconds/shift).

4.2. Cycle time simulation in an ideal and dynamic environment

The performance of a system is determined by cycle time (t_{cycle}), which shows how long it takes a machine to complete a complete transport task. The basic kinematics formula is as follows:

$$t_{cycle} = (2 \cdot \frac{s}{v}) + (2 \cdot t_{loading}) + t_{loss} \quad (1)$$

where:

- t_{cycle} : the total delivery cycle time [s]
- s: transportation distance [m]
- v: average speed of the machine [m/s]
- $t_{loading}$: the pick-up and drop-off time [s]
- t_{loss}: the time of loss [s].

Scenario 1: Ideal (barrier-free) environment If the warehouse aisle is completely empty, its t_{loss} value is zero. In this case, the raw physical performance of the technologies is up against it.

- Based on the equation (1), the ideal cycle time of AGV and AMR can be calculated as follows:

$$t_{cycle,AGV} = \left(2 \cdot \frac{120}{1,5}\right) + (2 \cdot 30) + 0 = 160 + 60 = 220\ s \quad (2)$$

$$t_{cycle,AMR} = \left(2 \cdot \frac{120}{1,2}\right) + (2 \cdot 30) + 0 = 200 + 60 = 260\ s \quad (3)$$

- *Conclusion:* In a sterile, barrier-free environment, a fixed-track AGV is clearly faster due to its higher travel speed. This is detailed in Fig. 6.

Figure 6. *Comparison of AGV and AMR cycle times in an ideal, accessible environment (own edited)*

Scenario 2: Dynamic environment (Industry 4.0 reality) Under real industrial conditions, there is a transverse material handling (forklift traffic) in the main aisle. During the model calculation, I assume that the machines encounter a dynamic obstacle on average 2 times per cycle on the transport route (see Fig. 7).

- **Operation of the AGV in the event of an obstacle:** The safety scanner of the AGV detects the obstacle and the machine applies the emergency brake. Since he cannot deviate from the magnetic tape, he is forced to wait. If the average wait time is 45 seconds per obstacle, then the loss time and the real cycle time are as follows:

$$t_{loss,AGV} = 2 \cdot 45 = 90\ s \quad (4)$$

$$t_{real,AGV} = 220 + 90 = 310\ s \quad (5)$$

- **AMR** Operation in the event of an obstacle: AMR reroutes the route in real time using the SLAM algorithm. Although it does not stop, the dodge increases the distance travelled (an average of 15 meters of extra distance per obstacle per cycle). The loss here is due to the time it takes to make the extra trip, so the real cycle time can be calculated as follows:

$$t_{loss,AMR} = \frac{2 \cdot 15}{1{,}2} = 25\ s \tag{6}$$

$$t_{real,AMR} = 260 + 25 = 285\ s \tag{7}$$

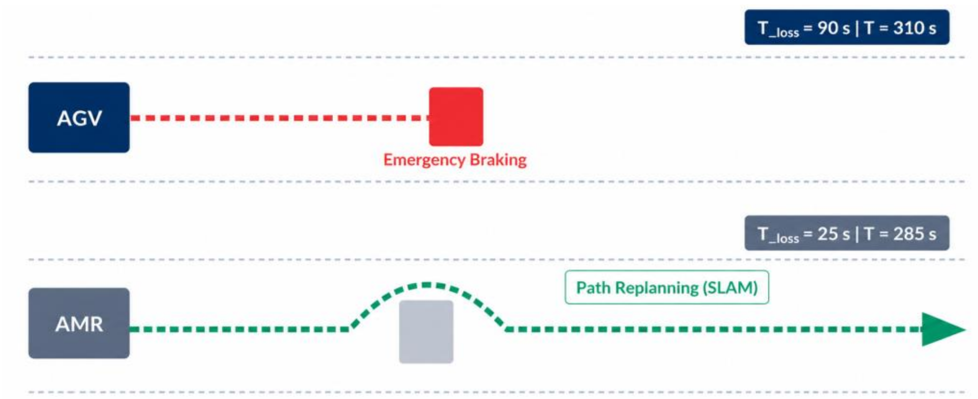

Figure 7. *Comparison of AGV and AMR cycle times in a dynamic, obstacle-filled environment (own edited)*

4.3. Throughput testing

Based on the real cycle times obtained in scenario 2 calculated above, it is possible to determine how many unit loads the two technologies can move during an 8-hour shift and a full 24-hour (3-shift) operating time.

$$Q = \frac{t_{active}}{t_{real}} \tag{8}$$

Where:

- Q: system throughput during the tested time interval [pallet]
- t_{active}: the actual available active operating time of the system during the given period [s]
- t_{real}: the real, dynamic cycle time [s] of the given machine.

8-hour shift (24’480 s active time): The $t_{active,8h}$ active operating time of an 8-hour shift is calculated as follows, taking into account 85% availability (OEE):

$$t_{active,8h} = 8\ h \cdot 3600 \frac{s}{h} \cdot 0{,}85 = 24480\ s \tag{9}$$

Based on this, the capacity of the machines in a single shift (8 hours):

$$Q_{AGV,8h} = \frac{24480}{310} = 78{,}9 \approx 78\ pallet/shift \tag{10}$$

$$Q_{AMR,8h} = \frac{24480}{285} = 85{,}8 \approx 85\ pallet/shift \tag{11}$$

24-hour operating time (taking into account battery charging cycles): During 24-hour operation, AGVs (lead-acid batteries) should expect 8 hours of charging time per day or battery replacement, which reduces fleet availability. In contrast, the Li-ion technology used in AMRs allows for the so-called occasional charging method in dead times.
During the 24-hour operation, AGVs can expect a charging time of 8 hours (1 full shift) per day or battery replacement due to conventional lead-acid batteries. Thus, the machine can only work actively in 2 shifts:

$$Q_{AGV,24h} = 2\ shift \cdot Q_{AGV,8h} = 2 \cdot 78 = 156\ pallet/day \quad (12)$$

In contrast, the Li-ion technology used in AMRs allows for continuous occasional charging during off-peak hours, allowing the fleet to operate in all 3 shifts with an estimated 90% 24-hour availability:

$$t_{active,24h} = 24\ h\ \cdot\ 3600 \frac{s}{h} \cdot 0{,}90 = 77760\ s \quad (13)$$

Based on this, the daily capacity of AMR is:

$$Q_{AMR,24h} = \frac{77760}{285} = 272{,}8 \approx 272\ pallet/day \quad (14)$$

4.4. Economic analysis: TCO and return on investment (ROI)

In addition to technical efficiency, investment decisions are determined by financial indicators. The cost structure of the two systems (CAPEX and OPEX) is fundamentally different. For the model, the introduction of a fleet of 3 planes was examined, based on a 5-year Total Cost of Ownership (TCO).

Investment (CAPEX) costs:

$$CAPEX = (n \cdot C_{machine}) + C_{infra} \quad (15)$$

Where:

- CAPEX: initial cost of capital (investment) [EUR]
- n: number of machines in the system [pcs]
- $C_{machine}$: unit price of one machine (AGV or AMR) [EUR/pcs]
- C_{infra}: fixed cost of infrastructure and software integration for the system [EUR].

For a fleet of 3 AGVs ($n = 3$), taking into account the price of the vehicles (25 000 EUR/piece) and the high infrastructure costs of magnetic tapes, reflectors and IT integration (30 000 EUR), the investment is based on the correlation (10):

$$CAPEX_{AGV} = (3 \cdot 25'000\ EUR) + 30'000\ EUR = 105'000\ EUR \quad (16)$$

In the case of the AMR fleet, the unit price of the vehicles is higher (35'000 EUR/piece) due to the more complex on-board sensors (LiDAR, 3D cameras). At the same time, the infrastructure cost is minimal (EUR 5'000) thanks to the virtual mapping, so the total investment:

$$CAPEX_{AMR} = (3 \cdot 35'000) + 5'000 = 110'000\ EUR \quad (17)$$

Operating and Conversion (OPEX) costs over 5 years: Industry 4.0 is characterized by short product life cycles, so the layout of production lines is changed on average once a year.

In addition, maintenance, failure and battery replacement costs must be taken into account during the 5-year operation for a realistic TCO calculation.

$$OPEX_{5\text{year}} = (5 \cdot n \cdot C_{maint}) + \left(5 \cdot C_{layout}\right) + (n \cdot C_{accu}) \tag{18}$$

Where:

- $OPEX_{5year}$: operating costs over 5 years [EUR]
- C_{maint}: annual maintenance and servicing costs per machine [EUR/machine/year]
- C_{layout}: annual system conversion and software modification cost [EUR/year]
- C_{accu}: the cost of a one-time battery replacement [EUR/machine].

For the AGV: Any layout change involves the demolition and reconstruction of the physical infrastructure (design, material costs, downtime), which occasionally involves a cost $C_{layout,AGV} = 8000\ EUR$. Calculated with the 4% annual maintenance fee $C_{maint,AGV} = 1000\ EUR/Machine$ and the one-time battery replacement $C_{accu} = 2000\ EUR/Machine$, the 5-year OPEX is based on the correlation (18): [24, 25]

$$OPEX_{5\text{year},AGV} = (5 \cdot 3 \cdot 1000) + (5 \cdot 8000) + (3 \cdot 2000) = 61'000\ EUR \tag{19}$$

For the AMR: Updating the map is a software operation. While the cost of physical remodelling can be saved, due to the engineering hours of software redesign and map optimization, this cost is not zero, but occasionally $C_{layout,AMR} = 1000\ EUR$. The maintenance cost $C_{maint,AMR} = 1500 \frac{EUR}{Machine}/year$ is higher due to the more expensive sensors, but there is no battery replacement cost. Thus, the 5-year OPEX: [24, 25]

$$OPEX_{5\text{year},AMR} = (5 \cdot 3 \cdot 1500) + (5 \cdot 1000) + 0 = 27'500\ EUR \tag{20}$$

The economic competitiveness of the two technologies examined is shown by the sum of the total lifecycle costs (TCO), which is the sum of the initial investment and the operating costs:

$$TCO = CAPEX + OPEX_{5\text{year}} \tag{21}$$

Substituting the previously calculated investment (CAPEX) and operating (OPEX) results in the context (21), the 5-year Total Cost of Ownership of the two systems is as follows:

$$TCO_{AGV} = 105'000 + 61'000 = 166'000\ EUR \tag{22}$$

$$TCO_{AMR} = 110'000 + 27'500 = 137'500\ EUR \tag{23}$$

This proves that, overall, the 5-year TCO (Total Cost of Ownership) model shows that although AMR's initial purchase price and annual service cost are higher, minimizing infrastructure rebuild costs (significant OPEX savings), less frequent battery replacements, and 10% higher daily delivery capacity will shift the return on investment (ROI) in favour of AMR technology at the end of the second year.

4. SUMMARY

In this article, we compared two key intralogistics technologies of the Industry 4.0 era, AGVs and AMRs based on technological, efficiency and economic aspects. The aim of the research was to prove that AMR systems with higher intelligence are capable of better performance than traditional AGV solutions in a modern, dynamically changing warehouse environment.

During the theoretical foundation, we explored the fundamental differences between the navigation logic of the two technologies, with special regard to the significance of the SLAM algorithm and sensor fusion. The model calculation and cycle time simulation performed clearly proved the hypothesis: although the top speed of AGV systems is often higher, the route replanning capability of AMRs can result in a capacity increase of almost 10% during unexpected obstacles and layout changes in a real industrial environment.

From an economic point of view, although the acquisition cost (CAPEX) of AMR fleets is higher due to advanced sensors, their return on investment (ROI) is much more favourable in flexible manufacturing systems due to the lack of physical infrastructure construction and lower conversion costs (OPEX). This was also confirmed by the model calculation: the 5-year total cost of ownership (TCO) of the 3-machine fleet examined was only EUR 137’500 for the AMR technology, compared to EUR 166’000 for the traditional AGV system.

The results of the article highlight that in order to implement the concept of Logistics 4.0, system-level optimization and the precise coordination of the software hierarchy (WMS/FMS) are essential. The direction of future research may be the further refinement of artificial intelligence-based fleet management algorithms and the study of 5G-based machine-to-machine (M2M) communication.

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AI use

During the preparation of this article, in accordance with the regulations from University of Miskolc's, Google's Gemini (gemini.google.com), ChatGPT and Microsoft’s embedded translator were used as artificial intelligence tools. AI technology has been used exclusively for the purpose of linguistic proofreading, stylistic refinements, and checking the formal settings of the chapters, the professional content and problem solving are our own intellectual creations. The text has been checked in detail, and we take responsibility for its content.

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