AMR-based Automated Pick To Pallet Systems: analysis of performance and investigation of item profile variations

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Logistics research group at the *Department of Management, Economics and Industrial Engineering*, Politecnico di Milano

Main research interests

- **synchronization of material flows in logistics systems & integrated decision making models**
    - Castellucci, T., Tappia, E., Moretti, E., & Melacini, M. (2024). Transition to synchronization-driven smart inbound logistics: an action research-oriented study. IFAC-PapersOnLine, 58(19), 1060-1065
    - Castellucci, T., Moretti, E., Tappia, E. & Melacini, M. (2025). Synchronizing Material Flows in Logistics Systems: Conceptual Framework and Research Opportunities. Production Planning and Control, third round of review.
    - Castellucci, T., Tappia, E., Moretti, E., & Melacini, M. (2025). AMR-enabled synchronization between replenishment and picking activities in automated pick to pallet systems: a simulation-based assessment. Euroma Conference, 13th – 18th June, Milan.
- **automated warehousing systems design and management**
    - Castellucci, T., Tappia, E., Moretti, E., & Melacini, M. (2023). Evaluating The Performance of Autonomous Mobile Robots in An Automated Palletizing System: A Simulation Model. In ECMS (pp. 380-386)
    - Castellucci, T., Tappia, E., Patrucco, A. & Melacini, M. (2025). Robotization of intralogistics activities: adopting mobile robots to enhance warehousing performance in dynamic environments. CSCMP European Research Seminar (ERS) & CSCMP European Conference, 19th - 20th June 2025, Verona.
    - Castellucci, T., Tappia, E., Moretti, E., & Melacini, M. (2025). Performance Analysis of Multi-Tote Storage and Retrieval Autonomous Mobile Robot Systems through Agent-Based Simulation. IFAC MIM2025 Conference, 30th June – 3rd July, Trondheim
- **reconfigurable warehousing systems (ONGOING RESEARCH PROJECT)**

Context

Changing customer requirements: from MASS PRODUCTION to MASS CUSTOMIZATION

- Shorter delivery lead times
- Increased product variety

→

- Frequent small-lot deliveries
- Large assortment of items

Changing role of warehouses: more responsibility in managing end customer demand

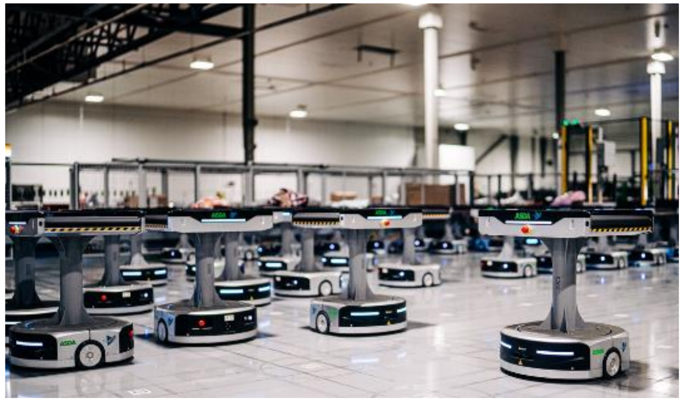
→

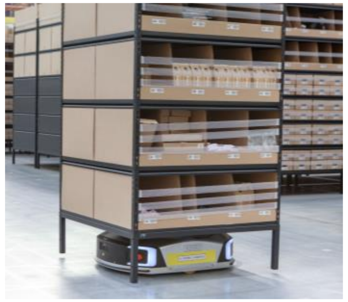
- Tight fulfilment schedules
- Highly volatile demand

Staff shortages in warehouses

Request for flexibility in material handling systems:
robotized solutions that replicate
manual systems' FLEXIBILITY and SCALABILITY

Autonomous mobile robots (AMR)





"industrial robots that use a decentralized decision-making process for collision-free navigation to provide a platform for material handling, collaborative activities, and full services within a bounded area" (Fragapane et al., 2021)

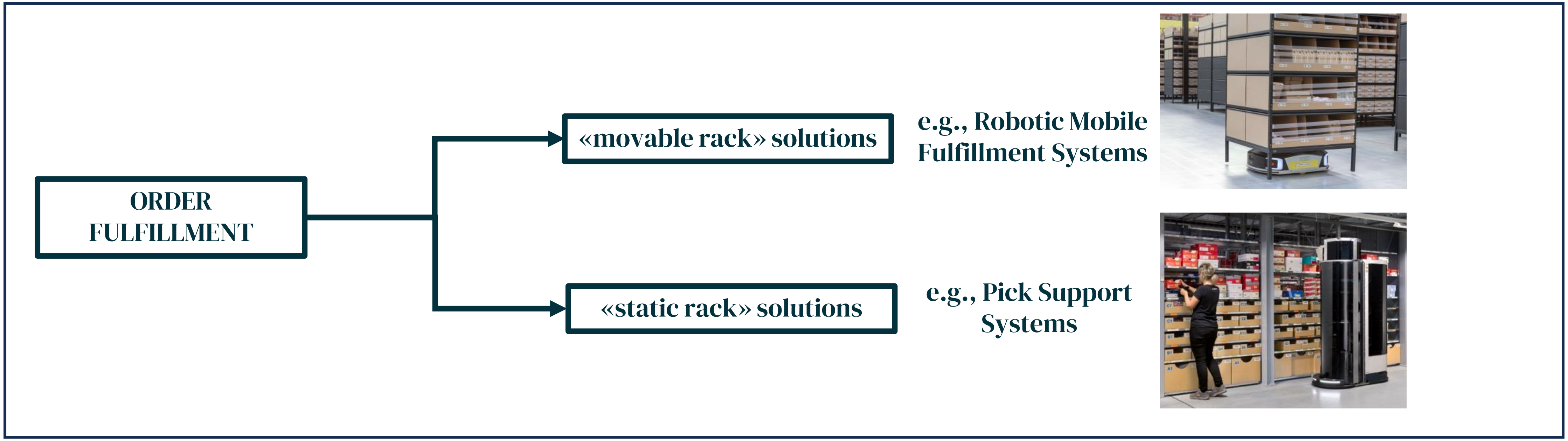
TECHNOLOGICAL FEATURES

- Network of sensors
- Data-processing capabilities
- Navigation autonomy

GROWING DIFFUSION

- Growing AMRs' sales
- Sales driven by logistics applications
- Diffusing adoption for order fulfillment

Research Objective



AMR-Based Order Fulfilment Solutions in literature. Source: adapted from Azadeh et al. (2019)

Extant literature has been investigating a variety of AMR-based solutions for order fulfilment (e.g., Robotic Mobile Fulfillment Systems, Pick Support Systems), yet some growingly diffused AMR-based systems recently developed by material handling providers remain uncovered.

RESEARCH OBJECTIVE:

Investigation of the performance and robustness of AMR-based Automated Pick To Pallet Systems (APPSs), robotized solutions for mixed-case palletizing operations that have been recently introduced in the market and have been scarcely investigated in scientific literature.

For such purpose a stochastic simulation model of an AMR-based APPS is developed.

AMR-based Automated Pick To Pallet Systems (APPSs)

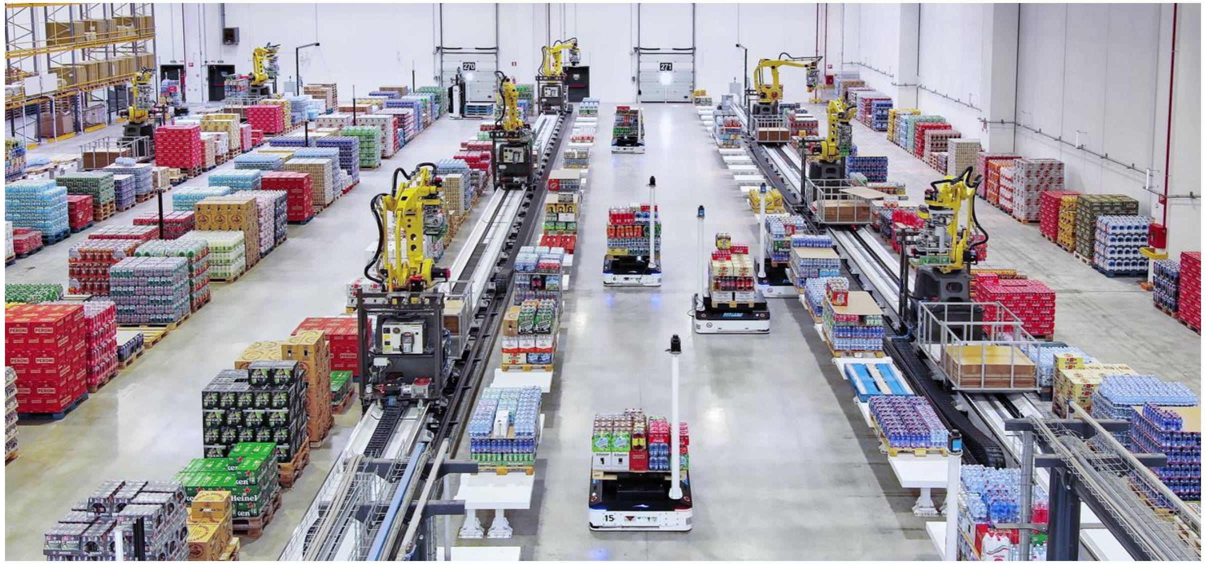
FULLY AUTOMATED PARTS-TO-PICKER CONFIGURATION in which mixed pallets are created by palletizing robots served by single-item full pallets

A robotic arm picks directly from single-item source pallets and place them on mixed pallets under construction

Transportation of pallets within the system is handled by AMRs

Compared to existing palletizing robotized systems: reduction in fixed mounted equipment

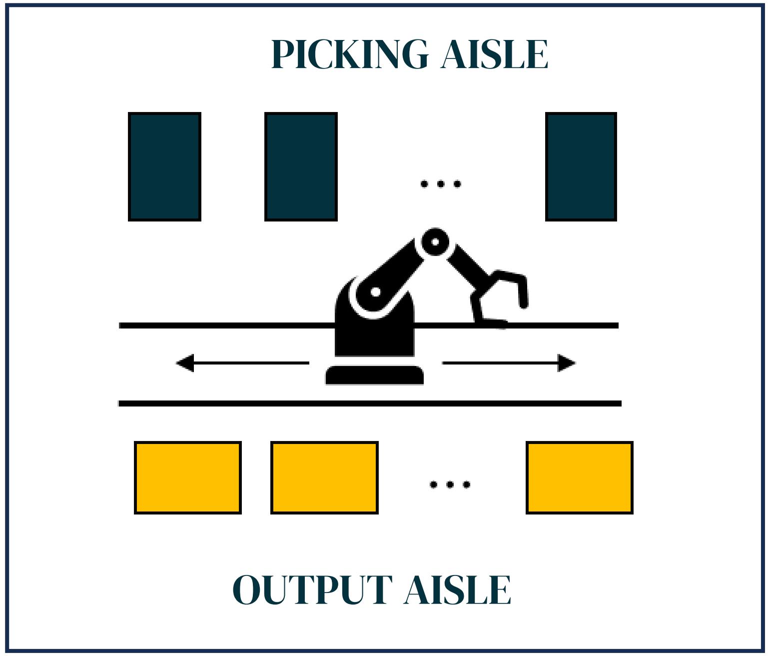
Compared to manual systems: higher performance and improved efficiency



Overview of the AMR-based APPS solution.
Source: System Logistics (Krones Group)

System layout

Picking station layout



Picking station layout

In AMR-based APPS, picking stations comprise three elements:

- a picking aisle with a set of locations for single-item full pallets
- a palletizing robot moving on a slide
- an output aisle with a set of locations for mixed pallets

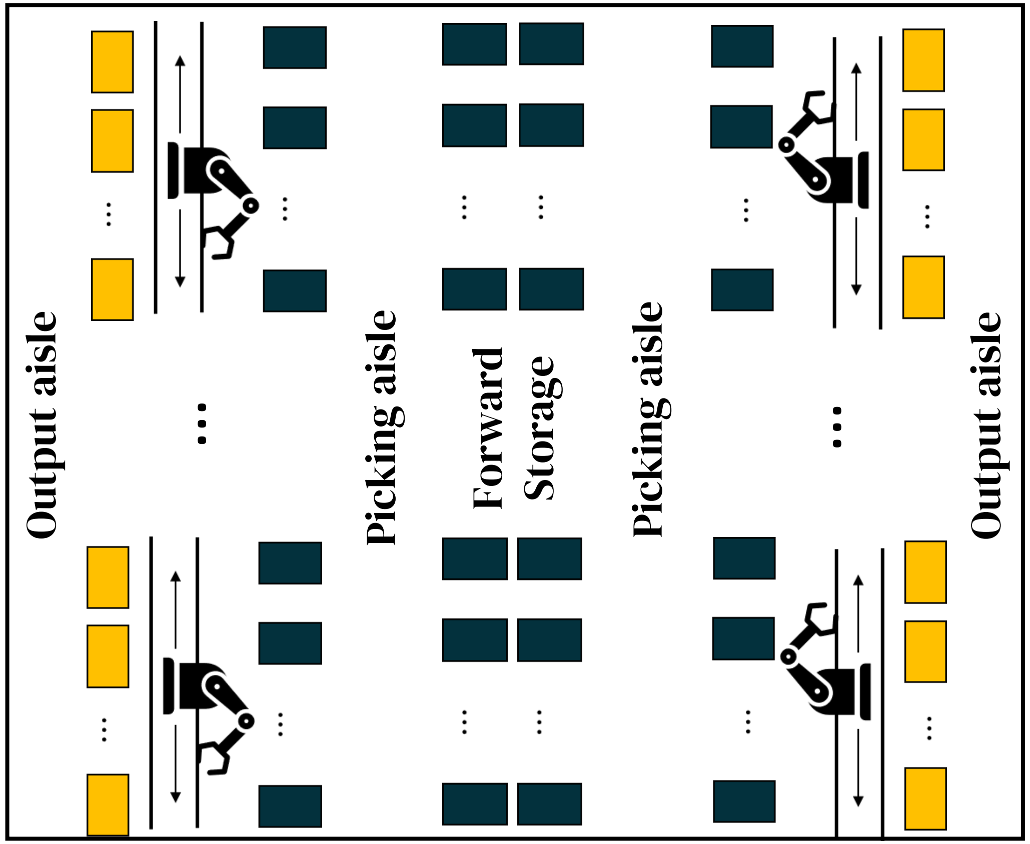
Detail of a picking station's output aisle.
Source: System Logistics (Krones Group)

System layout

AMR fleets

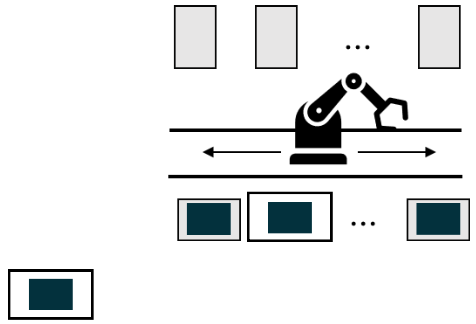
AMRs equipped with a lifting platform travelling along output aisles

AMRs equipped with forks travelling along picking aisles



Picking module

Fulfilment system - Creation and transportation of mixed pallets

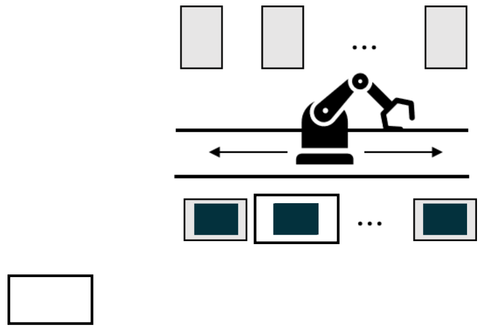


1 Palletization request released in the system

2 Empty pallet retrieval and transport to the first picking station to be visited

3 Picking process

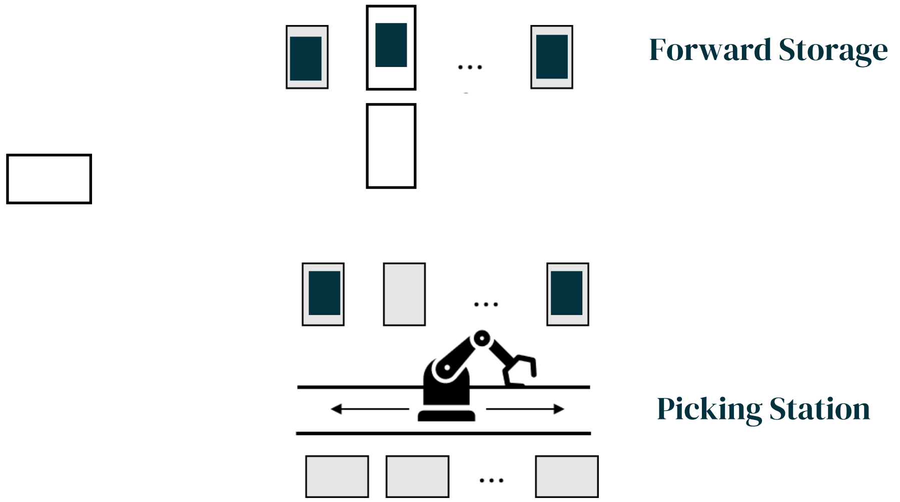
4 Transport to the following picking station or to the output point



Replenishment system - Feeding palletizing robots with new single-item full pallets

1 During the picking activity, a replenishment request is triggered

2 Retrieval of full pallet from forward storage and transport to the station



Agent-based simulation model

AGENTS

Central control unit

Fulfilment-system AMRs

Replenishment-system AMRs

Palletizing robots

PYTHON programming language - MESA module

Simulation tool selection

- General-purpose programming languages offer great modelling flexibility, yet model development is more challenging (Macal & North, 2008)
- Python has increased its worth as an agent-based simulation modelling tool thanks to the development of “mesa”, an open-source package that allows users to quickly create agent-based models, using built-in core components or customized implementations (Kazil et al., 2020)

STANDARD OBJECT CLASSES

Customer Orders

Mixed pallets

Model Structure

PRE-PROCESSING

- Generating orders and splitting them in mixed pallets
- Generating the picking sequence for each mixed pallet

SIMULATION TIME

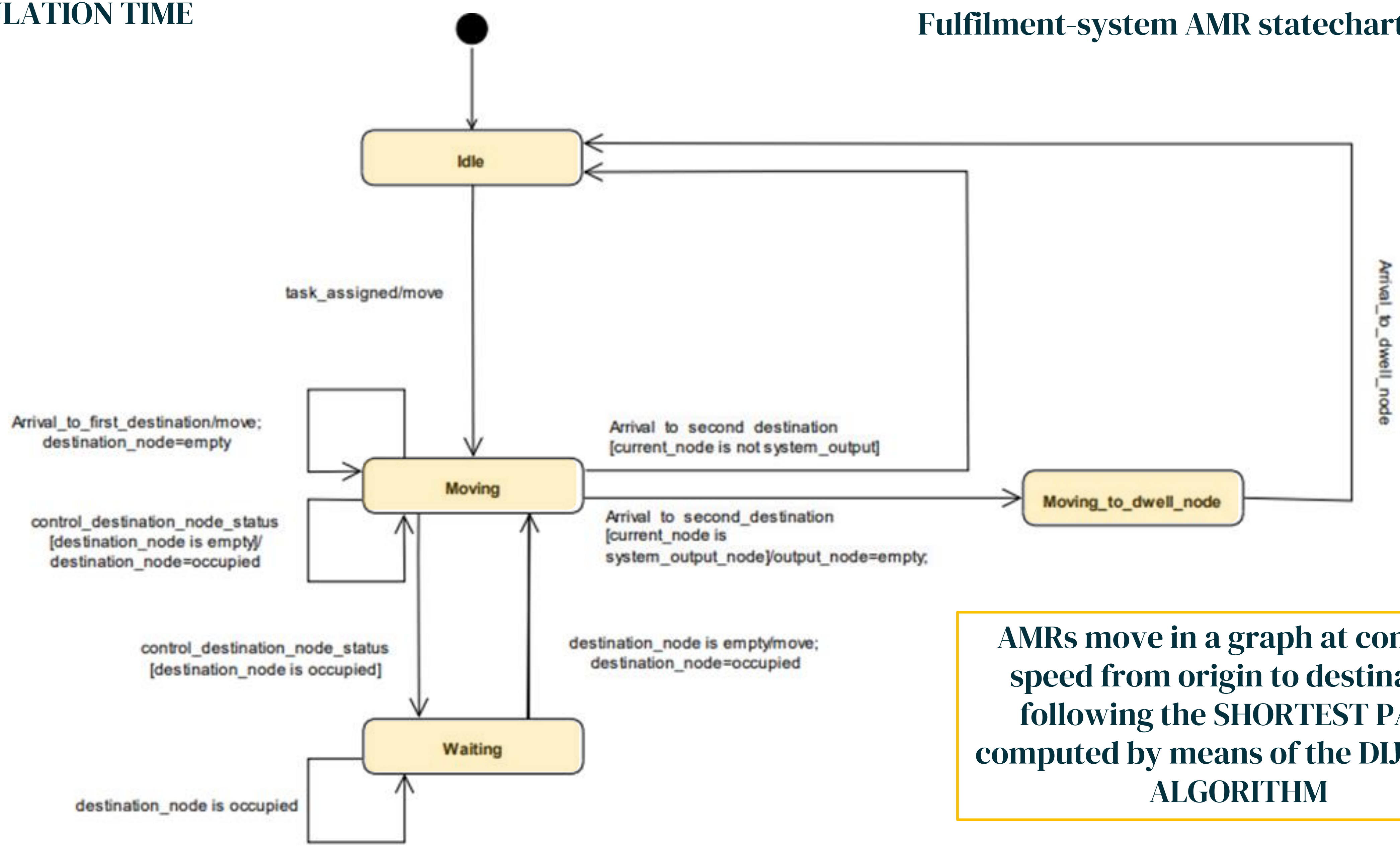
- Simulation of the system's operations
- Agents' behavior and interactions determine the advancement of the system's operations, causing periodic changes in the STATES of the agents themselves

POST-PROCESSING

Measuring performance:
- Nr. orders/mixed pallets completed
- Resources' utilization and productivity

SIMULATION TIME

Fulfilment-system AMR statechart diagram



AMRs move in a graph at constant speed from origin to destination following the SHORTEST PATH computed by means of the DIJKSTRA ALGORITHM

Model Validation - Conceptual model

Validation and verification concern the conceptual model, computer model, and simulation results

CONCEPTUAL MODEL VALIDATION aims at evaluating the accuracy of the model in representing the real-world research problem (Sargent, 2010)

- Based on research on AMR-based order fulfilment solutions
- Based on qualitative insights on the systems' structure and operating conditions from visits to two grocery distribution centers that have recently introduced AMR-based APPS for the creation of respectively fresh produce and beverage order pallets

Model Validation – Computer model

Validation and verification concern the conceptual model, computer model, and simulation results

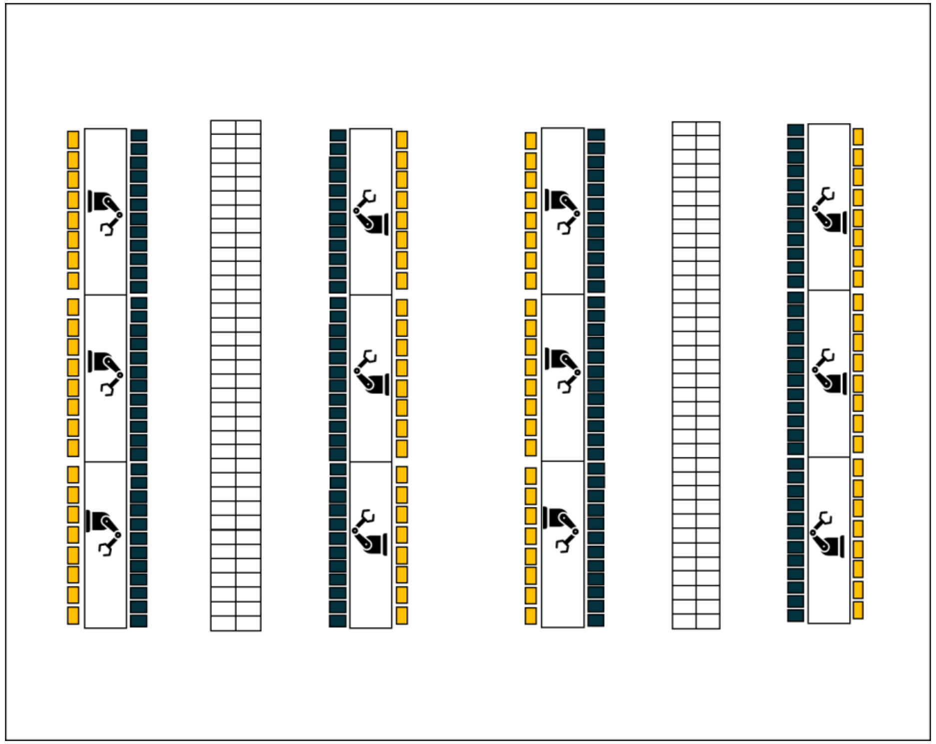
COMPUTER MODEL VERIFICATION makes sure that "the computer programming and implementation of the conceptual model are correct" (Sargent, 2010)

- **Debugging activity**
- **Bottom-up testing**

Model Validation – Simulation model output

Validation and verification concern the conceptual model, computer model, and simulation results

SIMULATION MODEL OUTPUT VALIDATION aims at determining whether the model is sufficiently accurate for its intended purpose (Sargent, 2010)



INPUT PARAMETERS

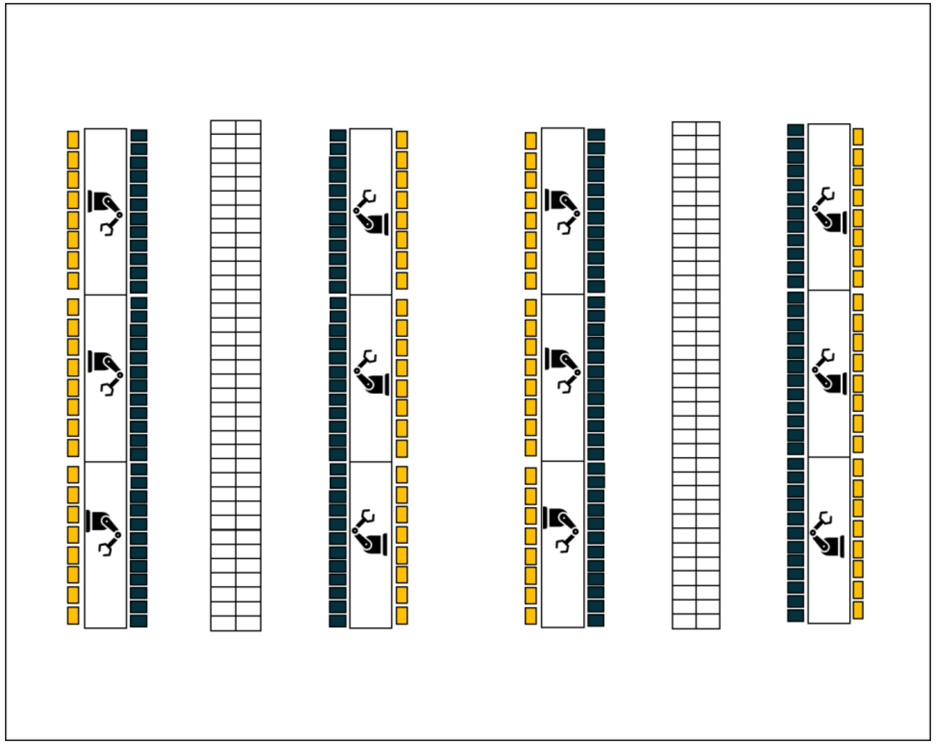
Data selected from different sources according to their availability and appropriateness

- 12 picking stations
- 8 mixed pallet locations per station
- 12 full pallet locations per station
- 3 replenishment-system AMRs/15 fulfilment-system AMRs

Model Validation – Simulation model output

Validation and verification concern the conceptual model, computer model, and simulation results

SIMULATION MODEL OUTPUT VALIDATION aims at determining whether the model is sufficiently accurate for its intended purpose (Sargent, 2010)



INPUT PARAMETERS

Data selected from different sources according to their availability and appropriateness

- 120 items
- 24 best-selling = 50% of the sales
- 4 picking stations dedicated to best-selling items
- 2 full pallet locations for each best-selling item, 1 for the remaining items

Model Validation – Simulation model output

Validation and verification concern the conceptual model, computer model, and simulation results

SIMULATION MODEL OUTPUT VALIDATION makes sure that "the computer programming and implementation of the conceptual model are correct"

- Simulation results have been obtained by performing 10 replications of a finite simulation horizon of 8 hours
- The number of replications has been selected to obtain a ratio between the half-width of the 95% confidence interval and the mean value of system productivity over the sample of runs lower than 0,5%

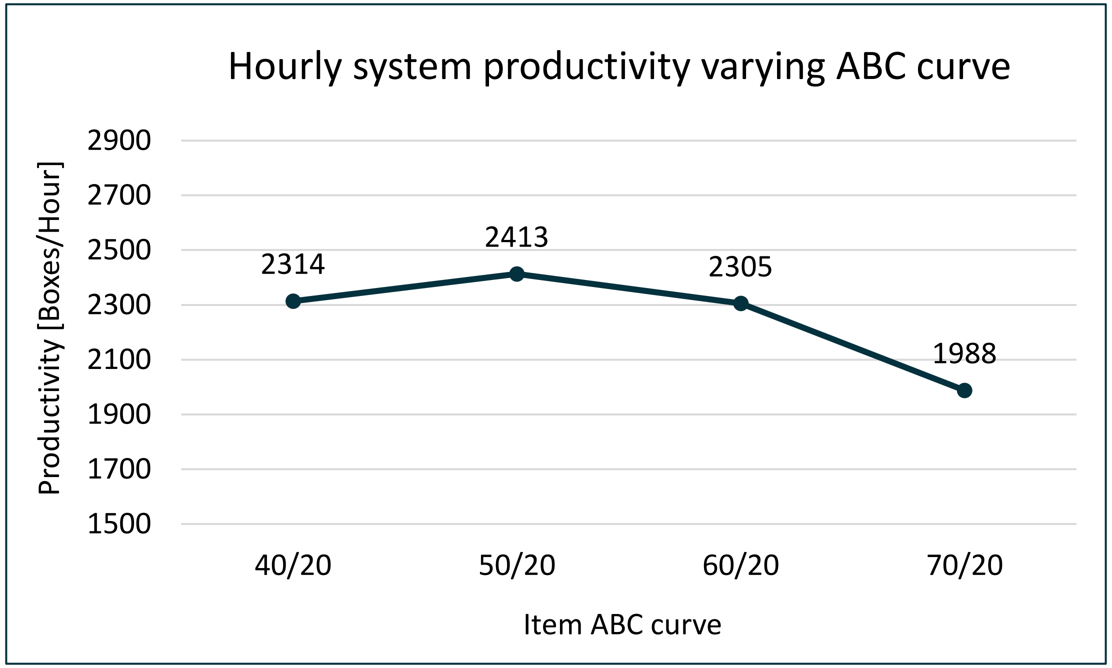
SIMULATION RESULTS

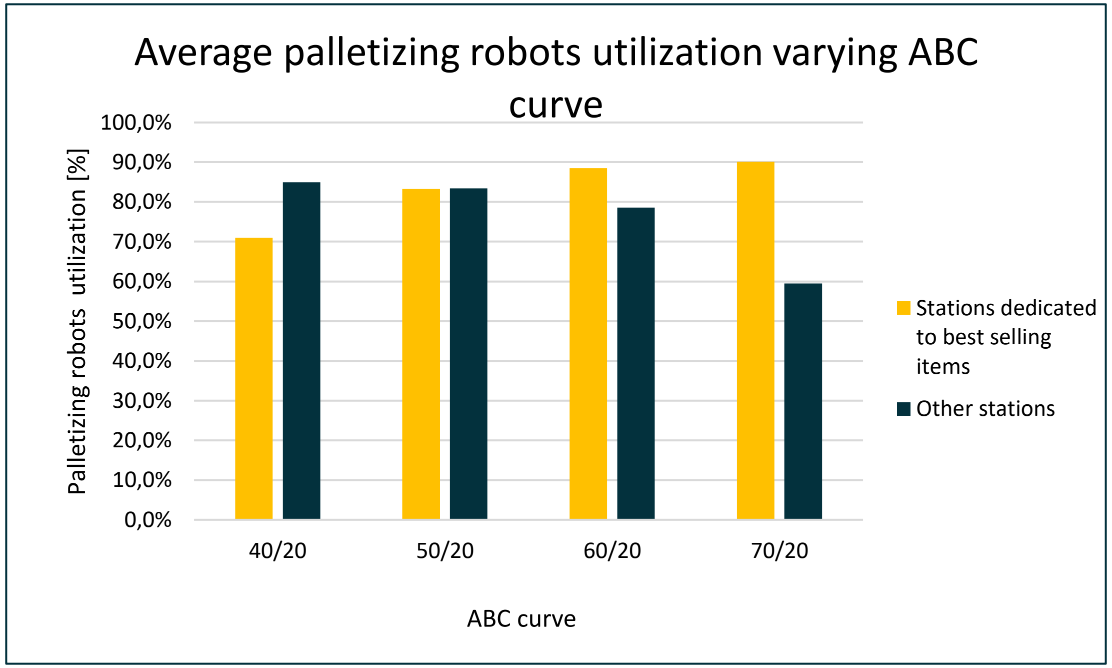
Performance measures (avg)	System	Palletizing Robots	Replenishment-system AMRs	Fulfilment-system AMRs
Productivity [boxes/hour]	2413	201	-	-
Utilization	-	83,4 %	22,2 %	82,5 %

- Resulting performance measures are in line with the expected values discussed with the technology provider for the visited distribution centers

Item profile variation

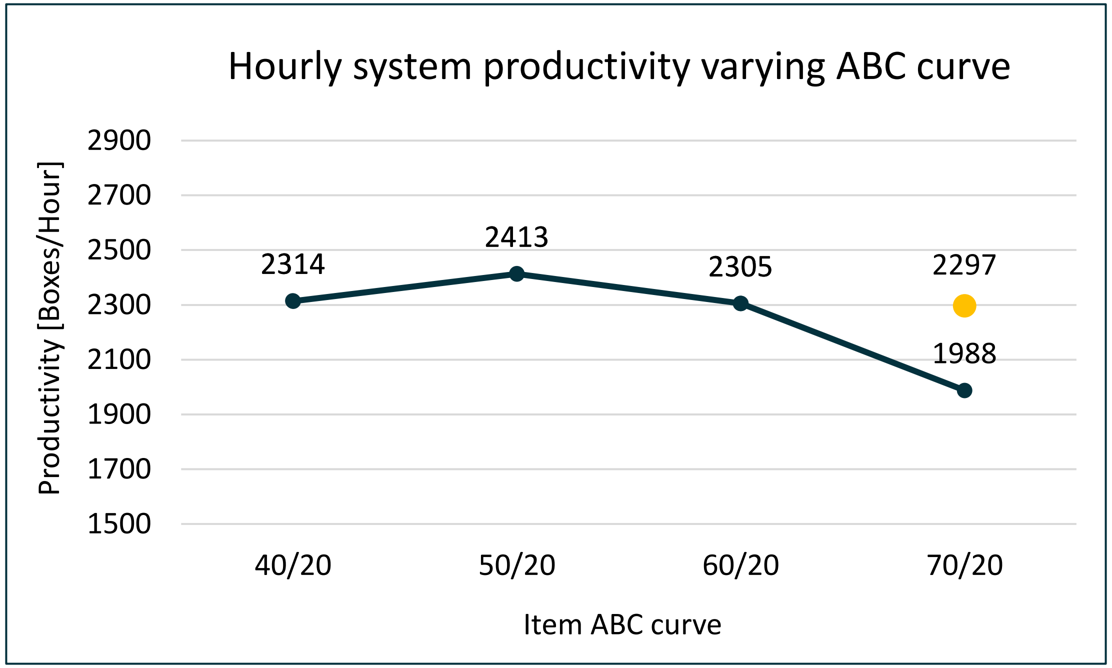
	Base case	Investigated scenarios		
Item ABC curve	50/20	40/20	60/20	70/20

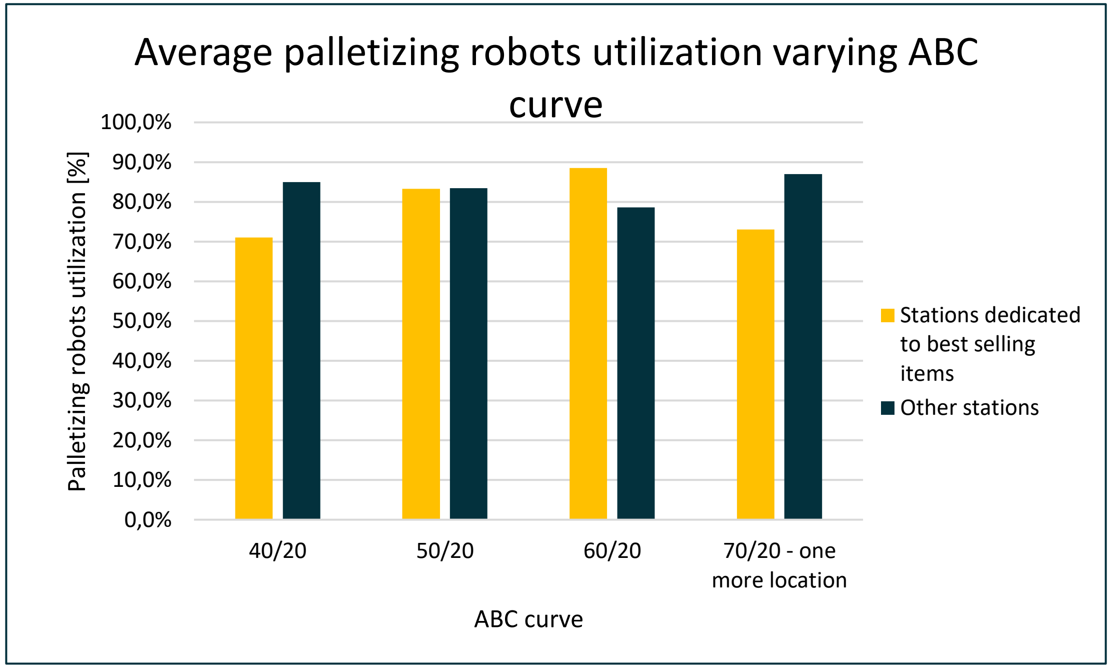




Item profile variation

	Base case	Investigated scenarios			
Item ABC curve	50/20	40/20	60/20	70/20	70/20 with an additional location per best-selling item





Conclusions

This work deals with AMR-based APPSs, robotized solutions for mixed-case palletizing operations that have been recently introduced in the market by technology providers and, thus, has yet to receive attention in scientific literature. This study provides a tool for the estimation of such solutions' performance and some preliminary insights on their robustness to varying demand characteristics.

→ BASE FOR FUTURE RESEARCH and SUPPORT FOR PRACTITIONERS in the adoption and management of AMR-based APPSs

- Investigation of different operating policies (e.g., comparison of alternative task dispatching rules to the AMRs or item allocation policies to picking stations)
- Economic evaluation in different fields, also in comparison with other systems in which palletizing stations are served by different transportation technologies
- Extension of the model to overcome some of its limitations, with a particular focus on considering the effects of congestion within the aisles and modelling the charging activity of AMRs

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