International Journal of Industrial Engineering & Production Research September 2026, Vol. 37, No. 3: 88-107
DOI: 10.22068/ijiepr.37.3.2245

RESEARCH PAPER

Simulation and Implementation of Autonomous Mobile Robots in Intralogistics

André Guimarães[1,*], Ana Carolina[2], João Pedro Teixeira[3], Filipe Gomes[4], Samuel Martins[5]

Received 30 December 2024; Revised 01 June 2026; Accepted 11 July 2026;
© Iran University of Science and Technology 2026

ABSTRACT
In the evolving landscape of Industry 4.0, Autonomous Mobile Robots (AMRs) are emerging as key enablers of innovation in intralogistics, particularly in material transport operations. These systems operate within innovative production environments where a central controller oversees high-level planning, while AMRs act with autonomy, interacting directly with equipment and systems to support decentralized operations. This shift challenges traditional planning and control practices by introducing new dynamics in decision-making. The present study investigates the implementation potential of AMRs for supplying assembly lines at the XYZ factory through simulation-based analysis. Rather than solely benchmarking against existing methods, the research aims to validate the efficiency and practicality of AMRs in this context. Several simulation models were built and iteratively refined using the SIMIO platform to examine different logistics configurations and scenarios. The insights derived from these simulations offer valuable support for decision-makers, helping to identify optimal setups and assess how AMR deployment compares to conventional intralogistics approaches regarding performance and flexibility.

KEYWORDS: *Logistics operations; Industrial digitalization; Intelligent automation; Logistics simulation; AMR technology; AGV technology.*

1. Introduction

Industry 4.0 (I4.0) was introduced in 2011 at the Hannover Technology Fair in Germany, marking the beginning of a new industrial era where companies started adopting advanced technologies to improve their operations [1, 2]. This fourth industrial revolution connects digital and physical systems, focusing on automation, digitalization, and robotics [3]. Meanwhile, the term "intralogistics" (or internal logistics) was introduced in 2004 by the VDMA, the German Mechanical Engineering Industry Association [4], and refers to the organization and improvement of internal material flows in factories [5].

The use of Industry 4.0 technologies in intralogistics has grown in recent years. Modern intralogistics systems involve smart, connected units sharing information, making real-time decisions, and working with little or no human input [6].

Traditionally, intralogistics relied on manual carts, tow trucks, conveyors, and forklifts to move materials inside factories. However, these methods still require significant human effort [7].

With the rise of Industry 4.0 and Smart Manufacturing, interest in intelligent intralogistics systems has increased. Technologies like Automated Guided Vehicles (AGVs), especially mobile robots, are key to this development [2]. Research is now focused on making intralogistics more efficient, safe, and profitable through the use of autonomous and IoT-based solutions, such as Autonomous Mobile Robots (AMRs), 3D transport systems, indoor drones, self-organizing transport systems, collaborative robots, smart containers, sorting systems, real-time simulations, and wearable exoskeletons [5].

Over recent decades, material handling technologies have advanced significantly, particularly in developing Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs). AGVs have evolved since 1955, incorporating various guidance technologies such as mechanical, optical, inductive, inertial, and laser systems [8]. AMRs, by contrast, provide greater flexibility, navigating freely through safe and obstacle-free environments [9]. AGVs and AMRs are now widely adopted in intralogistics, with market forecasts suggesting a growth rate of approximately 30% over the next

* *Corresponding author: André Guimarães*
andre.m.guimaraes@ubi.pt

1. *MSC- University of Beira Interior, Portugal*
   CISE- Electromechatronic Systems Research Centre
   CISeD- Centre for Digital Services Research
2. *School of Engineering of Polytechnic University of Porto, Portugal*
3. *School of Engineering of Polytechnic University of Porto, Portugal*
4. *School of Engineering of Polytechnic University of Porto, Portugal*
5. *School of Engineering of Polytechnic University of Porto, Portugal*

five years. Since the initial launch of AGVs, these technologies have seen substantial progress and are now a leading solution for automating internal logistics processes [10].

Although the idea behind AMRs is not new, the first patent dates back to 1987 [11], their relevance in logistics has grown considerably only in recent years. With over 13,000 AGV and AMR systems deployed globally [12] and many suppliers offering autonomous robotics solutions [9], their adoption continues to accelerate. AMRs are especially effective in intralogistics applications, such as supplying production lines with parts and materials [13]. Their functions can generally be grouped into three categories: (i) material handling tasks (e.g., transport, retrieval, sorting), (ii) collaborative tasks involving interaction with other systems or operators, and (iii) full-service operations [14, 15].

Despite high levels of automation in many industrial environments, internal transport often depends on human-operated equipment like manual carts and forklifts. This dependency increases labor costs and may introduce quality risks. Although fixed conveyors and other mechanical systems offer alternatives, AMRs provide a more adaptable and efficient approach for streamlining intralogistics [2].

Technological progress has made it easier to integrate AMRs into factory environments. Unlike fixed systems, AMRs can connect workstations through simple loading and unloading points, making them easier to install and reconfigure. Buffer zones can also be included, allowing AMRs to temporarily hold products between processing steps, which helps decouple consecutive production phases. This makes it possible to set up dedicated AMR zones before and after workstations that require batching or part separation [13, 16].

In contrast to AGVs. which often require time-consuming reprogramming when the layout changes, AMRs are highly responsive and can quickly adapt to new layouts or obstacles. Their ability to adjust to changing environments has driven advancements in navigation and expanded their operational capabilities. While AGVs are primarily used for straightforward horizontal transport, AMRs can perform more complex tasks and interact dynamically with the production environment [17].

AMRs operate autonomously, making ongoing decisions about how to act within their surroundings while following predefined rules. A major challenge is their need to function without human supervision, meaning they must self-monitor, detect errors, and respond appropriately to any issues [14]. Their decentralized decision-making enables them to react quickly to environmental changes and continue supporting material transport and other operations efficiently [9].

Beyond logistics, AMRs can also act as collaborative systems that work directly with humans. For example, in car manufacturing, AMRs equipped with robotic arms can help assemble heavy components, reducing strain on workers and improving productivity and quality [18, 9].

New technologies like AMRs must also support sustainability to ensure widespread and long-term success. This involves reducing environmental impact and meeting social and economic goals. Continued research and practical applications of Industry 4.0 solutions in intralogistics are key to achieving these goals. As smart intralogistics continues to evolve, it will offer increased flexibility and productivity, making it essential to explore and embrace the opportunities presented by Logistics 4.0 [19].

2. Literature Review

One of the key elements of Industry 4.0 is its application to intralogistics. This area deals with the internal movement and management of materials and information, covering all stages from receiving goods to feeding production lines [20, 3]. It involves coordinating various logistical processes to ensure efficient handling of raw, semi-finished, and finished materials.

Within the Industry 4.0 framework, human operators take on a more supervisory and strategic role. Instead of directly performing tasks, they collaborate with intelligent systems and robots, focusing on monitoring and oversight [3].

Material transport is a vital part of production logistics. Current systems still rely on equipment such as forklifts and pallet jacks, which require human operation [21]. However, to meet the flexibility and efficiency demands of modern manufacturing, there is a need to move away from rigid automation and adopt more adaptable solutions [22]. Growing productivity levels have added pressure on logistics systems, making innovation even more necessary [23]. In this context, mobile robots have emerged as a leading solution for delivering materials to assembly lines [24].

These robots must calculate the most efficient and safe routes between locations, often prioritizing the shortest path [25]. Their flexibility supports the redesign of production lines and allows existing

layouts to be easily reconfigured, which is critical for the dynamic environments of Industry 4.0 [24]. Autonomous Mobile Robots (AMRs) are a more advanced version of Automated Guided Vehicles (AGVs). Unlike AGVs, which depend on physical guides such as lines or magnetic strips to navigate, AMRs are equipped with sensors and onboard systems that allow them to move freely and adjust to changes in real-time [26, 10, 3].

Another key difference is their decision-making structure. AMRs operate under a decentralized system, allowing them to make independent decisions, unlike AGVs, which rely on a central controller [13, 2]. This autonomy enables AMRs to integrate more effectively into production networks and improve the efficiency of internal logistics operations, often at a lower cost [13, 27]. While AGVs follow a central command for routing and scheduling, AMRs can interact directly with other machines or systems and make real-time decisions based on their environment. This removes the need for central control and enhances system responsiveness [28].

In addition to simple transport tasks, AMRs can perform more complex functions such as surveillance and operator assistance. Their autonomy allows them to assess their surroundings continuously and adapt their actions according to rules and constraints, making them highly versatile tools for modern production environments [17].

Integrating Autonomous Mobile Robots (AMRs) into industrial environments requires rethinking assembly line layouts to maximize flexibility. As their adoption increases, managing large and diverse robot fleets becomes challenging, mainly because AMRs rely on a decentralized decision-making model, which differs from the centralized logic used in Automated Guided Vehicles (AGVs) [29]. Route planning must account for real-time robot positioning to assign tasks to the nearest available unit, helping reduce travel time and improve line productivity [24]. With built-in sensors, AMRs can operate independently and respond to their surroundings, enhancing route optimization, reducing component shortages, improving safety, and minimizing delays [23, 24].

AMRs' strength is their adaptability; they can be reprogrammed to perform different tasks as needed. Continuous improvements in hardware and navigation systems have increased their flexibility and suitability for dynamic industrial settings [2].

From a sustainability perspective, AMRs also support the transition to greener logistics. Their electric operation aligns with environmental goals, and financial incentives linked to green initiatives are expected to promote broader adoption shortly [30]. Ensuring that robots can safely operate alongside human workers is essential. Without effective human-robot interaction, productivity may suffer [31]. In shared spaces, human presence can impact robot performance [32], so collaboration must be seen as an advantage rather than a disruption. Cyber-physical systems (CPS) enable AMRs to adjust tasks based on human movement and other environmental factors [31].

AMRs allow companies to allocate human labor to higher-value tasks, helping address workforce shortages while improving overall efficiency [3]. Regarding safety, robots also reduce the risk of injuries by handling repetitive and physically demanding tasks, which can lead to musculoskeletal problems. This allows operators to focus on more skilled and less hazardous activities [3].

In the context of Industry 4.0, intralogistics is central to managing the internal flow of materials and information, from goods reception to assembly line delivery. AMRs are vital in this process, as they can be programmed to retrieve components from storage and deliver them directly to production areas, reducing the need for manual transport [20, 3]. Their ability to adapt to demand fluctuations, product changes, or layout adjustments makes AMRs highly effective in streamlining material supply. Once implemented, the system can be reconfigured with minimal effort or cost. By replacing manual systems with AMRs, companies can achieve higher efficiency, reduce downtime, and enhance safety. Furthermore, automation helps lower operational costs by reducing human error. In this setting, the operator's role evolves toward supervising and interacting with innovative technologies rather than performing repetitive physical tasks [3].

3. Methodology

This study was conducted following a structured approach, starting with a detailed literature review on the central topics of the research: intralogistics, the use of AMRs (Autonomous Mobile Robots), simulation, and assembly line supply.

The SIMIO software was used to simulate one of the relevant scenarios related to the identified problem to achieve the proposed objectives. The methodology followed the standard approach for simulation model development [33], comprising

the following stages:

1 Problem definition: Identify and define the problem being addressed.
2 Data collection and model design: Gather relevant data from the XYZ company and build a conceptual model that accurately represents the system.
3 Conceptual model validation: Check whether the conceptual model reflects real-world operations accurately.
4 Model implementation and testing: Develop the model using SIMIO software to verify it functions correctly without programming errors.
5 Model validation: Compare the simulated model with actual system behavior to confirm its accuracy and consistency.
6 Scenario design and analysis: Create and test scenarios to evaluate possible solutions.
7 Results documentation and reporting: Summarize and present the findings through reports and dashboards.

The models were developed based on information collected from the XYZ company, where the data was analyzed and organized. Subsequently, the models were implemented in SIMIO software, simulating various scenarios related to the identified problem. Finally, a comparison of the scenarios was conducted, directly evaluating the use of AMRs to identify the most suitable solution for the project's needs. This process ensured that the proposed solution was based on concrete data and rigorous analysis.

3.1. Model validation approach

The simulation model was developed based on real operational data from the XYZ factory, including transportation times, workstation processes, and production volumes. In addition, the conceptual model was reviewed and validated by internal logistics and operations managers to ensure practical alignment with the shop floor environment. While the simulation captures significant operational flows, it does not yet simulate all real-world constraints, such as dynamic traffic congestion, battery charging cycles, or unexpected delays. These limitations are acknowledged and discussed in the Conclusion and Future Work sections.

4. Case Study

This case study examines proposed enhancements to the internal logistics of a specific assembly area at the XYZ factory. The focus is on improving material handling and introducing automation to streamline operations. Technologies such as Autonomous Mobile Robots (AMRs) and conveyor systems are intended to boost efficiency and reduce human error, ultimately supporting a more flexible and sustainable production environment. The study outlines both the current logistics setup and the new solutions proposed for implementation.

4.1. Specific separate areas for carts of each frame type (stock zone)

Carts loaded with raw materials for each frame type are placed in a specific storage area, as shown in Figure 1. An operator manually pushes the carts to the appropriate workstations, covering a distance of about 60 meters. The carts can weigh between 100 and 300 kg, requiring significant physical effort. Mistakes can occur when carts are not identified, making it challenging to ensure they are sent to the correct location.

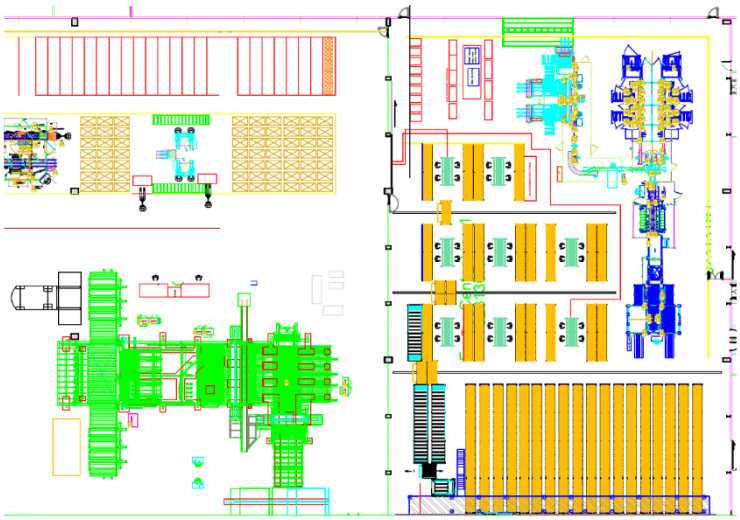


Fig.1. Existing layout

Proposed new solution: Carts will continue to be fully loaded in a designated stock area in the new setup, similar to the current arrangement. However, each cart will be clearly labeled and placed in a specific location assigned to its corresponding frame type. Multiple carts containing the same raw materials will be kept together to allow continuous production of identical or similar frames. For example, carts for Frame A will always be stored in the same fixed spot, enabling AMRs to locate and collect them efficiently. A separate area will also be designated for empty carts, where AMRs will drop them off after use. These empty carts will remain there until they are reloaded and moved back to the stock area, as shown in Figure 2.

4.2. Cart transport systems

- **Existing solution:** Currently, only one cart model is used to transport raw materials, and it comes in a single size. While standard frames fit on one cart, larger frames require two carts placed side by side to be moved.
- **Proposed new solution:** The new approach involves using two different cart sizes. A standard cart will serve most small and medium frames, while a larger cart will be introduced for transporting more oversized frames. This larger version includes design improvements, such as removable shelves that slide on rails, making loading and unloading more efficient.

4.3. Line feeding systems

- **Existing solution:** Currently, carts loaded with raw materials are placed near the operators, who manually pick the parts needed for frame assembly. The carts stay in place until they are fully emptied, after which they are returned to the cutting area to be refilled for future use.
- **Proposed new solution:** The new system introduces multi-level conveyor belts positioned next to the assembly operators. These conveyors are height-adjustable and designed to adapt ergonomically to each worker. AMRs (Autonomous Mobile Robots) will transport the loaded carts from the cutting area to the assembly zone, placing them near the conveyors. The materials are then transferred onto the conveyor, and the AMR immediately returns the empty cart for reloading and restocking.
- Throughout the day, operators pull materials from the conveyor as needed. The system ensures a continuous and accurate supply of parts tailored to each workstation's daily production requirements while reducing manual handling and improving efficiency.

4.4. Presentation and explanation of different scenarios

In the first scenario, it is assumed that all operators are assigned to produce the item requiring the highest material handling volume. Conversely, the second scenario considers the opposite situation, where every operator works on the product that involves the least material movement. The third scenario is based on weekly demand analysis, which showed that six products had notably higher demand than the others. In this case, the operators evenly distributed the production of those six items. In the fourth scenario, production was allocated proportionally according to weekly demand. This setup ensures that the required output for each product is met by the end of the week.

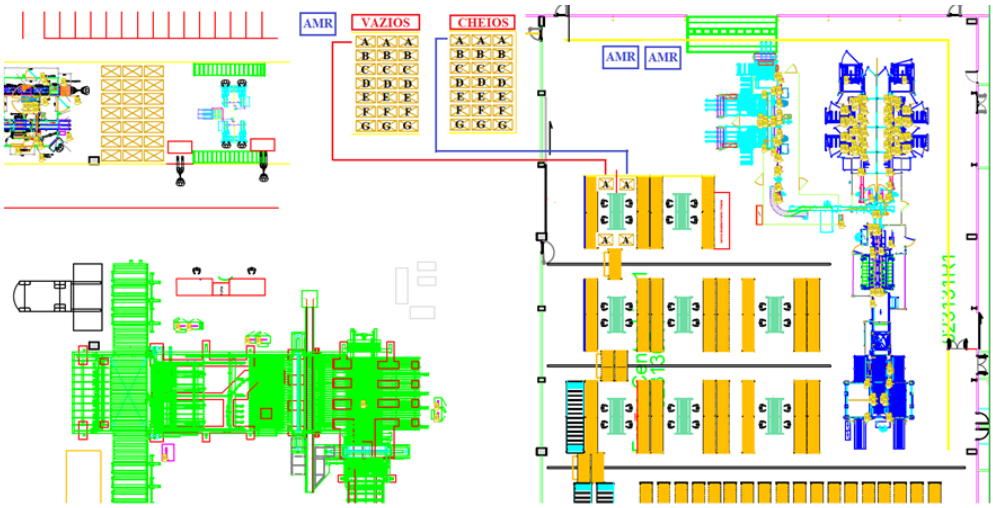


Fig.2. Proposed layout

4.5. Calculation of the number of AMRs required for each scenario

Four different scenarios were evaluated to determine the required number of AMRs. The calculation was based on an AMR speed of 1.8 meters per second and a travel distance of 126 meters per trip. A safety factor 2.58 was applied to account for possible delays or interruptions during operation.

The estimation followed this logic: the number of parts handled per hour was derived from each product's cycle time, and the average travel time was set at 3 minutes, considering speed, distance, and safety factors.

Production per hour = pieces per hour*Nº operators producing the part

$$\text{Travel per hour} = \frac{\text{Production per hour}}{\text{Nº Frames in the Cart}}$$

Travel Time per hour = Travel per hour*Travel time

$$\text{Nº AMR} = \frac{\text{PTravel Time per hour}}{60}$$

To calculate the total transport time required to meet demand, it is possible to determine how many AMRs will be needed. For this calculation, a Python script was created, which can be divided into seven sections:

1. **Importing libraries and initial data:** Load the dataset provided by company XYZ and set key variables, including cart travel time, number of operators, and total weekly production hours.
2. **Define the calculation function:** Create a function calculating how many AMRs are needed for each scenario.
3. **Create a function for best- and worst-case scenarios:** Develop a function to estimate the number of AMRs needed in the most and least demanding situations.

```
import pandas as pd
import os
import numpy as np
from matplotlib import pyplot as plt

directory = r"PCTC - Co-creation Project & Transferable Skills\IKEA Challenge"
file = 'Frame values.xlsx'

os.chdir(directory)

planning_file = pd.read_excel(file, 'Planning')
production_file = pd.read_excel(file, 'Production')

'''
Values used for travel time calculation
AGV speed = 1.8 m/s
Distance traveled by AGV (round trip) = 62.91 m * 2
Safety factor = 2.58
'''

# Travel time (min)
t = 3

# Number of operators
op = 32

# Total weekly production time (h) - Time per shift (8) * Shifts per day (2) * Days per week (5)
tp = 8 * 2 * 5
```

Fig.3. Code Setup

```
def calculo(production_file1):
    '''
    Creates a data frame for each scenario based on the production_file

    Parameters
    ----------
    production_file1 : TYPE
        DESCRIPTION.
    n_op : TYPE
        DESCRIPTION.

    Returns
    -------
    production_file1 : TYPE
        DESCRIPTION.
    '''
    # Add a column with production per hour to find the best and worst case
    production_file1['Production/per hour'] = production_file1['pc/hour'] * production_file1['No. Operators']
    #Add the number of trips per hour
    production_file1['Trips/hour'] = production_file1['Production/per hour'] / production_file1['Frames']
    #Add travel time per hour
    production_file1['Travel time/hour'] = production_file1['Trips/hour'] * t
    #Add the number of carts
    production_file1['Number of carts'] = production_file1['Travel time/hour'] / 60

    return production_file1
```

Fig.4. Function to calculate the number of AMRs

```python
def scenario1():
    """
    Calculate the extreme scenarios: maximum and minimum number of carts.
    """

    # Returns
    # --------
    worst_case : TYPE
          DESCRIPTION.
    best_case  : TYPE
          DESCRIPTION.

    ...

    # All operators manufacture the same part (24)
    production_scenario1 = production_file.copy()
    production_scenario1['Number of operators'] = op
    production_scenario1 = calculate(production_scenario1)

    # Find maximum and minimum 'Travel time (min)'
    id_max = production_scenario1['Travel time (min)'].idxmax()
    id_min = production_scenario1['Travel time (min)'].idxmin()

    # Select the maximum and minimum column 'Travel time (min)'
    production_scenario1_max = pd.DataFrame(production_scenario1.loc[id_max]).transpose()
    production_scenario1_min = pd.DataFrame(production_scenario1.loc[id_min]).transpose()

    return production_scenario1_max, production_scenario1_min
```

Fig.5. Function to create data frames with extreme scenarios

4. **Function for top 6 demand scenario:** Build a function that calculates the number of AMRs required when the six most requested products are produced, with tasks evenly distributed among all operators.
5. **Function for actual demand scenario:** Create a function that estimates the number of AMRs needed based on the real weekly production demand.
6. **Export results and generate chart:** Develop a function to export the scenario results as Data Frames to an Excel file and create a chart showing the number of AMRs required for each scenario.

```python
def scenario2():
    """
    Calculate the scenario with the top 6 items that have the highest demand,
    distributed equally among the operators.
    """
    # Returns
    # --------
    production_scenario2 : TYPE
            DESCRIPTION.

    production_scenario2 = production_file.copy()

    top_6 = planning_file.nlargest(6, 'Weekly Average')
    # Filter the production table to include only the top 6
    production_scenario2 = production_scenario2[production_scenario2['Product'].isin(top_6['Product'])]
    production_scenario2['Number of operators'] = op/6

    # Operators are also equally divided among the 6 products with the highest production need (24 / 6)
    production_scenario2 = calculate(production_scenario2)

    return production_scenario2
```

Fig.6. Function to create dataframe for the "top 6" scenario

```python
def scenario3():
    """
    Calculate the scenario based on the weekly production plan.
    """

    # Returns
    # -------
    production_scenario3 : TYPE
            DESCRIPTION.

    production_scenario3 = pd.merge(production_file, planning_file[['Product', 'Weekly Average']], on='Product', how='left')
    # Remove columns without values in Weekly Average
    production_scenario3 = production_scenario3.dropna(subset=['Weekly Average'])
    # Calculate the production time needed per product and the number of operators required daily to meet the weekly demand
    production_scenario3['Weekly Production Time (h)'] = production_scenario3['Weekly Average'] / production_scenario3['pc/hour']
    production_scenario3['Number of Operators'] = np.ceil(production_scenario3['Weekly Production Time (h)'] / tp)
    production_scenario3 = calculate(production_scenario3)

    return production_scenario3
```

Fig.7. Function to create data frame for the "current demand" scenario

```python
def get_results():
    """
    Save the results in an Excel sheet called "results.xlsx"
    """

    # Returns
    # -------
    None.
    ...

    worst_case, best_case = scenario1()
    top6 = scenario2()
    current_demand = scenario3()

    sum1 = np.ceil(worst_case['N_AMR'].sum())
    sum2 = np.ceil(best_case['N_AMR'].sum())
    sum3 = np.ceil(top6['N_AMR'].sum())
    sum4 = np.ceil(current_demand['N_AMR'].sum())

    # Create DataFrame with totals
    data = {
        'worst_case': [sum1],
        'best_case': [sum2],
        'top6': [sum3],
        'current_demand': [sum4]
    }
    totals = pd.DataFrame(data)

    # Bar chart with totals for data visualization
    totals.plot(kind='bar')
    plt.title('Totals')
    plt.ylabel('N_AMR')
    plt.show()

    # Export results to Excel
    with pd.ExcelWriter('results.xlsx') as writer:
        worst_case.to_excel(writer, sheet_name='MaxProd', index=False)
        best_case.to_excel(writer, sheet_name='MinProd', index=False)
        top6.to_excel(writer, sheet_name='Top6', index=False)
        current_demand.to_excel(writer, sheet_name='Current Demand', index=False)
        totals.to_excel(writer, sheet_name='Totals', index=False)
```

Fig.8. Results export function

7. **Execute the code:** Run the functions to calculate and generate the results.

```
179  get_results()
```

Fig.9. Line of code to execute the functions

8. **Review the results:** Examine the output to evaluate the number of AMRs required in each scenario and assess system performance.

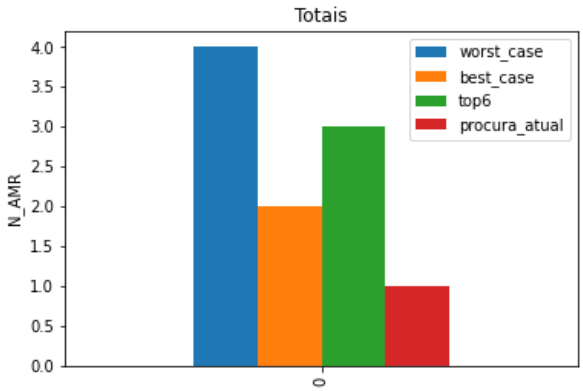


Fig.10. Graph created with scenario results

Figure 11 presents the exported results of the different calculated scenarios, such as "Worst_prod", "Best_prod", "Top6", and "Procura_atual". Based on the data analysis, it was observed that when all workstations are active, between 2 and 4 AMRs are needed, depending on the type of product being produced. However, a single AMR is enough to handle the required production volume under typical weekly demand where not all stations are used.

5. Results and Discussion

This chapter presents the development of the proposed solution using SIMIO simulation software. The goal was to build a model representing the transport of materials used to assemble frames, from the intermediate stock area to the assembly stations and then to a dispatch point for the next stage. The movement of carts between these areas is handled by Autonomous Mobile Robots (AMRs). Simulating the shop floor in this way provides a comprehensive view of how AMRs can sufficiently support and supply the different assembly workstations.

5.1. Creation of a production model in SIMIO

A production setup was created to support the model's logic, including the different frame types under analysis. A simulated production plan was also developed to test and validate the proposed solution.

Worst_prod:

Product	Frames	pc/min	pc/hora	Nº Operadores	Produção/hora	Viagens/hora	Tempo viagem/hora	N_AMR
S023MKFRSD05S	120	4,18	250,8	32	8025,6	66,88	200,64	3,344

Best_prod:

Product	Frames	pc/min	pc/hora	Nº Operadores	Produção/hora	Viagens/hora	Tempo viagem/hora	N_AMR
S023KXFRTB03	200	2.15	129	32	4128	20.64	61.92	1.032

Top 6:

Product	Frames	pc/min	pc/hora	Nº Operadores	Produção/hora	Viagens/hora	Tempo viagem/hora	N_AMR
S023KXFRTB01	160	3,43	205,8	5,333333333	1097,6	6,86	20,58	0,343
S023KXFRSD04	200	3,6	216	5,333333333	1152	5,76	17,28	0,288
S023KXFRSD01	100	2,09	125,4	5,333333333	668,8	6,688	20,064	0,334
S023MKFRTP03S	160	2,55	153	5,333333333	816	5,1	15,3	0,255
S023MKFRSD06S	120	4,06	243,6	5,333333333	1299,2	10,82666667	32,48	0,541
S023MKFRSD05S	120	4,18	250,8	5,333333333	1337,6	11,14666667	33,44	0,557

Current demand:

Product	Frames	pc/min	pc/hora	Weekly Average	Tempo Produção Semanal	Nº Operadores	Produção/hora	Viagens/hora	Tempo viagem/hora	N_AMR
S023KXFRTB01	160	3,43	205,8	15922	77,36637512	1	205,8	1,28625	3,85875	0,064
S023KXFRSD04	200	3,6	216	16148	74,75925926	1	216	1,08	3,24	0,054
S023KXFRSD01	100	2,09	125,4	16136	128,676236	2	250,8	2,508	7,524	0,125
S023MKFRTP03S	160	2,55	153	12799	83,65359477	2	306	1,9125	5,7375	0,096
S023MKFRTP02	150	2,83	169,8	3556	20,94228504	1	169,8	1,132	3,396	0,057
S023MKFRSD06S	120	4,06	243,6	12799	52,5410509	1	243,6	2,03	6,09	0,102
S023MKFRSD05S	120	4,18	250,8	12799	51,03269537	1	250,8	2,09	6,27	0,105
S023MKFRSD03	150	3,08	184,8	5126	27,73809524	1	184,8	1,232	3,696	0,062
S023MKFRBT0102	150	2,89	173,4	6400	36,9088812	1	173,4	1,156	3,468	0,058
S023MKFRTP05S	240	2,83	169,8	3140	18,49234393	1	169,8	0,7075	2,1225	0,035
S023LGFRTP04S	120	2,17	130,2	2037	15,64516129	1	130,2	1,085	3,255	0,054
S023LGFRTP03S	200	2,67	160,2	2338	14,59425718	1	160,2	0,801	2,403	0,040
S023LGFRTP02S	200	2,83	169,8	6456	38,02120141	1	169,8	0,849	2,547	0,042
S023LMFRTP11S	200	3,33	199,8	4017	20,10510511	1	199,8	0,999	2,997	0,050

Fig.11. Exported results

5.1.1. Demand calculation

The objective is to calculate the number of working hours per day required to meet the demand.

Tab.1. Calculation of hourly demand to meet weekly demand

Labels	SIMIO nomenclature (NS)	Weekly demand (units)	Hourly demand (units)	Rounded hourly demand (units)
SD01	A	16,136	3,227.20	202
SD04	B	16,148	3,229.60	202
TB01	C	15,922	3,184.40	200
TP02S	D	6,456	1,291.20	81
TP03S	E	2,338	467.60	30
TP04S	F	2,037	407.40	26
TP11S	G	4,017	803.40	51
T0102	H	6,400	1,280.00	80
SD03	I	5,126	1,025.20	65
SD05S	J	12,799	2,559.80	160
SD06S	K	12,799	2,599.80	160
TP02	L	3,556	711.20	15
TP03S	M	12,799	2,599.80	160
TP05S	N	3,140	628.00	40

5.1.2. Calculation of the capacity needed to meet the demand

This step shows that using 16 assembly stations is sufficient to meet the daily production targets, assuming that tasks requiring two workers are counted as two stations. Looking at the final column of the table, which indicates the number of working hours needed per frame type, most can be completed within a single shift. Although the model has not been optimized, doing so is not necessary at this stage. A more accurate production plan would be required in future evaluations. However, to show how simulation can support automated cart transport, the model assumes that all 16 stations are active throughout a 16-hour workday (Figure 12).

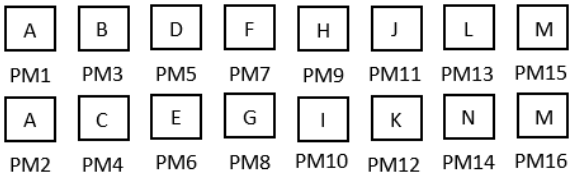


Fig.12. Allocation of frame types to the various workstations

5.1.3. Calculation of processing time

The processing time for a cart was determined using the number of pieces produced per hour per worker. The model was developed using software based on the analysis of the current situation and the previously presented data.

Tab.2. Calculation of the capacity required to meet the demand

NS	No. of operators per piece	Number of pieces produced/hour/worker	Load per cart	Demand /hour	Carts/ hour	Capacity /hour	Hours for demand
A	2	125	100	202	3	250	12h 55 min
B	1	216	200	202	2	216	14h 57 min
C	1	206	200	200	1	206	15h 28 min
D	1	170	200	81	1	170	7h 36 min
E	1	160	200	30	1	160	2h 56 min
F	1	130	200	26	1	130	3h 9 min
G	1	200	200	51	1	200	4h 2 min
H	1	173	200	80	1	173	7h 24 min
I	1	185	200	65	1	185	5h 33 min
J	1	251	200	160	1	251	10h 12 min
K	1	244	200	160	1	244	10h 30 min
L	1	170	200	15	1	170	4h 12 min
M	2	153	200	160	1	306	8h 23 min
N	1	170	200	40	1	170	3h 42 min

Tab.3. Processing time calculation

NS	Frame Type (Expression property in Model Entity)	Number of pieces produced/hour/worker	Frame assembly time (min)	Cart processing time (min)
A	1	125	2.08	48.00
B	2	216	3.60	55.56
C	3	206	3.43	58.25
D	4	170	2.83	70.59
E	5	160	2.67	75.00
F	6	130	2.17	92.31
G	7	200	3.33	60.00
H	8	173	2.88	69.36
I	9	185	3.08	64.86
J	10	251	4.18	47.81
K	11	244	4.07	49.18
L	12	170	2.83	70.59
M	13	153	2.55	78.43
N	14	170	2.83	70.59

5.2. Development of a model in software

5.2.1. Frame and cart entities

It was necessary to define entities representing the materials used to build each frame type listed in Table 3. These materials, labeled from A to N, were created as Model Entities, each with specific properties. Figure 13 shows these entities along with some of their characteristics within the system. A property called "Tipo Frame" assigns a numerical value from 1 to 14 to each entity, helping link each frame type to its corresponding assembly area and supporting the logical structure of the simulation model.

Creating an entity representing the cart was necessary to pair this material by type with carts, as occurs in the physical system (Figure 14).

5.2.2. Cart supply area

Two sources were created to generate the necessary entities in the simulation: incoming materials and carts. As shown in Figure 15, each frame type has its dedicated material source.

The material creation areas labeled "Frame A(...N)" were configured with the following parameters:

- **Entity type:** Each source is linked to the entity defined in Figure 13, corresponding to the specific material type.
- **Arrival mode and trigger:** Entity creation is triggered by the event "Output@Carrinhos_VaziosA(...N). Exited", indicating that a cart has exited its source. This event prompts the creation of the required material entities.
- **Entities per arrival:** Defines how many entities are generated each time the trigger occurs.

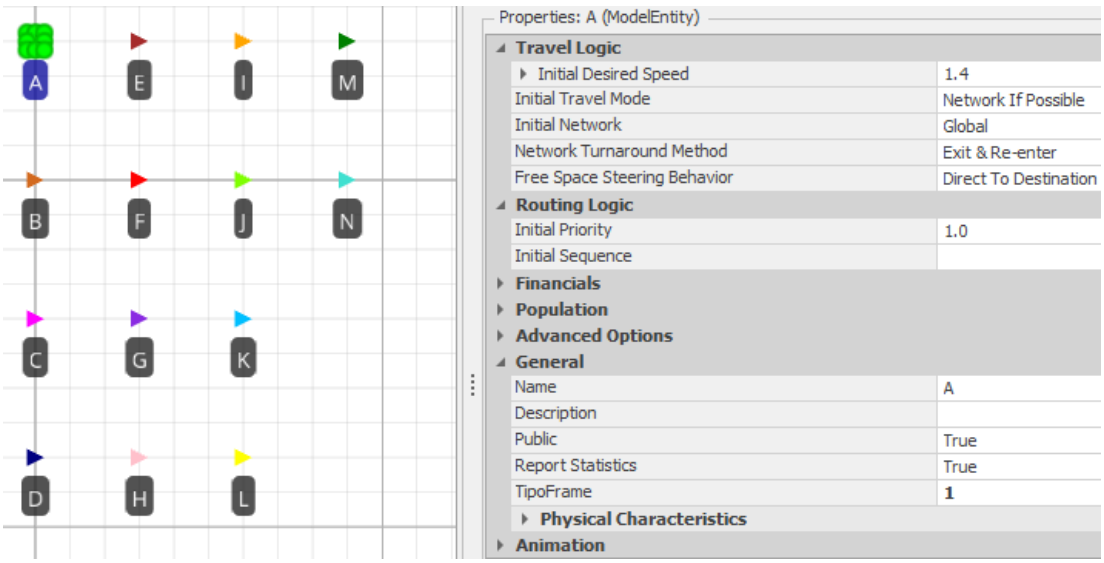


Fig.13. Entities represent the material for the 14 types of frames

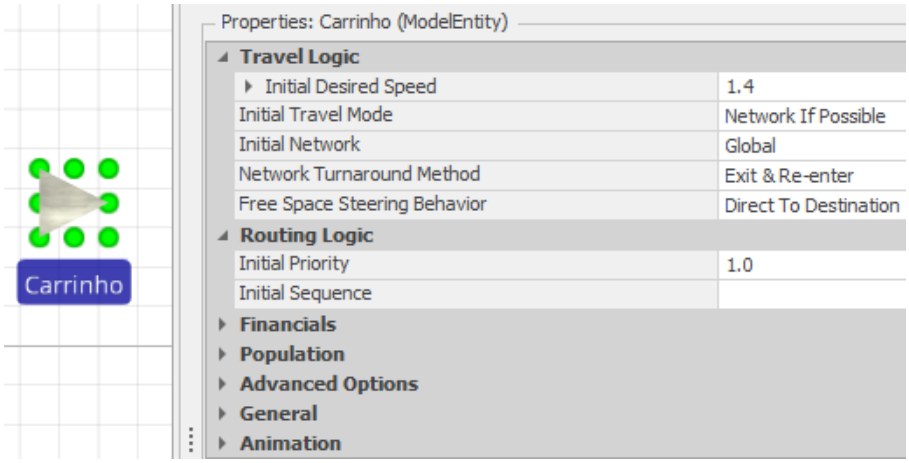


Fig.14. Entity representing the cart being transported with the respective material

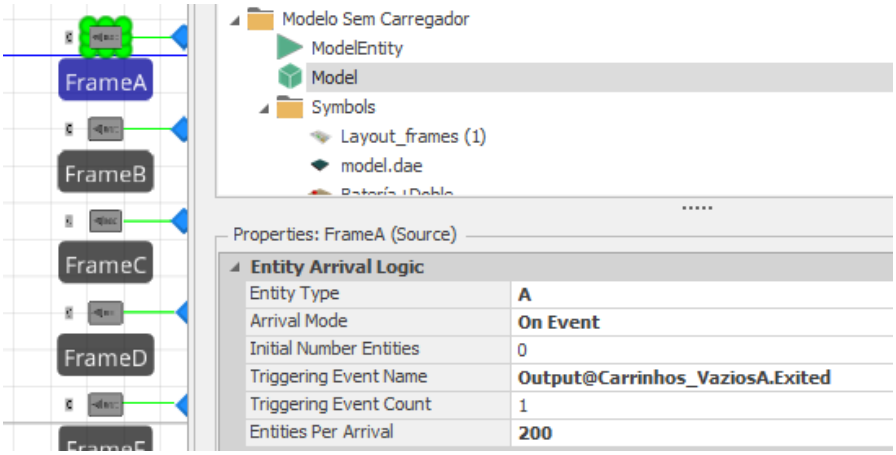


Fig.15. Material sources correspond to the various frame types

To generate empty carts for material supply, sources named "Carrinho_VazioA(…N)" were created, as shown in Figure 16. These sources were configured with the following settings:

- **Entity type:** All sources use the same cart entity defined in Figure 14, regardless of frame type.
- **Arrival mode and trigger:** Cart creation is triggered by the event "CriarCarrinhoA(…N)", which acts as a notifier sent by one component and received by others. This event is initiated by specific processes described later.
- **Number of entities:** This includes the initial number of carts and those generated during operation. For frames that require two operators (see Table 2), two carts must always be available to serve both workstations.

The event "CriarCarrinhoA(…N)" was designed to respond when no carts are available in the supply area named "Abastecimento_CarrinhoA(…N)". A table was set up to check the number of carts in that area and trigger the event that creates new carts when needed (see Figure 17).

The cart creation process is triggered when a cart filled with material exits the supply area, as shown later in the model. This process involves the following steps (Figure 18):

- **Token direction:** A Set Row block selects the relevant row from the "Criar Caixotes" table, followed by an Execute step that runs the "CriarCarrinho_Processo" process.
- **Cart creation:** A Decide block checks the condition specified in the first column of Figure 17. If the condition is met, the event defined in the second column is activated.

Once the model entities are created, they must be grouped to simulate the cart supply process. For this purpose, combiners with two inputs, "Parent Input" and "Member Input", were added. These combiners, named "Abastecimento_CarrinhoA(…N)", link the material entities to their respective carts. As shown in Figure 19, the cart supply areas are connected to the material creation points. Each combiner and a previously defined process are configured with the number of entities required per batch.

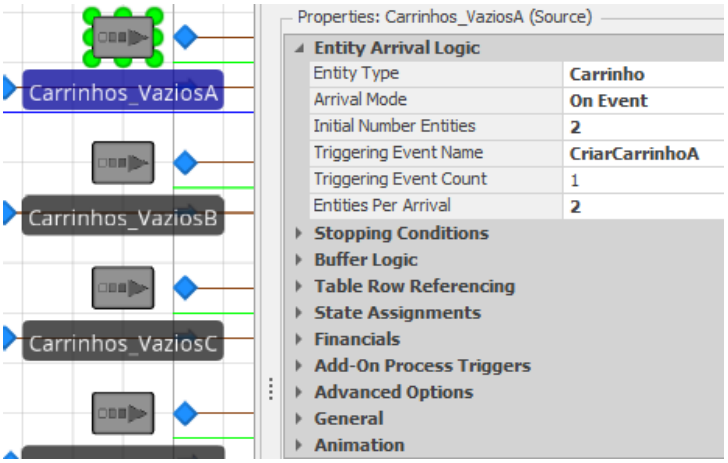


Fig.16. Sources of empty carts for supply

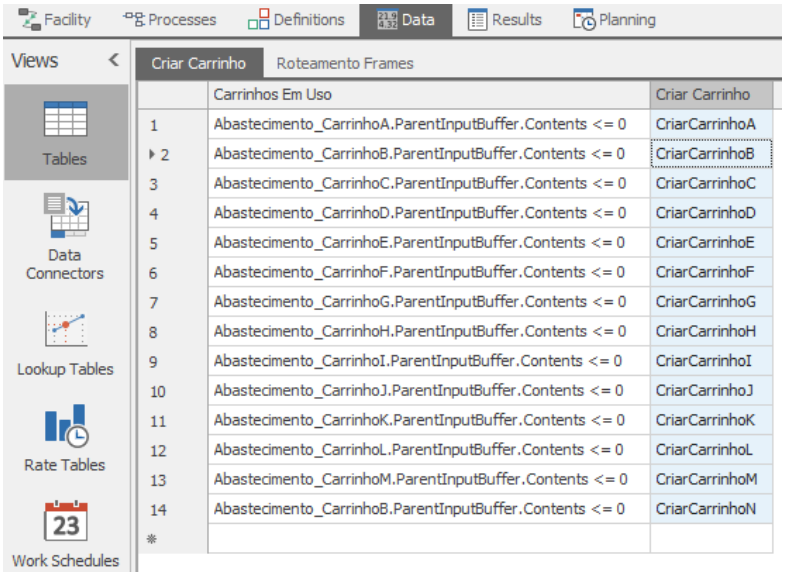


Fig.17. Cart creation table

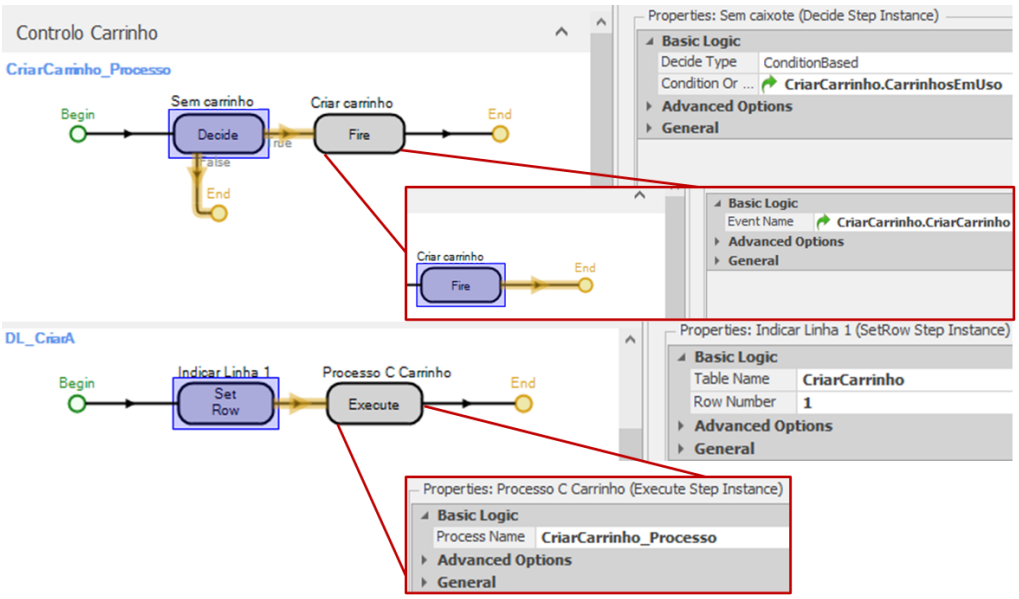


Fig.18. Cart creation processes at the exit of the supply area

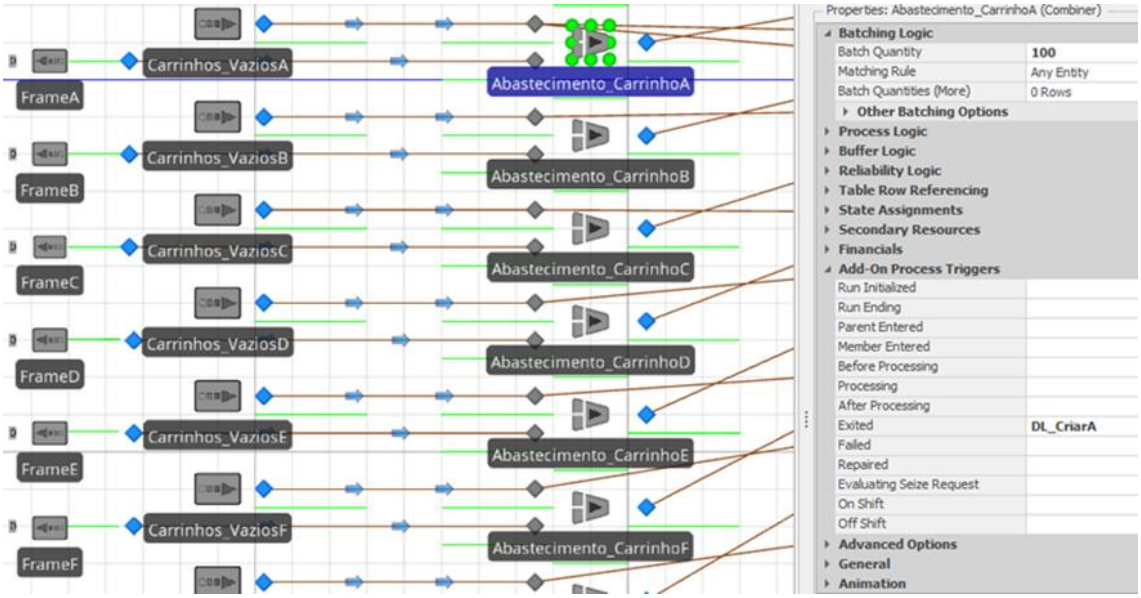


Fig.19. Cart supply areas

The movement of loaded carts to the stock area, each containing identified materials, is handled by an operator, as shown in the model (Figure 20). The type of transport used is defined at the exit point of each supply area.

5.2.3. Stock area for loaded carts

After being filled, the carts are directed to their assigned stock locations. As illustrated in Figure 21, these areas are organized according to the frame type based on the cart's materials.

The server settings indicate that each exit area is ideally limited to storing a maximum of three carts. When carts leave the stock area, the "Roteamento_ Entidades" process is triggered to direct them to the correct destination according to the production plan shown in Figure 12. A dedicated table (Figure 22) was created to manage this routing, linking each entity to its target node and corresponding frame type.

The routing table is used throughout the process shown in Figure 23, which follows these main steps:

- **Search:** The system looks through the "Roteamento_ Frames" table to find a match between the frame type at the stock area exit and the one listed in the table, using the condition ModelEntity. TipoFrame == RoteamentoFrames. Tipo_Frame. A variable called "Current Index" stores the matched row position.
- **Assign:** The index value is updated accordingly once a match is found.
- **Transfer:** The entity is then moved from its current location to the target station defined in the first column of Figure 22.

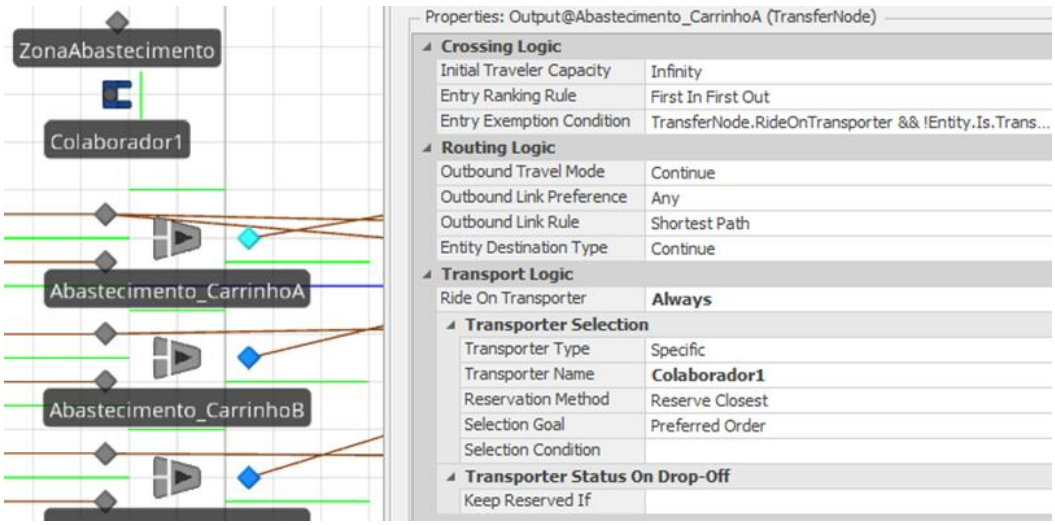


Fig.20. Transport between the supply area and the stock area

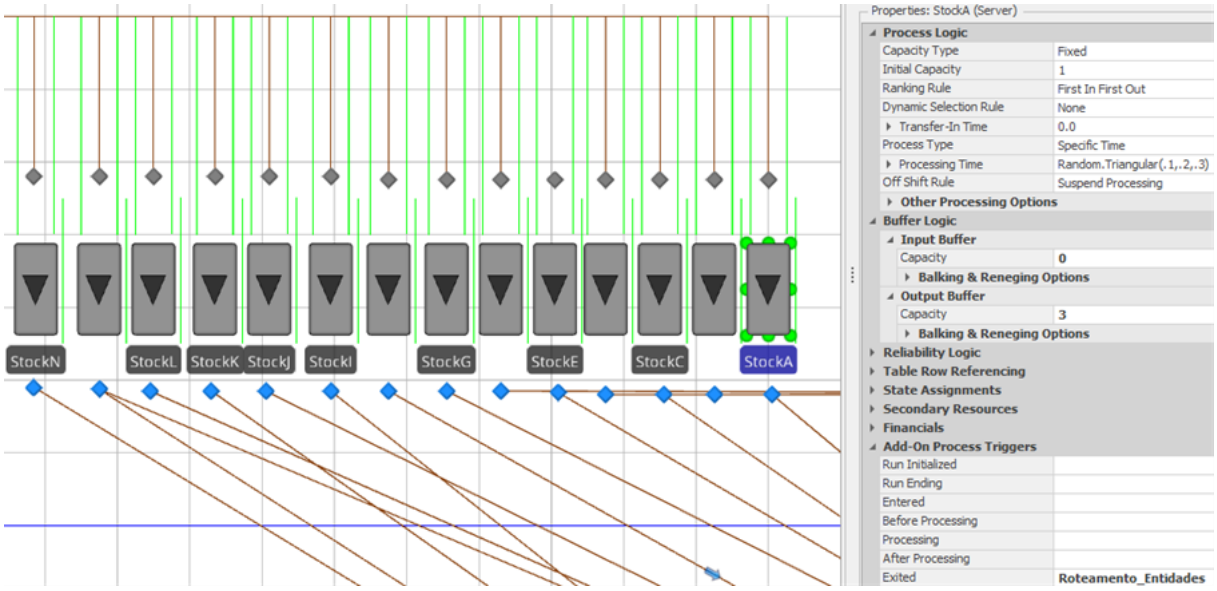
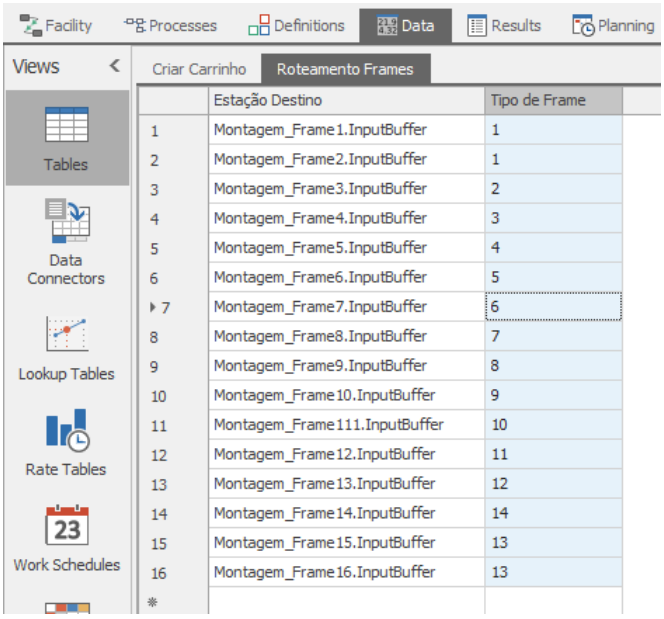


Fig.21. Stock area for loaded carts



	Estação Destino	Tipo de Frame
1	Montagem_Frame1.InputBuffer	1
2	Montagem_Frame2.InputBuffer	1
3	Montagem_Frame3.InputBuffer	2
4	Montagem_Frame4.InputBuffer	3
5	Montagem_Frame5.InputBuffer	4
6	Montagem_Frame6.InputBuffer	5
7	Montagem_Frame7.InputBuffer	6
8	Montagem_Frame8.InputBuffer	7
9	Montagem_Frame9.InputBuffer	8
10	Montagem_Frame10.InputBuffer	9
11	Montagem_Frame111.InputBuffer	10
12	Montagem_Frame12.InputBuffer	11
13	Montagem_Frame13.InputBuffer	12
14	Montagem_Frame14.InputBuffer	14
15	Montagem_Frame15.InputBuffer	13
16	Montagem_Frame16.InputBuffer	13

Fig.22. Routing table between carts and frame assembly areas

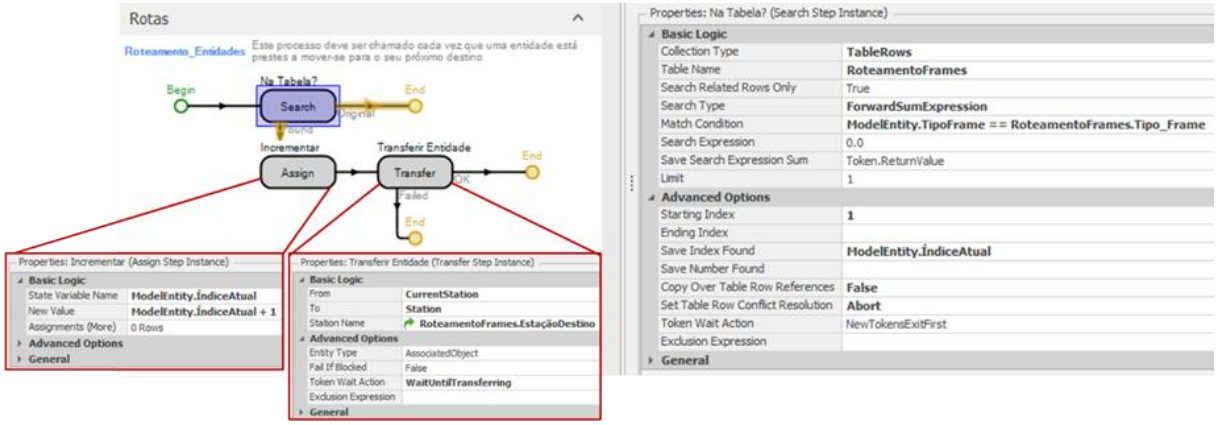


Fig.23. Entity routing process in the stock area

At the exit point of each stock area, a specific process is applied but only in zones with dual supply, as indicated in Table 2. This process checks whether the corresponding even-numbered assembly station is occupied (see Figure 24).

5.2.4. Frame assembly area

This section of the model includes several work-stations labeled "Montagem_Frame1(...32)" and a sink object named "Frames Montados" (Figure 25), which removes completed entities after processing. These stations function as separators and include the following components:

- **Input node:** Receives loaded carts from the stock area.
- **Parent output:** Returns empty carts to the designated area for reuse, with transportation handled by a vehicle.
- **Member output:** Sends the assembled frames forward; a worker manages this step manually.

The model's general properties include custom fields that store each assembly station's processing time. These times were calculated based on the values shown in the last column of Table 3.

Figure 26 presents the complete layout of the final model within the Facility tab.

5.3. Extraction of results and analysis in power BI

After simulating the model for over 24 hours, an Excel file was generated and imported into Power BI. This file includes detailed information about different system components, organized by data source, type, and statistics.

The main goal of this analysis was to validate the simulation and confirm that a single AMR can handle material supply under a standard production plan. Results showed that the AMR operates at 98% capacity, closely aligning with the estimates made in Chapter 4.3. The exported data also supports deeper analysis by creating dashboards, offering insights such as the total distance traveled by the AMR and the waiting times experienced by operators when replacing empty carts.

5.3.1. Consideration of AMR technical constraints

Although the simulation model was designed to represent the operational flow accurately, it does not yet account for the full range of technical constraints associated with current AMR technology. Limitations such as battery autonomy, limited payload capacity, and reduced navigation precision in high-traffic or unstructured environments were only considered through general safety factors. These factors may affect AMR performance in real applications and are essential for real-world deployment. Future work will incorporate these technical variables into the simulation logic and propose adaptive control mechanisms to mitigate their impact.

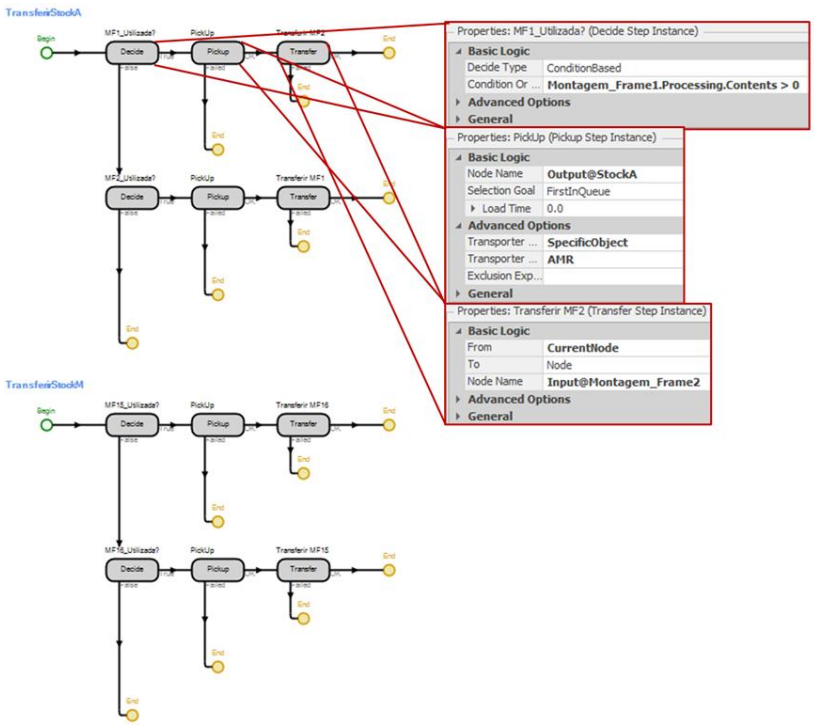


Fig.24. Entity transfers processes in dual stations

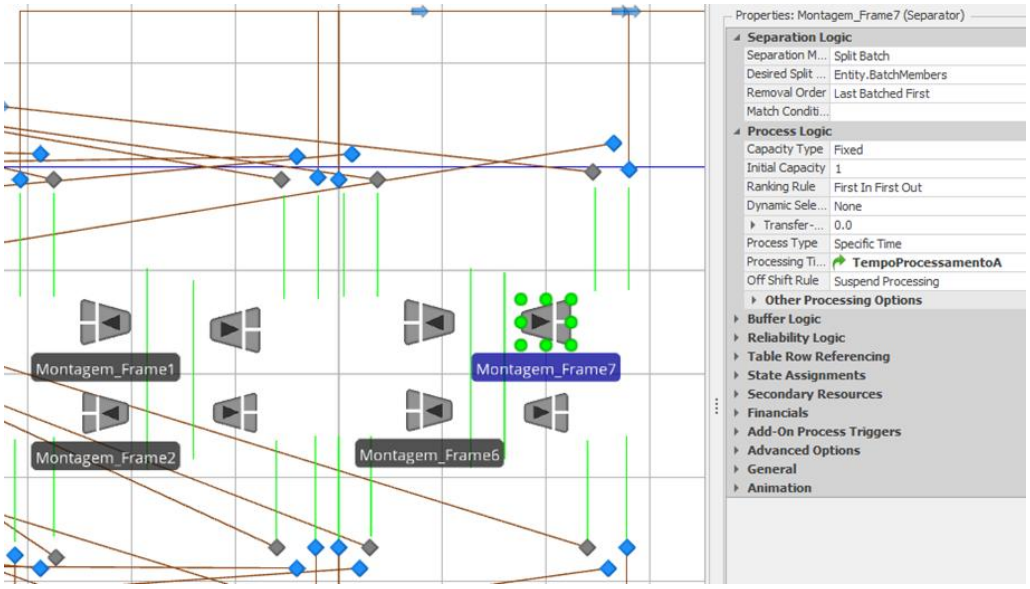


Fig.25. Frame assembly area

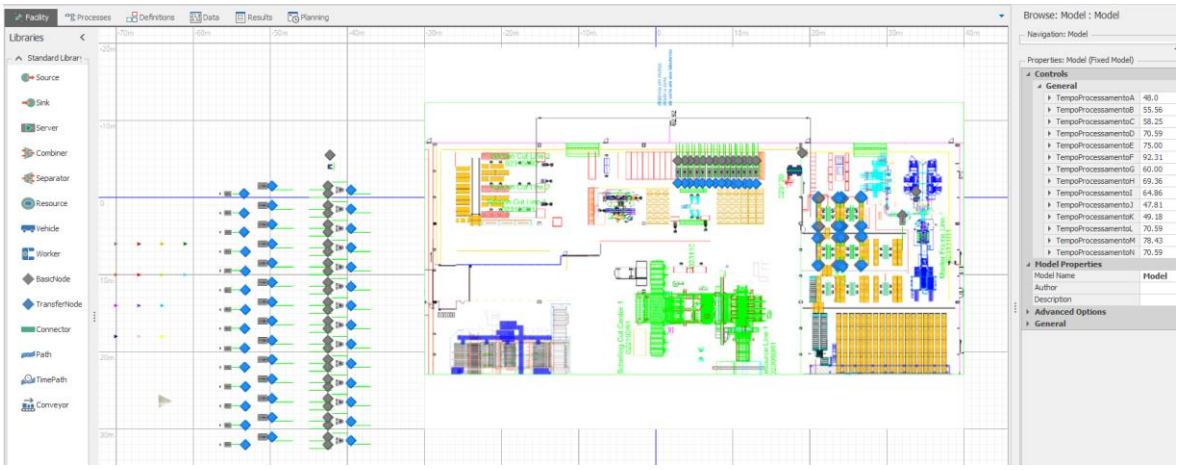


Fig.26. Final model

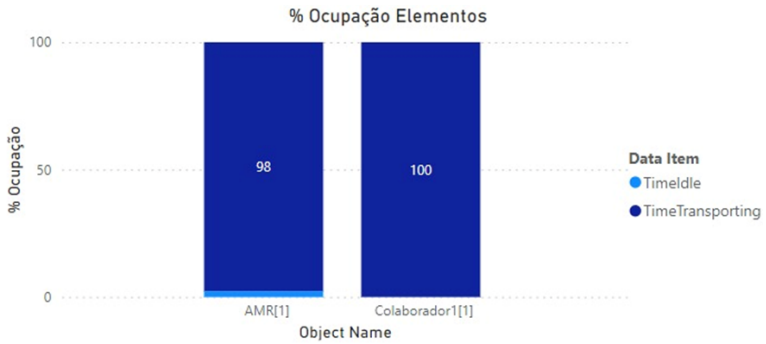


Fig.27. Simulation model validation through result extraction

6. Conclusion

This research aimed to identify an effective alternative to the current material transport system within the XYZ factory to enhance internal logistics performance. The proposed solution focused on integrating Autonomous Mobile Robots (AMRs), redesigning storage areas, and implementing automated conveyor belts to streamline workflows and reduce manual interventions.

A mathematical model was developed to support the implementation strategy to estimate the number

of AMRs required under different production conditions, including standard operations and peak demand scenarios. Simulation results indicated that between one and four AMRs would be sufficient depending on production intensity. These results were validated using the SIMIO simulation platform, confirming the model's operational feasibility and consistency.

Integrating AMRs into assembly line supply demonstrated significant advantages in flexibility, responsiveness to variability in production, and overall efficiency. These outcomes align with Industry 4.0 goals, providing a foundation for more autonomous and intelligent manufacturing systems. However, it is important to recognize certain limitations of the study. The simulation model simplifies various aspects of real-world factory dynamics. Specific technical constraints of current AMRs, such as limited payload capacity, reduced navigation precision in dynamic or congested environments, and limited battery autonomy, were not explicitly modeled. These factors may influence real-world feasibility and system performance, and they are recognized as critical challenges that require further investigation. Future research will address these issues through enhanced simulation scenarios and pilot implementations under actual operating conditions.

Additionally, although the study identifies AMR acquisition cost as a potential barrier, it does not include a detailed economic feasibility analysis across different factory sizes. This decision stems from the vast diversity of AMR models and factory configurations, which makes it impractical to establish a generalized cost-benefit framework within the current scope. Nevertheless, we acknowledge the relevance of this topic and recommend that future studies explore modular economic evaluation tools tailored to specific industrial profiles.

As a next step, pilot testing within the XYZ factory's real environment is proposed to validate performance under constraints, including charging logistics, robot coordination, traffic flow, and workload balancing. Furthermore, refinements to the simulation model will incorporate these real-world variables, contributing to a more robust and realistic decision-support tool with broader industrial applicability.

Another important consideration for future implementation is the system's resilience to unexpected real-world conditions, such as network outages, uneven floor surfaces, or unforeseen human activity in the operational area. Although these scenarios were not included in the initial simulation scope, they represent relevant risk factors. Future developments will explore fault-tolerant communication protocols, terrain-adaptive navigation systems, and human-robot interaction safety mechanisms. These enhancements will be validated through on-site pilot testing to assess the system's robustness under dynamic and uncertain environments.

References

[1]. H. Kagermann, W. D. Lukas and W. Wahlster, "Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution", VDI nachrichten, Vol. 13, No. 1, (2011), pp. 2-3.

[2]. K. Mahmood, K. Karjust and T. Raamets, "Production intralogistics automation based on 3D simulation analysis", Journal of Machine Engineering, Vol. 21, (2021).

[3]. M. Zoubek and M. Simon, "Evaluation of the level and readiness of internal logistics for industry 4.0 in industrial companies", Applied Sciences, Vol. 11, No. 13, (2021), pp. 6130.

[4]. T. Redaktion, "Intralogistik Definition" Logistik KNOWHOW, (2013).

[5]. H. Winkler and L. Zinsmeister, "Trends in digitalization of intralogistics and the critical success factors of its implementation", Brazilian Journal of Operations & Production Management, Vol. 16, No. 3, (2019), pp. 537-549.

[6]. T. Kirks, J. Jost, T. Uhlott and M. Jakobs, "Towards complex adaptive control systems for human-robot-interaction in intralogistics", IEEE. In 2018 21st International Conference on Intelligent Transportation Systems (ITSC), (2018), pp. 2968-2973.

[7]. M. H. Ashraf, Y. Chen and M. G. Yalcin, "Minding Braess Paradox amid third-party logistics hub capacity expansion triggered by demand surge", International Journal of Production Economics, Vol. 248, (2022), pp. 108454.

[8]. T. Muller, "Automated guided vehicles", (1983).

[9]. G. Fragapane, R. De Koster, F. Sgarbossa and J. O. Strandhagen, "Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda", European Journal of Operational

Research, Vol. 294, No. 2, (2021), pp. 405-426.
[10]. G. Klančar and M. Seder, "Coordinated multi-robotic vehicles navigation and control in shop floor automation", Sensors, Vol. 22, No. 4, (2022), pp. 1455.
[11]. P. J. Mattaboni, "Autonomous mobile robot", No. US 4638445, (1987).
[12]. D. Bechtsis, N. Tsolakis, D. Vlachos and E. Iakovou, "Sustainable supply chain management in the digitalisation era: The impact of Automated Guided Vehicles", Journal of Cleaner Production, Vol. 142, (2017), pp. 3970-3984.
[13]. G. Fragapane, D. Ivanov, M. Peron, F. Sgarbossa and J. O. Strandhagen, "Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics", Annals of Operations Research, Vol. 308, No. 1, (2022), pp. 125-143.
[14]. C. Hernández, J. Bermejo-Alonso and R. Sanz, "A self-adaptation framework based on functional knowledge for augmented autonomy in robots", Integrated Computer-Aided Engineering, Vol. 25, No. 2, (2018), pp. 157-172.
[15]. M. Indri, L. Lachello, I. Lazzero, F. Sibona and S. Trapani, "Smart sensors applications for a new paradigm of a production line", Sensors, Vol. 19, No. 3, (2019), pp. 650.
[16]. M. Scholz, S. Kreitlein, C. Lehmann, J. Böhner, J. Franke and R. Steinhilper, "Integrating intralogistics into resource efficiency oriented learning factories", Procedia CIRP, Vol. 54, (2016), pp. 239-244.
[17]. T. Le-Anh and M. B. M. De Koster, "A review of design and control of automated guided vehicle systems", European journal of Operational Research, Vol. 171, No. 1, (2006), pp. 1-23.
[18]. S. Angerer, C. Strassmair, M. Staehr, M. Roettenbacher and N. M. Robertson, "Give me a hand. The potential of mobile assistive robots in automotive logistics and assembly applications", In 2012 IEEE international conference on technologies for practical robot applications (TePRA), (2012), pp. 111-116.
[19]. N. Zrnić, T. Popović, G. Milojević, N. Kosanić, "A Survey of Research on Industry 4.0 in Intralogistics", In Proceedings of X International Conference Heavy Machinery-HM 2021, (2021), pp. B-1.
[20]. J. Fottner, D. Clauer, F. Hormes, M. Freitag, T. Beinke, L. Overmeyer and F. Thomas, "Autonomous systems in intralogistics–state of the art and future research challenges", Journal Logistics Research, (2021).
[21]. F. Sgarbossa, M. Peron and G. Fragapane, "Cloud material handling systems: Conceptual model and cloud-based scheduling of handling activities", Scheduling in Industry 4.0 and Cloud Manufacturing, (2020), pp. 87-101.
[22]. I. Reithner, M., Papa, M. Aburaia, W., Wöber, C., & Ambros, "Analysis of the interaction between safety and security demonstrated on a mobile robot and a production network", Annals of DAAAM & Proceedings, (2021).
[23]. C. C. Dosoftei, A. T. Popovici, P. R. Sacaleanu, P. M. Gherghel, C. Budaciu, "Hardware in the loop topology for an omnidirectional mobile robot using matlab in a robot operating system environment", Symmetry, Vol. 13, No. 6, (2021), pp. 969.
[24]. A. Dolgui, F. Sgarbossa, M. Simonetto, "Design and management of assembly systems 4.0: systematic literature review and research agenda", International Journal of Production Research, Vol. 60, No. 1, (2022), pp. 184-210.
[25]. H. Yang and X. Teng, "Mobile robot path planning based on enhanced dynamic window approach and improved a algorithm", Journal of Robotics, (2022).
[26]. Z. Ghelichi, S. Kilaru, "Analytical models for collaborative autonomous mobile robot solutions in fulfillment centers", Applied Mathematical Modelling, Vol. 91, (2021), pp. 438-457.
[27]. G. Fragapane, H. H. Hvolby, F. Sgarbossa and J. O. Strandhagen, "Autonomous mobile robots in sterile instrument logistics: an evaluation of the material handling system for a strategic fit framework", Production Planning & Control, Vol. 34, No. 1, (2023), pp. 53-67.
[28]. K. Furmans and K. R. Gue, "A framework for modeling material handling with decentralized control", (2018).
[29]. M. Cecchi, M. Paiano, A. Mannucci, A. Palleschi, F. Pecora, L. Pallottino, "Priority-based distributed coordination for heterogeneous multi-robot systems with realistic assumptions", IEEE Robotics and Automation Letters,

Vol. 6, No. 3, (2021), pp. 6131-6138.

[30]. V. Naumov, D. Kubek, P. Więcek, I. Skalna, J. Duda, R. Goncerz, T. Derlecki, "Optimizing Energy Consumption in Internal Transportation Using Dynamic Transportation Vehicles Assignment Model: Case Study in Printing Company", Energies, Vol. 14, No. 15, (2021), pp. 4557.

[31]. A. Bonci, P. D. Cen Cheng, M. Indri, G. Nabissi and F. Sibona, "Human-robot perception in industrial environments: A survey", Sensors, Vol. 21, No. 5, (2021), pp. 1571.

[32]. L. Martin, M. González-Romo, M. H. Sahnoun, B. Bettayeb, N. He, J. Gao, "Effect of human-robot interaction on the fleet size of AIV transporters in FMS", IEEM-In 2021 1st International Conference on Cyber Management and Engineering (CyMaEn), (2021), pp. 1-5.

[33]. A. M. Law, "How to build valid and credible simulation models", IEEE-In 2022 Winter Simulation Conference (WSC), (2022), pp. 1283-1295.

Follow this article at the following site:

André Guimarães, Ana Carolina, João Pedro Teixeira, Filipe Gomes, Samuel Martins. "Simulation and Implementation of Autonomous Mobile Robots in Intralogistics" IJIEPR 2026; 37 (3): 88-107
URL: http://ijiepr.iust.ac.ir/article-1-2245-en.html