

# Implementation of Autonomous Mobile Robots in Intralogistics: Simulations in a Case Study

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## Keywords:

Intralogistics, Industry 4.0, Automation, Simulation, Autonomous Mobile Robot, Automated Guided Vehicle

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## ABSTRACT

Autonomous Mobile Robots (AMRs) are increasingly being integrated into intralogistics operations, playing a pivotal role in material handling within the Industry 4.0 framework. In this context, a central unit oversees programming and planning decisions, while AMRs independently communicate and negotiate with other resources, such as machines and systems, decentralizing decision-making processes. These advancements have significantly impacted traditional methods and decision-making processes for planning and control. This study analyzes the use of simulation to evaluate AMRs in supplying XYZ factory assembly lines, with a view toward future implementation on the factory floor. Beyond comparisons, the study aims to assess AMR performance to determine their feasibility and provide analytical validation. Various simulation models were developed using SIMIO software to achieve these goals, followed by iterative adaptations and testing through simulation. The findings provide valuable insights into the role of AMRs in Industry 4.0-based production networks. They offer production managers practical guidance for determining optimal configurations and evaluating the performance impacts of AMR-based production networks compared to traditional assembly lines.

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## 1. INTRODUCTION

### 1.1 Context and Relevance

The concept of Industry 4.0 (I4.0) emerged in 2011 during the Hannover Technology Fair in Germany, marking the beginning of a new industrial era where companies adopted a more advanced approach to integrating technologies into their operations [1], [2]. This industrial revolution emphasizes the connection between the virtual and physical worlds, focusing on automation, digitalization, and robotics [3].

On the other hand, the term “intralogistics”, also known as internal logistics, was first introduced in 2004 by VDMA, a German association of the mechanical engineering industry [4], describing the organization and optimization of internal material flows [5].

Recently, there has been a growing application of Industry 4.0 technologies in intralogistics. Intelligent intralogistics systems consist of interconnected active agents capable of decentralizing information coordination, making real-time decisions, and performing tasks with minimal or no human supervision [6].

Traditionally, intralogistics operations have relied on technologies such as manual carts, tow trucks, mechanical conveyors, forklifts, and others to optimize material flow within manufacturing facilities. However, many workers need to handle materials and equipment physically [7].

Recent industry trends, including Industry 4.0 and Smart Manufacturing, have sparked researchers' interest in intelligent intralogistics within factories. Automated Guided Vehicles (AGVs), particularly mobile robots, play a crucial role in this development [2]. Research focuses on making intralogistics more efficient, safe, and profitable. Intelligent intralogistics systems integrate autonomous and IoT-based technologies, such as Autonomous Mobile Robots (AMRs), 3D transport systems, indoor drones, self-organizing transport systems, collaborative robots, smart container systems, grid sorters, real-time simulations, and wearable smart exoskeletons [5].

Over the past decades, material handling technology has evolved rapidly, with significant advancements in AGVs and AMRs. AGVs have evolved since 1955 [8] with mechanical, optical, inductive, inertial, and laser guidance improvements. AMRs offer even greater navigation flexibility, moving freely within accessible and collision-free areas [9]. Mobile robots, such as AGVs and AMRs, have been widely used in intralogistics, with market growth projections of around 30% over the next five years. Since the introduction of the first AGV, these devices have undergone significant developments, becoming the primary choice for intralogistics automation [10].

Although the concept of AMRs is not new, with the first generic patent issued in 1987 [11], their use in logistics has only recently gained prominence. Their importance is expected to grow significantly, with more than 13,000 AGV and AMR systems installed worldwide [12]. Currently, hundreds of suppliers offer autonomous robots globally [9].

AMRs are particularly well-suited for intralogistics operations, such as transporting and feeding parts into production lines [13]. The activities performed by AMRs can be categorized into three main groups: (I) material handling (retrieval, movement, transportation, sorting, etc.), (II) collaborative and interactive activities, and (III) full-service tasks [14], [15].

Despite the high level of automation in production and intralogistics, significant reliance on human labor still exists for material transportation, involving manual carts and forklifts. This reliance results in additional labor costs and product quality risks. While alternative approaches, such as fixed, overhead, or ground conveyors, exist, AMRs are a potential solution to improve flexibility and efficiency in internal logistics [2].

Technological advances have facilitated the large-scale integration of AMRs into production systems. Traditional transport connections between workstations can be easily replaced and complemented with simple loading and unloading stations alongside an AMR system [16]. AMR systems are often implemented with an intermediate buffer, temporarily storing products during transfers, enabling two consecutive production phases to have independent loading and unloading stations. AMRs can be installed before and after workstations where grouping and individualization activities occur [13].

Small changes, such as machine layout modifications, typically require considerable time for most AGV guidance systems, leading to downtime and economic losses while reducing productivity. However, AMRs can quickly adapt to environmental changes. The demand for greater flexibility has driven AMR development in navigation capabilities and the range of services they can offer. Compared to AGVs, which are primarily computer-controlled for horizontal transportation, AMRs perform various tasks beyond basic transportation and material handling [17].

AMR autonomy involves continuous decision-making about operating behaviors within a given environment, adhering to rules and constraints. A significant challenge is the complete absence of human supervision, requiring AMRs to monitor their own state, detect potential system failures, and respond appropriately [14]. Decentralized decision-making enables systems to dynamically react to environmental changes, supporting material handling, collaborative tasks, and full-service operations within defined areas [9].

In addition to material handling and transportation, AMRs can serve as assistance systems, interacting with humans as co-workers. For example, in automotive assembly, AMRs equipped with manipulators can assist workers in assembling heavy car body parts at various stages along the production line, increasing productivity and quality while reducing worker fatigue [18], [9].

For new technologies to be successful and globally applicable, sustainability is essential. This requires addressing economic, social, and environmental factors. Ongoing research and effective utilization of Industry 4.0 contributions to intralogistics are crucial. Smart intralogistics systems will lead to greater flexibility and productivity in the future, and all possibilities should be considered when embracing the changes brought by (Intra)Logistics 4.0 [19].

## **2. Literature Review**

### ***2.1 Intralogistics in Industry 4.0***

One of the core principles of Industry 4.0 is the application of its concepts and technologies in the field of intralogistics. Intralogistics encompasses the interactions between various logistical functions and involves planning, implementing, controlling, and efficiently managing material flows, whether finished or semi-finished. This sector is responsible for managing the entire internal flow of materials and information, from reception to the supply of assembly lines [20], [3].

From the perspective of Industry 4.0, the operator becomes an intelligent and skilled element, collaborating with robots and other smart entities. In logistics, human contribution shifts towards monitoring and supervising activities rather than direct intervention [3].

#### ***2.1.1 Mobile Robots***

Material transportation is an essential component of material flow in production systems. Current material transportation systems rely on various equipment with different levels of automation. Standard equipment includes forklifts and pallet jacks requiring human intervention [21].

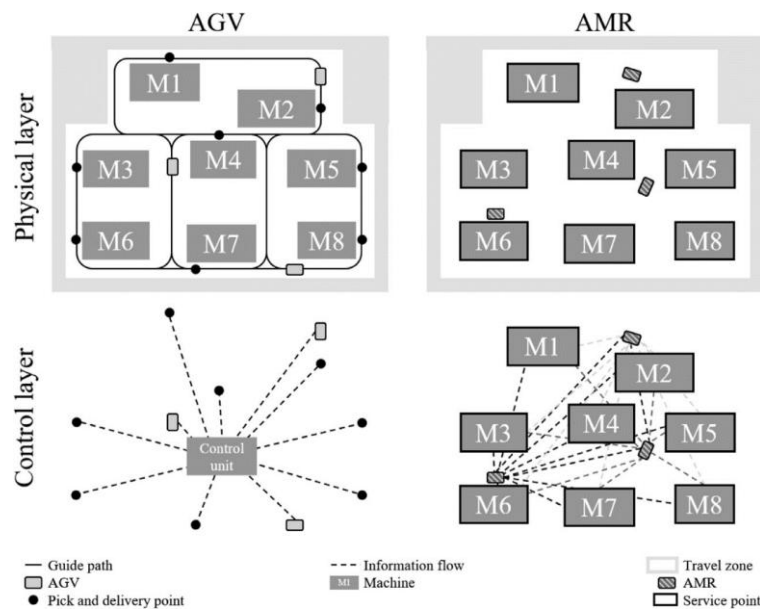
To meet the demands of the 4th Industrial Revolution, it is necessary to reduce reliance on traditional automation systems and adopt more flexible approaches [22]. The increased efficiency in production activities, which has created logistical constraints, reinforces this need [23]. To address these challenges, mobile robots have become the most explored technology for supplying assembly lines [24].

These transport vehicles must plan their routes between two points, ensuring efficiency and safety by traveling the shortest possible distance [25]. Thanks to their flexibility, mobile robots enable the creation of new assembly line configurations and the reconfiguration of existing ones, transforming assembly lines into networks. These changes are essential for the new era of Industry 4.0 [24].

### 2.1.1.1 AMRs: A Preliminary Reflection

Autonomous Mobile Robots (AMRs) represent an evolution of Automated Guided Vehicles (AGVs), being more advanced and autonomous. While AGVs rely on markings or magnetic tapes to follow predefined routes, AMRs are more flexible, equipped with sensors and devices that enable them to navigate autonomously and dynamically [26], [10], [3].

Moreover, AMRs operate within a decentralized structure, unlike AGVs, which function based on a centralized framework. This grants AMRs autonomy in decision-making [13], [2], as illustrated in Figure 1.



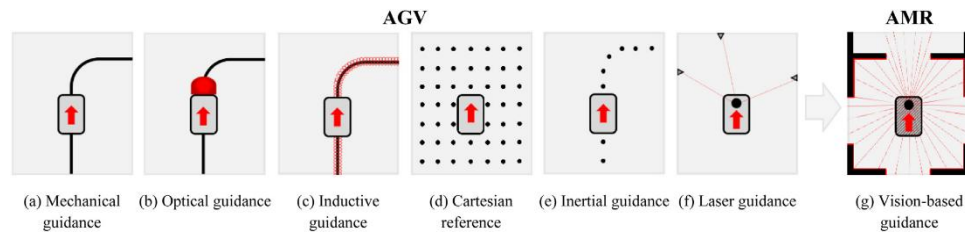
**Figure 1.** Centralized AGV Control and Decentralized AMR Control [9].

AMRs are considered ideal for integrating production networks and, particularly, increasing intralogistics operations' efficiency, offering cost-effective solutions for material transportation [13], [27].

Compared to an AGV system, where a central unit controls decisions such as routing and dispatching for all AGVs, AMRs can independently communicate and negotiate with other resources, such as machines and systems, and make decisions autonomously. This reduces the need for centralized external control [28].

In contrast to AGVs, computer-controlled load carriers designed for horizontal transportation without an onboard operator for repetitive transport tasks, AMRs can provide various services beyond simple transport and material handling, such as patrolling and collaborating with operators. With their autonomous decision-making capabilities, these mobile platforms offer flexible solutions. The autonomy of AMRs involves continuous decision-making regarding their behavior in an operational environment, adhering to applicable rules and constraints [17].

The following Figure 2 illustrates the guidance systems for both AGVs and AMRs.



**Figure 2.** Guidance systems for AGVs and AMRs [9].

### 2.1.1.2 AMRs: *In an Industrial Context*

Implementing Autonomous Mobile Robots (AMRs) in the industry requires careful consideration of the new assembly line configurations made possible by their introduction. The growing popularity of AMRs brings challenges in managing large and heterogeneous fleets of robots [29]. Unlike Automated Guided Vehicles (AGVs), AMRs operate with a different decision-making framework, requiring new approaches. Real-time location tracking of robots must be considered when planning routes, ensuring that only the robots closest to the components to be transported to the assembly line are assigned to the task. This minimizes travel time, increasing assembly line productivity [24].

The integration of sensors in mobile robots opens up new routing possibilities. These sensors enable robots to operate autonomously and interact with the resources within their environments. Improved routing enhances productivity and reduces travel times, increases safety levels, and minimizes downtime caused by a lack of components [24], [23].

AMRs are versatile, as they can be easily reprogrammed for various tasks. With technological advancements, these vehicles have enhanced components and more advanced navigation techniques, increasing their flexibility within designated work environments [2].

Additionally, AMRs play a crucial role in the energy transition within logistics. In the future, the increased use of these robots is expected to be encouraged by funding initiatives for green projects, addressing potential financial barriers to acquiring and implementing these vehicles [30].

### 2.1.1.3 AMRs: *Human Presence*

Adapting robots to human presence is crucial. Without this adaptation, the cooperation between humans and robots can hinder productivity [31]. The mere presence of humans in production environments with mobile robots affects the proper functioning of material transport systems [32]. Tasks manually performed by operators and the shared workspace with robots should be viewed as an advantage rather than a potential cause of inefficiency.

The collaboration between autonomous robots and humans is increasing, emphasizing the importance of cyber-physical systems (CPS). These systems must be capable of reprogramming their activities in response to the presence of human resources or other mobile elements [31].

Using AMRs provides an opportunity to deploy human resources more efficiently and with more excellent added value while also addressing labor shortages [3].

In terms of workplace safety, the use of mobile robots enhances safety by reducing human error. Furthermore, by performing monotonous and repetitive tasks that could lead to musculoskeletal injuries, robots help decrease workplace injuries, allowing operators to take on more valued roles [3].

### 2.1.2 *Assembly Line Supply by AMRs*

One of the pillars of Industry 4.0 is the introduction of its principles and technologies in the field of intralogistics. This sector is responsible for the entire internal flow of materials and information, from receiving materials to supplying assembly lines. In the context of assembly line supply, AMRs play a crucial role in optimizing material flow by being programmed to retrieve components from warehouses or

storage areas and deliver them directly to production lines, thereby eliminating the need for human intervention in manual transport [20], [3].

AMRs are highly adaptable and reconfigurable, meaning they can be easily adjusted to handle changes in demand, new products, or factory layouts. The adoption of AMRs streamlines and facilitates material supply since the system can be easily reconfigured after implementation without significant additional costs.

By replacing traditional manual supply methods with AMRs, companies can increase efficiency, reduce downtime, and improve workplace safety. Additionally, operational costs can be reduced in the long term due to automation and the minimization of human errors. In the Industry 4.0 context, the operator becomes an intelligent and skilled element, collaborating with robots and other smart entities. In logistics, human contribution shifts towards monitoring and supervising activities rather than direct intervention [3].

### 3. Sizing of the Crusher

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 formulation:** Identification and precise definition of the problem under study.
- 2 **Data collection and conceptual model development:** Gathering information from the XYZ company and creating a conceptual model that accurately represents the system.
- 3 **Conceptual model validation:** Ensuring the conceptual model correctly reflects the actual system.
- 4 **Model programming and verification:** Implement the model in SIMIO software and verify it to ensure there are no programming errors.
- 5 **Programmed model validation:** Comparing the programmed model with the real system to ensure its accuracy and reliability.
- 6 **Design and analysis:** Developing and simulating different scenarios to analyze alternative solutions.
- 7 **Documentation and presentation of results:** Compiling analyses and creating reports and dashboards to present the findings.

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.

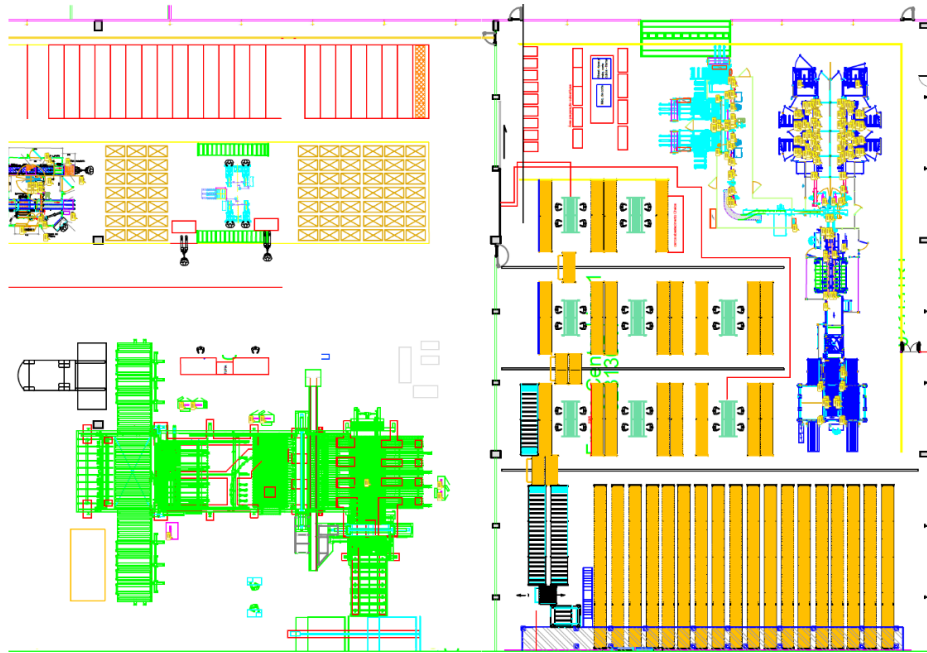
### 4. Case Study

This case study provides a detailed analysis of proposed improvements to the internal logistics of one of the assembly sectors at the XYZ factory, focusing on optimizing material transportation and automating processes. By implementing innovative solutions, such as using Autonomous Mobile Robots (AMRs) and conveyor belts to support workers, the aim is to enhance operational efficiency and reduce human errors, thereby contributing to a more agile and sustainable production system.

The study will present, in detail, the various existing and proposed solutions for this project.

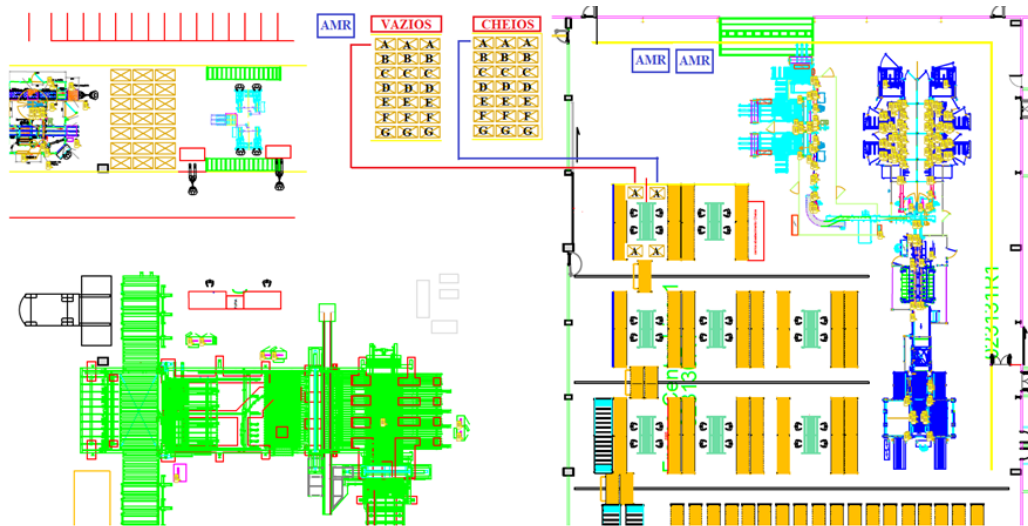
#### 4.1 Specific Separate Areas for Carts of Each Frame Type (Stock Zone)

Existing Solution: The carts are stored in a designated storage area, loaded with the raw materials for each frame type to be produced, as illustrated in Figure 3. An employee then manually moves these carts, requiring physical effort to push them over a distance of approximately 60 meters, with weights ranging from 100 to 300 kg. Human errors may occur due to the lack of proper identification and detection of the cart type that needs to be transported to the correct workstation.



**Figure 3.** Existing layout.

Proposed New Solution: The carts will be stored fully loaded in a stock area similar to the current scenario. Each cart will be positioned in its designated spot, adequately identified, and within a dedicated space to produce each frame type. A stock of multiple carts with the same raw material will be maintained to make the same frame types or frames that share common parts. A specific area will be assigned to each frame type; for example, carts loaded to produce Frame A will always be placed in the exact location, and the AMRs will know they need to go to that area to retrieve a cart. Additionally, there will be a dedicated area for empty carts, where the AMRs will deposit them once emptied, as illustrated in Figure 4. These carts will wait to be reloaded and returned to the stock area.



**Figure 4.** Proposed layout.

#### 4.2 Cart Transport Systems

- **Existing Solution:** Currently, there is only one cart type for transporting raw materials in a single size. Standard frames are transported using a single cart, while more extended frames require two carts placed side by side for transportation.
- **Proposed New Solution:** It is suggested that two types of carts be used for transporting raw materials: a standardized cart to accommodate most small- and medium-sized frames and a larger cart to meet the transportation needs of large frames. This larger cart features design modifications compared to the current models, including a configuration that allows it to transport "shelves" that can be easily removed by sliding along rails.

#### 4.3 Line Feeding Systems

- **Existing Solution:** Currently, carts remain "parked" near the operators while they retrieve the parts (raw materials) needed to assemble the frames. Only after the carts are emptied are they moved back for replenishment. The empty carts are then transported to the cutting area, reloading with raw materials for future use (transportation).
- **Proposed New Solution:** The proposed system involves implementing multi-level conveyor belts near the assembly operators. These conveyors are easily adjustable and flexible, allowing them to adapt ergonomically to each individual worker. Carts loaded with raw materials will be transported by AMRs (Autonomous Mobile Robots) from the cutting area (stock) to the assembly area, where they will be positioned near the conveyor belts. Once the raw materials are placed on the conveyor, the AMR returns the empty cart to the cutting area to be reloaded and put back in the stock zone. Operators simply guide and move the raw materials closer to themselves as they are transported by the conveyor. This process is repeated continuously throughout the day. Operators only consume the materials on the conveyor. At the same time, the fully automated system ensures that the correct quantity and type of raw materials are always available for the daily production requirements of each assembly station on an individualized basis.

#### 4.4 Presentation and Explanation of Different Scenarios

The first scenario assumes that all operators produce the product requiring the most significant material movement. In contrast, the second scenario is the opposite of the first, where all operators produce the product requiring the least movement.

In the third scenario, we analyzed the weekly demand and observed that six products had higher demand than the others. The production of these products was evenly distributed among the operators. The fourth scenario was calculated based on weekly demand, where the production of products was distributed among the operators proportionally to the demand, ensuring that the required quantities had been produced by the end of the week.

#### 4.5 Calculation of the Number of AMRs Required for Each Scenario

##### Calculation of the Number of AMRs Required for Each Scenario

Four distinct scenarios were analyzed to calculate the number of AMRs needed. An AMR speed of 1.8 m/s was used, with a travel distance of 126 meters per trip. Additionally, a safety factor 2.58 was included to account for potential slowdowns or interruptions in the AMR's operation.

The calculation method was as follows: parts per hour = cycle time of each product, and travel time = 3 minutes, considering the variables of speed, distance, and the previously defined safety factor.

*Production per hour = pieces per hour \* N<sup>o</sup> operators producing the part*

$$\text{Travel per hour} = \frac{\text{Production per hour}}{N^{\circ} \text{ Frames in the Cart}}$$

*Travel Time per hour = Travel per hour \* Travel time*

$$N^{\circ} \text{ AMR} = \frac{P \text{Travel Time per hour}}{60}$$

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 Required Libraries:** Import the file containing the data provided by company XYZ and define variables such as cart travel time, the number of operators, and weekly production time.

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

directory = r"PCCT - Projeto Cocriação & Competências Transferíveis\Desafio IKEA"
file = 'Frame values.xlsx'

os.chdir(directory)

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

'''
Valores utilizados para calculo de tempo de viagem
Velocidade AGV =1.8 ms
Distancia a percorrer pelo AGV (ida e volta) = 62.91 m * 2
Fator de Segurança = 2.58
'''

# Tempo de viagem (min)

t = 3

# N° de operadores

op=32

# Tempo total de produção semana (h) - Tempo por turno (8) * Turnos por dia (2) * Dias por semana (5)

tp = 8 * 2 * 5
```

**Figure 5.** Code Setup.

- 2. Define the "calculation" function:** This function will determine the number of AMRs required for each scenario.

```

33 def calculo(production_file1):
34     """
35     Cria Data Frame de cada cenário com base no production_file
36
37     Parameters
38     -----
39     production_file1 : TYPE
40         DESCRIPTION.
41     n_op : TYPE
42         DESCRIPTION.
43
44     Returns
45     -----
46     production_file1 : TYPE
47         DESCRIPTION.
48     """
49
50     # Adicionar coluna com produção por hora para achar melhor e pior caso
51     production_file1['Produção/hora'] = production_file1['pc/hora'] * production_file1['Nº Operadores']
52     #Adicionar o numero de viagens/hora
53     production_file1['Viagens/hora'] = production_file1['Produção/hora'] / production_file1['Frames']
54     #Adicionar tempo de viagem por hora
55     production_file1['Tempo viagem/hora'] = production_file1['Viagens/hora'] * t
56     #Adicionar nº carrinhos
57     production_file1['N_AMR'] = production_file1['Tempo viagem/hora'] / 60
58
59     return production_file1
60

```

**Figure 6.** Function to Calculate the Number of AMRs

### 3. Function to Calculate the Best and Worst-Case Scenarios.

```

61 def scenariol():
62     """
63     Calcula cenários extremos max e min de carrinhos
64
65     Returns
66     -----
67     worst_case : TYPE
68         DESCRIPTION.
69     best_case : TYPE
70         DESCRIPTION.
71
72     """
73
74     # Todos os operadores a fabricar a mesma peça (24)
75     production_scenariol = production_file.copy()
76     production_scenariol['Nº Operadores'] = op
77     production_scenariol = calculo(production_scenariol)
78
79     # Achar maximo e minimo 'N_AMR'
80     id_max = production_scenariol['N_AMR'].idxmax()
81     id_min = production_scenariol['N_AMR'].idxmin()
82
83
84     # Selecionar coluna maxima e minima 'N_AMR'
85     production_scenariol_max = pd.DataFrame(production_scenariol.loc[id_max]).transpose()
86     production_scenariol_min = pd.DataFrame(production_scenariol.loc[id_min]).transpose()
87
88
89     return production_scenariol_max, production_scenariol_min
90

```

**Figure 7.** Function to Create DataFrames with Extreme Scenarios.

### 4. Function to Calculate the Scenario Considering the Top 6 Most Demanded Items with Production Equally Distributed Among Operators.

```

91 def scenario2():
92     """
93     Calcula cenario com top 6 artigos com mais procura distribuidos igualmente entre os operadores
94
95     Returns
96     -----
97     production_scenario2 : TYPE
98     DESCRIPTION.
99
100     """
101
102
103     production_scenario2 = production_file.copy()
104
105     top_6 = planning_file.nlargest(6, 'Weekly Average')
106     #Filtrar tabela de produção para só incluir top 6
107     production_scenario2 = production_scenario2[production_scenario2['Product'].isin(top_6['Product'])]
108     production_scenario2['Nº Operadoes'] = op/6
109
110     #Os operadores são divididos igualmente entre os 6 produtos com maior necessidade de produção (24 / 6)
111     production_scenario2 = calculo(production_scenario2)
112
113     return production_scenario2
114

```

Figure 8. Function to Create DataFrame for the "Top 6" Scenario.

##### 5. Function to Calculate the "Real" Scenario Based on Weekly Demand.

```

115 def scenario3():
116     """
117     Calcula cenario com baseado plano de produção semanal
118
119     Returns
120     -----
121     production_scenario3 : TYPE
122     DESCRIPTION.
123
124     """
125     production_scenario3 = pd.merge(production_file, planning_file[['Product', 'Weekly Average']], on='Product', how='left')
126     #Remove colunas sem valores em Weekly Average
127     production_scenario3 = production_scenario3.dropna(subset=['Weekly Average'])
128     #Calcula o tempo necessário de produção semanal para cada produto e o numero de operadores necessários diariamente para satisfazer a procura semanal
129     production_scenario3['Tempo Produção Semanal'] = production_scenario3['Weekly Average'] / production_scenario3['pc/hora']
130     production_scenario3['Nº Operadoes'] = np.ceil(production_scenario3['Tempo Produção Semanal'] / tp)
131     production_scenario3 = calculo(production_scenario3)
132
133     return production_scenario3
134

```

Figure 9. Function to Create DataFrame for the "Current Demand" Scenario.

##### 6. Function to Export DataFrames with Results for Various Scenarios to an Excel File and Create a Chart of the Number of AMRs per Scenario.

```

135 def get_results():
136     """
137     Grava resultados numa Folha de excel chamada "resultados.xlsx"
138
139     Returns
140     -----
141     None.
142
143     """
144     worst_case, best_case = scenario1()
145     top6=scenario2()
146     procura_atual = scenario3()
147
148     sum1 = np.ceil(worst_case['N AMR'].sum())
149     sum2 = np.ceil(best_case['N AMR'].sum())
150     sum3 = np.ceil(top6['N AMR'].sum())
151     sum4 = np.ceil(procura_atual['N AMR'].sum())
152
153     # Criar Data Frame com totais
154     data= {
155         'worst_case': [sum1],
156         'best_case': [sum2],
157         'top6': [sum3],
158         'procura_atual': [sum4]
159     }
160
161     totais = pd.DataFrame(data)
162
163     # Gráfico com totais para visualizar os dados
164     totais.plot(kind='bar')
165     plt.title('Totais')
166     plt.ylabel('N AMR')
167     plt.show()
168
169
170     #Exportar resultados para excel
171     with pd.ExcelWriter('resultados.xlsx') as writer:
172         worst_case.to_excel(writer, sheet_name='MaxProd', index=False)
173         best_case.to_excel(writer, sheet_name='MinProd', index=False)
174         top6.to_excel(writer, sheet_name='Top6', index=False)
175         procura_atual.to_excel(writer, sheet_name='procura Atual', index=False)
176         totais.to_excel(writer, sheet_name='Totais', index=False)
177
178

```

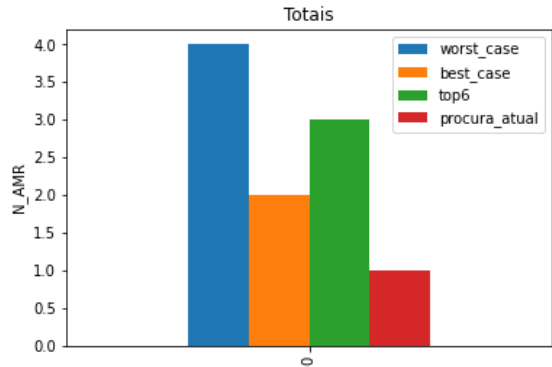
**Figure 10.** Results Export Function.

7. Run the Code

```
179 get_results()
```

**Figure 11.** Line of Code to Execute the Functions.

8. Analyze Results



**Figure 12.** Graph Created with Scenario Results.

Figure 13 presents the exported results of the different calculated scenarios, such as “Worst\_prod”, “Best\_prod”, “Top6”, and “Procura\_atual”.

**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

**Top6:**

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
S023KXFRB01	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
S023LGFRTPO4S	120	2,17	130,2	2037	15,64516129	1	130,2	1,085	3,255	0,054
S023LGFRTPO3S	200	2,67	160,2	2338	14,59425718	1	160,2	0,801	2,403	0,040
S023LGFRTPO2S	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

**Figure 13.** Exported Results.

After analyzing the collected data, it was found that when all workstations are occupied, the number of AMRs required ranges between 2 and 4, depending on the manufactured products. However, when considering the weekly demand data, where not all workstations operate, a single AMR is sufficient to meet production requirements.

## 5. Results and Discussion

The present chapter focuses on developing the proposed solution using the SIMIO simulation software. The authors aimed to create a model that illustrates the transportation of material for the construction of frames from the intermediate stock area to the assembly workstation and from that assembly workstation to a dispatch point for the next zone. The transportation of carts through the different phases is carried out with the assistance of an AMR. However, the simulation of the shop floor will allow for a holistic visualization and evaluation of the carts' transportation by mobile robots (AMRs), which will assist and supply the various assembly workstations.

### 5.1 Creation of a Production Model in SIMIO

To ensure the logic of the model, it was necessary to develop a production model that included the types of frames to be considered and to create a fictitious production plan to simulate and validate the proposed solution.

- **Demand Calculation**

**Table 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

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

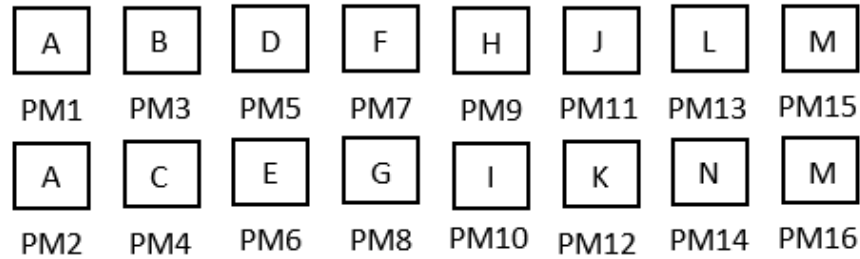
- Calculation of the capacity needed to meet the demand.

**Table 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
<b>A</b>	2	125	100	202	3	250	12h 55min
<b>B</b>	1	216	200	202	2	216	14h 57min
<b>C</b>	1	206	200	200	1	206	15h 28min
<b>D</b>	1	170	200	81	1	170	7h 36min
<b>E</b>	1	160	200	30	1	160	2h 56min
<b>F</b>	1	130	200	26	1	130	3h 9min
<b>G</b>	1	200	200	51	1	200	4h 2min
<b>H</b>	1	173	200	80	1	173	7h 24min
<b>I</b>	1	185	200	65	1	185	5h 33min
<b>J</b>	1	251	200	160	1	251	10h 12min
<b>K</b>	1	244	200	160	1	244	10h 30min
<b>L</b>	1	170	200	15	1	170	4h 12min
<b>M</b>	2	153	200	160	1	306	8h 23min
<b>N</b>	1	170	200	40	1	170	3h 42min

Through this step, it can be indicated that with 16 assembly stations, it is possible to meet the daily demand, considering that parts requiring two workers also count as two assembly stations.

By analyzing the last column of the table, which represents the working hours needed to meet the demand, it is evident that most frame values correspond to just one work shift. Although the model is not optimized, its optimization is not essential to proceed with the task. In a subsequent phase of model evaluation, including the correct production plan would be crucial. However, since the aim is merely to demonstrate that simulation can be an ally in the automatic transport of carts, the authors considered that the 16 stations in the following diagram are fully operational during the 16 working hours (Figure 14).



**Figure 14** - Allocation of frame types to the various workstations.

- **Calculation of Processing Time**

The processing time for a cart was determined using the number of pieces produced per hour per worker.

**Table 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

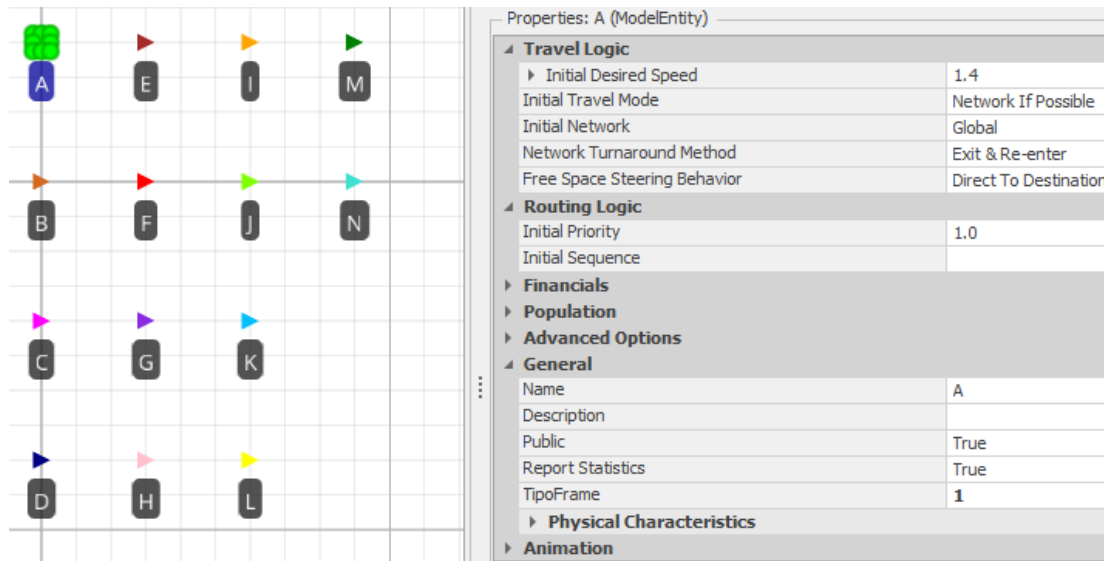
The model was developed using the software based on the analysis of the current situation and the previously presented data.

### 5.2 Development of a Model in the Software

- **Frame and Cart Entities**

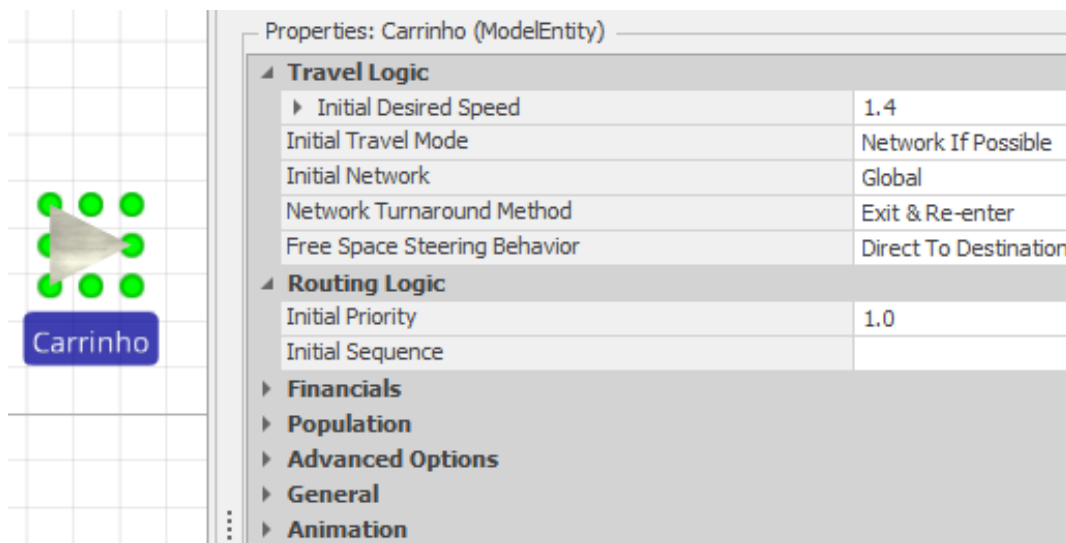
It was essential to create entities to represent the material that constitutes the various types of frames listed in Table 3 and their supply to carts. The nomenclature for this material ranges from A to N, as previously presented, and these are entities of the Model Entity, with specific characteristics defined accordingly. Figure 15 illustrates these entities and some of their properties within the system. The “TipoFrame”

property identifies them numerically, from 1 to 14, and its creation aims to support the logical construction of the model, associating a specific Frame Type with an assembly area.



**Figure 15.** Entities representing the material for the 14 types of frames.

It was necessary to create an entity representing the cart to pair this material by type with carts, as occurs in the physical system (Figure 16).



**Figure 16.** Entity representing the cart being transported with the respective material.

- **Cart Supply Area**

To ensure the creation of these entities in the system, two sources were defined: one for the arrival of materials and another for the arrival of carts. Figure 17 illustrates some of the sources created for the material, with each frame type having its own source.

Each material creation zone “Frame A(...N)” was configured with the following parameters adjusted by the authors:

- **Entity Type:** The source must contain the entity shown in Figure 15, responsible for creating the

corresponding material.

- **Arrival Mode and Trigger:** The creation of entities is activated by the event “Output@Carrinhos\_VaziosA(...N). Exited,” which represents the exit of a cart from its source. Thus, when a cart exits, the entities required for its supply are created.
- **Entities per Arrival:** This value represents the entities created with each trigger.

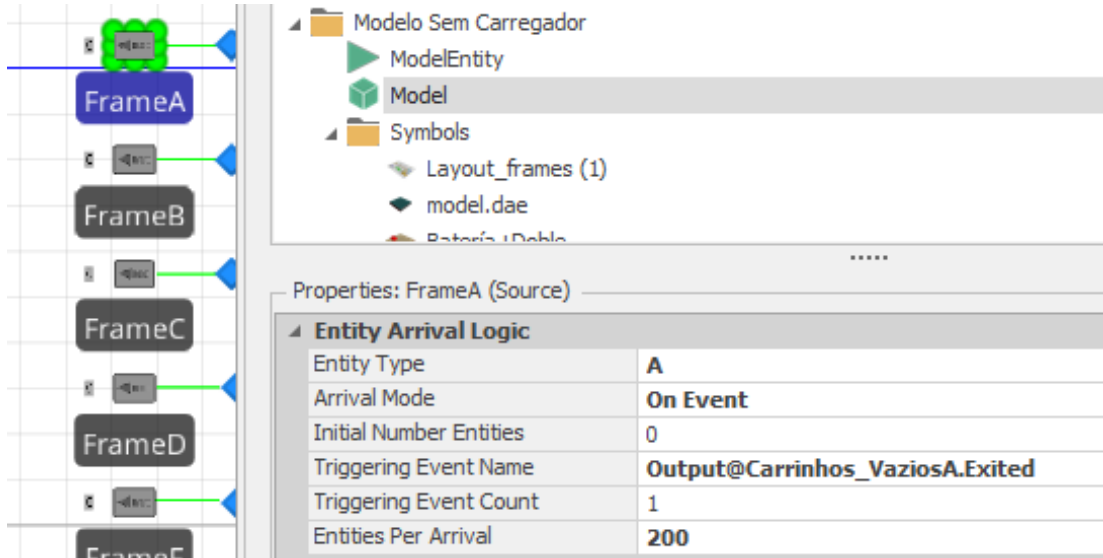


Figure 17. Material sources corresponding to the various frame types.

To create empty carts for supply, sources named “Carrinho\_VazioA(...N)” (Figure 18) were defined and configured with the following parameters:

- **Entity Type:** The source uses the entity from Figure 16, with the same cart for all frame types.
- **Arrival Mode and Trigger:** The creation is activated by the event “CriarCarrinhoA(...N),” a notifier that can be sent by one object and responded to by others. This event is triggered by processes detailed later.
- **Number of Entities:** Includes initial entities and entities per arrival. In cases where two operators per piece are required (Table 2), two carts must always be available for the two workstations.

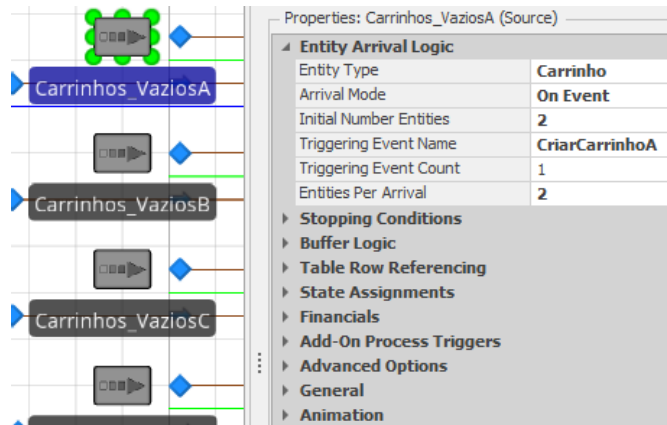


Figure 18. Sources of empty carts for supply.

The design of the event “CriarCarrinhoA(...N)” replicates the need for empty carts when the supply area,

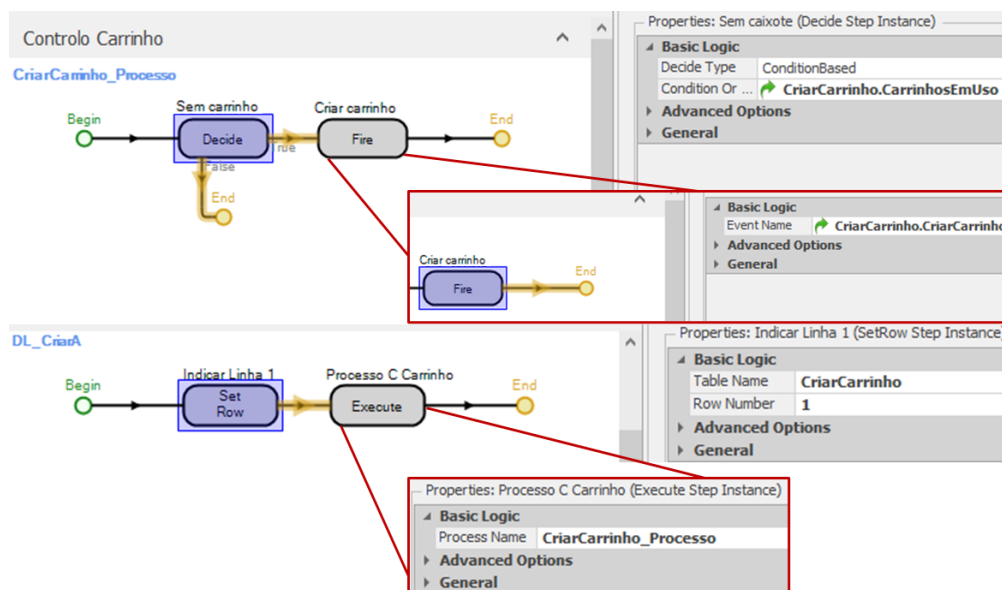
“Abastecimento\_CarrinhoA(...N),” has no carts available. A table was created containing the expression that evaluates the number of carts present in the supply area and the corresponding event for triggering their creation (Figure 19).

	Carrinhos Em Uso	Criar Carrinho
1	Abastecimento_CarrinhoA.ParentInputBuffer.Contents <= 0	CriarCarrinhoA
2	Abastecimento_CarrinhoB.ParentInputBuffer.Contents <= 0	CriarCarrinhoB
3	Abastecimento_CarrinhoC.ParentInputBuffer.Contents <= 0	CriarCarrinhoC
4	Abastecimento_CarrinhoD.ParentInputBuffer.Contents <= 0	CriarCarrinhoD
5	Abastecimento_CarrinhoE.ParentInputBuffer.Contents <= 0	CriarCarrinhoE
6	Abastecimento_CarrinhoF.ParentInputBuffer.Contents <= 0	CriarCarrinhoF
7	Abastecimento_CarrinhoG.ParentInputBuffer.Contents <= 0	CriarCarrinhoG
8	Abastecimento_CarrinhoH.ParentInputBuffer.Contents <= 0	CriarCarrinhoH
9	Abastecimento_CarrinhoI.ParentInputBuffer.Contents <= 0	CriarCarrinhoI
10	Abastecimento_CarrinhoJ.ParentInputBuffer.Contents <= 0	CriarCarrinhoJ
11	Abastecimento_CarrinhoK.ParentInputBuffer.Contents <= 0	CriarCarrinhoK
12	Abastecimento_CarrinhoL.ParentInputBuffer.Contents <= 0	CriarCarrinhoL
13	Abastecimento_CarrinhoM.ParentInputBuffer.Contents <= 0	CriarCarrinhoM
14	Abastecimento_CarrinhoB.ParentInputBuffer.Contents <= 0	CriarCarrinhoN
*		

**Figure 19.** Cart creation table.

The control processes for cart creation occur when a cart loaded with material leaves the supply area, as will be illustrated later. These processes consist of the following steps (Figure 20):

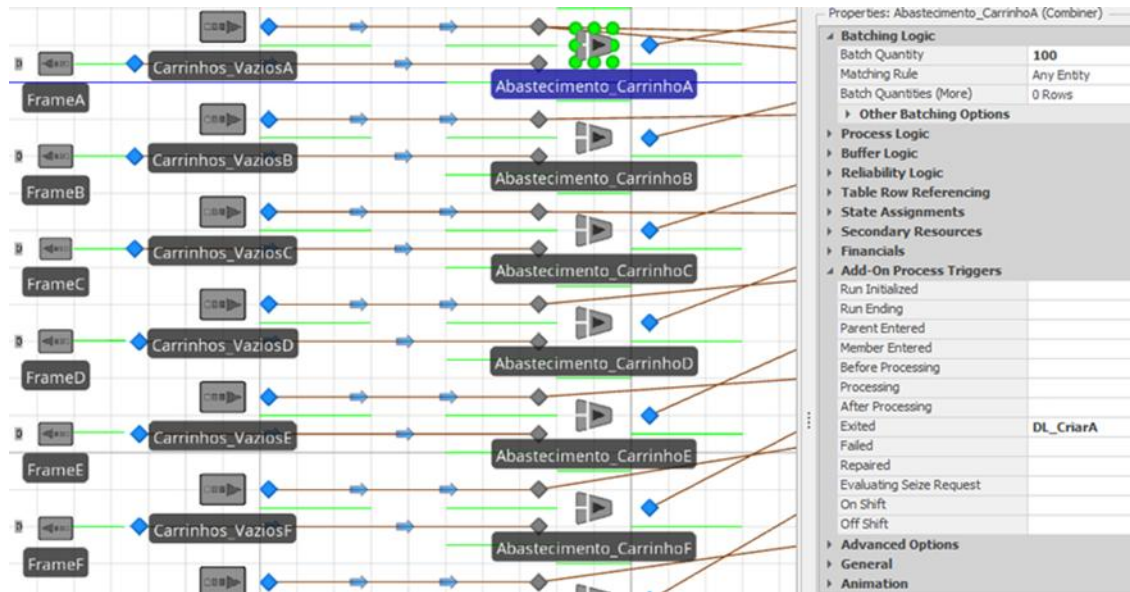
- **Token direction process:** Uses a Set Row to reference a row in the “Criar Caixotes” table and an Execute to run the “CriarCarrinho\_Processo” process.
- **Cart creation process:** Uses a Decide to check the condition in the first column of Figure 19. If true, it triggers the event listed in the second column.



**Figure 20.** Cart creation processes at the exit of the supply area.

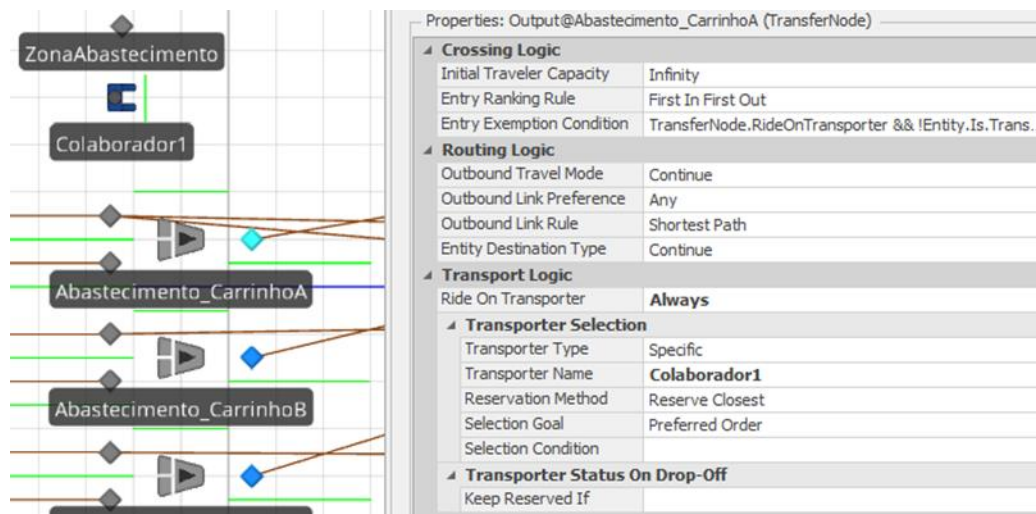
After creating the model entities, they must be grouped to simulate cart supply. Combiners with two

branches, “Parent Input” and “Member Input”, were created for this. These combiners, responsible for grouping batch entities to the parent entity, are named “Abastecimento\_CarrinhoA(...N)”. Figure 21 shows the cart supply areas connected by paths to the entity creation zones. Their properties display the number of entities per batch and an additional process explained earlier.



**Figure 21.** Cart supply areas.

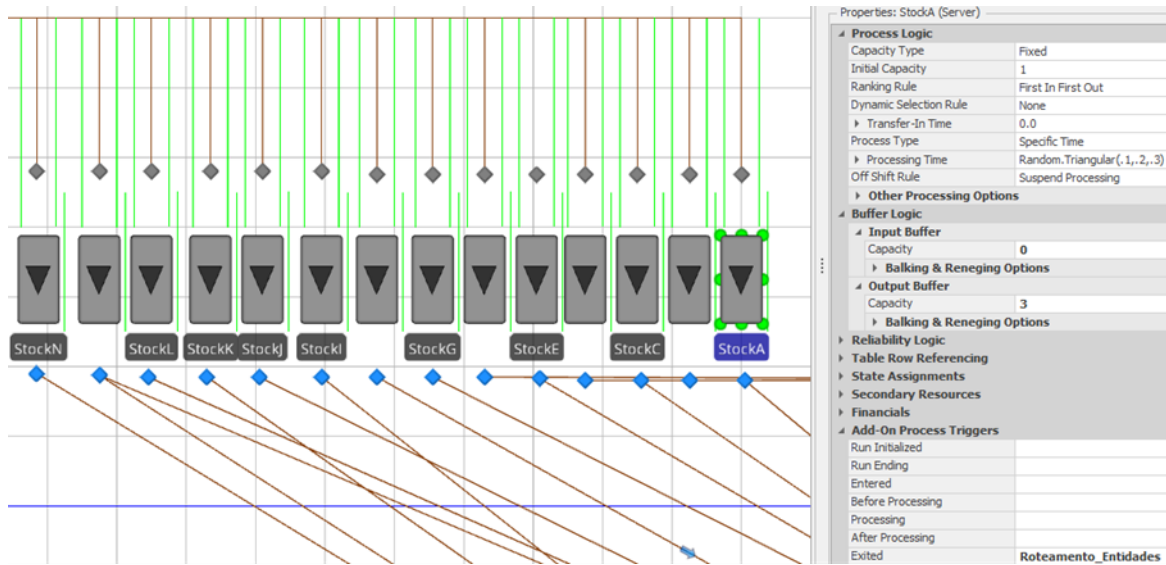
The transport of the loaded carts to the cart stock area, with the material adequately identified, is carried out with the assistance of an operator, also illustrated in the model (Figure 22). At each supply area's exit node, the transport type to be used is specified.



**Figure 22.** Transport between the supply area and the stock area.

- **Stock Area for Loaded Carts**

Once the loaded carts are ready, they move to their designated stock area. Figure 23 shows the regions created according to the type of frame produced based on its material.



**Figure 23.** Stock area for loaded carts.

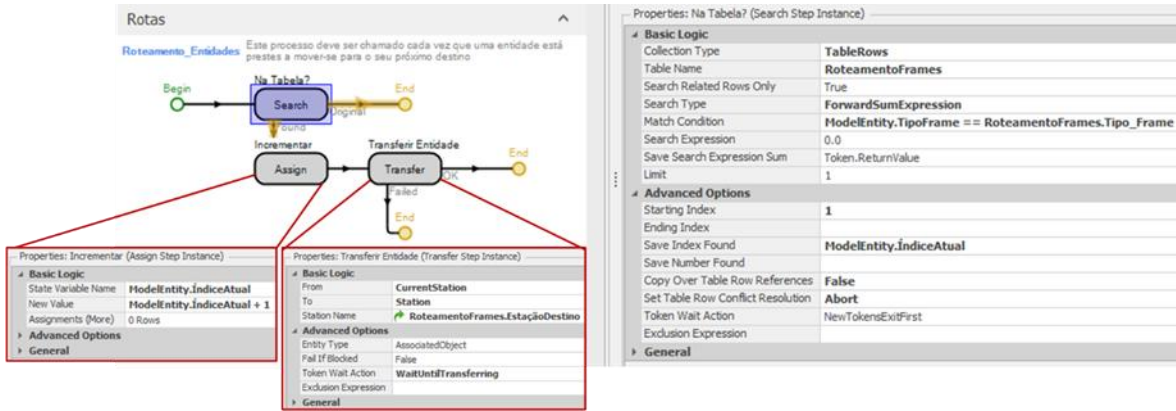
The server properties show that the exit area ideally stores only three carts. Alongside entity departures from the stock area, the “Roteamento\_Entidades” process routes entities to their destinations based on the production plan in Figure 14. A table was created to track the allocation, specifying each entity's destination node and the corresponding frame type (Figure 24).

Id	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_Frame11.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

**Figure 24.** Routing table between carts and frame assembly areas.

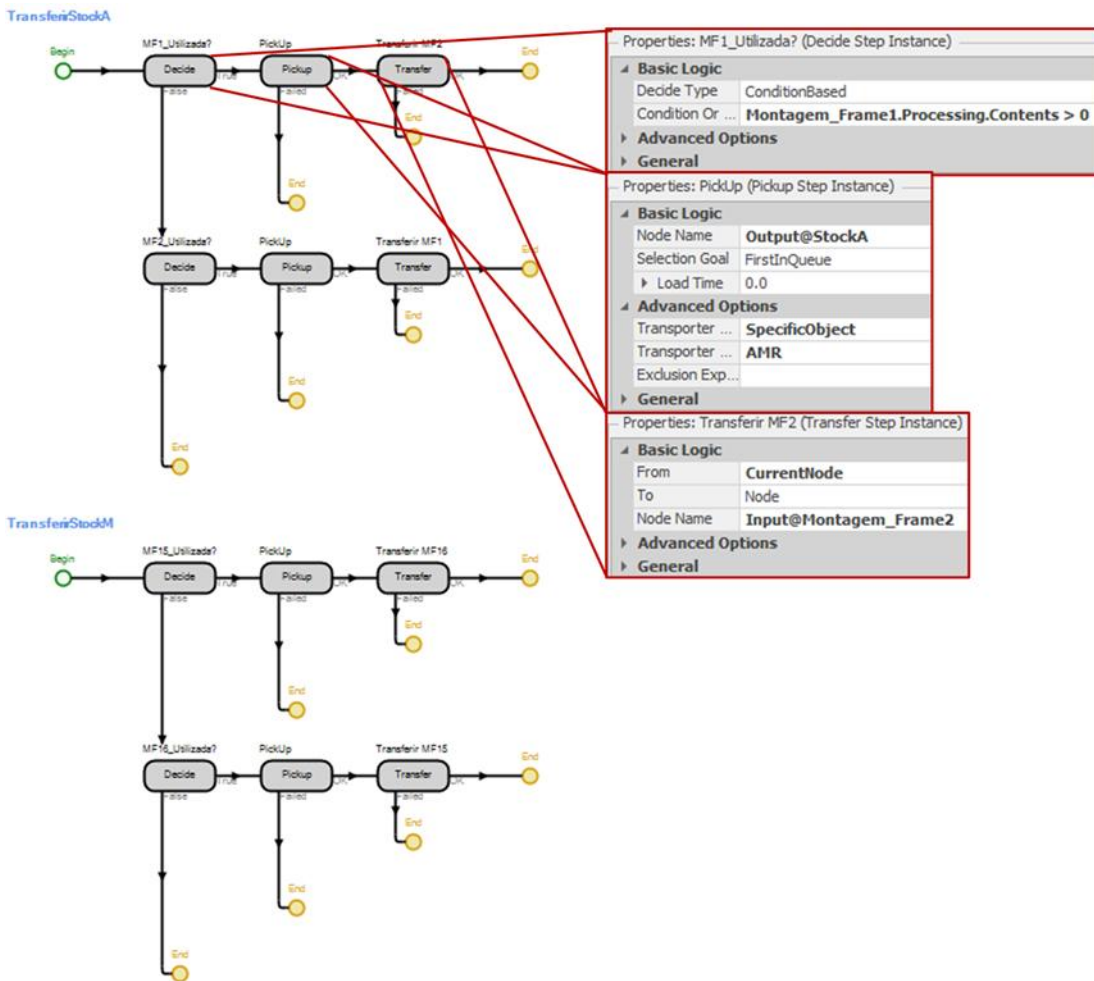
The table is referenced throughout the routing process (Figure 25), which includes the following steps:

- **Search:** Searches for rows in the “Roteamento\_Frames” table, checking if the frame type at the stock area exit matches the one in the table using the expression `ModelEntity.TipoFrame == RoteamentoFrames.Tipo_Frame`. The variable “Current Index” was created in Model Entity to store the position in the table.
- **Assign:** When a match is found, the index value is incremented.
- **Transfer:** Moves the entity from the current station to the destination station specified in the first column of Figure 24.



**Figure 25.** Entity routing process in the stock area.

At the entry of the exit node for each Stock Area, there is a process present only in zones with dual supply, as shown in Table 2. This process verifies the occupancy of the even Assembly Zone (Figure 26).



**Figure 26.** Entity transfer processes in dual stations.

- **Frame Assembly Area**

The frame assembly area includes multiple workstations, “Montagem\_Frame1(...32)”, and a sink object called “Frames Montados” (Figure 27) that removes entities after processing. These stations are of the separator type and consist of:

- **Input Node:** Receives carts from the stock area.
- **Parent Output:** Sends empty carts back to the empty cart area after supplying the assembly zone, with transport assisted by a vehicle.
- **Member Output:** Transfers assembled frames. A worker at this node handles the transport of the assembled frames.

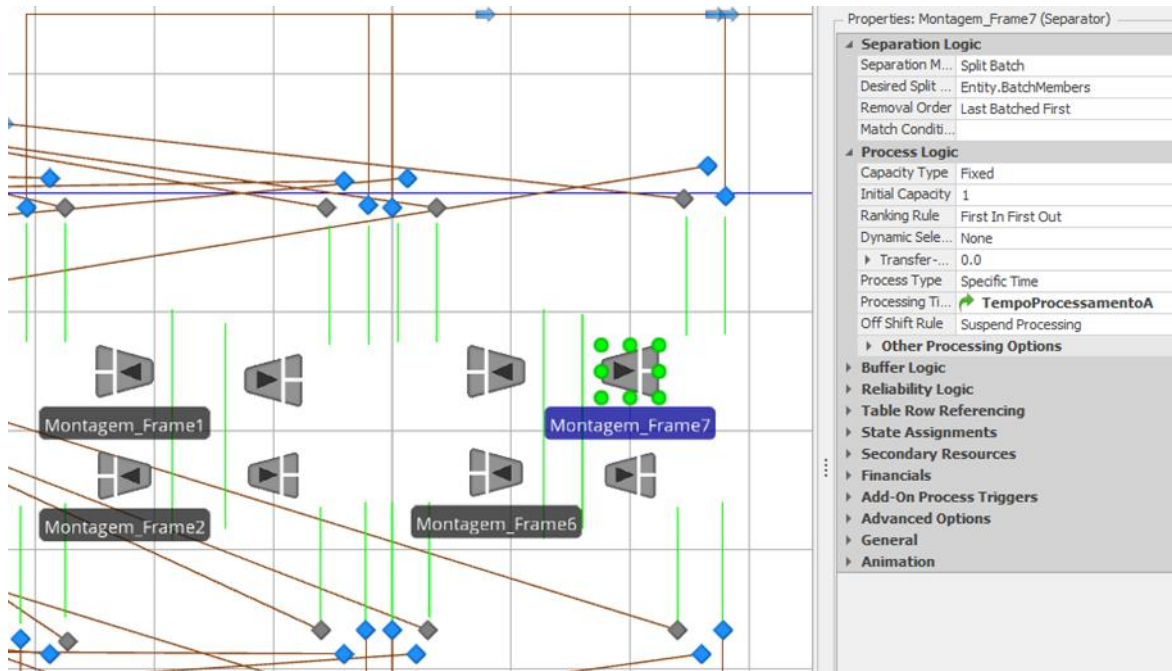


Figure 27. Frame assembly area.

In the general properties of the model, properties were created to store the processing time at each assembly station, calculated using the values in the last column of Table 3.

Finally, Figure 28 shows the final model in the Facility tab.

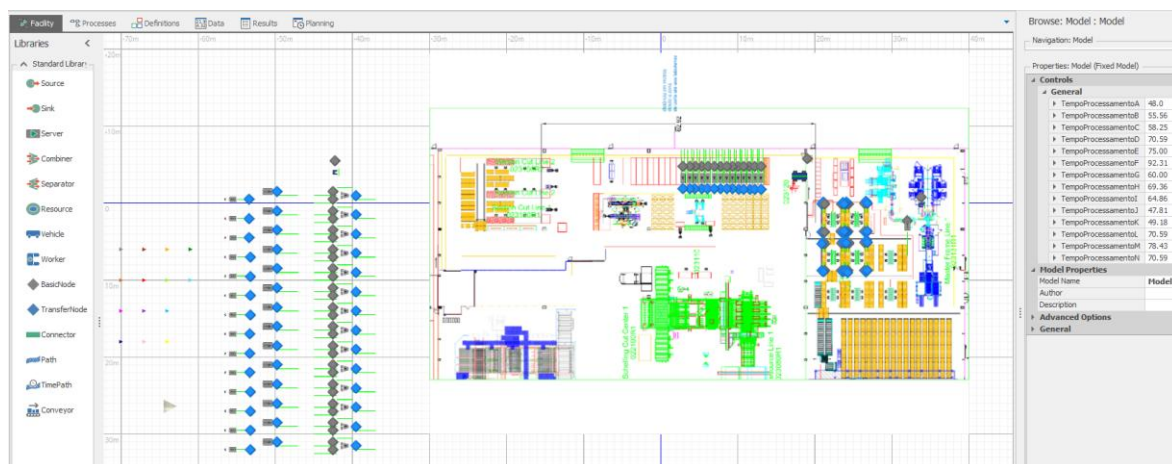


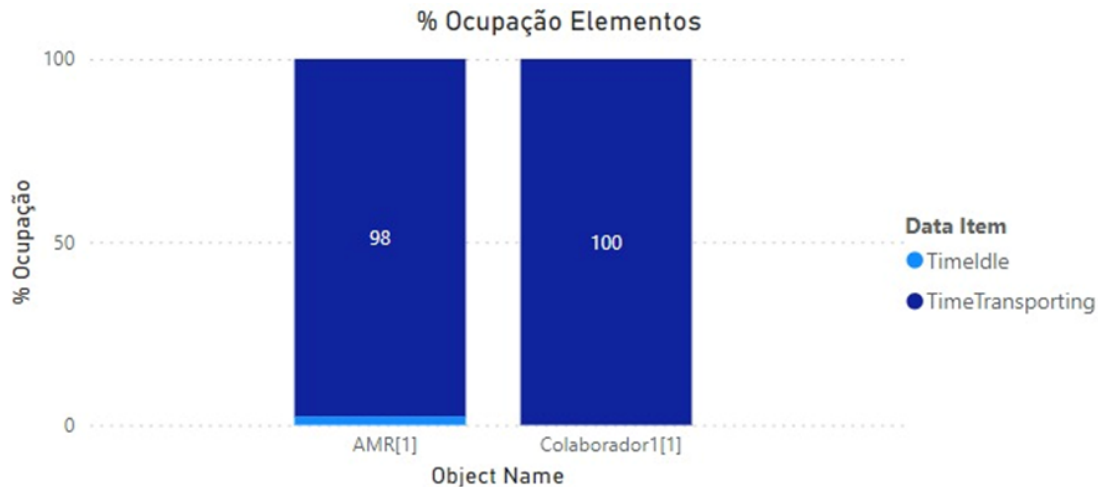
Figure 28. Final model.

### 5.3 Extraction of Results and Analysis in PowerBI

After running a 24-hour simulation of the model, an Excel file was generated and integrated into PowerBI. This file contains detailed data about various objects, categorized by data source, type, and statistics.

The primary objective of this analysis is to validate the simulation model and confirm that a single AMR is sufficient to supply the designated areas for a typical production plan. The results show that the AMR operates at a 98% occupancy rate, closely matching the calculations performed in Chapter 4.3.

The extracted data also enables further insights, allowing the creation of a dashboard to address additional production analysis needs, such as the distance traveled by the AMR or the waiting time of the operator replenishing empty carts.



**Figure 36** - Simulation model validation through result extraction.

## 6. Conclusion

The study aimed to develop a solution to improve the intralogistics process at the XYZ factory, considering alternatives to the current system. The final decision focused on implementing AMRs (Autonomous Mobile Robots), complemented by adjustments to the storage system and the installation of automated conveyor belts to ensure process efficiency.

A mathematical model was developed to calculate the number of AMRs required, considering different production scenarios, including typical periods and demand peaks. The results indicated the need for 1 to 4 AMRs, validated through a Simio software simulation, confirming the initial model.

The study demonstrated that production lines utilizing AMRs are better prepared to handle demand fluctuations, offering greater flexibility and productivity without requiring a complete redesign of the lines. Integrating AMRs in assembly line supply represents a significant advancement in Industry 4.0, enhancing efficiency, flexibility, and competitiveness.

While the benefits are clear, the primary limitation to implementation is the high cost of AMRs and associated systems, which may influence business decisions regarding investment in such equipment.

As future work, it is suggested to develop new simulation scenarios that consider additional factors on the shop floor, further aligning the model with real-world operational conditions.

## 7. Acknowledgements

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