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MAS-based Distributed Cyber-physical System in Smart Warehouse

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Abstract: This paper presents an approach for a multi-agent-based cyber-physical system dedicated to operating the warehouse plant with a distributed approach. The recent technological evolution has improved the quality and robustness of the services for current warehouses. However, systems that operate warehouses do not follow this evolution, presenting predominantly central monolithic or hierarchical approaches, resulting in fragility related to flexibility, scalability, and robustness in the face of disturbances. In the proposed approach, each warehouse physical component has a computational unit associated, i.e. a cyber agent, with communication, negotiation, and data analysis capabilities. Agents contain all the information, algorithms, and functions necessary to operate the physical component, and instead of receiving orders from higher-layer agents, they negotiate and collaborate to perform the tasks. The proposed system was tested in a laboratory testbed, composed of six racks and up to eight robots for transporting products. Extensive experiments show the feasibility of the approach.

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Keywords: Cyber-physical system, Smart warehouse, Multi-agent system, Distributed system

1. INTRODUCTION

Efficiency in the operation and management of warehouse plant is one of the keys to maintaining the competitiveness of companies in the current globalized market. Routine tasks such as order management, inventory monitoring, and automated product transport began to apply disruptive technologies related to 4th industrial revolution (I4.0), such as the internet of things (IoT), cyber-physical system (CPS), big data, artificial intelligence (AI) and cloud and edge computing. For example, big players like Amazon have invested massively in technologies and infrastructure, optimizing tasks such as storage, transport, and shipping products with stochastic and seasonal patterns. In this scenario, in 2011, Amazon acquired 1300 autonomous mobile robots (AMR) from the Kiva company to apply in its warehouses for the autonomous transport of products. After positive results and a significant improvement, in 2012, Amazon acquired Kiva company for 775 million dollars, now renamed as Amazon Robotics (Bogue, 2016). Other companies followed Amazon's example and are applying automation and technologies in its warehouse, such as Alibaba using AI to recommend improvements in resource and worker utilization. (Zhang et al., 2021).

However, despite significant investments and incorporation of technologies, there are still challenges to be overcome to improve the warehouse's capabilities to a smart warehouse.

A relevant issue is the transfusion of centralized models, where the data information and decisions are in a central node, to a distributed model, where different warehouse components communicate to coordinate their actions and make decisions through data exchange. Centralized systems are limited in terms of flexibility (difficulty adapting to disturbances), scalability (addition or removal of system components), and robustness (if the central node fails, it compromises the rest of the system). With the advancement of processing power, it is now possible to develop agents with autonomy to negotiate and make decisions, eliminating the hierarchy by attributing orders to perform tasks. Implementing agents with such characteristics in cyber-physical systems that integrate disruptive technologies using the distribution system can improve warehouse environments' robustness, flexibility, and scalability.

The work contribution lies in applying and evaluating distributed multi-agent system (MAS) based CPS to warehouse plant operation. In developed experiments, each warehouse component, namely robots, racks, and products, is represented by an autonomous agent, which interacts with each other to coordinate the warehouse operations in the CPS context. The developed approach was tested and validated in a laboratory-scale case study and showed robustness through the scalability of products and robots to operate essential warehouse tasks.

The rest of paper is organized as follows: Section 2 overviews the related state of art. Section 3 describes the proposed MAS-based distributed CPS for smart warehouse and the types of agents. Section 4 present the experiment applied in the case study. Finally, Section 5 rounds with the conclusions and points out future works.

2. STATE OF ART

CPS results from computing technologies, networking infrastructures, and real systems integration, aiming to monitor, control and operate physical processes. CPS architecture comprises two main layers: the physical layer and the cyber counterpart. The physical layer materializes a set of assets, sensors, and actuators, which input information from the environment and act in the physical system. On the other hand, the cyber layer is responsible for communication infrastructure, exchanging information, data processing for decision-making and control (Januário et al., 2019).

MAS is composed of independent systems with intelligence, autonomy, and cooperation, called agents, which interact and coordinate their tasks, based on the local knowledge and skills to achieve their goals. The use of the MAS paradigm to model CPSs has gained considerable attention in the last few years, and the overviews in (Guan et al., 2016) reveal a significant amount of research devoted to applications of agents in industrial CPS. Different solutions with centralized, hierarchical, hybrid and distributed architectures are applied in production planning, manufacturing and process control, scheduling, and reconfiguration (Leitao et al., 2016).

The warehouses represents a fundamental link in the industrial process, having an operational complexity due to highly dynamic demand with irregular order patterns within short periods and seasonality demand peaks (Liu et al., 2018). This chaotic scenario is accentuated due to the expansion of e-commerce, representing an estimated market revenue of more than 6 trillion dollars in the year 2023 (Clement, 2021). Traditional warehouses, with central monolithic architectures, without autonomy and information exchange between components, do not meet the current demand. In (van Geest et al., 2021), is point out several drawbacks for traditional warehouses as inefficient space management, damaged objects or products, operations that consume unnecessary time or resources, over-handling material, waste labor, and idle components.

In this sense, approaches dedicated to smart warehouse operation emerged with similar proposals as in this work. In (Jabbar et al., 2018) an architecture was proposed with several IoT sensors spread across the warehouse, sensing products, forklifts, and warehouse environments, where the data is collected and processed by a web administrative module that receives the information through a REST-based framework. In this approach, IoT sensors are passive, with decisions made by the administrative module, i.e., centralized architecture. In (Lee et al., 2018), an IoT approach for warehouse management systems was proposed, using a fuzzy logic algorithm for order picking based on RFID and barcode data acquired by employers. In (Basile et al., 2016) is presented results related to applying a flexible, modular system based on colored modified

hybrid Petri Net for distributed control of warehouses from a CPS perspective. The authors aim to model a general warehouse as a system of cooperating agents.

Despite the current system for warehouse operations integrating technologies related to I4.0, architectures are predominantly centralized or hierarchical, limiting the system's flexibility, scalability, and robustness. In this sense, there is a gap in the academic literature for distributed systems to perform warehouse operations, such as product entry, transport, storage, and exit. This work presents a decentralized approach to operating the logistics warehouse without hierarchy or centralization. The proposal implements a MAS-based CPS with three agents: product, rack, and robot. The components perform their tasks through communication, negotiation, and collaboration, with each agent running its algorithms independently.

3. DISTRIBUTED SYSTEM FOR WAREHOUSE

Warehouse operation can be simplified by associating a transport agent to move a product (or batch of products) to a rack and after the time required for storage transport the product to the exit, meeting time requirements and storage conditions. In this sense, if there are many products with different needs, with several racks and multiple robots to carry out the transport, the process becomes complex resulting in an NP-hard problem in finding the best solution. The solutions for this problem must have properties consistent with the warehouse's functions, such as divisibility, characterized by the work/tasks performed by the resources must be optimized to result in an equal distribution. A second property to be considered is scalability so that the increase in resources (products, robots, or racks) does not compromise the warehouse operation. Flexibility represents the warehouse's ability to adapt during a disturbance, new tasks, or orders, such as changing the deadlines or new products entering the warehouse. Finally, the warehouse must have responsiveness with high achievement in dynamic situations.

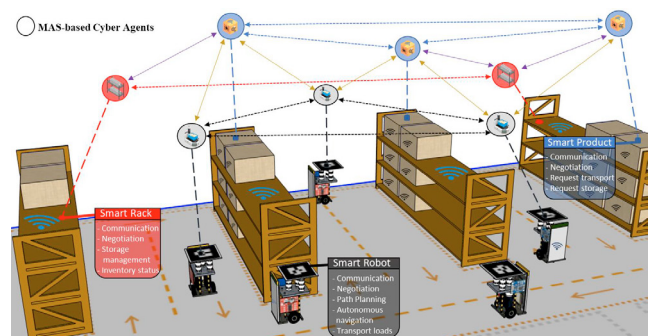


Fig. 1. MAS-based distributed CPS for smart warehouse.

Fig. 1 represents the distributed CPS applied to a warehouse environment containing racks, products, and robot agents. Each physical device is associated with a cyber layer. The cyber layer receives information from sensors and the state of the physical component to process data and make decisions for actions on actuators. In addition, cyber layers exchange information and negotiate with each other to carry out product transport and storage operations. There is no centralization or orders received

from hierarchical structures. Each device can decide its operation and negotiate its action. This procedure results in a warehouse ecosystem where each agent has autonomy.

3.1 Rack Agent

The racks are responsible for storing the products respecting the space conditions, stacking size, temperatures, and humidity required. In this sense, there is no dedicated rack for specific product categories, but the racks can achieve the particular product's storage conditions. Racks have space limitations and cannot receive products beyond their capacity. Additionally, racks have temperature and humidity sensors to obtain information on their environmental and storage conditions. Based on all this information, this agent negotiates storage slots with products. Depending on warehouse typology and layout, there may be dedicated racks agents to process the products, such as performing quality control on products upon arrival or departure.

The Petri net model in Fig. 2 was designed to represent racks behavior. Upon receiving a call for proposal (CFP) allocation (T1), the agent will participate according to its current stock conditions, that is, carry out the proposal according to its typology, free space, and temperature (P2). If it does not reject or is not rejected, it will receive the product and count it in its current stock, updating the parameters for future negotiations in stock management (P1). In parallel, the agent can receive data on its physical structure (T6), and go through a processing step to analyze whether the temperature, humidity and occupied space are within the expected standards (P5), updating the management parameters as a means of detecting possible storage failures. Another possibility is that a product indicates an exit intention (T8), following the product process plan. Then, the product will leave the rack, and its space (T9) will be released to update the parameters of the stock management (P1).

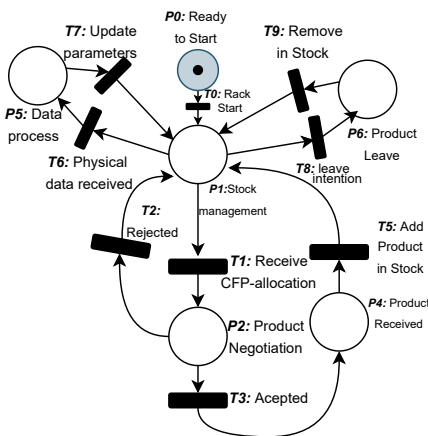


Fig. 2. Rack agent Petri net model.

3.2 Product Agent

In the proposed system, the products digitize information such as position, characteristics, transport type, storage conditions, and process plan. Fig. 3 shows the behavior of the product agent modeled by Petri net. Upon arrival in the warehouse, the product makes registration (P1,

T1). Then start the negotiation to execute the process plan (P2). After defining the storage (T2), the agent will negotiate transport with robots to be transported (P3 and T3). In concurrence, the product communicates with others products through a broadcast message to update parameters and improve negotiation metrics (P5-P6).

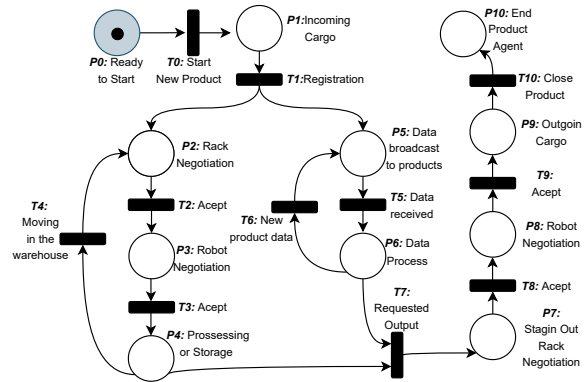


Fig. 3. Product agent Petri net model.

When the product intends leave the warehouse, the negotiation is carried out with the staging area, which will receive the product and check the quality conditions for departure, and then the last negotiation for transport is executed (T7-P9).

3.3 Robot Agent

For robot, the physical layer consists mainly of actuators, sensors, and hardware responsible for control and transport. The cyber layer is responsible for negotiating transportation with the products based on criteria such as distance, battery, and time to perform the task. In addition, the cyber agent processes data for path planning, collision avoidance, robot control, and navigation.

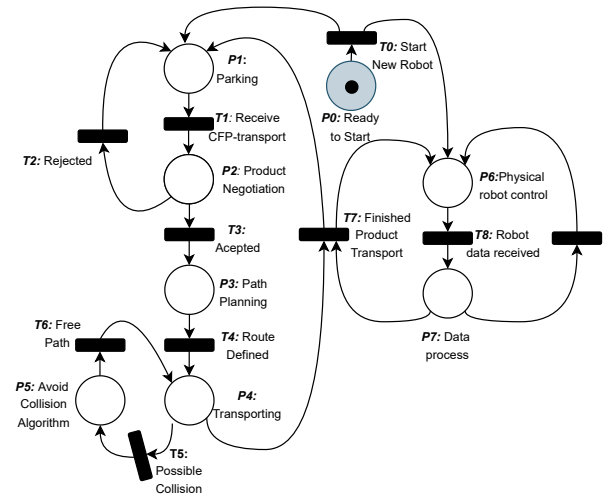


Fig. 4. Robot agent Petri net model.

The Petri net presented in Fig. 4 model the behavior of a robot agent. When idle, the robot move to the parking area (P1). When the agent receive a CFP-transport (T1), negotiations begin to transport a product (P2). If both parties agree (T3), path planning (P3) is carried out. If, during the route, a potential collision is detected (T5),

the avoidance collision algorithm is executed, avoiding obstacles (P5). The moment the robot finishes its transport (T7), it will be directed to the parking area, and during the return journey, it will be able to negotiate a new transport. In parallel, the robot controller is executed (P6) based on sensor data and position received from physical layer (T8).

3.4 Interaction Protocol

To implement the negotiation properties to warehouse operations, a communication solution based on CNET protocol with market based negotiation policies was applied. Fig. 5 shows the auction process. Each agent product individually assumes the auctioneer's role, responsible for proactively initiating negotiations with agents racks to select the ideal position within the warehouse, executing a broadcast for all existing agent racks. Therefore, the auctioneer sends a call for proposal (CFP) to all m racks in the warehouse. The active n racks (in faultless conditions $m = n$) can respond with rejection if there is no space to allocate a new product, these racks being called i . The j rack that already have space send the storage cost. The product will accept the rack at the lowest cost identified by I and reject the others. After defining the rack, a similar process begins to define which robot will carry out the transport, and therefore, the robot T .

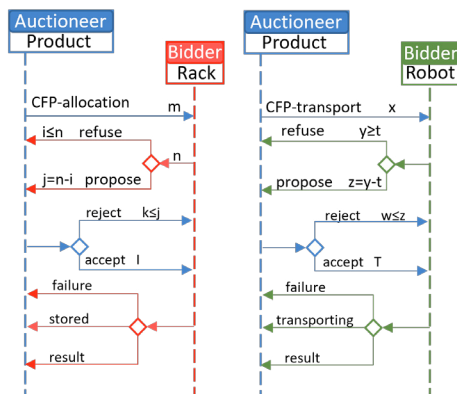


Fig. 5. CNET interaction protocol between agents.

4. CASE STUDY AND EXPERIMENTAL ANALYSIS

The case study is a warehouse developed for laboratory scale named ARENA. The warehouse components consists of up to eight robots operating simultaneously. In addition, four racks can store products, and two are dedicated to quality control (checking and staging area). The warehouse layout has traffic rules regulating the robot's trajectory and aisles to access the racks. The products are virtual elements plotted with augmented reality. Fig. 6 presents the developed structure and case study. Information related to ARENA development can be found in (Piardi et al., 2019).

The distributed CPS was developed using Robot Operating System (ROS) infrastructure and communication based on publish and subscribe. The agents and algorithms were implemented with python. The cyber agents run on microcomputers Raspberry pi 3b+ with a 64-bit A53 (ARMv8) quad-core processor with a 1.4GHz clock and 1GB RAM, with Lubuntu 18.04 OS. Each agent robot

is executed by dedicated Raspberry. All racks run on a single Raspberry with exclusive threads without sharing variables or memory. On the other hand, the products were divided into two Raspberry and did not share memories and variables.

To demonstrate the system approach, a series of experiments for smart warehouse was applied to ARENA. First, components scalability was analyzed, checking the capability of increasing robots in the system. The second experiment defines a scenario for a logistic operation to analyze the transport time for each product by varying the amount of products or robots in the system. The last experiment investigates the resources divisibility, more specifically the system's ability to divide the robot resources for transport products.

4.1 Scalability Analysis

To evaluate the scalability performance, it compared a centralized and a distributed approach. For the robot navigate and carry out the transport safely, the communication rate between the robot cyber and physical layer need to be 30 hertz. Therefore, when monitoring this interaction, it is possible to verify if the robot agent fulfills the expected behavior and functions, such as negotiation, route planning, communication, control, and data analysis.

The data collection was divided into two parts, totaling forty tests. The first twenty tests corresponding to the centralization of decisions, i.e., transport assignment and path planning of all robot agents, are assigned to a central decision agent. Starting from one to twenty robot agents (each running on its Raspberry), it sent data to the central decision agent (running on a extra Raspberry) to assign the product and path planning to each robot. In this part, one to twenty Raspberries were used for the robot agents and one for the decision agent. In the second part, the decision agent was removed, and each robot agent negotiated to accept the transport task and then executed the path planning. One to twenty Raspberries were used for this second part.

To quantify the cyber and physical communication rate, 2000 samples of time data were measured for each agent. As the number of agents in the experiments increases, the 2000 samples for each agent are maintained, and an average is calculated. Fig 7 presents the data from the centralized and distributed approach experiment.

During all tests, the decentralized agents were able to maintain the desired communication rate around 30 Hz, as intended. However, considering the centralized approach, there is a slight attenuation in the communication rate. The time that the decision-maker takes to generate a assignment solution and path planning reflects in the communication rate. This small attenuation gradually increases up to an operation of fourteen robots simultaneously, with a frequency of 26Hz. With fifteen robots in operation, a considerable attenuation of the communication rate is observed.

4.2 Transporting Time Analysis

A setup was established to validate the warehouse operation with the proposed distributed system, measuring

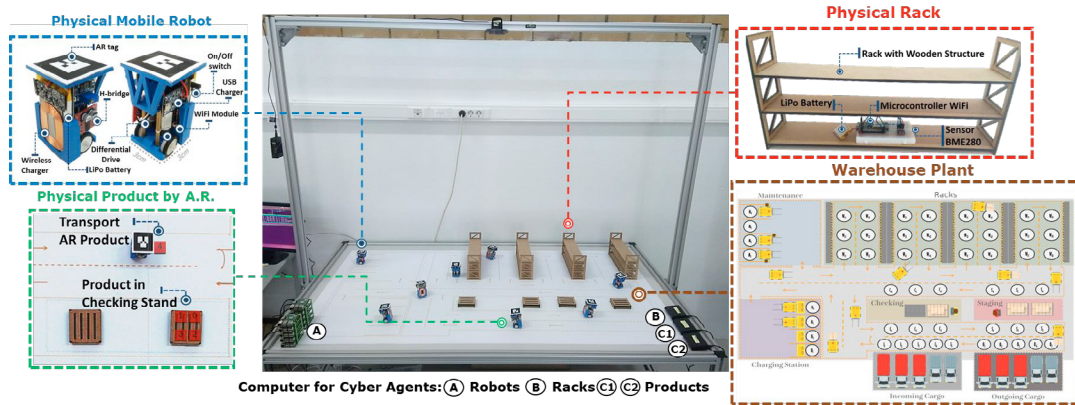


Fig. 6. Warehouse of case study in laboratory scale, composed by robots, racks and products.

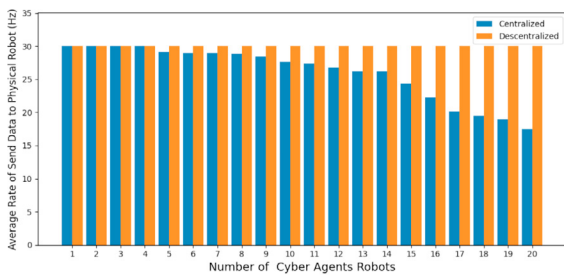


Fig. 7. Communication rate of the centralized vs decentralized system by increasing the number of agent robots.

the transportation time in two stages: (I) increasing the number of products and (II) increasing the number of robots. The objective is to transport products from the “incoming position” area to the “checking” area (named Transport A) and then to a rack where the product will be stored (named Transport B), as shown Fig. 8 and Fig. 9. To standardize the route and not affect the result, “rack 2” was defined to always win the CFP-allocation for this experiment. The processing time per product at the “checking” area was set to ten seconds.

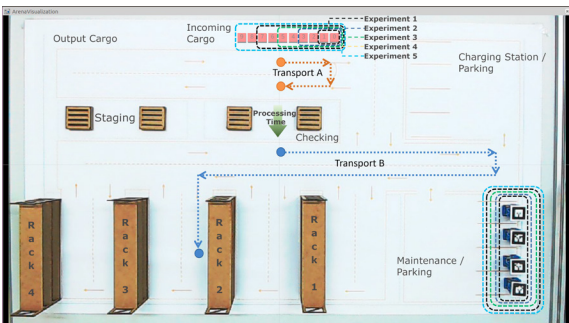


Fig. 8. Setup to time analysis when increasing products.

In the first stage, four agent robots were used to transport agent products that arrived at the warehouses to “rack 2”, as shown in Fig 8. In this stage, five experiments were carried out, starting with two-agent products (P1 and P2), and with each new experiment, two-agent products were increased to a total of ten products (P1 to P10).

For the second stage, a quantity of eight product agents was used (P0 to P7), which will be transported from “incoming cargo” to “rack 2”, as can be seen in Fig. 9.

In this stage, a total of four experiments were conducted, starting with two robot agents (R1 and R2) increasing two robot agents per experiment up to a total of eight robots (R1 to R8) to carry out all eight products to the “rack 2”.

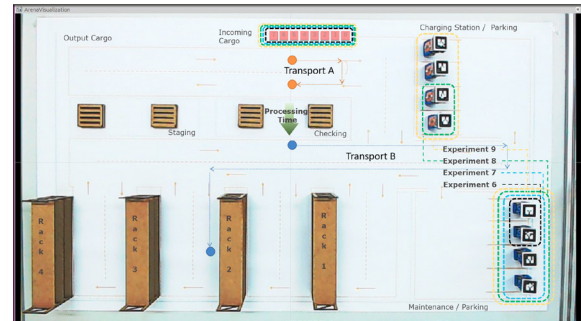


Fig. 9. Setup to time analysis when increasing robots.

Table 1 summarizes all the experiments performed that quantified transport times. It is possible to observe that Waiting Transport A depends on the number of robots per product. For experiments with more products than robots, this time tends to be longer for products that exceed the number of robots. As the number of products is greater than the number of robots, the system adapts to distribute this discrepancy in waiting transport times A and B.

4.3 Resource usage or divisibility

Two tests were carried out with four robots to analyze the divisibility and the use of resources. The first trial has six products, and the second has ten products. In both tests, all products take the following process plan:

The product starts at the “incoming cargo” and is transported to the “checking” where it passes through a process that takes ten seconds. Then, the product is transported to the rack that won CFP-allocation, where the product spends random time varying from five to ten seconds. Once the storage period is complete, the process of leaving the warehouses begins, requesting transport to the “staging” area where they will be processed for ten seconds. After processing time is over, they are transported to the “outgoing”, leaving the warehouse.

In the first trial, there are twenty-four transport actions (four for each product) performed by the four robots. In

Table 1. Statistical results nine experiments for transport time (robot (R) and product (P)).

Experiment	Waiting Transport A [s]				Transport A [s]				Waiting Transport B [s]				Transport B [s]			
	avg	std	min	max	avg	std	min	max	avg	std	min	max	avg	std	min	max
1 (4R - 2P)	82.50	2.12	81.00	84.00	6.50	2.12	5.00	8.00	41.00	2.83	39.00	43.00	32.00	0.00	32.00	32.00
2 (4R - 4P)	86.50	5.51	81.00	93.00	8.50	2.89	5.00	12.00	72.50	5.92	64.00	77.00	36.25	2.50	33.00	39.00
3 (4R - 6P)	93.83	14.51	81.00	113.00	7.33	1.37	5.00	9.00	91.33	13.26	73.00	103.00	33.50	1.64	32.00	36.00
4 (4R - 8P)	98.63	16.44	82.00	122.00	7.13	1.73	5.00	10.00	121.88	35.61	83.00	173.00	34.75	1.83	32.00	37.00
5 (4R - 10P)	113.90	30.65	82.00	176.00	9.20	2.04	6.00	12.00	137.00	42.83	72.00	196.00	35.20	1.81	33.00	38.00
6 (2R - 8P)	205.25	153.00	69.00	398.00	8.38	1.92	6.00	11.00	115.63	37.85	72.00	181.00	34.13	1.81	31.00	37.00
7 (4R - 8P)	98.38	14.94	83.00	120.00	7.50	1.07	6.00	9.00	120.88	33.81	83.00	168.00	35.75	1.04	34.00	37.00
8 (6R - 8P)	98.00	12.77	79.00	118.00	10.25	1.16	9.00	12.00	89.63	12.86	78.00	111.00	37.75	2.82	35.00	42.00
9 (8R - 8P)	100.38	11.15	84.00	115.00	9.75	3.15	5.00	15.00	83.75	9.11	65.00	94.00	39.88	3.31	34.00	45.00

the second trial, there are 40 transport actions performed by the four robots. The video available in https://youtu.be/MNn_VnH-w18 shows the execution of these experiments. Fig. 10 shows the number of products transported by each robot. The result indicate that the approach presents a distribution of resources to carry out the transport of robots without the need for centralization.

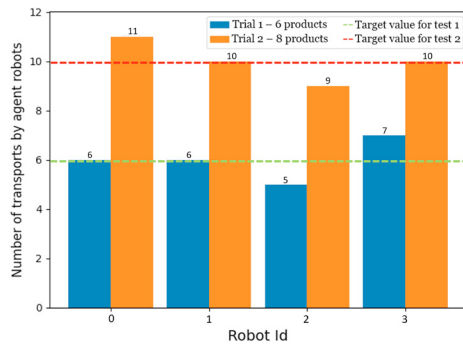


Fig. 10. Divisibility of the robots to transport products.

5. CONCLUSION AND FUTURE WORKS

Flexibility, robustness, and scalability are fundamental requirements of smart warehouses. The integration of new technologies has been cooperating to advance these aspects. However, the traditional adoption of central monolithic or hierarchical systems limits the benefits of technologies in warehouses operation. This work presents a distributed methodology using MAS-based CPS. Through the exchange of information and negotiations, the warehouse operation occurs based on the autonomy and collaboration of robots, racks, and product agents. The proposed approach was extensively tested using a small-scale warehouse scenario, analyzing scalability, transport time, and resource divisibility. The results show the approach's feasibility, motivating the improvement to be tested and applied in a real warehouse.

Future work will be devoted to improving and optimizing the negotiation metrics to adapt to and reconfigure in the presence of disturbance. Additionally, efforts are being directed toward validations on a larger scale to complete the analysis of the approach's feasibility.

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