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FEATURES OF WAVE ALGORITHM APPLICATION IN WAREHOUSE LOGISTICS TRANSPORT SYSTEMS

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The relevance of research in the field of storage organization using automated transportation systems, including pallet transport technology using Radio Shuttle as part of Warehouse 4.0, is due to the rapid development of modern industry [1–3]. With the emergence of Warehouse 4.0 concept, warehouse systems have become an integral part of enterprises digital transformation within the framework of Industry 4.0 concept [4–6]. Automated transportation systems make it possible to significantly improve the productivity and efficiency of warehouse operations. This made it possible to improve the technologies of pallet storage and transportation moved to a new level became more flexible and adaptable thanks to Warehouse 4.0. This allows enterprises to cope with the growing volume of goods, meet the needs of customers and reduce costs. Robotic transportation systems using Radio Shuttle not only ensure pallets uninterrupted movement, but also integrate with other technologies, such as data analytics, artificial intelligence and the Internet of Things, enriching the warehouse system with valuable information data [7]. In addition, in the context of sustainable development, automated transportation systems based on Radio Shuttle allow to reduce energy consumption and reduce the impact on the environment, which corresponds to modern standards of responsible production and allows companies to implement environmentally sustainable practices.

But despite all the positive aspects of the implementation of automated transportation systems based on Radio Shuttle as part of Warehouse 4.0, these systems have a number of significant disadvantages. One of them is the limited flexibility when using the Radio Shuttle system, which refers to limitations in the ability to change or reorganize warehouse space without serious technical changes [8–10]. Here are some aspects that make the system less flexible:

– Radio Shuttle works inside certain rails and specially designed racks. These structural elements are specially designed to work together with the system. Because of this, it is impossible to simply change the configuration of the warehouse, move racks or rails. Changing the warehouse structure will require a complete restructuring of the system, which is difficult and expensive;

– due to fixed rails and racks, storage options are limited. The system does not allow quick adaptation to new types of goods or changes in demand. New products may not meet the system parameters, this creates difficulties in their effective storage and use;

– because the system works within a limited space, products that require turning or flipping for optimal storage can cause complications. In some cases, this can lead to inefficient use of warehouse space;

– difficulties with manual access. If manual access to the goods is necessary (for example, for inventory or processing of defective goods), the Radio Shuttle system could become an obstacle due to its fixed elements. It will be necessary to disrupt the normal operation of the system to carry out such operations.

So, the limited flexibility of the Radio Shuttle system means that warehouse operations become less adaptable to changes, which can lead to inefficient use of resources and hinder the company's ability to adapt to changing market requirements [11–13]. As a result, there is a task of developing a new or upgrading existing robotic systems based on Radio Shuttle, which will reduce the impact of limited flexibility and achieve a more additive approach to the storage of goods within the framework of Warehouse 4.0 [14].

Radio Shuttle systems, like many other automated storage systems within the framework of Warehouse 4.0 [15], can interact with various storage methods, such as LIFO (Last-In-First-Out) and FIFO (First-In-First-Out). We will compare the main disadvantages of these methods and present them in Table 1.

Table 1

The LIFO and FIFO Storage Methods Main Disadvantages Comparison

Disadvantages	Radio Shuttle Method	
	LIFO	FIFO
Goods management	1. Difficulties in handling the goods last taken. 2. Difficulties with distribution of goods due to different sizes and characteristics of goods new batches	1. Difficulties in managing the order of movement of goods. 2. Difficulty in managing the use of space due to the need to store old goods closer to the exit
Accessibility	Limited access to old products due to their remoteness within the system	Difficulties in changing the order, especially if it is necessary to take the old goods first.
Space	Restrictions in the effective use of space due to the location of the last goods closer to the exit.	Difficulties in optimizing the use of space due to the need to store old products closer to the exit
Flexibility	Difficulties in changing the configuration of the system due to fixed rails and racks	Difficulties in managing the goods movement order and making changes due to the non-optimal structure of the system.
Interference	Difficulty in reordering in the occasion of an intervention requiring old items to be taken first	Difficulties in intervening in order due to the need to maintain order when issuing goods

As can be seen, the existing disadvantages of LIFO and FIFO storage methods are influenced by Radio Shuttle design features, such as:

– limited flexibility of Radio Shuttle design: The disadvantages of LIFO and FIFO methods reinforce the limited flexibility of Radio Shuttle design. For example, if the system is LIFO, it is more difficult to distribute new goods and rearrange the storage of old goods due to fixed rails and racks. Such restrictions can make it difficult to optimize warehouse space and manage the movement of goods;

– difficulties in managing access to goods: If the system uses the LIFO method and the latest goods are stored closer to the exit, this may create restrictions on access to old goods, especially if there is a need for manual access to them. Similarly, in the case of FIFO, it is more difficult to organize quick access to new goods, since old goods may take up more accessible space within the system;

– optimizing space usage: Disadvantages in storage methods can increase the challenges of optimizing space usage within Radio Shuttle structures. Difficulties in efficient space using may arise due to the system's inability to adapt to different sizes and goods characteristics that require storage using certain methods (LIFO or FIFO);

– difficulties in configuration changes: If LIFO and FIFO methods require changes in goods distribution, this may require major changes in the configuration of the Radio Shuttle system. This, in turn, can be a labor-intensive and costly process, which creates difficulties in System control [16].

Thus, the disadvantages of LIFO and FIFO storage methods may exacerbate limitations and weaknesses in Radio Shuttle design, creating additional challenges in optimizing and cotrolling warehouse operations. The optimal solution in this situation requires a careful analysis of warehouse requirements and selection of a storage method that best meets the characteristics of the goods and warehouse operations[17, 18]. The main types of Radio Shuttle that are used within Warehouse 4.0 are presented in Figure 1 [19].

a) b) c) d)

Fig. 1. Main Radio Shuttle Types That Are Used within Warehouse 4.0
a) Radio Shuttle; b) Multi-deck Shuttle carrier;
c) Four-way Shuttle system; d) Shuttle Carrier

Based on the design features of the above Radio Shuttle, we will conduct a study and compare the permissible movement trajectories, which are presented in Table 2.

From the presented table it can be seen that each of the systems has its own advantages and limitations regarding permissible movement trajectories. The use of Mecanum wheels can significantly improve the efficiency and flexibility of these designs.

Table 2

Acceptable Radio Shuttle Movement Trajectories Comparison

Parameters/ Systems	Radio Shuttle [19]	Multi-deck Shuttle carrier [19]	Four-way Shuttle system [19]	Shuttle Carrier [19]
Trajectory Limitation	Restricted to rails and racks	Multi-link system with different levels	Multi-tasking system with four-way movement capability	Limited to a specific trajectory in the warehouse
Space Efficiency	Limited due to fixed rails and shelving.	Effective use of many levels	Efficient use of space due to flexible trajectories	Limited due to fixed trajectories
Flexibility and Customizability	Limited flexibility due to fixed trajectories	More flexibility due to the ability to move at different levels	High flexibility due to four-way movement	Limited flexibility due to fixed trajectories
Difficulties in Control	May require complex setup and control due to limited trajectories.	May require additional control when moving to different levels	Requires careful control to avoid collisions when driving in different directions	Requires precise control to avoid collisions on fixed trajectories

Here are the conclusions that can be drawn to justify the improvement of these structures through the use of Mecanum wheels:

– good flexibility and maneuverability, Mecanum wheels have the ability to move in any direction without the need to turn the entire structure. This adds high agility and flexibility when moving goods in tight spaces. This is a key advantage when working in warehouse environments;

– easy access to goods, thanks to the ability to move sideways and diagonally, Mecanum wheels provide easy access to goods located at various levels and angles, reducing the complexity of moving goods in systems with many levels and complex configurations;

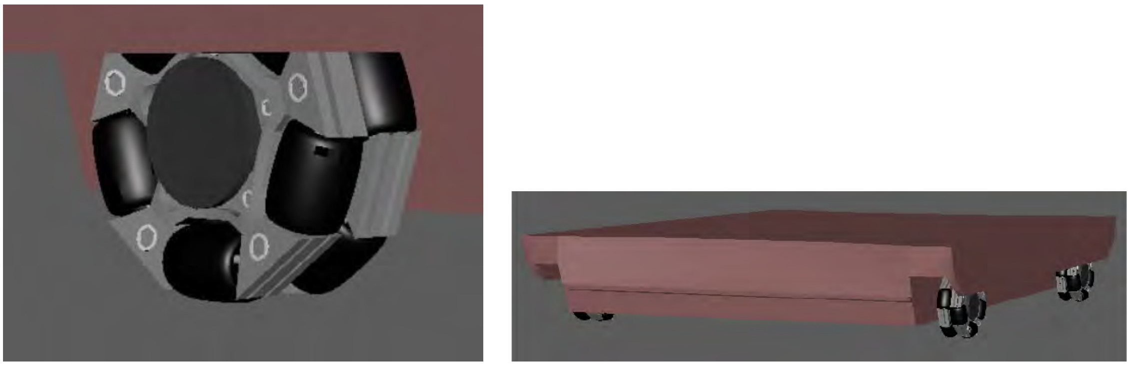
– efficient space using, Mecanum wheels allow optimal space using in the warehouse, as they allow movement in different directions without the need to rebuild the entire system, which is especially useful in systems with limited space;

– simplified control, moving in any direction without turning, systems with Mecanum wheels can be controlled more efficiently and accurately. This allows you to avoid collisions and optimize the planning of goods movements;

– easy implementation and integration, Mecanum wheels are easy to install and integrate, making it easy to upgrade existing designs without having to completely replace the system.

Thus, the use of Mecanum wheels improves the flexibility, maneuverability, accessibility and controllability of existing structures, making them more efficient and adaptable to different working conditions in the warehouse. These advantages justify the decision to improve systems using Mecanum wheels [20].

Using 3D modeling, let us design a Radio Shuttle robotic platform with built-in Mecanum wheels; an example of implementation is shown in Figure 2.



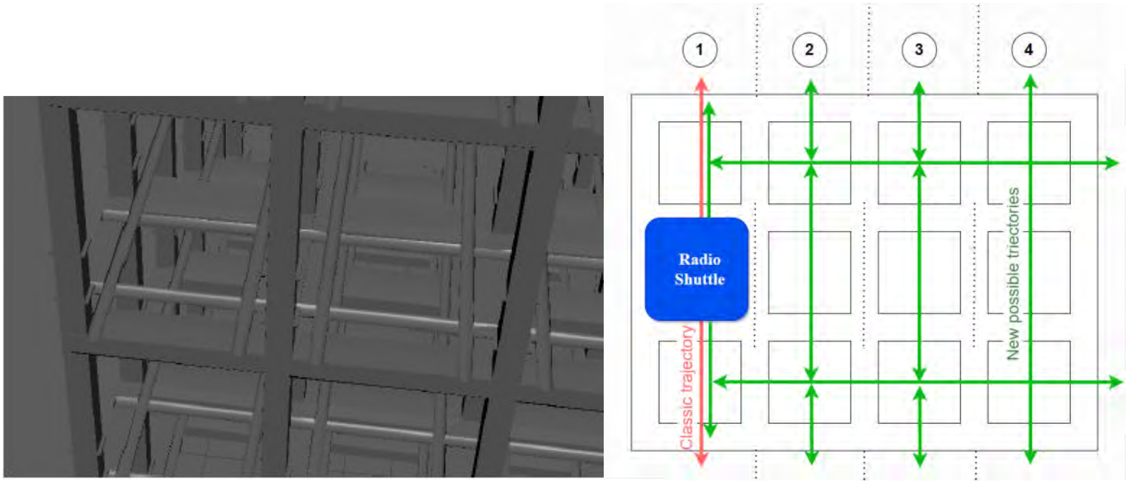
a) b)

Fig. 2. Mecanum Wheels 3D Model on 3D Radio Shuttle Robotic Platform
a) Mecanum Wheels 3D Model;
b) Radio Shuttle Robotic Platform 3D Model General View

So, it is necessary to improve the supporting structure of the racks in order to realize the benefits of Mecanum wheels on the Radio Shuttle platform. A 3D model of rack structure and a schematic representation of permissible movement trajectories are presented in Figure 3.

Let's improve the wave algorithm in accordance with the schematic representation of the permissible trajectories of Radio Shuttle movement when using Mecanum wheels.

Let W – wavefront matrix of size $M \times N$, where M – number of lines, N – number of columns. We denote the initial position of the robot by (x_{start}, y_{start}), since the route is arranged in two-dimensional space, therefore the final position where the robot should deliver/pick up the cargo will be denoted by (x_{end}, y_{end}). Let us fill in the wavefront matrix $M \times N$ by values -1. This will indicate that a given cell in the matrix W, Radio Shuttle was not visited. Let us set $W(x_{start}, y_{start}) = 0$, this entry will make it possible to indicate that Radio Shuttle is in this position. Now we can move on to a description of wave propagation. Wave propagation is a key step in the wave propagation algorithm. In this step, the wave propagates from the starting position of the Radio Shuttle to the remaining cells in the work area. In each iteration of this step, the wave propagates one cell further from the starting position. The robot uses this wave to determine the shortest path to each cell in the warehouse. Based on this, we can say that the first cell in the wave front will be $W(x_{start}, y_{start}) = 0$. From this we can conclude that every cell that has a value of 0 in the wavefront matrix is the first wave.



a) b)

Fig. 3. Rack Design 3D Model and Acceptable Radio Shuttle Moving Trajectory Schematic Representation: a) Rack Design 3D Model
b) Acceptable Radio Shuttle Moving Trajectory Schematic Representation

For each cell that is part of the current wave $W(x_i, y_i) = current\_wave\_value$, all its admissible neighbors are considered. If the neighboring cell has a value -1, then we set the value of the wavefront in this cell equal to the current value of the wavefront $+1$. This means that the wave propagates to this cell from the previous wave to a distance 1.

Formally, this can be written as follows for the cell (x, y) and its neighbor (x', y').

$$W(x, y) = current\_wave\_value$$
$$W(x', y') = -1 \tag{1}$$
$$W(x', y') = current\_wave\_value + 1$$

This part means that if the current cell (x, y) has a wavefront value equal to $current\_wave\_value$, and its neighboring cell (x', y') hasn't been visited yet. That is, its value in the matrix $M \times N$ is equal to -1, then, accordingly, the new value of the wave front for the cell (x', y') will be $W(x', y') = current\_wave\_value + 1$. This update occurs when a wave propagates to a new cell, through the current cell.

$$W(x', y') \neq -1 \tag{2}$$

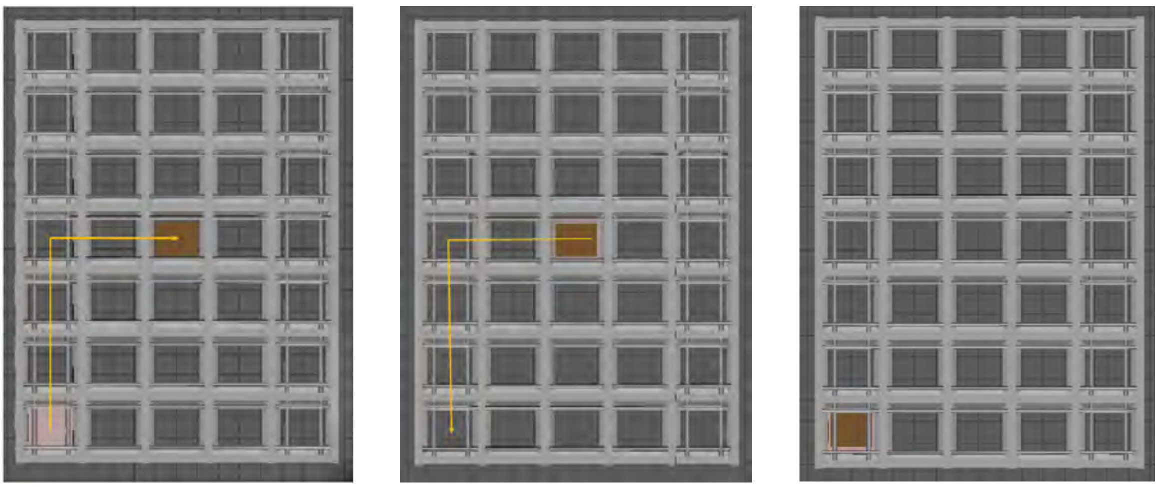
Means that if an neighboring cell (x', y') already has a wavefront value (i.e., its value is not -1), then this value is retained. There is no wavefront update because the wave does not propagate to cells that have already been visited. Thus, it is determined how to update the value of the wavefront during wave propagation, taking into account the current value of the wavefront in the cells (x,y) and neighboring cell (x',y') state.

The next step in finding the shortest path in the wave propagation algorithm occurs after the wave has been successfully propagated from the initial position to all other cells in the working area. The process of finding the shortest path consists of going back from the final position to the starting position, choosing a path through cells with decreasing wavefront values. This process ensures that the path found using wave propagation is the shortest path as it follows cells of decreasing wavefront values from the final position to the starting position. Let's describe it like this: let (x,y) be the current position, we look for neighboring cells (x',y') that satisfy the following condition

$$W(x',y') = W(x',y') - 1 \ . \tag{3}$$

In expression 3, $W(x,y)$ is the value of the wavefront in the cell (x,y). After finding such a cell, we add it to the path and set $(x,y) = (x',y')$. The process is repeated until we reach the starting position. The resulting path will be the shortest path from the end position to the start position.

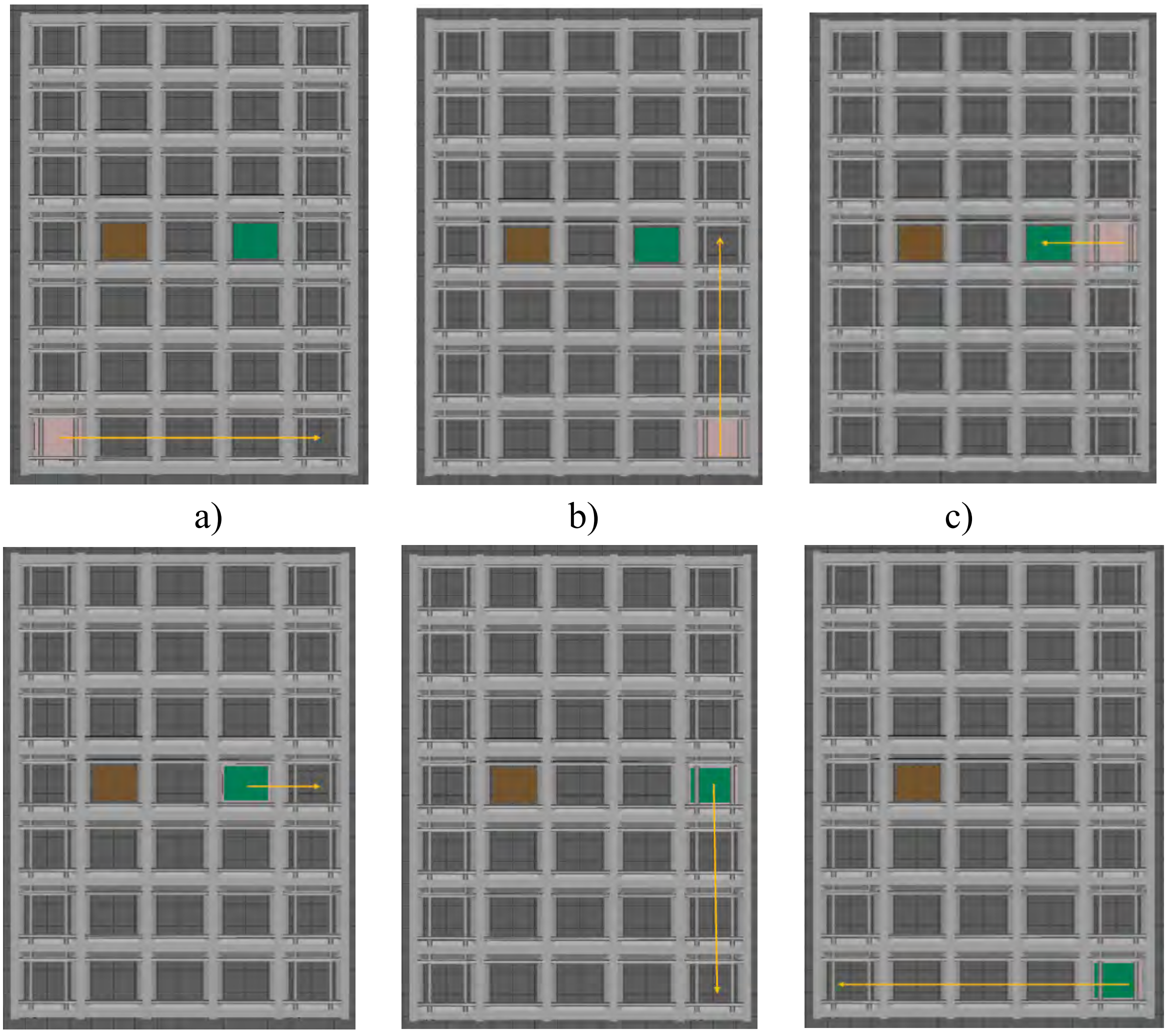
To check the correctness of decision-making, let us conduct several experiments to simulate the movements of the Radio Shuttle. Let the Radio Shuttle be in the lower left part of the storage system, and the cargo that needs to be retrieved be in the center of the storage system. Using the improved wave algorithm (1–3), we will simulate route construction in the developed 3D model of the storage system. The simulation results are presented in Figure 4.



a) b) c)

Fig. 4. Results of the First Experiment in Modeling the Route Construction of an Improved Radio Shuttle: a) starting point (with a constructed route); b) end point (route back); c) Radio Shuttle delivered the cargo

Let's complicate the experiment, install 2 cargoes, among which we need to pick up only the green one, and build a route based on the improved wave algorithm, the starting point will be the same as in Figure 4, a. The simulation results are presented in Figure 5.



a) b) c)

d) e) f)

Fig. 5. Results of the Second Experiment of Modeling the Route Construction of an Improved Radio Shuttle

Let's carry out the third experiment, install 4 cargoes, among which we need to pick up the yellow one, and take it to the starting point, the starting point will be the same as in Figure 4, a. The simulation results are presented in Figure 6.

Based on the results obtained during the experiments (Fig. 4–6), a graph was constructed that shows the effectiveness of the improved wave route search method for Radio Shuttle. Graph of the number of sections passed versus the amount of interference is presented in Figure 7.

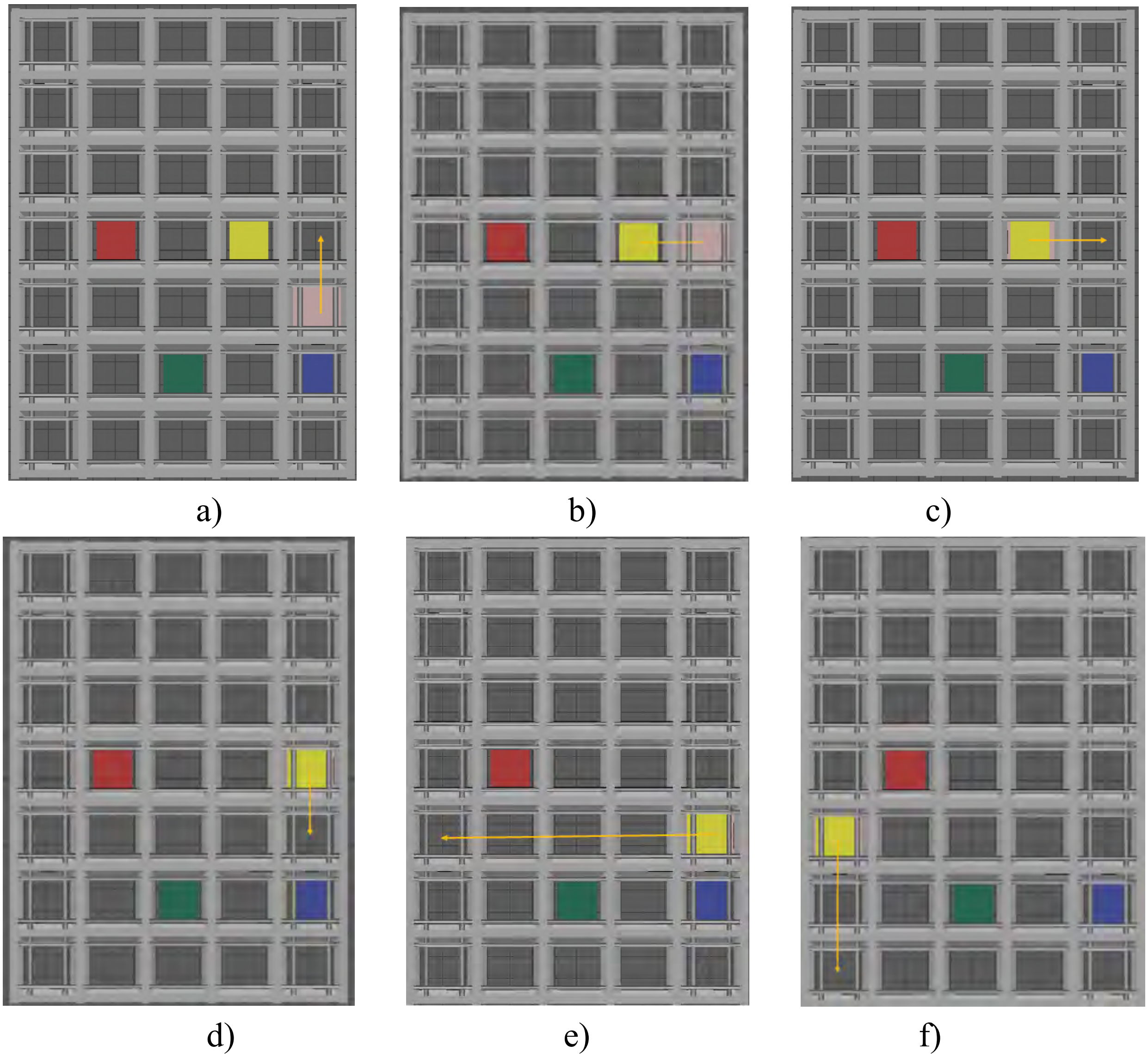


Fig. 6. Results of the Third Experiment
in Modeling the Route Construction of an Improved Radio Shuttle

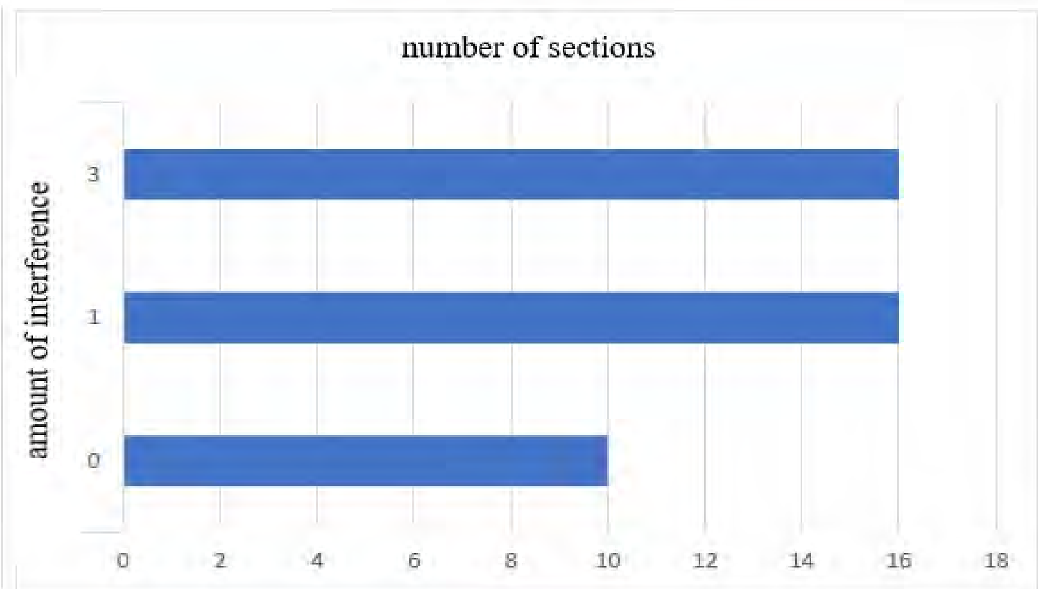


Fig. 7. Graph of the Number of Sections Passed Versus the Amount of Interference

Conclusions

In the proposed section of the collective monograph, the authors present an innovative approach to improving the Radio Shuttle design using Mecanum wheels. This improvement significantly increases the system functionality and mobility, allowing the Radio Shuttle to move freely horizontally and vertically in any plane. The main result of the study is the development and implementation of an improved wave algorithm for constructing Radio Shuttle moving routes in new conditions.

The integration of Mecanum wheels into the Radio Shuttle design has led to significant changes in the design of product storage racks. These changes created a more flexible and efficient storage system capable of moving in any direction and vertically, which was not previously possible with the Radio Shuttle system.

To confirm the effectiveness of the proposed solution and the correctness of the decisions made, the researchers developed a 3D model of the Radio Shuttle and the racks. After this, a series of simulations were carried out, which demonstrated the successful operation and high efficiency of the new system. Simulation results confirmed the improved performance, mobility and accuracy of the Radio Shuttle, making this improvement highly promising for practical implementation in warehouse systems and improving the efficiency of logistics processes. The findings highlight the significance of the proposed changes and their potential to optimize warehouse operations and improve overall performance in the logistics and storage of goods within Warehouse 4.0.

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