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DISCRETE EVENT SIMULATION MODEL FOR EXPECTED CYCLE TIME OF AS/RS WITH DOUBLE DEEP PALLET RACK

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Abstract

Automated storage and retrieval systems are widely used in highly dense tall warehouses as an important part of material handling systems, as they can efficiently reach highly positioned loads and their footprint is narrow. Their performance within the system can be evaluated using discrete event simulation techniques. The model created and described in this paper is a model of an automated storage and retrieval system working on a single and double deep pallet rack storage system. The parameters obtained through the simulation were the average single command cycle time and throughput.

Keywords*: Expected cycle times, Automated storage and retrieval systems, Discrete event simulation.*

1 INTRODUCTION

Warehouses have a significant importance in multiple segments of supply chains, as part of production as well as distribution of goods. Even though the focus of a supply chain designer is to reduce the need for warehousing, as explained in [1], storing production materials and produced goods has a strategic importance for compensating the fluctuations in production and market. Considering that in many cases warehousing is necessary, it is often the polygon for performing various experiments for optimization purposes since the costs of the warehousing can be significantly increased if the operations within are run inefficiently.

The design of the warehouse is a complicated, iterative process and it is consists of the design of various subsystems, such as systems for storing and keeping the material, and the material handling systems which is the bloodline of every warehouse tying all processes together. Authors have recognised the complexity of the warehouse design and some have created algorithms to help ease the process. Peter Baker and Marco Canessa did a review of many design algorithms in the paper [2]. Discrete event simulation is prevalent for performing experiments when picking an optimal warehouse design because of its cost and time effectiveness. Agalianos et al. [3] did a comprehensive review of discrete event simulation and digital twin models in logistics. Ardiansyah et. al. [4] used discrete event system simulation approach to improve warehouse layout effectivness and process picking efficiency.

The use of automated storage and retrieval devices in high-bay double-deep pallet racking warehouses has numerous advantages as they enable efficient use of vertical space. They are widely used as they are very robust, and based on mature technologies. According to the authors of [5], AS/RS systems can be studied from two perspectives, one of which is the dynamic behaviour of such a system. The authors of [6] studied the 2n-cycle with the goal of finding a schedule which maximises the capabilities of the multi-shuttle cranes in automated warehouses.

In this paper a simulation model of the AS/RS device within a single aisle with the focus on determining the average cycle time of the transportation devices embedded in a simple software solution made using Lazarus 4.2 will be presented.

2 SIMULATION MODEL

The average throughput is the most important parameter for evaluating the performance of an AS/RS device according to [7]. The average throughput depends on multiple factors such as the geometrical and technical characteristics of the AS/RS devices and storage devices, the configuration of the system, task scheduling, the position of the input and output points, as well as the position of the resting point if there is such where the AS/RS device places itself when it is inactive. It can be calculated using the following expression:

$$C = 3600 \frac{n}{\sum_{i=1}^{n} T_{sc_i}} \quad (1)$$

…where $C\ [h^{-1}]$ is throughput, n is the total number of completed cycles, and T_{sc_i} is the time it took for the device to complete the i-th cycle.

The cycle times T_{sc_i} can be obtained through the discrete event simulation. There are many discrete event simulation models, and this paper will propose an alternative, easy to program, simulation model.

The process of creating a simulation can be divided into several steps illustrated with Fig. 1. The first step is to define the rack and isle geometry. This can be accomplished by defining the dimension of the characteristic storage cell and by defining the number of storage cells within a storage rack by each dimension. Once that is accomplished, the number of racks should also be defined as there can be a single rack per aisle, or two racks on each side of the aisle. If it is assumed that the length of the aisle is dependent on the length of the storage racks, the width of the aisle is the only required parameter. The second step is to generate a storage cell database which is consisted of the storage cell numbers, coordinates of the storage cells, as well as the information about if the storage cell is occupied or not, or if it is accessible or not. The coordinates of the storage cells are obtained from the previously defined rack and aisle geometry. The next, third step is to define AS/RS technical characteristics, which include the velocities in each direction, acceleration and breaking times, as well as defining the coordinates of the characteristic positions of the AS/RS device, such as input points, output points, and the resting place if there is such. The fourth step is defining simulation conditions.

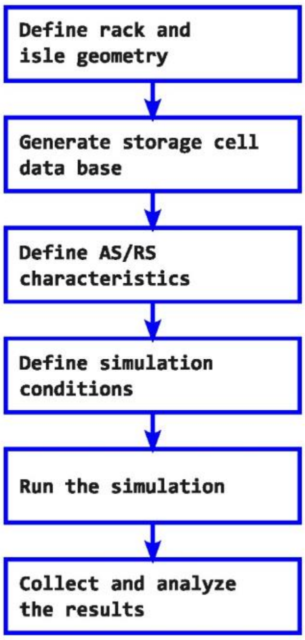

***Fig. 1** Flowchart of the AS/RS Simulation Process*

1.1. Geometry input

The observed geometry of the model is focused on a single aisle and the pallet racks by which it is surrounded, so the model of the storage space is consisted of the left and the right rack with the aisle in the middle.

The centre of the coordinate system O (0,0,0) can be placed in the lower left corner of the left rack, as it is displayed in the Fig. 2.

These racks have their geometrical characteristics such as: storage cell dimensions, total width, total height and depth, as well as total storage capacity. Some of these characteristics are dependent on others. Within the created software displayed in Fig. 3, the characteristics of the racks are determined through the dimensions of the storage cells, gaps between the cells, and the number of storage cells by each axis. The number of racks tells the software if there is only a left or right pallet rack, or if there are racks on both sides of the corridor. This parameter can take only integer values: 1 or 2. After the “Define racks” button is pressed, the table with coordinates of the storage cells is being generated and displayed.

Each storage cell is represented with two points: $P_i(x_i, y_{i_1}, z_i)$ and $P_i'(x_i, y_{i_2}, z_i)$, where $i = 1, 2 \dots n$. These points are placed at the bottom of the storage cells, where the forks of the AS/RS devices access the storage cells. The horizontal and vertical coordinates can be calculated using the following expressions:

$$x_i = n_{x_j} \cdot (x_{cell} + dx) - \frac{x_{cell}+dx}{2}, j = 1, 2, \dots n_x \quad (2)$$

$$z_i = n_{z_k} \cdot (z_{cell} + dz),\ \ k = 0, 1, \dots n_z - 1 \quad (3)$$

In these expressions, n_x and n_z denote the number of storage cells by x and z axis, respectively, n_{x_j} and n_{z_k} denote the order number of the i-th storage cell in the row and the order number within the column respectively, x_{cell} and z_{cell} denote the width and height of the storage cell, dx and dz denote the spacing between the storage cells within the rack in each respective direction.

The y_{i_1} and y_{i_2} coordinates can be determined after the width of the aisle between the racks is defined, and the way of determining the coordinates is illustrated in the Fig. 2.

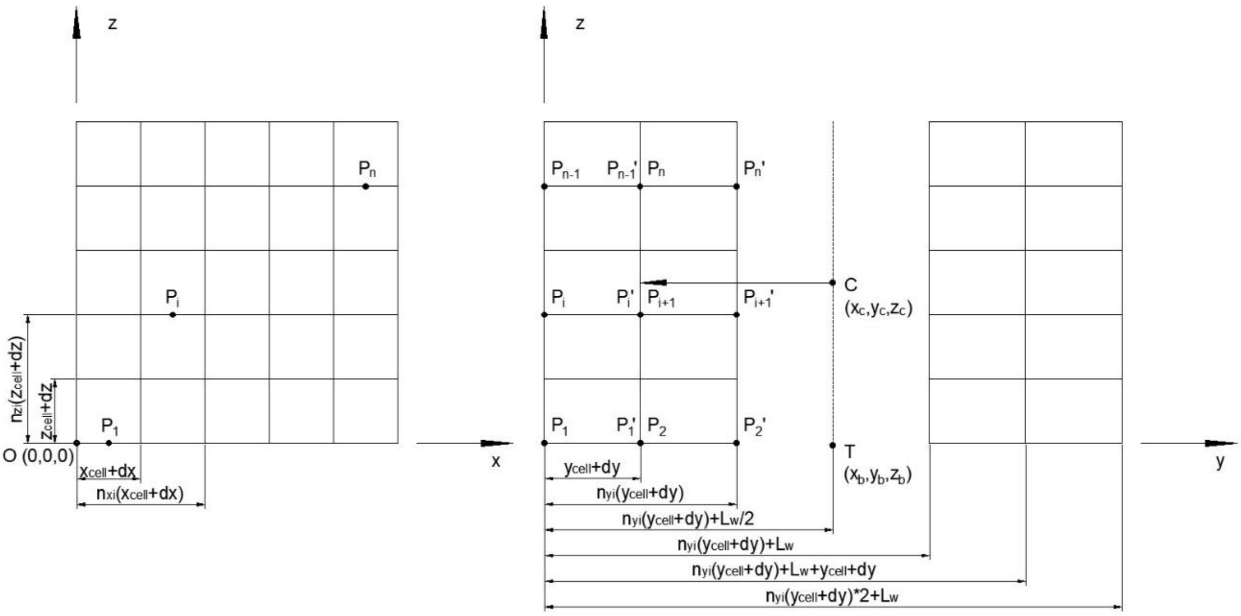

***Fig. 2** Illustration of a model containing two pallet racks and an aisle in between*

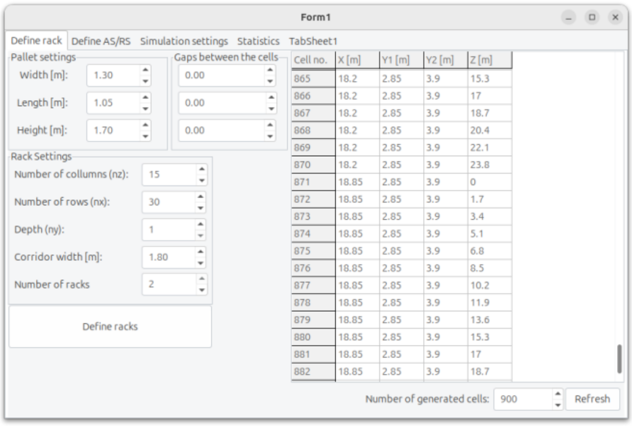

Fig. 3 *AS/RS warehouse configuration window*

If there is a need for keeping the information about the state of the storage cell, if it is occupied, empty, accessible or not, an additional column containing that information can be added to the table within the software presented in Fig. 3.

1.2. Defining the AS/RS device

An AS\RS device can be represented as a dot that moves through the three-dimensional space of previously defined aisle and pallet racks. The coordinates of the dot represent the position of the forks of the AS\RS device, and the dot mimics the movement. In this case, the model of the AS\RS device is created using the following assumptions:

- the acceleration and deceleration of the AS\RS device are infinite;
- the mass of the load does not influence the velocity of the device;
- the device moves along the aisle and it performs lifting at the same time, but the forks are fixed during the main motion;
- time for fine manipulation is constant.

Even though in this case it is assumed that the mass of the load does not influence the velocity of the device, the software allows the use of different velocities for each moving direction when the AS\RS device is loaded or not, as can be seen in the Fig. 4.
When the AS\RS device completes the single cycle commands, it starts the movement from its resting place, or "the base point". The coordinates of the base point can be defined in the "Base coordinates" section displayed in the Fig. 4. By default, it is placed to be in the middle of the isle, but if it is needed, these coordinates can be manually defined. These devices perform two different operations: storing newly arrived pallets inside the pallet racks, or taking the existing, already stored pallets, out of the pallet racks and transporting them to the output point. When the device is storing in the newly arrived pallet, from the base point, it moves to the previously defined input coordinates, it picks up the pallet, moves back to the middle of the isle, and then it travels to the storage cell in which the picked pallet is assigned to be stored. Once the AS\RS device reaches the coordinates of the storage cell, it extends the forks perpendicular to the vertical plane of the middle of the aisle until the end of the storage cell, and it performs fine manipulation for dropping the pallet into its place. After that is completed, the forks return to the middle of the isle and the device can return to its base point from where it waits for another task.
When the AS\RS device is assigned to take the pallet out of the pallet rack, the cycle also starts from the base point, contrary to the previous case, it travels to the coordinates of the storage cell from which it should retrieve the pallet first. The forks then travel to the end of the storage cell, performs fine manipulation for picking the load up, and then it retreats its forks with the load to the middle of the isle from where it travels to the place it needs to unload the pallet, the output point, where it, again, performs the fine manipulation while unloading the pallet and returns to the middle of the aisle. Once the device is located in the middle of the aisle, it travels back to its base point where it waits for another task.
Input point and output point can be defined through coordinates, which can be seen in the Fig. 4, along with the fine manipulation time.

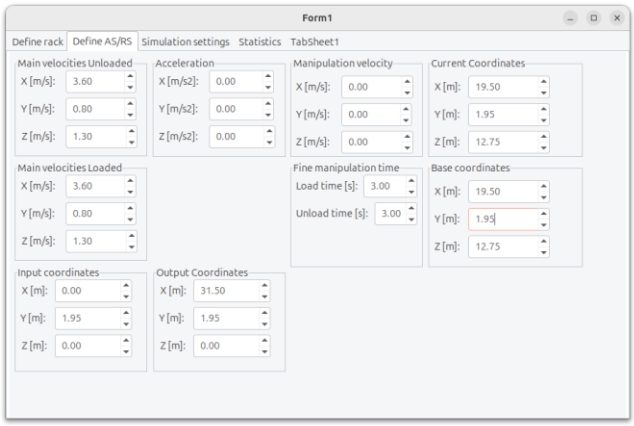

Fig. 4 *AS/RS device parameters window*

3 THE AS/RS MATHEMATICAL MODEL

The automated storage and retrieval system can be simplified to the material dot which completes the movements of the AS/RS device. The AS/RS device has two main motions along the horizontal and vertical axis of the aisle, and the third motion, perpendicular to the plane defined by the two main motion directions, as well as the motion for fine manipulation. The speed of the AS/RS device, while performing the main motion along the aisle is:

$$\vec{v} = \frac{d\vec{r}}{dt} = \frac{dx}{dt}\vec{\imath} + \frac{dz}{dt}\vec{k} \qquad (2)$$

The time it takes for the AS/RS device to complete the main movement can be calculated using the following expression:

$$|\vec{v}| = \frac{s_1}{t_1} \rightarrow t_1 = \frac{s_1}{|\overrightarrow{v_{max}}|} \qquad (3)$$

From Eq. (2), the velocity can be calculated as:

$$|\overrightarrow{v_{max}}| = \sqrt{|\overrightarrow{v_x}|^2 + |\overrightarrow{v_z}|^2} \qquad (4)$$

When the AS\RS moves through the aisle conducting the main motion, crossing the path from one point to another, the path it is taking depends on the relation between the angle of speed vector during the main motion α and the imaginary line that connects the current destination of the AS\RS device and its destination φ, as displayed in the Fig. 5. Five cases can be distinguished following this relation, and they are illustrated in the Fig. 6-10.

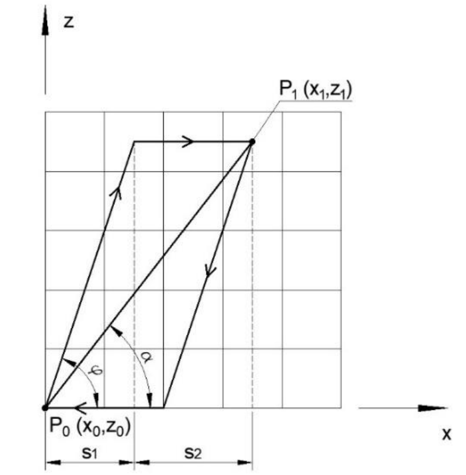

Fig. 5 *AS/RS speed vector and destination line angle relation*

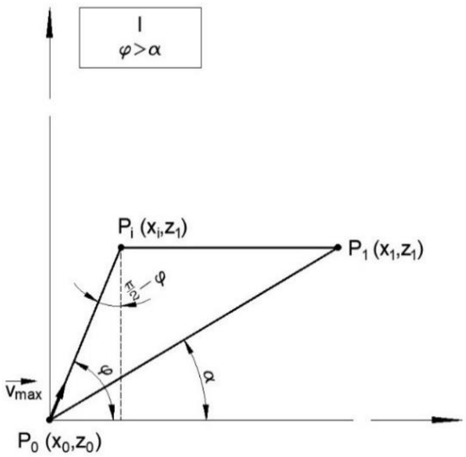

Fig. 6 *AS/RS device movement case 1*

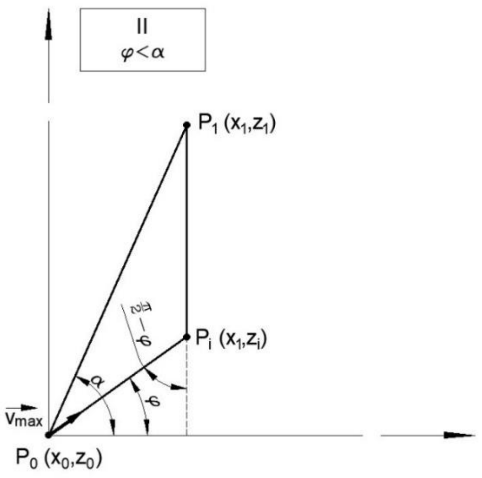

Fig. 7 *AS/RS device movement case 2*

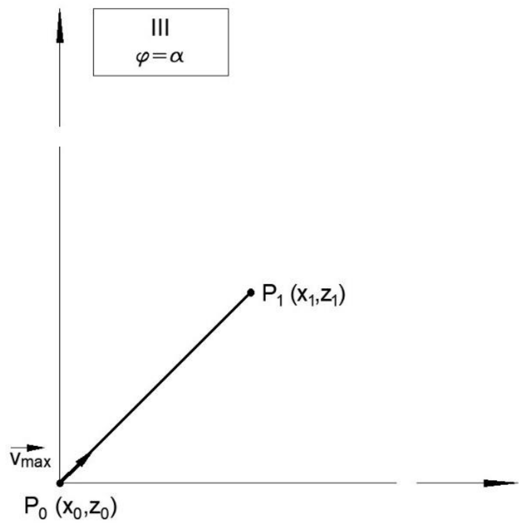

Fig. 8 *AS/RS device movement case 3*

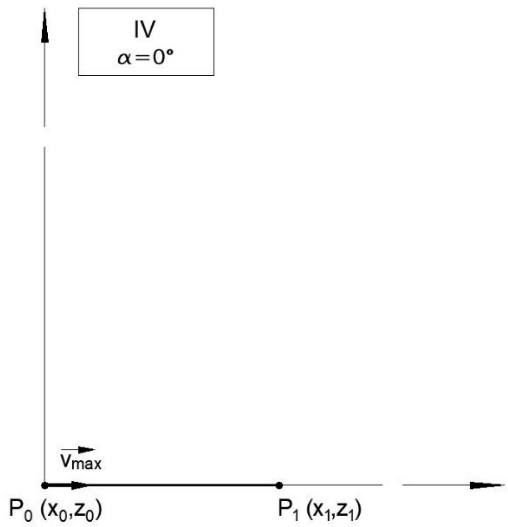

Fig. 9 *AS/RS device movement case 4*

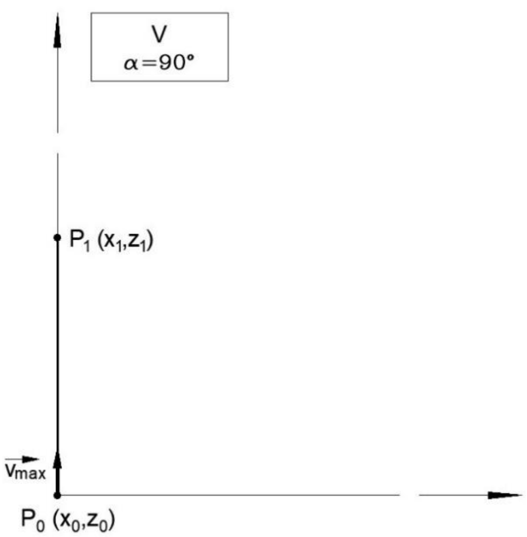

Fig. 10 *AS/RS device movement case 5*

The time it takes for the main motion to be completed, when the AS\RS device is travelling through the aisle t_M can be used as previously mentioned t_1, t_5, and t_9, but with updated current coordinates x_0, y_0, z_0 and the destination coordinates x_1, y_1, z_1 using the following expression:

$$t_M = \begin{cases} \dfrac{\Delta z_1 \cdot \sqrt{(\mathrm{ctg}^2(\varphi) + 1)}}{\sqrt{|\vec{v_x}|^2 + |\vec{v_z}|^2}} + \dfrac{\Delta x_u - \Delta z_1 \cdot \mathrm{ctg}(\varphi)}{|\vec{v_x}|}, & \alpha < \varphi \\ \dfrac{\Delta x_1 \sqrt{1 + \mathrm{tg}^2(\varphi)}}{\sqrt{|\vec{v_x}|^2 + |\vec{v_z}|^2}} + \dfrac{\Delta z_u - \Delta x_1 \cdot \mathrm{tg}(\varphi)}{|\vec{v_z}|}, & \varphi > \alpha \\ \dfrac{\Delta x_1 \sqrt{1 + \mathrm{tg}(\varphi)}}{\sqrt{|\vec{v_x}|^2 + |\vec{v_z}|^2}}, & \varphi = \alpha \\ \dfrac{|x_1 - x_0|}{|\vec{v_x}|}, & \varphi = 0° \\ \dfrac{|z_1 - z_0|}{|\vec{v_z}|}, & \varphi = 90° \end{cases}$$

…where:

- x_0, y_0, z_0 – current coordinates of the point representing the AS/RS device;
- x_1, y_1, z_1 – the point towards the AS\RS device is travelling;
- x_i, y_i, z_i – the point after which the AS\RS device moves along only one axis, in vertical or horizontal direction;
- $\Delta x_u = |x_1 - x_0|$ – horizontal projection of the total path;
- $\Delta z_u = |z_1 - z_0|$ – vertical projection of the total path;
- $\Delta x_1 = |x_i - x_0| = |z_1 - z_0| \cdot ctg(\varphi)$ – horizontal projection of the path the AS\RS device is travelling using both vertical and horizontal motion through the aisle;
- $\Delta z_1 = |z_i - z_0| = |x_1 - x_0| \cdot tg(\varphi)$ – vertical projection of the path the AS\RS device is travelling using both vertical and horizontal motion through the aisle.

The angles φ and α can be calculated through the following trigonometric functions:

$$cos(\varphi) = \frac{|\vec{v_x}|}{|\vec{v}_{max}|} = \frac{|\vec{v_x}|}{\sqrt{|\vec{v_x}|^2 + |\vec{v_z}|^2}} \quad (5)$$

$$sin(\varphi) = \frac{|\vec{v_z}|}{|\vec{v}_{max}|} = \frac{|\vec{v_z}|}{\sqrt{|\vec{v_x}|^2 + |\vec{v_z}|^2}} \quad (6)$$

$$cos(\alpha) = \frac{|x_1 - x_0|}{\sqrt{|x_1 - x_0|^2 + |z_1 - z_0|^2}} \quad (7)$$

$$sin(\alpha) = \frac{|z_1 - z_0|}{\sqrt{|x_1 - x_0|^2 + |z_1 - z_0|^2}} \quad (8)$$

4 SIMULATION SETTINGS

The simulation settings for in the developed software are located in the Simulation settings tab which is shown in the Fig. 11.

Basic settings include a couple of checkboxes, notable are:

- "Include I/O time" - the time for fine manipulation during the loading and unloading processes is taken into consideration or it is ignored if unchecked;
- "Lift while moving forward" – during the main motion the AS\RS device can perform translation in the direction of the axis of the aisle as well as vertical axis performing the lifting or lowering of the load, if this checkbox is not checked, the device would perform first the translatory movement through the aisle after which it would stop moving and the vertical movement would start;
- "Output coordinates are the same as input coordinates" – overwrites the coordinates for the defined output point and it is performing both actions, bringing pallets into the racks and retrieving them to the same point.

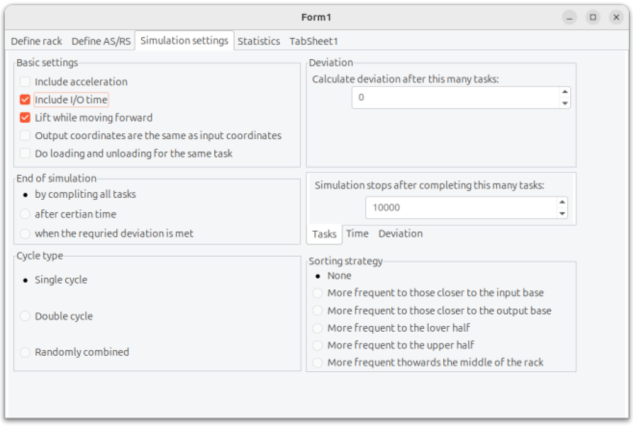

Fig. 11 *Simulation settings tab*

The "End of simulation" decides when the simulation will stop. There are three options that are available:

- by completing all tasks – the simulation stops once all of the tasks are completed;
- after a certain time – after previously defined simulated time is completed, the simulation would stop;
- when the required deviation is met - the simulation stops when the average cycle time deviation is lower than the previously defined percentage.

Sorting strategy within the racks is a complex problem, and within this software solution, there are options where the AS/RS device can be instructed to prefer some characteristic regions of the pallet racks. The "none" option uses a random number generator to select a storage cell to which or from which the device is going to travel.

5 NUMERIC EXAMPLES

For numeric examples, the work of three different AS\RS devices was simulated on single and double deep pallet racks. Characteristics of the devices are represented in the Table 1.

Table 1 AS/RS device characteristics

Device	Single depth rack			Double deep rack		
	v_x	v_y	v_z	v_x	v_y	v_z
	m/s	m/s	m/s	m/s	m/s	m/s
Mecalux MTB-3 [8]	3,6	0,5	1,1	3,6	0,7	1,1
MURATA MACHINERY LTD. - PC Series: For heavy load [9]	3,33	0,67	1,5	3,33	0,83	1,5
MURATA MACHINERY LTD. - PC Series: High Speed type [9]	4,0	1,25	2,8	4,0	1,25	2,8

In the case of a single depth pallet rack, the geometry was defined with parameters displayed in the Fig. 12, and for the double deep pallet rack the geometry was defined with parameters displayed in Fig. 13. as can be seen, the dimensions of the storage cell within the racks in each case are adjusted for a standard 800x1200 mm euro pallet. Distances for the manipulation space are taken to be 100 mm which falls within those proposed by the authors of the [10]. For the single depth pallet rack case, the total number of 480 storage cells was generated, and for the double deep, that number is 960.

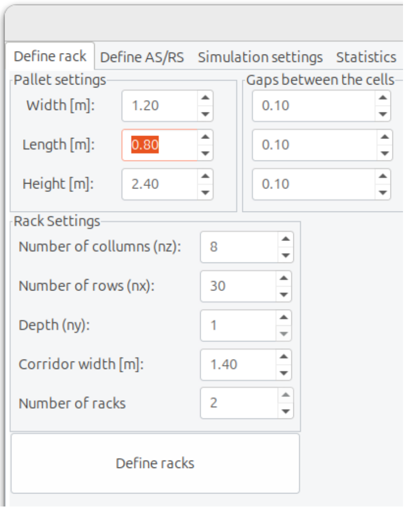

Fig. 12 Parameters for the single depth pallet rack

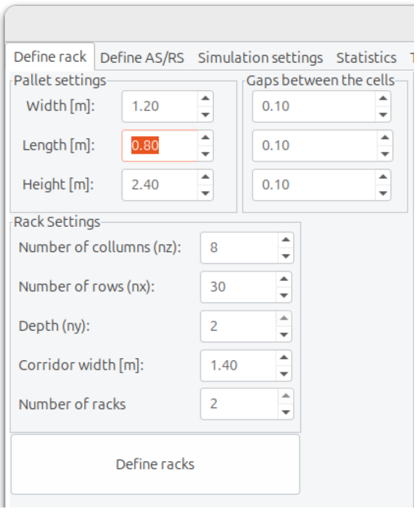

Fig. 13 Parameters for the double deep pallet rack

The input and output point coordinates can be seen in the Fig. 14, as well as the coordinates of the base point which is automatically placed in the middle of the aisle.

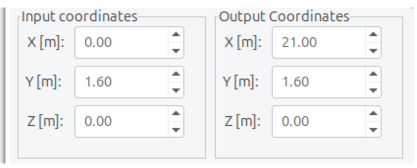

Fig. 14 Input and output point coordinates

Time for fine manipulation while loading and unloading the pallets to and from the forks was set to be fixed in all cases with a value of 3 s.

The end of the simulation is set to be after 1000 tasks were completed, the acceleration was not included in the simulation model (it is infinite, as stated in the initial assumptions), and there is no strategy for the pallet placement within the racks. The results of the simulation is given in the Fig. 15 - Fig. 20 and in the Table 2. The throughput was calculated for both actions, when the pallet is being stored in the racks C_i and when the pallet leaves the racks C_o.

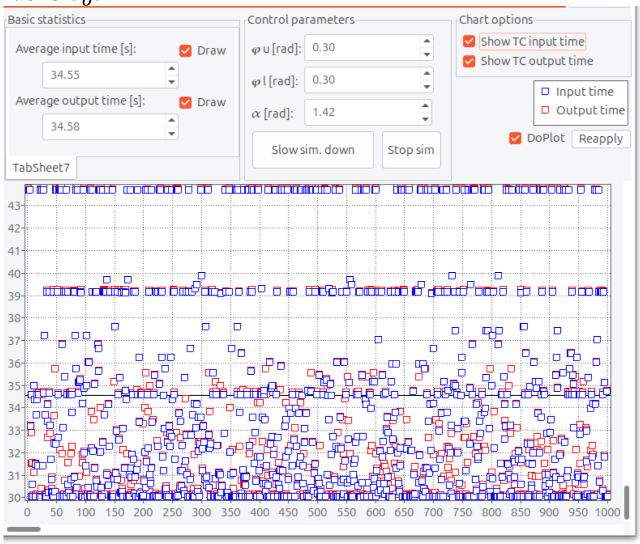

Fig. 15 Mecalux MTB-3 – Single depth rack

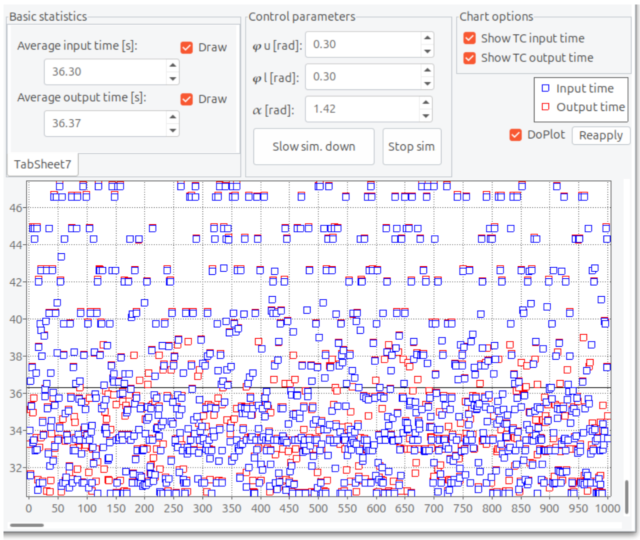

Fig. 16 Mecalux MTB-3 – Double deep rack

The software was run on Dell Inspiron 15 5583, Ubuntu 24.04 LTS, and the simulations were completed in couple of seconds.

The results show that the slight difference in the placement of the input and the output point is reflected in the average cycle time. The faster movement of the crane increases the throughput, which was the expected result. From the Table 2. it can also be seen that, from the throughput stand point the use of double deep pallet racks impacts it negatively.

In the numeric examples, Mecalux MTB-3 the difference between throughput with a single and double deep racks is around 5%, while for the MURATA MACHINERY LTD. - PC Series: High Speed type, the throughput is up to 8% lower when the double deep pallet racks are used However, the double deep pallet racks have double the amount of storage units, which means that there is a trade off between the throughput and available number of storage units which has to be taken into consideration in the initial stages of warehouse planning.

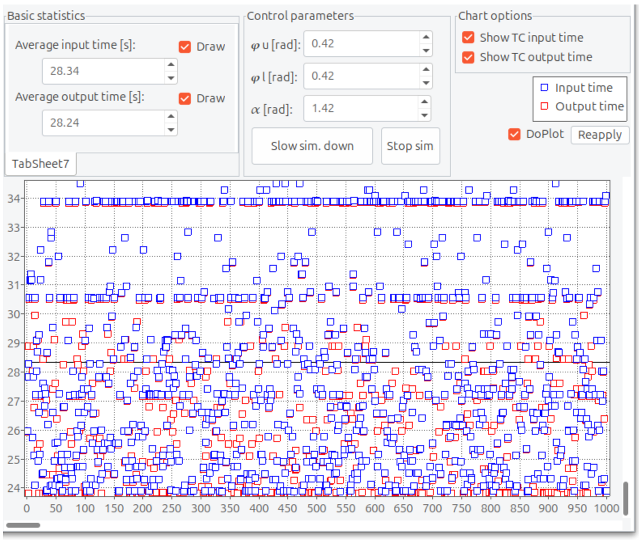

Fig. 17 MURATA MACHINERY LTD. - PC Series: For heavy load – Single depth rack

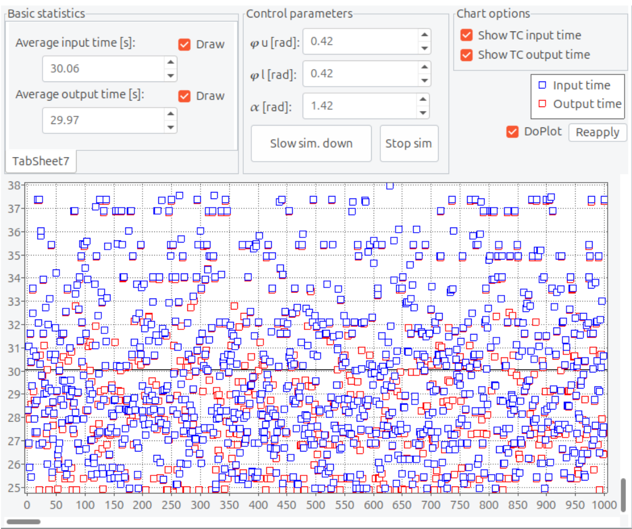

Fig. 18 MURATA MACHINERY LTD. - PC Series: For heavy load – Double deep rack

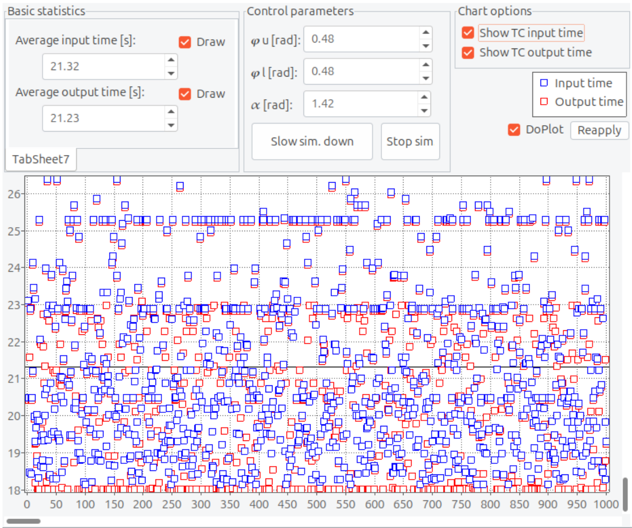

Fig. 19 MURATA MACHINERY LTD. - PC Series: High Speed type – Single depth rack

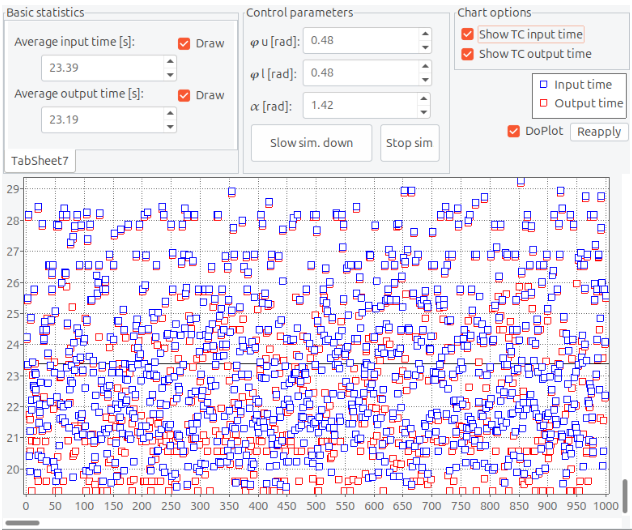

Fig. 20 MURATA MACHINERY LTD. - PC Series: High Speed type – Double deep rack

Table 2 Simulation results

Device	Single depth rack				Double deep rack			
	T_{SCi}	T_{SCo}	C_i	C_o	T_{SCi}	T_{SCo}	C_i	C_o
	s	s	tasks/h	tasks/h	s	s	tasks/h	tasks/h
Mecalux MTB-3 [7]	34.5517	34.5841	104.192	104.094	36.3	36.370	99.1846	98.9819
MURATA MACHINERY LTD. - PC Series: For heavy load [8]	28.3400	28.2429	127.029	127.466	30.061	29.974	119.755	120.104
MURATA MACHINERY LTD. - PC Series: High Speed type [8]	21.3152	21.2339	168.894	169.54	23.3865	23.1901	153.935	155.239

6 CONCLUSION

Simulating the warehouse transportation system can be a very challenging task, but it is necessary for optimal planning and choosing the proper equipment. This paper offers a simple model for the simulation of a single AS/RS device within a single aisle. This model can be used for making simple tools, such as the one introduced in this paper, which can be adjusted for specific use cases or requirements.

Based on results obtained through the simulation within numeric examples, it can be seen that a lot of parameters effect the throughput, especially the geometry of the aisle and pallet racks and the velocities of the AS/RS devices.

By deepening the pallet racks throughput of the transportation device can be reduced, depending on the AS/RS device characteristics, up to 8%. If the high throughput is required for some use case, this can be a problem. However, if the high throughput is not required, the double deep pallet rack can be used for incresed storage cappacity.

The purposed tool in the current form is simple and lacks a lot of functionality that commercial software suits for a similar purpose contain. Reducing the difference in functionality will be a subject of future research.

ACKNOWLEDGMENT

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