Multi-aisle automated rack warehouse simulation for average travel time

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Increased consumption of various goods in modern society requires efficient logistic systems. In order to accomplish high efficiency automated systems for internal transport of goods within a storage unit have been widely employed. Widespread use of these systems induces the need for adequate simulation models that imitate realistic warehouse workflow and can adapt to dynamic changes in operation. Travel time is one of the parameters with great impact on operational costs of the warehouse. Accurate estimation of average travel time can be used to evaluate efficiency of the logistic chain. The new three-dimensional warehouse simulation model which was proposed in this paper takes into consideration the dynamic changes in operation for obtaining average travel time estimation closer to the realistic warehouse operation

Keywords: Internal transport, Average travel time, Three-dimensional warehouse model, Warehouse simulation

1. INTRODUCTION

Nowadays, thousands of tons of goods are transported from producers through sellers to end users, i.e. customers. After the goods have been delivered by the manufacturer to the seller, they can be stored for a certain period of time in the warehouse, where they await collection. In this sense, warehouses can be divided into two types: distribution warehouses, where products from several different suppliers can be stored, and production warehouses for storing raw materials, semi-finished products, and finished products. In this regard, the storage process, as one of several logistics processes, represents an irreplaceable link in logistics systems and supply chains. The efficiency and correct function of the warehouse itself (storage capacity and speed) mostly depend on the technical parameters: the size of the warehouse, the means used for transporting and placing pallets units (forklifts, racks, rack cranes), hardware and software [1].

In order to achieve the best efficiency of the warehouse, it is important to manage it in the best possible way through the entire supply chain, from the point of receipt of goods to the warehouse, to the point of delivery of goods. Warehouse management represents an important activity in the entire process and involves managing new stock of goods, monitoring the movement of products within the warehouse and optimal arrangement of stored goods, which aims to minimize total costs and improve the satisfaction of end users. Many companies from the distribution and storage sector use developed software solutions for warehouse management (WMS - Warehouse Management System) that enable monitoring of input parameters, movement within the warehouse, output parameters of materials, semi-finished products and finished products within the warehouse in real time.

With the progress and development of economic systems, storage and distribution systems have been developed in parallel in terms of process automation in order to meet the demands of the market and production. One of the main characteristics of the automated warehouse process is reflected in very little or almost no human involvement and direct contact with goods or materials, which in some cases is one of the requirements in order to preserve product quality.

The main advantages of using automatic storage systems (AS/RS) are reflected in the increased flow of storage units, efficient use of space inside the warehouse, high reliability in operation, more precise control of stocks in the warehouse, improved conditions for storing goods inside the warehouse in terms of safety, reduction of complaints regarding damage to goods. The very concept of the operation of these systems meets the requirements of "green" logistics and reduction of CO_2 emissions and ergonomics. There are several types of automatic storage systems (AS/RS) [2]:
- automatic warehouses served by cranes that transport pallets (unit-load AS/RS),
- automatic warehouses served by cranes that transport small loads - containers (mini-load AS/RS),
- automatic warehouses served by autonomous vehicles that transport pallets (AVS/RS).

Modeling of automatic storage systems represents an extensive and responsible procedure, depending on the complexity of the system itself and the goals that the system must meet in terms of end user requirements. When modeling automatic storage systems, it is necessary to take into account all relevant parameters related to the facility, transport devices, as well as the type and size of the units that are placed in the warehouse. The level of complexity of the warehouse model depends on what is expected from the simulation results. Based on the level of complexity of the storage system and the parameters incorporated, the simulation results can vary significantly regarding the performance and efficiency of the entire storage system [3].

In the paper presented by Manzini et. all [4], a warehouse model was presented using alternative design and operational configurations, which identified the most critical factors and combinations of factors that affect the efficiency of the warehouse system and presented the most significant results of the analysis.

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Since automated storage and retrieval systems (AS/RS) represent a significant investment and significant

This reality creates a need for robust and efficient system evaluation models that can be found in [5]. This paper complements previous research on AS/RS by focusing on a specific research question related to dynamic models based on intra-warehouse travel time modeling.

In the paper [6] new analytical models are presented in order to evaluate the performance of AS/RS warehouses related to racks with deep pallet spaces. These models extend the state of the art by (1) taking into account actual criteria related to item storage and retrieval, (2) taking into account the ability of transport devices to perform different tasks simultaneously, and (3) estimating the standard deviation of the cycle time, in addition to its average values. The presented models are validated through simulations performed on different warehouse layouts, in different implementation scenarios. The ultimate goal of such models is to support storage equipment designers in evaluating the performance of their systems, taking into account a variety of realistic scenarios.

Automated storage and retrieval systems (AS/RS) and autonomous vehicle storage and retrieval systems (AVS/RS) are two competing technologies for handling, storing, and retrieving unit loads in the spare part of the automated warehouse presented in [7]. In this paper, variants of the two systems are modeled as open queuing networks (OCNs) and we use an existing OCN analysis tool, called the production system performance analyzer (MPA), to analyze the performance of AS/RS and AVS/RS. Experimental results are provided to show that MPA is a better choice than simulation for rapidly evaluating alternative configurations of two systems. We use MPA to answer a series of design questions to conceptualize AS/RS and AVS/RS designs [8].

2. 3D WAREHOUSE MODEL

In the previously mentioned works, different approaches were presented in the formation of analytical models of warehouses and storage systems in order to implement various procedures related to the calculations of the average duration of the pallet cycle within the warehouse. In the text that follows, the authors of the paper proposed a new concept in the three-dimensional representation of the warehouse with the aim of greater flexibility in terms of the configuration of storage places and corridors within the building (Fig. 1).

In the first step, a 3D model of the warehouse is formed based on overall dimensions, which can be adjusted at any time by entering new parameters. In the next step, the structure of the racks (storage places) is defined based on the width, length and height parameters of the racks as shown in the picture above. Within the same step, the warehouse is filled with pallets, which are displayed with the corresponding coordinate system in step 3. In this way, a complete three-dimensional view of the warehouse is formed, in which a number of parameters are implemented that can be exported to a table (step 4) and used in further calculations and simulations related to logistics. The entire procedure from the initial step to the final step is performed with the help of an application made in Matlab software.

In this way, the advantages of using alternative solutions for simple configuration of the design of the warehouse and storage space are demonstrated, as well as the possibility of forming different layout configurations, which contributes to the faster generation and acquisition of parameters related to the contents in the warehouse necessary for calculations of the movement of transport devices (crane, elevators or forklifts). Another of the advantages of the mentioned concept lies in the fact that there is no limit regarding the dimensions of the warehouse and the number of storage units, and the same can be applied to high-rack warehouses with a height of several tens of meters, as shown in the case studies [9].

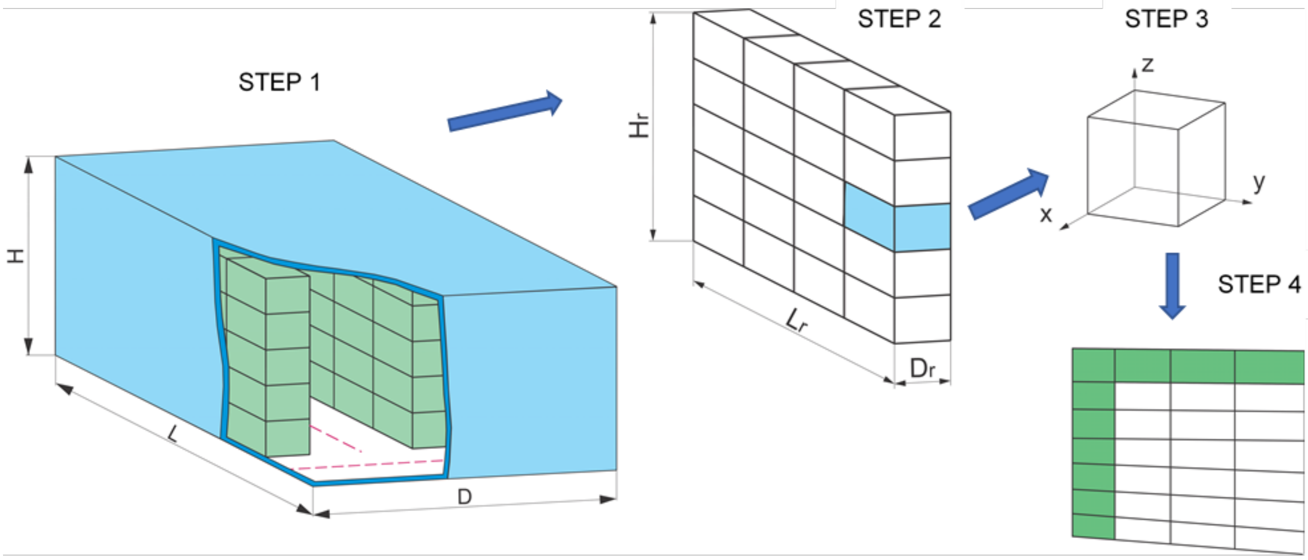

Figure 1: Schematic representation of the formation of the 3D model of the warehouse and obtaining the necessary parameters

3. MODELING OF WAREHOUSE TRANSPORTATION DEVICES

The transportation system of the described warehouse consists of a single shuttle which can travel only along a single dimension, and AS/RS devices which can transport the package along two axis. According to the illustration of the layout of the warehouse which is displayed in the figure 1, this transportation device occupies the corridor 1 and moves along the x axis. The AS/RS devices occupy corridors 2, 3 and 4, and they can move packages along y and z axis.

In this simulation, these transportation devices are idealized and constant velocity curves for all movements are assumed, meaning the acceleration times are neglected. The tasks that the transportation system of the warehouse have to perform are generated randomly, and only one task can be active at the time. These tasks cover the most common three operations that take place in a warehouse, and those are:

- a new pallet is brought to the warehouse and it needs to be transported to its storage unit where it should be stored;
- a pallet that is already stored within the warehouse needs to transported outside of the warehouse;
- a pallet that is already in the warehouse needs to be relocated to another storage unit.

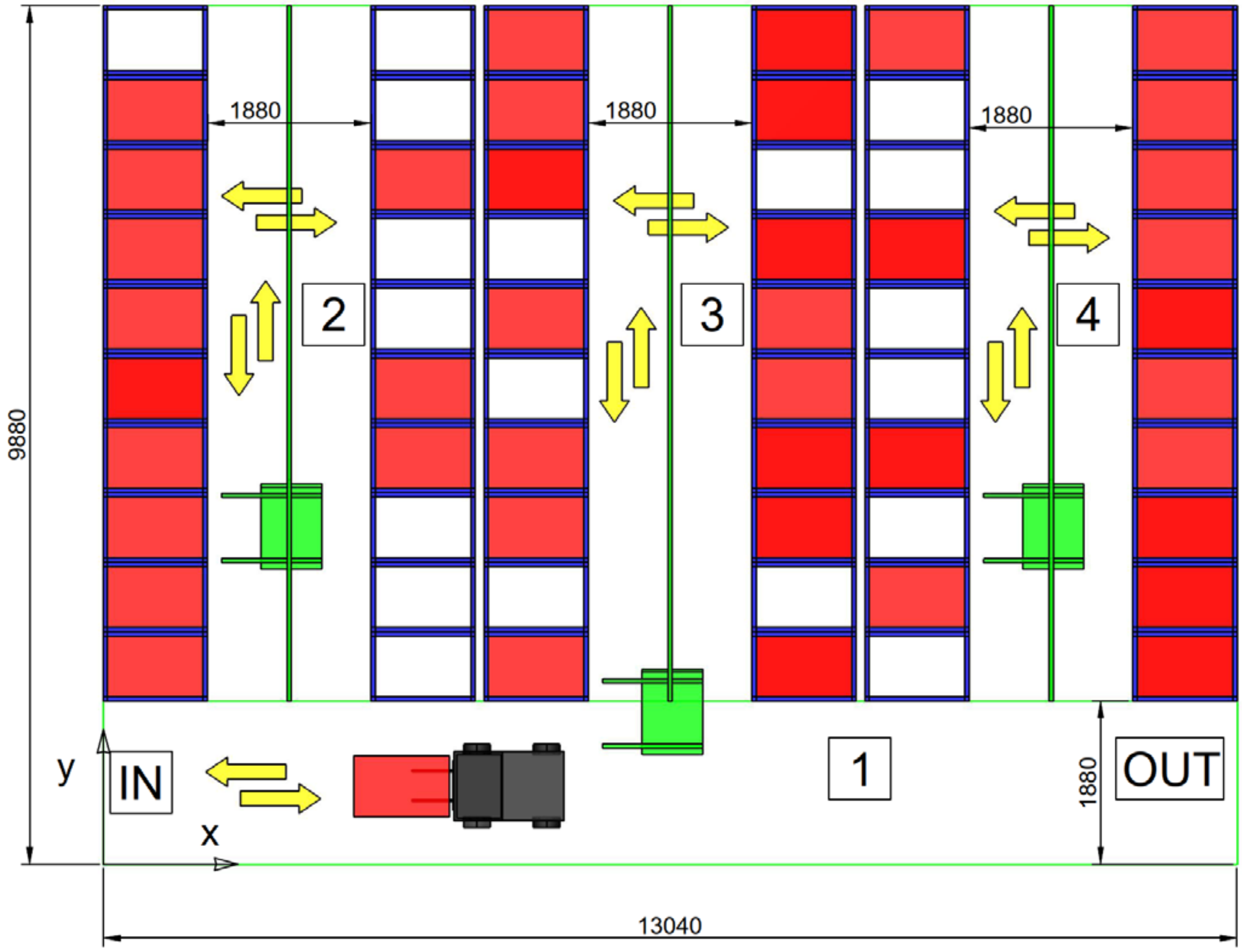

Figure 2: Illustration of the warehouse layout with marked corridors and possible directions of movement for the transportation devices in horizontal xy plane

After each task had been generated, the time needed for its completion t_i, $i=1,2,\ldots,m$ was calculated. Each operation consists of several actions. The operation of bringing a new pallet into its storage unit from the warehouse input point consists of the following actions:

- the shuttle in the corridor 1 travel from their current position x_{c1} to the warehouse input point x_{IN} with the velocity v_{x1}, the duration of this action is denoted as t_{i1}, and it can be calculated as follows:

$$t_{i1} = \frac{|x_{IN} - x_{c1}|}{V_{x1}} \tag{1}$$

- the shuttle picks the pallet up from the input point, the duration of this action is taken to be constant t_{i2}=5 s;
- the shuttle drives the pallet to the place the appropriate AS/RS device can pick it up x_r with the velocity v_{x1}, the duration t_{i3}:

$$t_{i3} = \frac{|x_{IN} - x_r|}{V_{x1}} \tag{2}$$

- the AS/RS device travels from its current position P_C (y_j, z_j), $j=2,3,4$ to the pallet P_i (y_i, z_i) where it is assumed the AS/RS device takes the shortest path s_{i4} between the two points, and the maximum velocities along the y and z axis are $v_{(y,max)}$, and $v_{(z,max)}$ respectively, so the duration of the action t_{i4} is:

$$t_{i4} = v_{y,\max}\left|\Delta y\right| + v_{z,\max}\left|\Delta z\right|; \quad \Delta y = y_i - y_j;\ \Delta y = z_i - z_j \tag{3}$$

- the AS/RS device takes the pallet by elongating its forks to the furthest end of the pallet x_{pe} and retracting them to their neutral position x_j with the velocity of v_{xj}, the duration of this action t_{i5} is:

$$t_{i5} = 2 \cdot \frac{\left|x_{pe} - x_j\right|}{V_{xj}} + 5 \tag{4}$$

- the AS/RS takes the pallet to the storage unit location matching its y and z coordinate, the duration of this action t_{i6} can be calculated using the expression shown in (4), and the movement is being done under the same assumptions;

- the AS/RS deploys the pallet within the storage unit by extracting its forks, lowering them a bit, and then retracting them back to their neutral position along the x axis with velocity v_{xj}, and the duration of this action t_{i7} can be calculated using the expression (5).

With the task completed, the completion time for the task represents the sum of the mentioned durations [10]:

$$t_i = \sum_{k=1}^{n=7} t_{ik} = t_{i1} + t_{i2} + t_{i3} + t_{i4} + t_{i5} + t_{i6} + t_{i7} \tag{5}$$

The operation of taking the pallet out of the warehouse through the warehouse output point is similar to previously described operation, only the actions are being done in reversed order, so the (1)-(5) equations can be used for the task duration calculation. Moving the pallet within the warehouse has two variations: moving the pallet within the single corridor, and moving the pallet between corridors. The first variation is simpler because it employs only one AS/RS device, and the required actions are:

- the AS/RS device travels from its current position to the position of the pallet that needs to be moved, the duration of this action can be denoted as t_{i1} and it can be calculated with (3);
- the AS/RS device elongates its forks in order to pick up the pallet from the storage unit after which it retracts its forks to neutral x position, the duration of this action t_{i2} can be calculated with (4);
- the AS/RS device travels with the pallet to the new storage unit matching its y and z coordinates, the duration of the action is t_{i3} and it can be calculated as (3);
- the AS/RS device puts the pallet into its new storage unit, and retracts its forks to their neutral x position, this action takes t_{i4} time which can be calculated with (4).

The second variation employs two AS/RS devices and shuttle for moving the pallet between the corridors, so the time it takes to complete the task consists of more action durations. However, these durations can all be calculated using the expressions (1-4), and these durations are:

- t_{i1} – the time it takes for the AS/RS device to travel from its current position to the pallet that needs to be relocated;
- t_{i2} – the time it takes for the AS/RS device to take the pallet from its storage unit and put it in neutral x position;
- t_{i3} – the time it takes for the AS/RS device to travel with the pallet to the place where the shuttle can take the package;
- t_{i4} – the time it takes for the empty AS/RS device to return to its neutral position;
- t_{i5} – the time it takes for the shuttle to get to the pallet from its current position;
- t_{i6} – the time it takes for the shuttle to load the pallet;
- t_{i7} – the time it takes for the shuttle to travel with the pallet to the proper corridor;
- t_{i8} – the time it takes for the shuttle to unload the pallet;
- t_{i9} – the time it takes for the new AS/RS device to travel to the coordinate of the pallet from its current position;
- t_{i10} – the time it takes for the AS/RS device to load the pallet;
- t_{i11} – the time it takes for the AS/RS device to travel to new, empty storage unit;
- t_{i12} – the time it takes for the AS/RS device to unload the pallet to the storage unit and retract its forks to the neutral position.

In this case, the time it takes to accomplish this task, according to (5) can be calculated as:

$$t_i = \sum_{k=1}^{n=12} t_{ik} = t_{i1} + t_{i2} + \ldots + t_{i11} + t_{i12} \tag{6}$$

The average duration time for m completed operations T_{avg} can be then calculated by:

$$T_{avg} = \frac{\sum_{i=1}^{n} t_i}{m} \tag{7}$$

The second variation of pallet relocation in this simulation only happens when the racks sharing the same corridor are more than 70% full.

4. RESULTS

The parameters of the members of the transport system with the corresponding values used in the warehouse simulation according to illustration presented on Fig. 2 are shown in Table 1. The transport unit under number 1 represents a shuttle that moves only along the x axis, while with the numbers from 2 to 4 are marked stacker cranes used for transport of pallets in the indicated corridors along all three axes (x, y, z).

Table 1: Velocities of transport units in warehouse

Transport unit No.	v_x [m/s]	v_y [m/s]	v_z [m/s]
1	0.1	-	-
2	0.2	0.2	0.2
3	0.2	0.2	0.2
4	0.2	0.2	0.2

The results of the simulation are visualised using graphs in Fig. 3 with corresponding values for several important parameters such as average task duration, average input/output time and average pallet relocation time.

From the graph for average pallet relocation time, it can be concluded that the sudden change after 800 completed tasks is a consequence of that before this change, pallets were moved only through corridor 2 using stacker crane. After that, when the occupancy of racks reach 70%, relocation of pallets is done between corridors 2-4, using the relation stacker crane- shuttle-stacker crane.

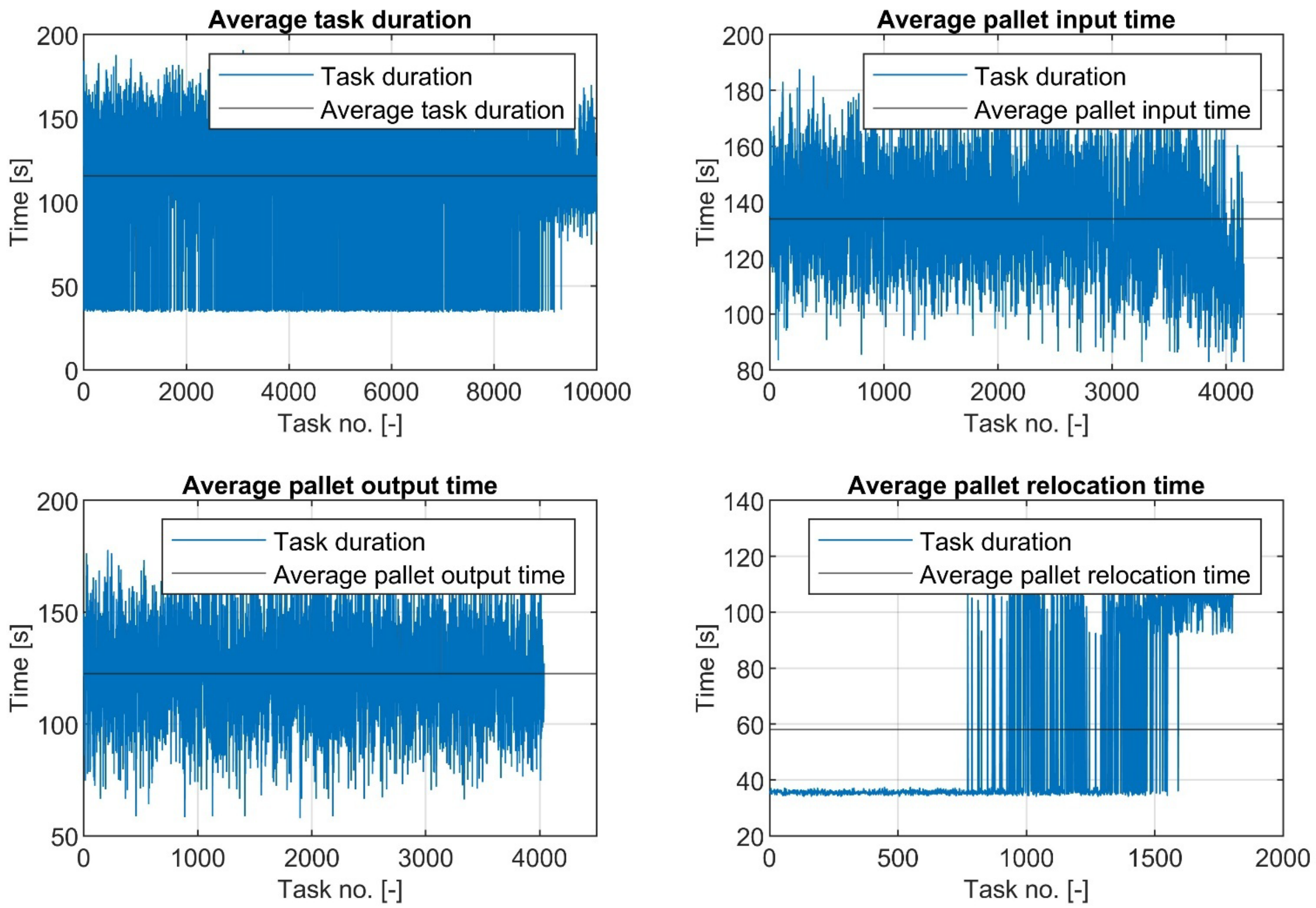

Figure 3:Graphs of simulation with corresponding values

From the graphs shown in Figure 3, the mean values of the duration time for the above-mentioned parameters can be read as well as obtained explicitly as a result of the simulation. The values of these parameters are:

Average task duration time = 115.6536 [s]
Average pallet input time = 133,9905 [s]
Average pallet output time = 122,5585 [s]
Average pallet relocation time = 57,9759 [s]

Using a random arrangement inside the warehouse, it was observed that the number of manipulative operations inside the warehouse (out of a total of 10000 in the list) is as follows:

Total number of input operations = 4157
Total number of output operations = 4038
Total number of relocation operations = 1805

5. CONCLUSION

This paper describes a tool that can be used for efficiency assessment of the automated AS/RS warehouse material handling system as a part of the internal logistic chain. The model and the simulation connect different kinds of devices with their unique characteristics, where the output from the simulation can indicate how these devices function within the observed system allowing the designers of the warehouses to see where bottlenecks are, and what and in which way should be changed in order to obtain the optimal solution either by changing the layout or picking the material handling equipment with different characteristics. Considering the way the parameters of the warehouse were modelled and the way the simulation is being done, it can also be used together with other tools such as metaheuristic biology inspired optimization algorithm.

The focus of further research in this area will be on the attempt to incorporate some of the biologically-inspired optimization methods for solving wide range of engineering problems, all with the aim of obtaining the best possible simulation results [11 ,12].

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