Concept Development and Evaluation of Order Assignment Strategies in a Highly-dynamic, Hybrid Pallet Storage and Retrieval System

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Abstract: In this paper, we propose and evaluate various order assignment strategies for a new, highly-dynamic hybrid pallet storage and retrieval system or dynamic hybrid pallet warehouse (DHPW). The research gap we fill is the identification of the order assignment strategies, which guarantees the highest performance for this new warehouse system in different operational conditions. First, we present a brief description of the system under consideration. We then go on to present a brief literature review on order assignment strategies for stacker-crane-based AS/RSs and AVS/RSs. Next, we develop our concept of order assignment strategies for a DHPW with sequenced retrieval and storage, followed by a discrete event simulation and an evaluation of the concepts according to the level of performance they enable. Finally, we identify the operations of the process whose order assignment strategy has the greatest impact on performance, and suggest an optimum combination of order assignment strategies.

1 INTRODUCTION

In this contribution, we propose a number of order assignment strategies for a dynamic hybrid pallet warehouse (DHPW) and evaluate these strategies and their combinations using discrete event simulation to determine which strategies provide the best performance for this newly developed warehouse system. The goal for this new system is to combine the advantages of stacker-crane-based warehouses and shuttle-based ones (Eder et al., 2019; Siciliano et al., 2020). A shuttle system forms the base tier, with a multiple-depth channel storage system constructed above it (see Fig. 1). A transfer buffer, served by stacker cranes with satellites, connects the base tier and the channel storage system. Fig. 2 shows the various elements of the base tier, including the transfer buffers. For retrieval, a stacker crane takes a pallet from the multiple-depth channel storage and brings it to the transfer buffer on the base tier. A shuttle then brings the pallet to the output location

Figure 1: DHPW (image courtesy of Gebhardt Fördertechnik GmbH).

(O location). The moment a shuttle receives an order with a certain location on the transfer buffer as the start position and the O location as the destination, it reserves that start location on the transfer buffer. For storage, a shuttle takes a pallet from the input location (I location) and brings it to the transfer buffer. A stacker crane then takes the pallet and places it in the multiple-depth channel storage system. The moment a shuttle is preparing to leave the I location with a pallet to store, it selects and reserves the destination location on the transfer buffer.

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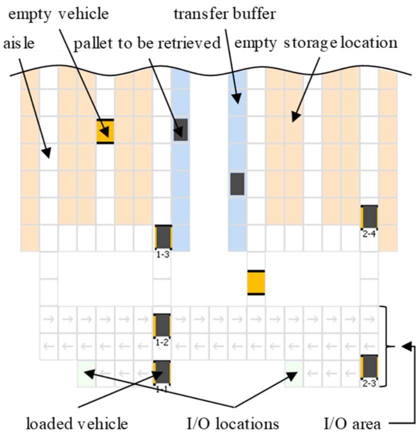

Figure 2: Shuttle base tier in the simulation model (Siciliano et al., 2020).

In this paper, order assignment strategies determine which job order should be assigned to which stacker crane or shuttle. They are also employed to determine which idle shuttle to activate. We therefore present a brief literature review of those order assignment strategies for stacker-crane-based and shuttle-based warehouses that form the basis of our concept.

1.1 Order Assignment Strategies for Stacker-Crane-based Warehouses

The order assignment decision taken by a stacker-crane-based AS/RS concerns the I/O location from which the stacker crane should take a pallet and the I/O location to which it should deliver the pallet. In a stacker-crane-based warehouse with more than one I/O location, the simplest strategy is to randomly select the I/O location to which the stacker crane delivers the pallet (Arantes and Kompella, 1993). However, other strategies may enable a higher throughput. In fact, (Lantschner, 2015) proposes two additional strategies. The first selects the I/O point nearest to the stacker crane's current position. The second selects the I/O location nearest to the next job. (Lantschner, 2015) demonstrates analytically that these two strategies provide a shorter mean driveway for a stacker-crane-based AS/RS with one stacker crane, in which the number of I/O locations is varied between two and five. (Gagliardi et al., 2014) provides an extensive literature review on operational decisions that can be taken in AS/RSs.

1.2 Order Assignment Strategies for Shuttle-based Warehouses

An essential decision to be taken in a shuttle-based AS/RS concerns which shuttle should take which order, which requires selecting a dispatching strategy. The majority of authors investigated dispatching strategies for automated guided vehicles (AGVs) but not directly for shuttles. According to (Grunow et al., 2006), the two dispatching strategies adopted the most frequently in the literature are assigning the next available job to the vehicle nearest to the pick-up location or assigning it to the vehicle that has completed the least transportation orders. More recently, (Habl et al., 2020) proposed order assignment strategies in a single-tier, double-deep shuttle level and evaluated them by means of discrete event simulation.

The next section describes the operations that take place in the DHPW and explains when a decision is required during those operations. We then suggest several strategies by which to address this decision.

2 CONCEPT DEVELOPMENT: RETRIEVAL IN SEQUENCE

The operations for retrieving in sequence are as follows:

I. A stacker crane retrieves a pallet from the channel storage and brings it to an available position on the transfer buffer;

II. The stacker crane activates an idle shuttle;

III. The activated shuttle retrieves a pallet from the transfer buffer and brings it to the I/O locations.

We now describe various strategies for addressing the decision to be taken in each operation. For the sake of clarity, the strategies are numbered.

2.1 Retrieval Strategies, Group I

In the first group of strategies relating to retrieval in sequence, the stacker crane selects an available transfer buffer position to which the pallet can be brought. The following strategies are available:

1. Random Position

The stacker crane randomly chooses the position from those available on the transfer buffer.

2. Nearest Position to O Location

The stacker crane chooses the available transfer buffer position at the smallest distance from the O location. The result of this is that the positions on the transfer buffer nearest to the O location are constantly occupied by retrieved pallets. This reduces the distance the shuttles travel from the O location to the transfer buffer to retrieve pallets, which minimizes their travel time. However, concentrating all shuttles in a small area of the shuttle base tier causes increased interference between the shuttles as they move. They thus spend more time waiting to give way to shuttles that have priority on certain routes.

3. Shortest Path for the Stacker Crane

The stacker crane chooses the available transfer buffer position that provides the shortest path for the stacker crane. When retrieving, both the stacker crane's idle position (IP) or dwell point and the position P2, where the pallet to be retrieved in the channel warehouse is stored, are fixed. Therefore, the position in the transfer buffer ensuring the shortest path for a single stacker crane cycle has the coordinates (P2x, 0), as shown in Fig. 3:

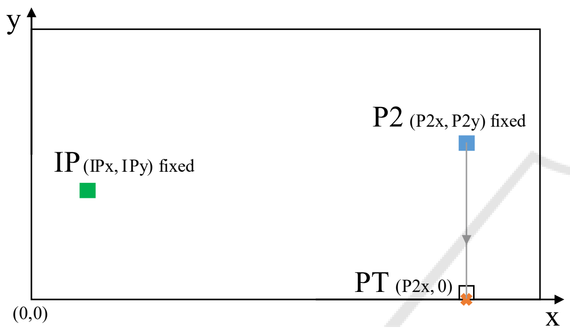

Figure 3: Determination of PT, the retrieval location of the transfer buffer ensuring the shortest path for the stacker crane.

4. Position Available for the Longest Time

The stacker crane chooses the transfer buffer position that has been available for the longest time. A shuttle deletes its reservation of a transfer buffer location once its chassis has fully exited it. From that moment on, the position is therefore available again. This strategy aims to balance the distribution of orders among the different transfer buffer locations. As a result, the routes of the shuttles are distributed over a larger area. This increases their travel distances but reduces interference between shuttles on their routes.

2.2 Retrieval Strategies, Group II

In the second group of strategies relating to retrieval in sequence, the stacker crane selects an idle shuttle to activate and to which to assign a new retrieval order. For retrieval in sequence, idle shuttles wait at storage locations. The following strategies are available:

5. Random Shuttle

The stacker crane randomly activates a shuttle among those available at the storage locations on the shuttle base tier.

6. Longest Shuttle Idle Time

The stacker crane awakens the shuttle that has been waiting at a storage location for the longest time. Shuttles wait at storage locations as long as no retrieval order is available. The aim of this strategy is to distribute the orders among the shuttles and avoid some shuttles being overloaded while others are underused. This makes maintenance more easily predictable and more delayed in time, thus reducing maintenance costs.

7. Nearest Shuttle to the Job

The stacker crane awakens the shuttle that is waiting at the storage location with the shortest distance to the pallet to be retrieved. The aim of this strategy is to reduce shuttle travel distances and, in turn, their travel times.

8. Least Utilized Shuttle

The stacker crane awakens the shuttle that has executed the fewest orders since the commencement of the retrieval process. Balancing the distribution of jobs among shuttles in this way avoids some shuttles being used more than others.

2.3 Retrieval Strategies, Group III

In the third group of strategies relating to retrieval in sequence, an active shuttle selects an available pallet on the transfer buffer for retrieval. The following strategies are available:

9. Random Pallet

The shuttle randomly chooses a pallet from those available on the transfer buffer.

10. Nearest Position to O Location

The shuttle chooses the available transfer buffer pallet with the smallest distance to the O location. The aim is to reduce the travel distance of the shuttles. If multiple stacker cranes are in a single aisle, the stacker crane serving the transfer buffer area nearest to the O location is used more than the others.

11. Smallest Sequence Number

The shuttle chooses the pallet available on the transfer buffer with the smallest sequence number. A loaded shuttle is only permitted to depart from the transfer buffer when the shuttle containing the pallet with the preceding sequence number has left the transfer buffer. The aim of this strategy is to reduce the time a loaded shuttle has to wait on the transfer buffer before being permitted to depart. When there are only a small number of shuttles in the base tier, this strategy is the only one that avoids deadlocks.

However, with a large number of shuttles, other strategies may provide shorter shuttle travel times and, in turn, a higher throughput than the one achievable with this strategy.

3 CONCEPT DEVELOPMENT: STORAGE

The operations for storage are as follows:

I. An available shuttle receives a storage order. It chooses an updated transfer buffer destination location. It takes the pallet from the I location and delivers it to the chosen transfer buffer location;

II. A stacker crane chooses a pallet from the transfer buffer that is available for storing. It takes it and brings it to the channel of the warehouse in which this type of product is stored.

We now describe various strategies for addressing the decision to be taken in each operation.

3.1 Storage Strategies, Group I

In the first group of strategies relating to storage, a shuttle selects a position available on the transfer buffer to which to bring a pallet for storing. The following strategies are available:

12. Random Position

The shuttle randomly chooses the position from those available on the transfer buffer.

13. Nearest position to I location

The shuttle chooses the available transfer buffer position with the smallest distance to the I location.

14. Position Available for the Longest Time

The shuttle chooses the available transfer buffer position that has not been occupied by a pallet for the longest time. An empty location on a transfer buffer is available from the moment a satellite of a stacker crane has exited it with its whole chassis until a shuttle reserves it.

3.2 Storage Strategies, Group II

In the second group of strategies relating to storage, the stacker crane selects an available pallet on the transfer buffer. The following strategies are available:

15. Random Pallet

A stacker crane chooses a pallet randomly from the ones available on the transfer buffer.

16. Nearest Pallet to I Location

The stacker crane chooses the available transfer buffer pallet that is at the smallest distance to the I location.

17. Shortest Path for the Stacker Crane

The stacker crane chooses the available transfer buffer pallet whose position provides the shortest cycle path for the stacker crane. In the case of storing, IP and P1 (the position of the channel warehouse where the pallet will be stored by the stacker crane) are fixed. Therefore, the position (PT) on the transfer buffer, where it is necessary to pick up the pallet in order for the stacker crane to have the shortest path, can be calculated using the optical law of reflection. The stacker crane takes the available pallet that is as close as possible to the calculated position. As shown in Fig. 4, we locate PT graphically by considering the x axis as a symmetry axis and projecting P1 onto the other side of it. Then we join the projection of P1 and the idle position with a straight-line s. The intersection between the s and x axes is PT. We calculate the abscissae of PT analytically as the point belonging to s whose ordinate is zero:

$$\frac{\mathrm{PTy} - (-\mathrm{P1y})}{\mathrm{PTx} - \mathrm{P1x}} = \frac{\mathrm{IPy} - (-\mathrm{P1y})}{\mathrm{IPx} - \mathrm{P1x}} \quad (1)$$

$$PTx = \mathrm{P1y}\,\frac{\mathrm{IPx} - \mathrm{P1x}}{\mathrm{IPy} - \mathrm{P1y}} + P1x \quad (2)$$

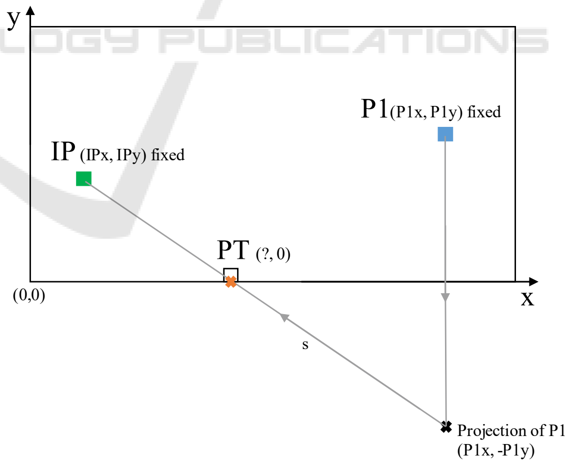

Figure 4: Determination of PT, the storage location of the transfer buffer that ensures the shortest path for the stacker crane.

18. Pallet Available for the Longest Time

The stacker crane chooses the pallet that has been available on the transfer buffer for the longest time. A pallet delivered by a shuttle is available from the moment when the shuttle has exited a delivery location with its entire chassis.

4 SIMULATION STUDY

In this section, we analyze the results of the simulation study and evaluate the order assignment strategies described above as well as their combinations. The performance evaluation criteria are warehouse throughput, shuttle utilization ratio, and length of time spent by shuttles on different operations (Lienert et al., 2018).

4.1 Model Description

The model is implemented using the Plant Simulation discrete event simulation environment. (Siciliano et al., 2020) provides a detailed description of the system's modelling and implementation. We validated the model comparing the analytically calculated travel time of individual shuttles with the simulation. Moreover, we compared the simulated travel times of shuttles and stacker crane with the real-world subsystems.

4.2 Parameters

In this paper, we consider a system with two stacker cranes in a single aisle, serving 56 transfer buffers arranged in two rows alongside the stacker cranes (see Fig. 2). 512 storage locations for intermediate buffering are in the base tier. Each half of the base tier has three storage aisles. Four cross aisles are positioned within the storage area. Two I/O areas are located on either side of the system. Two bidirectional lanes connect them. One I/O area is dedicated to incoming pallets and the other to outgoing pallets. Furthermore, within each I/O area there are two I/O locations (see Fig. 2). In the channel storage, 56 storage channels are on each of the eight tiers. Each channel has a capacity of nine pallets.

In the following experiments, five replications are performed with the parameters in Tab. 1 and Tab. 2. Each replication lasts for 24 hours simulated time.

4.3 Evaluation: Retrieval in Sequence

We evaluate by simulation the throughput of the warehouse for each of the 48 combinations of retrieval in sequence strategies (see Fig. 5).

Combination {3, 8, 11} achieves the highest throughput. However, this combination only displays a higher throughput than random 'sequenced' combination {1, 5, 11} when the stacker cranes become the bottleneck of the system, i.e. for 10 or more shuttles.

Table 1: Stacker crane parameters.

Parameter	Value
Travel speed x	4.0 m/s
Travel acceleration x	0.5 m/s^2
Lifting speed y	1.0 m/s
Lifting acceleration y	1.0 m/s^2
Satellite speed z	1.2 m/s
Satellite acceleration loaded z	0.5 m/s^2
Satellite acceleration unloaded z	1.0 m/s^2
Time of pallet handover	2.0 s
Time of satellite handover	6.0 s
Time for positioning in channel	1.0 s
Time for positioning before channel	1.0 s

Table 2: Shuttle parameters.

Parameter	Value
Speed (loaded)	0.6 m/s
Speed (empty)	1.0 m/s
Acceleration (loaded)	0.3 m/s^2
Acceleration (empty)	0.6 m/s^2
Turning time	6.6 s
Handover time	10.0 s

Combination {2, 8, 11} has the highest throughput for eight shuttles, which is when the shuttles are still the bottleneck of the system.

One interesting finding is that with less than 12 shuttles, random combination {1, 5, 9} results in a very low throughput.

We also investigate the utilization ratio and time components of the shuttles (see Fig. 6). We define the utilization ratio as the sum of column components in Fig. 6, which are dark-green, light green and yellow.

We note that combination {3, 8, 11} has the highest utilization ratio. In fact, in combination {3, 8, 11} the shuttles spend less time waiting for available transfer buffer pallets than in combinations {1, 5, 11} and {2, 8, 11}.

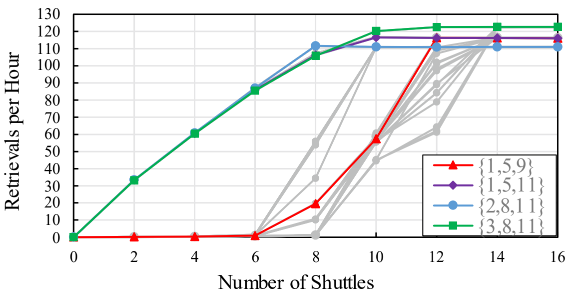

Figure 5: Throughput provided by 48 combinations of order assignment strategies for retrieval in sequence.

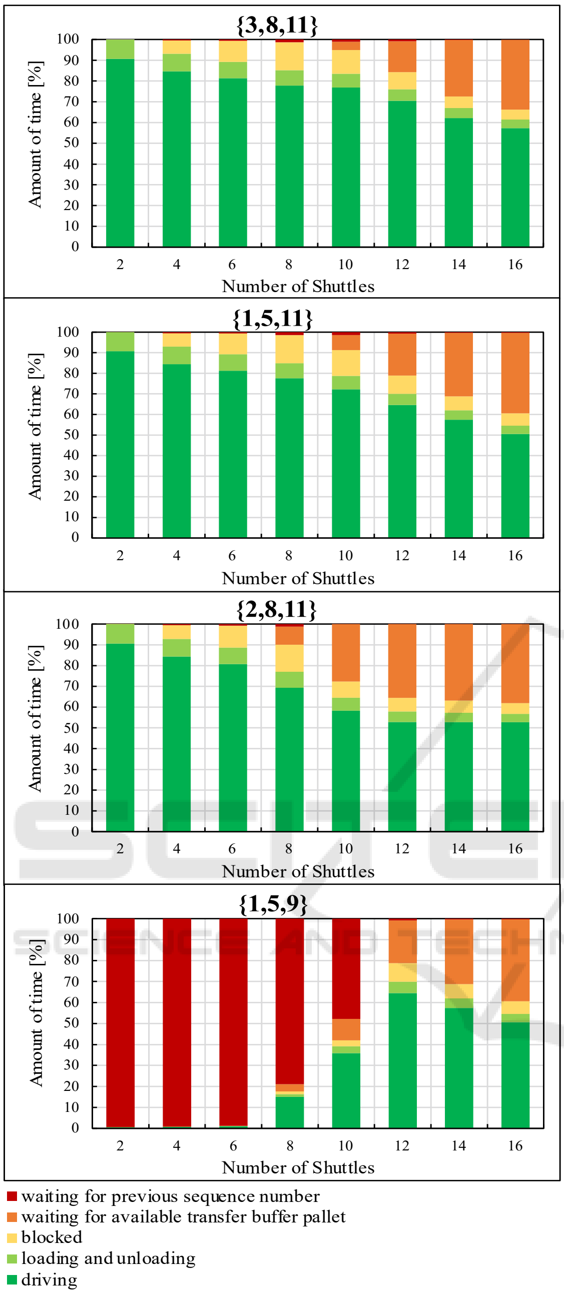

Figure 6: Time components of significant combinations for retrieval in sequence.

With random combination {1, 5, 9}, loaded shuttles spend most of their time waiting on the transfer buffer for the pallet with the previous sequence number to be taken.

Next, we investigate which operation for retrieval in sequence has the greatest impact on throughput. For this purpose, we filter the throughput results of the simulation, considering one operation at a time (see Fig.7).

On one hand, the *shuttle chooses an available pallet on the transfer buffer* operation has the biggest effect on throughput when the shuttles are the bottleneck of the system.

On the other hand, the *stacker crane chooses an available position on the transfer buffer* operation has the biggest effect on throughput when the stacker cranes are the bottleneck of the system.

The *stacker crane chooses a shuttle to awaken* operation has virtually no influence on throughput.

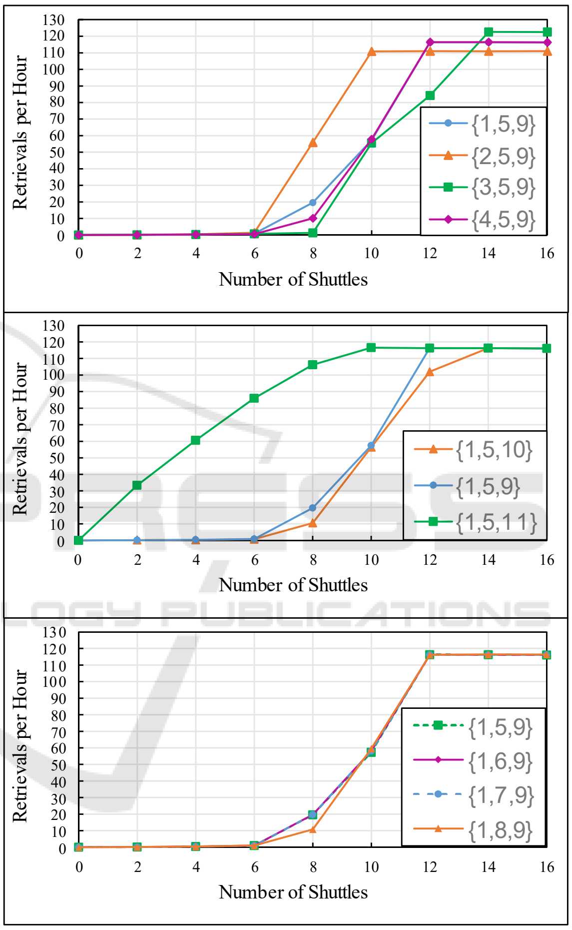

Figure 7: (from top) Influence of operations *stacker crane chooses an available position on the transfer buffer*, *shuttle chooses an available pallet on the transfer buffer* and *stacker crane chooses a shuttle to awake* on throughput.

4.4 Evaluation: Storage

We evaluate by simulation the throughput of the warehouse for each of the eleven combinations of strategies for storing (see Fig. 8).

Combination {13, 18} achieves the highest throughput when the stacker cranes are the bottleneck of the system, i.e. for eight or more shuttles.

Combination {13, 15}, provides the highest throughput when the shuttles are the bottleneck of the system, i.e. for six or fewer shuttles. Note that random combination {12, 15} achieves a low throughput.

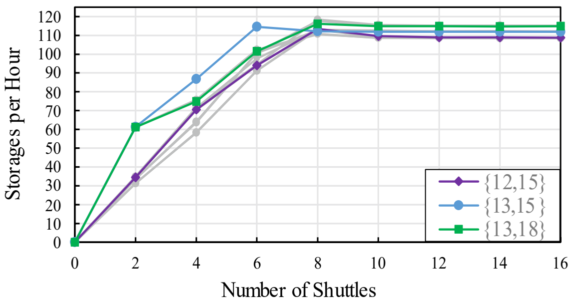

Figure 8: Throughput achieved by eleven combinations of order assignment strategies for storing.

In addition, we investigate the utilization ratio and time components of the shuttles (see Fig. 9).

When the shuttles are the bottleneck, combinations {13, 18} and {13, 15} achieve a higher utilization ratio than random combination {12, 15}. In fact, in combinations {13, 18} and {13, 15}, the shuttles spend less time being blocked due to mutual route interferences than in random combination {12, 15}. When the stacker cranes are the bottleneck, combination {13, 18} ensures the highest utilization ratio.

Next, we investigate which storage operation has the biggest impact on throughput. For this purpose, we filter the throughput results of the simulation, considering one operation at a time (see Fig 10).

On one hand, the *shuttle chooses a free position on the transfer buffer* operation has the greatest impact on throughput when the shuttles are the bottleneck of the system.

On the other hand, the *stacker crane chooses an available pallet on the transfer buffer* operation has the greatest influence on throughput when the stacker cranes are the bottleneck of the system.

4.5 Evaluation: Double Cycle

We define a double cycle as the combination of a storage and a retrieval in sequence. Specifically, in a double cycle, each shuttle takes a pallet to store from the I location, brings it to the transfer buffer, takes a retrieval pallet on the transfer buffer, brings it to the O location – while respecting the correct sequence – and returns to the I location to restart the double cycle. In the meantime, each stacker crane alternates a storage cycle with a retrieval cycle.

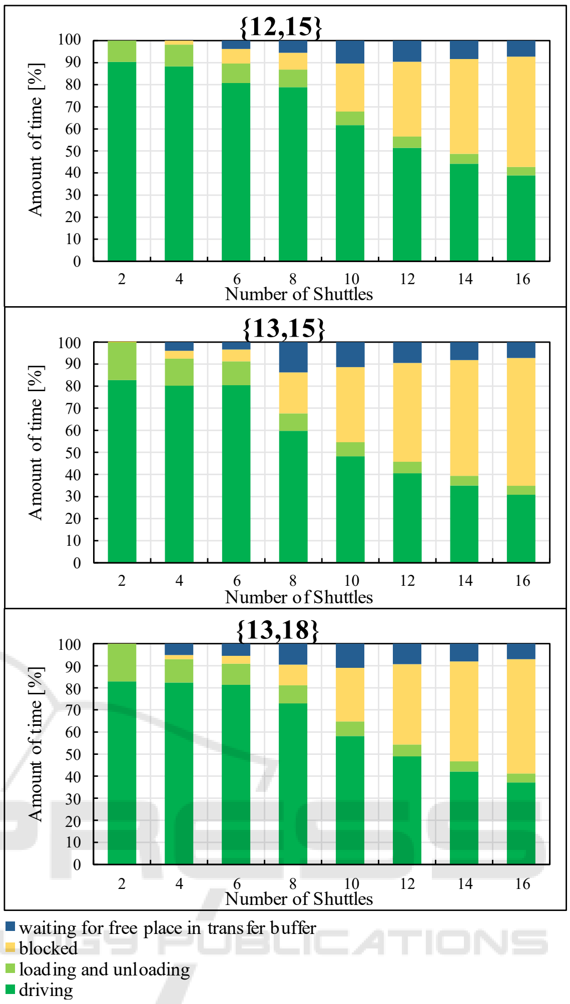

Figure 9: Time components of significant combinations for storage.

We evaluate by simulation the throughput of the warehouse for each of the 48 combinations of the strategies for storing and retrieving in sequence, as applied to double cycles (see Fig. 11). We consider only 48 combinations, because we always choose the pallet with the smallest sequence number for the retrieval operation *shuttle chooses an available pallet on the transfer buffer* and we always choose a random idle shuttle for the retrieval operation *stacker crane chooses a shuttle to awake*.

The results show that all combinations achieve a very similar throughput when the shuttles are the bottleneck. When the stacker cranes are the bottleneck, the combination {3, 5, 11, 13, 17} achieves the highest throughput. Combination {3, 5, 11, 13, 17} means that each shuttle takes a pallet to store from the I location and brings it to the nearest available position on the transfer buffer. Next, the

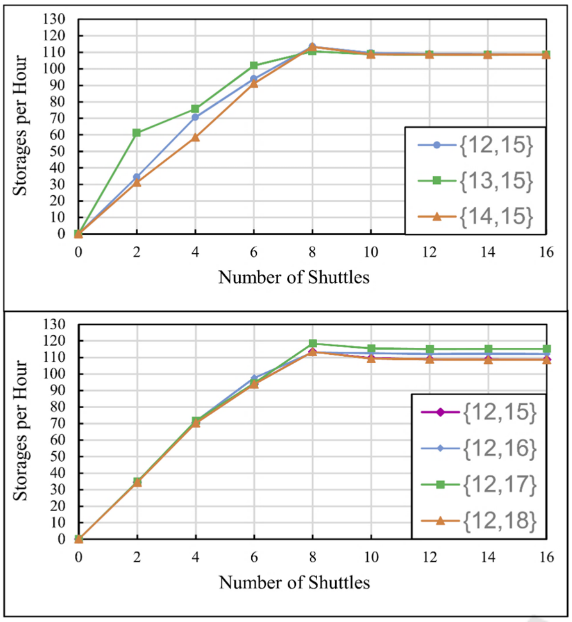

Figure 10: (from up to down) Influence of operations *shuttle chooses a free position on the transfer buffer* and *stacker crane chooses an available pallet on the transfer buffer* on throughput.

shuttle takes the available retrieval pallet with the smallest sequence number on the transfer buffer and brings it to the O location. Each stacker crane alternately takes the storage and the retrieval pallets whose locations on the transfer buffer ensure the shortest path for the stacker crane.

Note that random 'sequenced' combination {1, 5, 11, 12, 15} also achieves a high throughput compared to the majority of the other combinations. We also investigate the utilization ratio and time components of the shuttles (see Fig. 12). Combination {3, 5, 11, 13, 17} achieves the highest utilization ratio. Specifically, in combination {3, 5, 11, 13, 17}, the shuttles wait for a shorter time for an available transfer buffer pallet than in random 'sequenced' combination {1, 5, 11, 12, 15}.

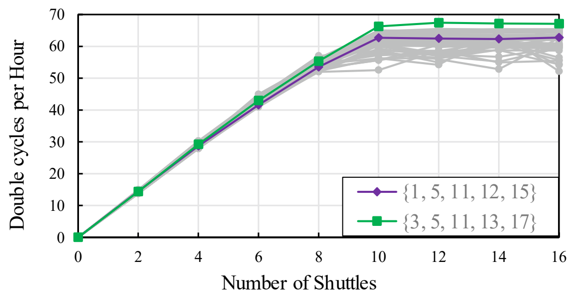

Figure 11: Throughput achieved by 48 combinations of order assignment strategies for double cycles.

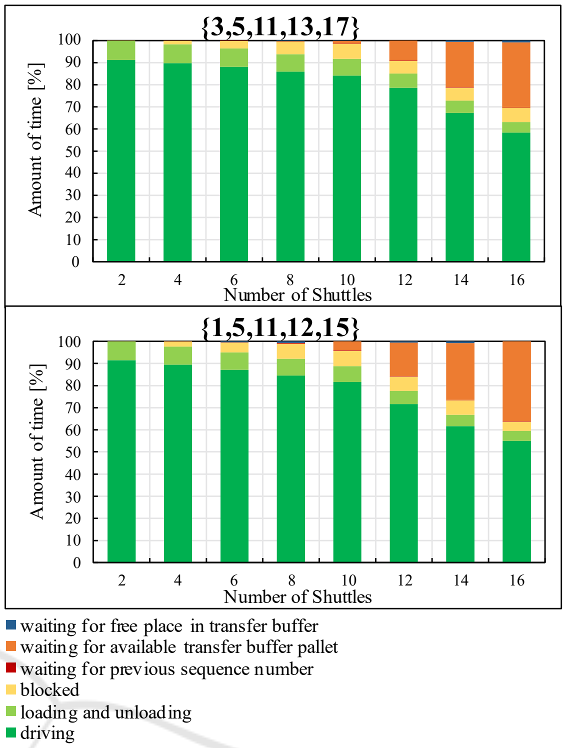

Figure 12: Time components of significant combinations for double cycles.

5 CONCLUSION AND OUTLOOK

In this paper, we develop and evaluate different order assignment strategies for a DHPW by discrete event simulation, considering retrieval in sequence, storage and double cycles. As evaluation criteria, we analyze warehouse throughput and the utilization ratio and time components of the shuttles. We also investigate which retrieval in sequence and storage operations have the greatest impact on warehouse performance. Finally, we suggest an optimum combination of order assignment strategies, which guarantees the highest performance in the different operational conditions.

Our main results are as follows:

- To achieve the best performance for retrieval in sequence, each shuttle takes the pallet of the transfer buffer with the smallest sequence number. Each stacker crane brings its pallet to the transfer buffer location that ensures the shortest path for the stacker crane. Stacker cranes awaken those idle shuttles first that have executed the fewest orders since the commencement of retrieval.

- To achieve the best storage performance, each shuttle brings its pallet to the available transfer buffer location nearest to the I location. For stacker cranes, the following two cases are possible: when the shuttles are the bottleneck, each stacker crane takes a random pallet from the transfer buffer; when the stacker cranes are the bottleneck, each stacker crane takes the pallet from the transfer buffer that has been available for the longest time.
- To achieve the best double cycle performance, each shuttle brings storage pallets to the available position of the transfer buffer that is nearest to the I location. Each shuttle takes available retrieval pallets with the smallest sequence number on the transfer buffer. Each stacker crane alternately takes storage and retrieval pallets whose locations on the transfer buffer ensure the shortest path for the stacker crane.

For future research, we suggest investigating the influence of layout on performance. Examples of characteristic layout parameters that can be varied are the dimensions of the shuttle base tier, the arrangement of the retrieval and storage positions in the transfer buffer, and the zoning strategy used.

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