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Simulation Study on the Influence of Design on the Performance of Dynamic Hybrid Pallet Warehouses

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Abstract

Dynamic Hybrid Pallet Warehouses (DHPWs) are a novel class of automated warehouses, combining the advantages of shuttle-based and stacker crane-based warehouses by using shuttles for transport in the horizontal direction and stacker cranes for the vertical connection of the tiers. The literature for conventional shuttle-based and stacker crane-based warehouses shows that the design influences the performance considerably. In this paper, we investigate the influence of the main design elements that characterize the performance of DHPWs through discrete element simulations for different types of DHPWs and in different operating modes. The design elements under investigation are the configuration of the transfer buffers, the location of the input/output area, the number of levels and the size of the shuttle fleet.

Keywords: shuttle; stacker crane; automated warehouse; design optimization; layout

1. Introduction

Dynamic Hybrid Pallet Warehouses (DHPWs) are automated warehouses that are created by hybridizing shuttle-based and stacker crane-based warehouses. They are referred as "dynamic", because the advantage of such hybridization is that the flexible connection between shuttles and stacker cranes enables them to achieve higher dynamics, i.e. higher performances, than conventional systems.

There are three types of DHPWs:

- Layout 1, i.e. hybridization of a multi-depth channel storage served by satellite stacker cranes with a tier of shuttles on the base (Eder, Klopfenstein, and Gebhardt, 2019; Siciliano, Lienert, and Fottner, 2020);
- Layout 2, i.e. hybridization of a shuttle-based warehouse with multiple stacker cranes in a single aisle used to connect the levels. The shuttles are not able to move among levels (Malik, 2014; Siciliano, Yu, and Fottner, 2022);
- Layout 3, i.e. as layout 2, but shuttles can move between levels carried by stacker cranes (Malik, 2014; Siciliano, Yu, and Fottner, 2022).

Shuttles exchange pallets with conveyors, which bring them to the trucks, at input/output (I/O) locations as in Figure 1. Layout 1 only has a transfer buffer on the base, whereas layout 2 and 3 have transfer buffers at every level.

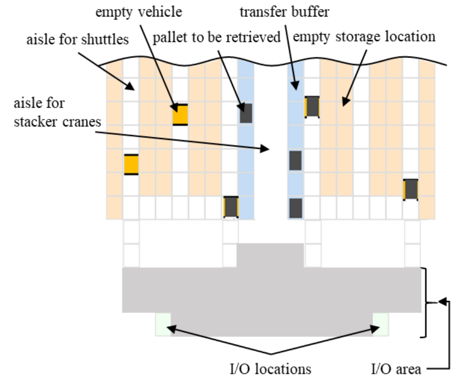

Figure 1. Base tier model adapted from (Siciliano, Yu, and Fottner, 2022)

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2. Main Design Features of Automated Warehouses

DHPWs are combinations of shuttle-based and stacker crane-based warehouses. Thus, we believe the variables found in literature that influence the performance of these two conventional systems are also a good starting point to examine the design of DHPWs. In stacker crane-based warehouses, the length of racks, their height, the number and location as well as the buffer capacity of I/O-points are design features that influence performance (Roodbergen and Vis, 2009). In shuttle-based warehouses, the number of levels, aisles, and rows of storage, as well as the speed and number of shuttles and lift systems have a strong influence on performance (Lerher, Ekren, and Rosi, 2016). Consequently, it seems logical to investigate the throughput of DHPWs while varying the number of levels and the length of aisles. Siciliano, Yu, and Fottner (2022), among other results, have already investigated the variation of throughput for DHPWs for different length of aisles. Lantschner (2015) investigated the influence on throughput based on the number and position of transfer locations for a stacker crane-based warehouse. Thus, we examine the influence on throughput of DHPWs when the configuration of the transfer buffer is varied. Recently, Xu, Zhao, Zou, Gong, and Wang (2020) investigated the throughput of a stacker crane-based warehouse while varying the allocation of I/O-points. Therefore, it seems to us meaningful to investigate the I/O areas of DHPWs.

3. Concept Development: Design Features for DHPWs

In this section, we illustrate the relevant elements for characterizing the design of a DHPW. A specific characteristic of DHPWs is the presence of transfer buffers along the whole aisle. To enable a smooth material flow, some locations of the transfer buffers are reserved for either storage or retrieval. The sequence resulting from the alternation of these storage or retrieval locations constitutes the configuration of the transfer buffer. Different configurations of transfer buffers allow us to increase, decrease or shift the area where shuttles and stacker cranes operate most. In Appendix A, we present possible configurations of transfer buffers, when one or two stacker cranes are operating in the aisle. Each configuration is identified by TB followed by a number. The influence of these configurations on throughput is the object of the study, by means of the simulation in Section 4.1. Another design feature of DHPWs is the I/O area. We have already studied its optimal configuration for high dynamics in (Siciliano, Durek-Linn, and Fottner, 2022). In that case, the I/O area was present on both sides of the warehouse. However, the area of a plant reserved for shipping trucks is generally positioned on only one side of the warehouse to save space. Therefore, it is important to investigate the loss of throughput if just one I/O area is used compared to two I/O areas. When using one I/O area for single cycles, both I/O locations can be used to perform a type of single cycle. Since shuttles cannot change sides in the warehouse, the implementation of double cycles for one I/O area requires a different control strategy than that for two I/O areas. One possible strategy is that shuttles on the left side of the warehouse perform only retrieval, and shuttles on the right only storage tasks. According to this strategy, stacker cranes can continue to execute double cycles. We investigate the effect of this control strategy for double cycles in Section 4.2. One more design element that influences the throughput of DHPWs is the number of shuttle levels. In fact, the trade-off between the reduction in throughput due to the longer travel path of the stacker crane when more levels are used and the increase in throughput due to the introduction of additional shuttles for each further level is different for each type of DHPW. We study this trade-off in Section 4.3. Finally, for layout 2, the fleet of shuttles that has the most influence on throughput is that on the base tier. In fact, all retrieval and storage orders are completed or initiated by shuttles on the base, driving to O location or starting from I location. This leads to a higher utilization of shuttles on the base than shuttles on the different levels. In Section 4.4, we demonstrate that it is possible to reduce a certain number of shuttles on the levels without decreasing the overall throughput of the warehouse.

4. Simulation Study

The aim of this section is to investigate the influence of the design elements on throughput and individuate their negligible

. For this purpose, we performed experiments on the models of layout 1, 2 and 3 in the discrete event simulation environment Plant Simulation Tecnomatix. Five replications are performed per experiment, each lasting 24 hours. The layouts used for experiments have an aisle length of 83 m, i.e. they have five sections. A section is the area of a tier between two cross aisles (Siciliano, Yu, and Fottner, 2022). Therefore, each side of the warehouses has three storage aisles and two cross aisles. Moreover, unless otherwise indicated, the models have eight levels for layout 1 and four levels for layout 2 and 3, including the base. Unless otherwise indicated, two stacker cranes are considered per aisle with fixed operational intervals. These dimensions and number of stacker cranes represent the expected average application of DHPWs. Unless otherwise indicated, there are two I/O areas in total, each of them collocated at the extremes of the aisles, and the transfer buffers are as TB 1. We considered the processes of retrieval and of double cycles, i.e. shuttles alternate between storage and retrieval orders. This is because they are more relevant than the storage process for a characterization of the performance of a warehouse. A manufacturer provided the parameters used (see Table 1 and 2).

Table 1. 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

Table 2. Stacker cranes 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 in layout 1	1.2 m/s
Satellite acceleration loaded z in layout 1	0.5 m/s^2
Satellite acceleration unloaded z in layout 1	1.0 m/s^2
Time of pallet handover in layout 1	2.0 s
Time of satellite handover in layout 1	6.0 s
Time for positioning in channel in layout 1	1.0 s
Time for positioning before channel	1.0 s
Time of pallet handover in layout 2 and 3	6.0 s
Time for positioning before channel in layout 2 and 3	1.0 s

In the following subsections, we illustrate and discuss the results in terms of throughput when varying each of the relevant design elements.

4.1. Configurations of Transfer Buffers

We simulate the behavior of DHPWs for the different configurations of transfer buffers in cases where no stacker cranes are used, as in Figure 2. We then perform simulations introducing one and two stacker cranes per aisle for layout 1, 2 and 3 respectively, see Figure 3, 4 and 5.

As can be seen in Figure 2, TB 28 is the configuration of transfer buffer that provides the highest throughput for retrieval and double cycles without stacker cranes. The reason is that in this configuration, the storage and retrieval locations of the transfer buffer are near I and O locations respectively. This results in short cycle paths, thus short cycle times, for shuttles. The difference in throughput corresponding to the different transfer buffer configurations is higher for retrieval (see Figure 2a) than for double cycles (see Figure 2b). One explanation is that in the case of double cycles, the shuttles alternate between a storage and a retrieval cycle, and on average balance the path differences between transfer buffer and I/O locations better.

We now consider layout 1 in Figure 3. In line with the bottleneck of one or two stacker cranes, i.e. plateau of the curves, the difference in throughput between different transfer buffer configurations becomes negligible for both retrieval and double cycles. However, when the shuttles are the bottleneck in the system, a non-negligible difference remains between

The resulting longer paths divide the layouts into the groups described above, with TB 1 having the lowest throughput. A similar behavior occurs for retrieval with two stacker cranes (see Figure 4b) after the bottleneck of stacker cranes, i.e. for 64 or more shuttles. The effect of splitting groups after the stacker cranes' bottleneck is juxtaposed in double cycles (see Figures 4c and d) by

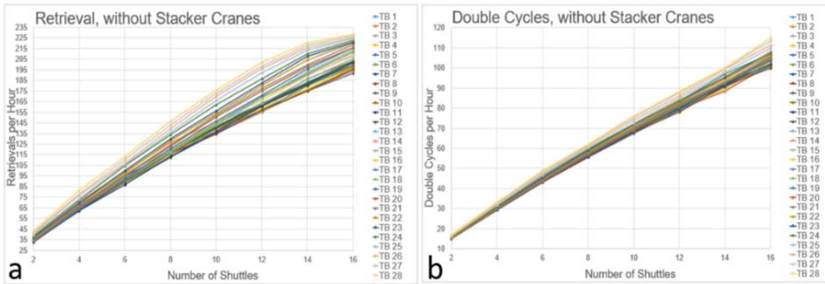
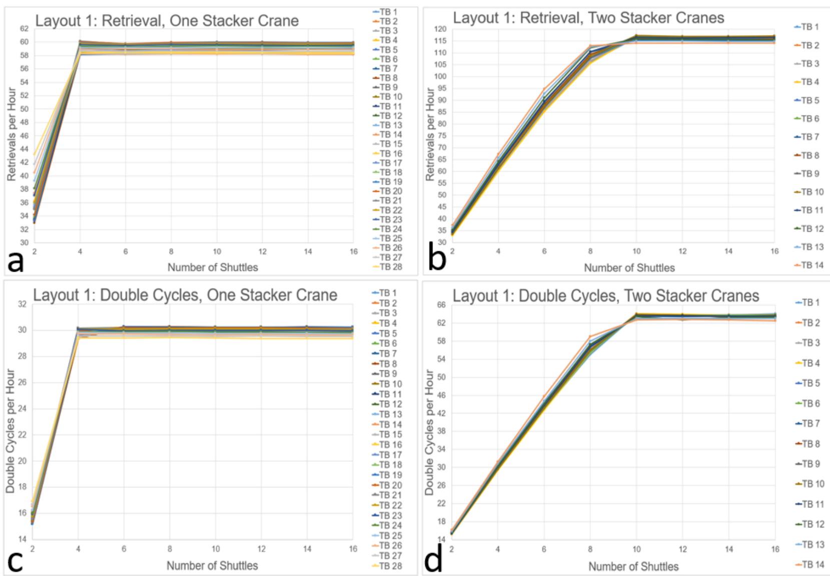


Figure 2. Throughput of the shuttle base tier when varying the configuration of the transfer buffer without stacker cranes.



the configurations. As for the layout without stacker cranes, this difference increases with the increasing number of shuttles. The highest throughput is achieved before the bottleneck by TB 28 for one stacker crane (see Figures 3a and c) and by TB 14 for two stacker cranes (see Figures 3b and d). TB 14 is the corresponding configuration for two stacker cranes as TB 28 for one stacker crane.

Considering the layout 2 for retrieval shown in Figure 4a, once the bottleneck of a stacker crane for 24 or more shuttles is reached, the transfer buffer configurations are divided into two groups, with TB 18 to 28 forming the group with the highest performance. The minimum difference between these groups is approximately 5 pallets per hour. While TB 28 has highest throughput before the bottleneck, TB 19 takes over afterwards. Compared to TB 28, this configuration has only 18 instead of 28 retrieval locations in the buffer and these are arranged centrally. This means that the path of the stacker crane is much shorter on average. The longer distance of the shuttles in the base from the transfer buffer to the O location compared to TB 28 is irrelevant because the stacker crane is the bottleneck.

the distance balancing introduced by performing alternate storage and retrieval tasks.

We now focus on layout 3, as shown in Figure 5. The stacker crane's bottleneck is already reached with 8 shuttles (see Figure 5a) if only one stacker crane is used. The difference in throughput between different transfer buffer configurations is small for layout 3 with one or two stacker cranes and for retrieval or double cycles, because the storage and retrieval locations of the transfer buffer are used not only for exchange

Figure 3. Throughput of layout 1 when varying the configuration of the transfer buffers for one and two stacker cranes in a single

pallets, but also for transferring empty shuttles from one level to another. This results in a balancing of the lengths of paths travelled by the shuttles to move between storage/ retrieval locations of the transfer buffer and I/O locations.

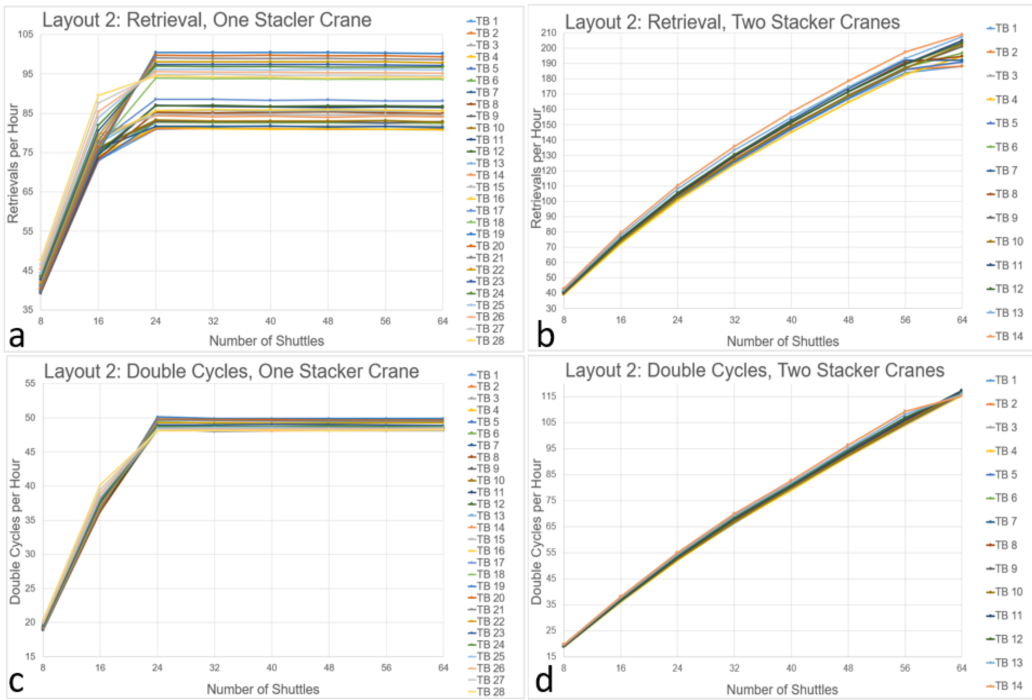


Figure 4. Throughput of layout 2 when varying the configuration of the transfer buffers for one and two stacker cranes in a single aisle.

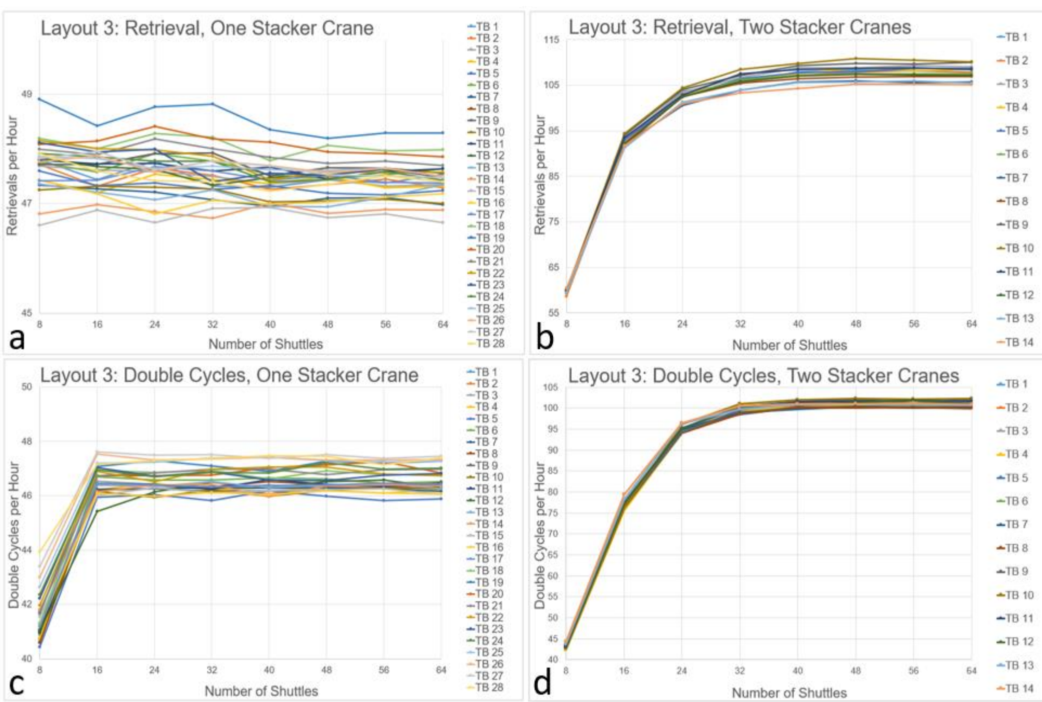


Figure 5. Throughput of layout 3 when varying the configuration of the transfer buffer for one and two stacker cranes in a single aisle.

4.2. Number of I/O Areas

We now consider the behavior of the system if the I/O area is on both sides of the warehouse or on just one side in layout 1, 2 and 3 in case of double cycles, as shown in Figure 6.

In layout 1 (see Figure 6a), there is a shift in the stacker crane's bottleneck when using one I/O area compared to two I/O areas. The reason is that shuttles have to cover a longer distance due to the lack of an I/O area. Thus, they are the bottleneck in the system up to 12 shuttles. The lower throughput with one I/O area becomes noticeable with six shuttles and the throughput difference increases up to the stacker cranes' bottleneck. When the stacker cranes are the bottleneck, i.e. for 12 or more shuttles, the throughput difference between the two design variants becomes smaller and remains approximately constant. The maximum difference in throughput between the two warehouses occurs with eight shuttles and measures six double cycles per hour.

Layout 2 (see Figure 6b) shows a similar behavior to layout 1: the difference in throughput increases as the number of shuttles increases, up to a difference of 15 retrievals per hour for a total of 64 shuttles in the warehouse. Since no bottleneck occurs, no statement can be made about the shift of the bottleneck.

In contrast to layout 1, the bottleneck of the stacker cranes occurs earlier for the design with one I/O area than for that with two in layout 3 (see Figure 6c). Similarly, the throughput difference in layout 3 between the two designs is much larger than that in layout 1 and 2, reaching a maximum of 46 double cycles per hour. This great difference can be explained by the strategy used to implement the single I/O area. The shuttles on the left side of the warehouse only perform retrievals, as the O location is also located on the left side in the I/O area. The shuttles on the right side perform only storages. As a consequence, the shuttles on the left side must return to a level other than the base after a retrieval on the base and have to travel empty until they reach that level. With two I/O areas, on the other hand, shuttles pick up one more pallet for storage on the base. This means that the efficiency of the double cycles, and therefore the throughput, is much higher with two I/O areas, since the shuttles do not have to return empty.

4.3. Number of Levels

We consider the behavior of layout 1, 2 and 3 when varying the number of levels in Figure 7.

In layout 1 (see Figure 7a), the difference in throughput between the different warehouse sizes for a retrieval is negligible until the stacker cranes with ten shuttles become a bottleneck. In accordance with the stacker crane bottleneck, i.e. with ten or more shuttles, the configuration with two levels offers the highest throughput. The paths of the stacker crane, which mainly determine the throughput from the bottleneck onwards, depend on the number of levels. The more levels there are in the warehouse, the longer the vertical distances that the crane has to travel. For example, if there are two levels in the warehouse model, the stacker crane only has to travel the vertical distance between the first and second level. As a result, the lower the number of levels, the higher the performance in layout 1. The same applies for double cycles (see Figure 7b). In layout 2 and 3, there are shuttles not only in the base, but also at each level of

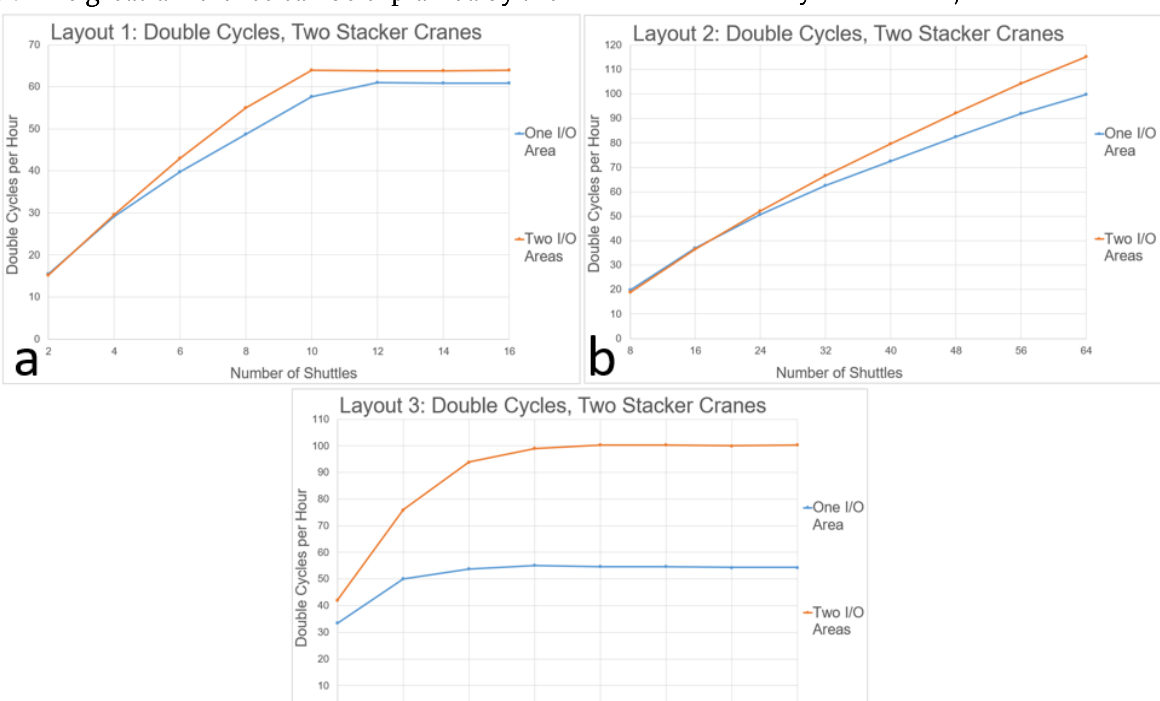


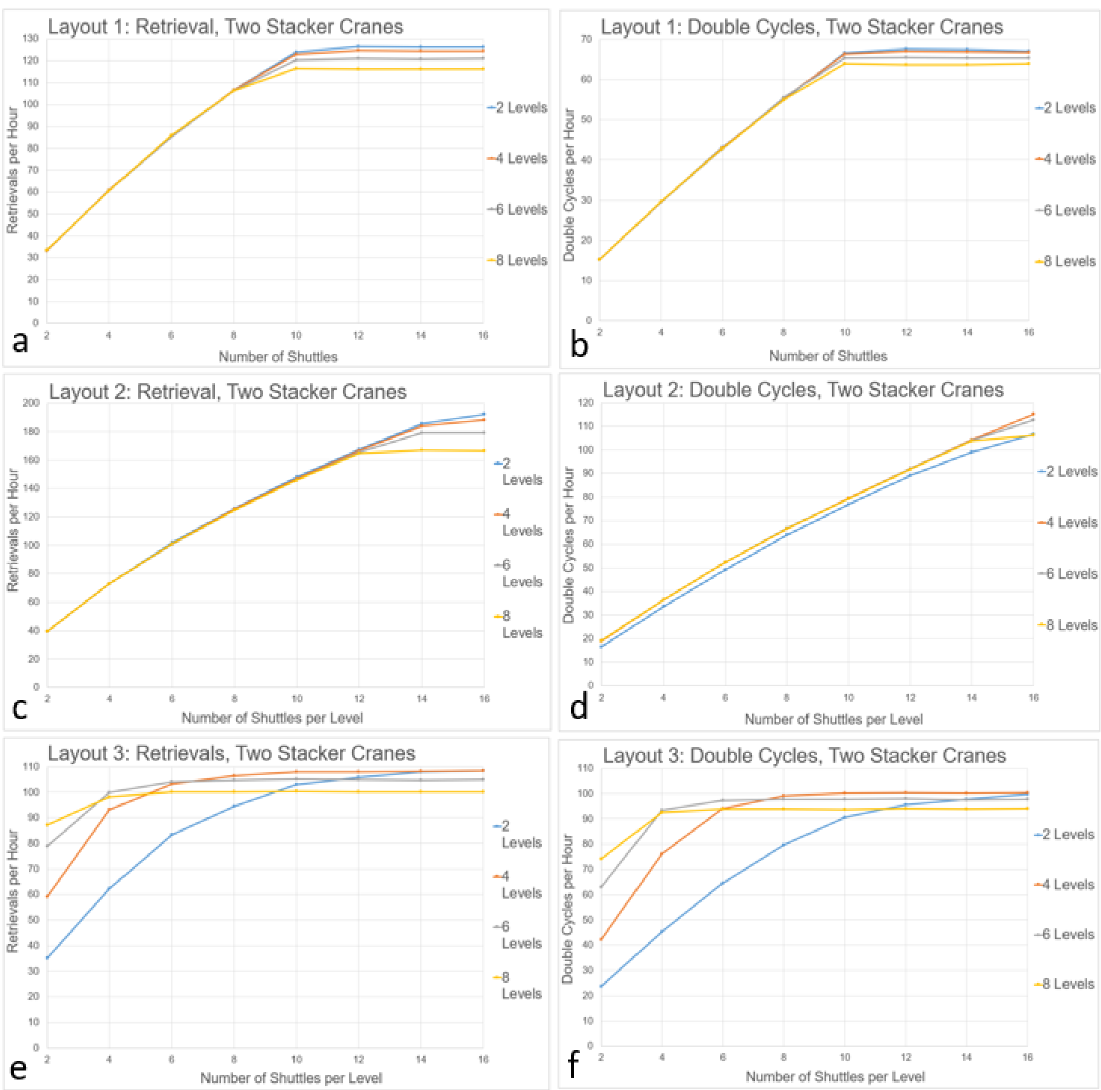
Figure 6. Throughput of layout 1, 2 and 3 when varying the number of I/O Areas.

the warehouse. Since the total number of shuttles increases with the number of levels, the number of shuttles on each level is considered in the graphs of Figure 7 to obtain results that are comparable. In contrast to layout 1, the bottleneck of the stacker cranes is shifted according to the number of levels in layout 2 (see Figure 7c). Before this bottleneck, the difference in throughput for the different number of levels is negligible. The more levels there are in the warehouse, the earlier the stacker cranes' bottleneck occurs. This is due to the higher number of shuttles in the warehouse serving the transfer buffers. At the same time, the throughput becomes lower the more levels there are due to the longer vertical paths of the stacker cranes. Even in the double cycles with two stacker cranes (see Figure 7d), the stacker cranes for the configuration with eight levels are the first to become the bottleneck. The model with two levels shows the lowest throughput, because the total number of shuttles in the warehouse is less than for a higher number of levels.

As with layout 2, the higher the number of levels, the earlier the stacker crane bottleneck occurs in layout 3 (see Figures 7e and f). This is because the total number of shuttles increases with each additional level, thus the stacker cranes receive more orders. Before the stacker cranes' bottleneck, the configuration with the most levels has the highest throughput, while the configuration with only two levels has the lowest performance because it has the fewest shuttles. As with layouts 1 and 2, when the stacker crane bottleneck is reached, the vertical path is the decisive factor for performance in layout 3. Subsequently, the throughput of the warehouse with eight levels is the lowest.

4.4. Fleet Size

In Figure 8, we demonstrate that the number of shuttles on the base is decisive for throughput for layout 2. In fact the throughput does not decrease with a certain reduction in the number of shuttles on the levels. In particular, during retrieval with one or two stacker cranes (see Figures 8a and b), the throughput remains at the same level as with eight shuttles per level, although the number of shuttles on each level is reduced to two, provided eight shuttles remain on the



base. The same behavior is found for layout 2 with an initial number of six or four shuttles per level. In the case of double cycles for one or two stacker cranes (see Figures 8c and d), the throughput remains constant by decreasing the number of shuttles per level from eight to four as long as there are eight shuttles on the base. The same behavior is found if the initial number of shuttles per level is four or six. The reason why the minimum number of shuttles required per level is twice as high for double cycles as it is for retrieval is that approximately twice as many orders have to be executed in double cycles.

reasonable choice for layout 1 and 2 in double cycles. However, for DHPWs with layout 3 this leads to a very high loss in throughput compared with the case of I/O areas on both sides of the warehouse.

- For retrievals and double cycles, increasing the number of levels for layout 1 and 2 has a negligible impact on throughput until the stacker cranes' bottleneck is reached.
- For DHPWs with layout 2, the of fleet of shuttles that has the most influence on throughput is that on the base tier. Thus, the

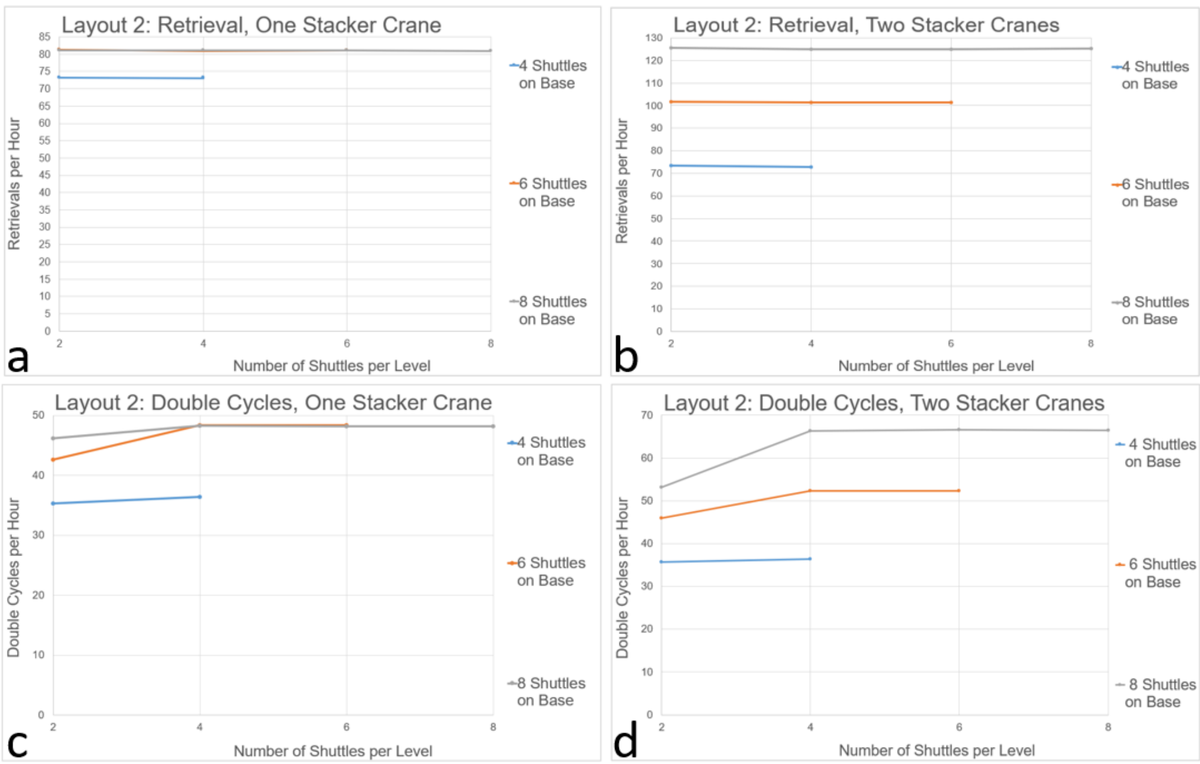


Figure 8. Throughput of layout 2 when reducing the number of shuttles on levels for fixed number of shuttles on base.

number of shuttles per level can be reduced to a certain minimum without reducing throughput as long as the number of shuttles on the base is not reduced.

5. Conclusions

In this paper we investigated the influence of the main design features on throughput for three types of DHPWs using discrete event simulation. Layout 1 is a stacker crane-based warehouse with an additional shuttle layer at the bottom. In layout 2, all tiers are served by shuttles that cannot travel between tiers. The vertical connection is made via stacker cranes. With layout 3, the stacker cranes can transfer shuttles between tiers as needed. The main results are as

Figure 7. Throughput of layout 1, 2 and 3 when varying the number of levels.

follows:

- The influence of the transfer buffer configuration is critical for DHPWs with layout 2 in case of retrieval, especially when the stacker cranes' bottleneck is reached.
- Using an I/O area on one side only is a

A design optimization framework could be developed for future research to determine the optimal overall design of a DHPW. Such a framework should provide suggestions for configuring design features to optimize not only throughput but also operating costs and energy consumption.

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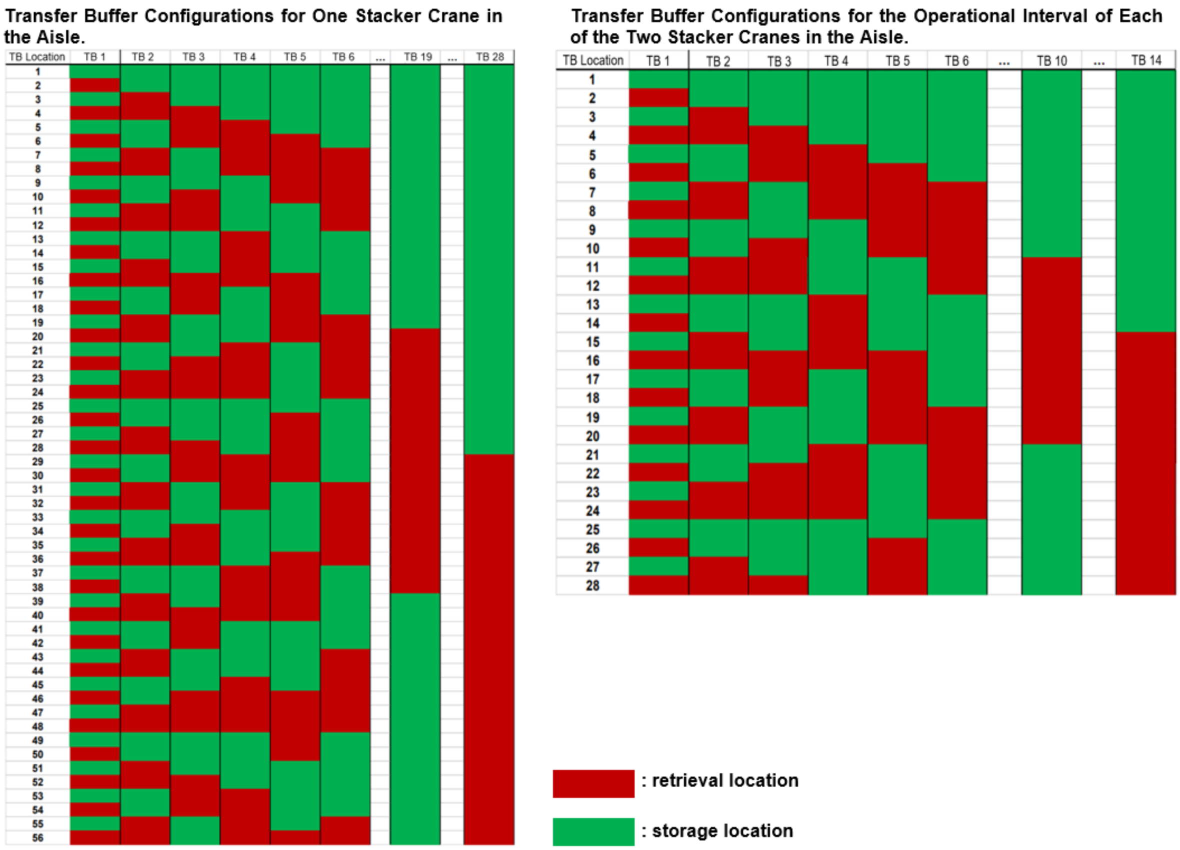

Figure A-1. Transfer Buffer configurations for a DHPW with one or two stacker cranes per aisle.

Appendix A

In Figure A-1 there are possible transfer buffer configurations for a DHPW having transfer buffers of 56 locations on each side of the aisle.

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