SYNERGY BETWEEN SHUTTLES AND STACKER CRANES IN DYNAMIC HYBRID PALLET WAREHOUSES: CONTROL STRATEGIES AND PERFORMANCE EVALUATION

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KEYWORDS

Dynamic Hybrid Pallet Warehouse, Shuttle, Stacker Crane, Discrete Event Simulation, Control Strategies

ABSTRACT

This article considers two dynamic hybrid pallet warehouses obtained hybridizing a shuttle-based warehouse with stacker cranes. We begin by describing their design and characteristics. Afterwards, we explain the control algorithms that were developed for them. Next, we illustrate the modalities of the discrete event simulation study we ran to investigate their performance. In conclusion, we discuss the results in terms of throughput of the simulation study to individuate the field of application for the two layouts of dynamic hybrid pallet warehouses in comparison to stacker crane-based and shuttle-based warehouses.

INTRODUCTION

A dynamic hybrid pallet warehouse (DHPW) is a new kind of storage and retrieval system that has a shuttle tier on the base connected to the overlying storage layers through satellite stacker cranes. This arrangement allows a combination of the advantages of shuttle-based and stacker-crane-based warehouses (Eder et al., 2019) (Siciliano et al., 2020).

In recent years, another warehouse was investigated that contemplates the simultaneous use of shuttles and a stacker crane. This warehouse is denoted as autonomous shuttles and stacker crane (AS/SC) warehousing system. Its shuttles move orthogonally to the stacker crane's aisle and therefore can only use the Last In First Out (LIFO) policy. In addition, so far only one stacker crane per aisle has been implemented. (Wang et al., 2020)

On the contrary, the shuttles of a DHPW can move in both directions of the plane and up to three stacker cranes per aisle have been coordinated and investigated in (Siciliano et al., 2022). To increase the throughput of a DHPW, specific order assignment strategies (Siciliano and Fottner, 2021) and specific stacker cranes' coordination policies (Siciliano et al., 2022) should be applied that take into consideration the complex nature of the connection between shuttle tier and multiple stacker cranes in a single aisle. To investigate the nature of the connection between shuttles and stacker cranes in more detail, and to find further applications for DHPWs, this article examines two additional warehouse arrangements, which we define as layout 2 and layout 3. We call the original DHPW with the channel storage above the shuttle base layout 1. In the following section, we describe the characteristics of layout 2 and layout 3 compared to layout 1.

Systems under consideration

Layout 2 and layout 3 have shuttle tiers on not only the base but also on the levels (Malik 2014), see Fig.1.

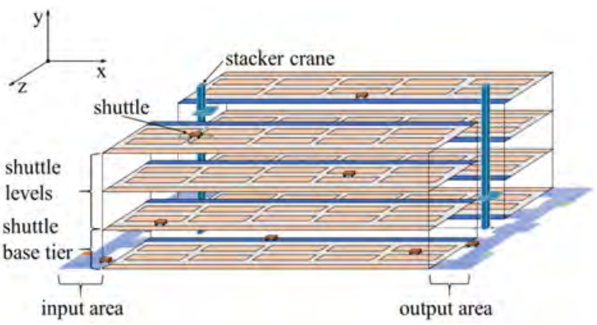

Figure 1: Structure of both Layouts 2 and 3

Communications of the ECMS, Volume 36, Issue 1,
Proceedings, ©ECMS Ibrahim A. Hameed, Agus Hasan,
Saleh Abdel-Afou Alaliyat (Editors) 2022
ISBN: 978-3-937436-77-7/978-3-937436-76-0(CD) ISSN 2522-2414

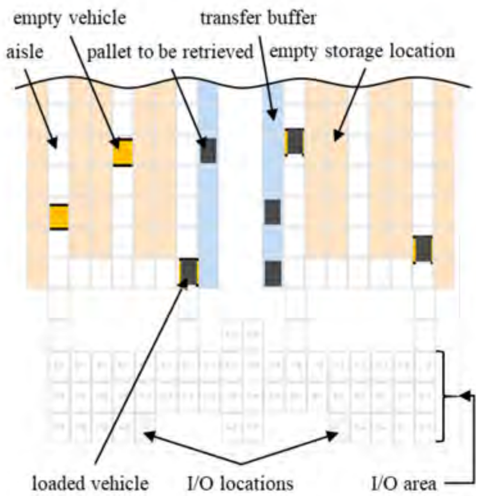

Figure 2: Screenshot of the Base Tier Model for both Layouts 2 and 3

Fork lift stacker cranes serve the transfer buffers of base tier and of the levels. Each shuttle remains in its zone i.e. left or right side of the aisle on a certain level in the warehouse. In layout 2, the shuttles cannot leave their level, while in layout 3 the shuttles can be transported by the stacker cranes between levels. The elements that make up the base tier of layout 2 and 3 are shown in Fig.2. The levels contain the same elements as the base tier, except for the fact that they lack input/output (I/O) areas. On one hand, having shuttle tiers on every level increases the investment and operational costs compared to layout 1. On the other hand, it enables better access to stored products compared to channel storage. Therefore, layout 1 can be seen as the result of the hybridization of a stacker crane-based warehouse through shuttles, while layout 2 and layout 3 are the hybridization of a shuttle-based warehouse through stacker cranes. Compared to a conventional shuttle-based warehouse with lifts, the stacker cranes' aisles in layout 2 and layout 3 offer a much more efficient means of material exchange between the base and upper levels. In fact, the transfer buffers on the base and on all levels along the whole length of the aisle provide many more exchange locations than the conventional few I/O locations of lifts. Thus, layouts 2 and 3 can achieve a higher throughput than conventional shuttle-based systems. In the following section we propose control strategies for layout 2 and layout 3.

CONCEPT DEVELOPMENT

To explain the control algorithms that were developed, we have to consider layout 2 and layout 3 separately. We implemented the algorithms in the cases of retrieval, storage and double cycles. A double cycle is the alternation of retrieval and storage orders for the shuttles. The same is true for the stacker cranes in the aisle. Therefore, retrieval and storage control strategies can be derived from the strategy for double cycles. We only discuss double cycles for the sake of brevity.

Layout 2

We first consider layout 2. The control strategy we developed for this in the case of double cycles is described in Fig. 3 for the shuttles on the base, in Fig. 4 for the shuttles on the levels, and in Fig. 5 for the stacker cranes. Abbreviations "C*n*S" and "C*n*E" indicate respectively start and end of connection *n* between shuttles and stacker cranes. The challenge compared to layout 1 is to connect and coordinate the stacker cranes with the shuttles on not only the base, but also on the different levels. For sake of completeness, we illustrate the connections between shuttles and stacker cranes for the execution of a double cycle. First, a shuttle on base executes a storage order by bringing a pallet from the I location to an available location of the transfer buffer. The shuttle then creates a storage order for the stacker crane to transport that pallet from the transfer buffer on the base to the transfer buffer of the target level, where it will be stored. The creation of such an order represents the start of one of four connection points between the control system of shuttles and that of stacker cranes. The end of connection is represented in the logic of the stacker crane by the examination of the availability status of the stacker crane. In case a stacker crane is available the storage order is executed and the pallet is delivered to the transfer buffer of the target level. At this point, the stacker crane creates a storage order for the shuttles on that level. This constitutes the start of another connection between shuttles and stacker cranes.

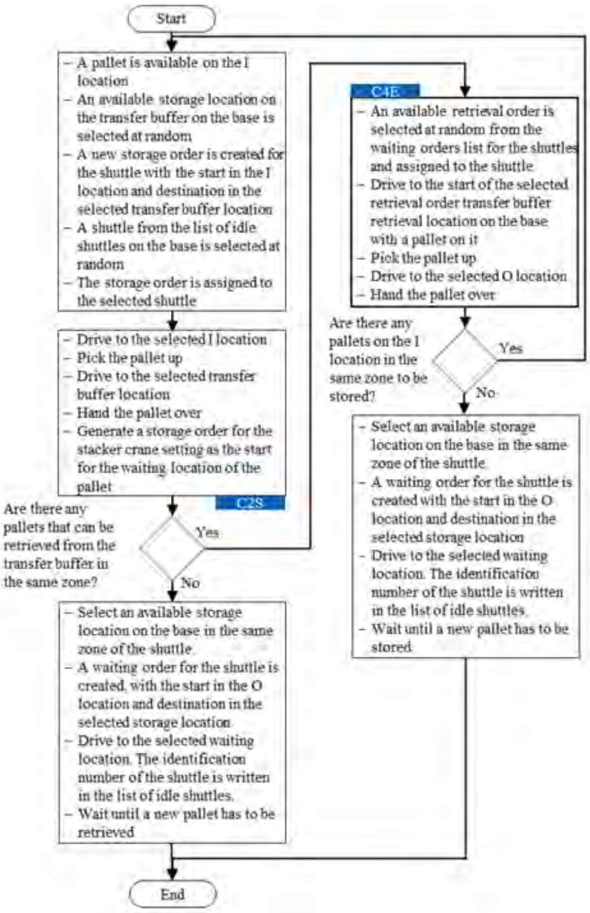

Figure 3: Control Logic – Layout 2, Double Cycles, Shuttles on Base

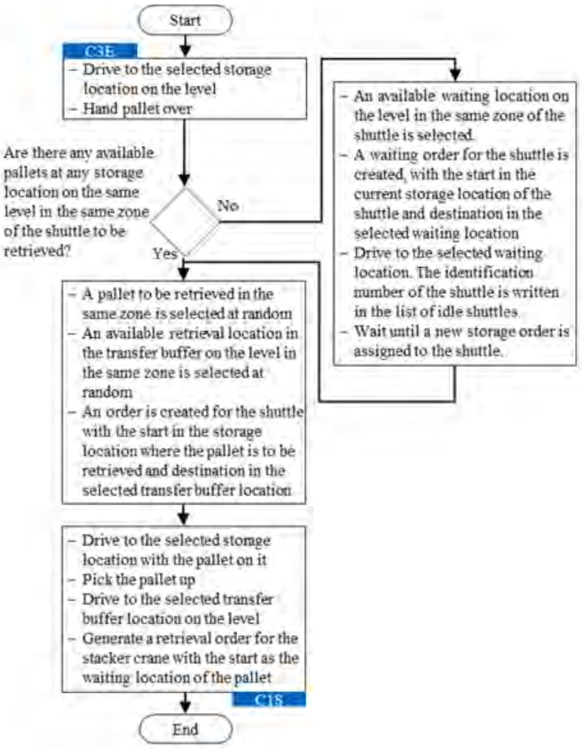

Figure 4: Control Logic – Layout 2, Double Cycles, Shuttles on Level

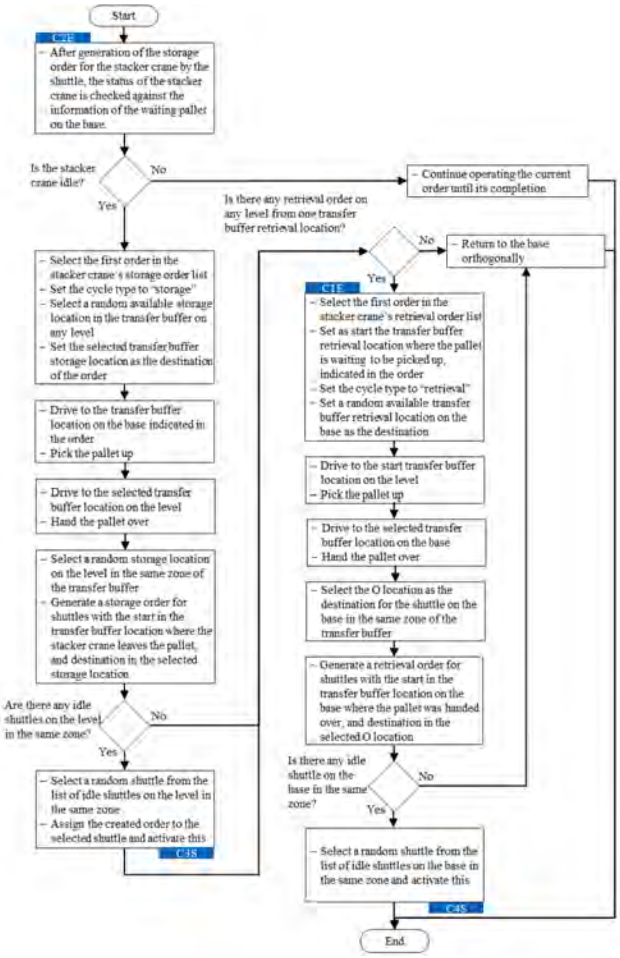

Figure 5: Control Logic – Layout 2, Double Cycles, Stacker Cranes

The end of the connection is in the logic of shuttles on level and is represented by the shuttle starting its route to pick the pallet on the transfer buffer and bring it to its final storage place. In the meantime, a shuttle on a level executes a retrieval order by moving a target pallet from its storage location to the transfer buffer. The shuttle generates then a retrieval order for the stacker crane. This generation is another connection between shuttles and stacker cranes. The end of connection is constituted by the stacker crane examining if there are retrieval orders to be executed. Next, the stacker crane performs the retrieval order by transporting the pallet to an available location of the transfer buffer on base. At this moment, another connection between stacker cranes and shuttles starts when the stacker crane generates a retrieval order for the shuttles on base. The end of connection is represented by the shuttle on base starting its route to execute the retrieval order. The shuttle transports the pallet from the transfer buffer to the O location and the double cycle is completed.

Layout 3

We now examine layout 3. The control algorithms we generated for the double cycles process in layout 3 is explained in Fig. 6 for the shuttles on the base, in Fig. 7 for the shuttles on the levels, and in Fig. 8. for the stacker cranes. The challenge, as opposed to layout 2, lies in the generation and correct assignment of transportation orders for the stacker crane to move shuttles between the different levels and the base, and of motion orders for the

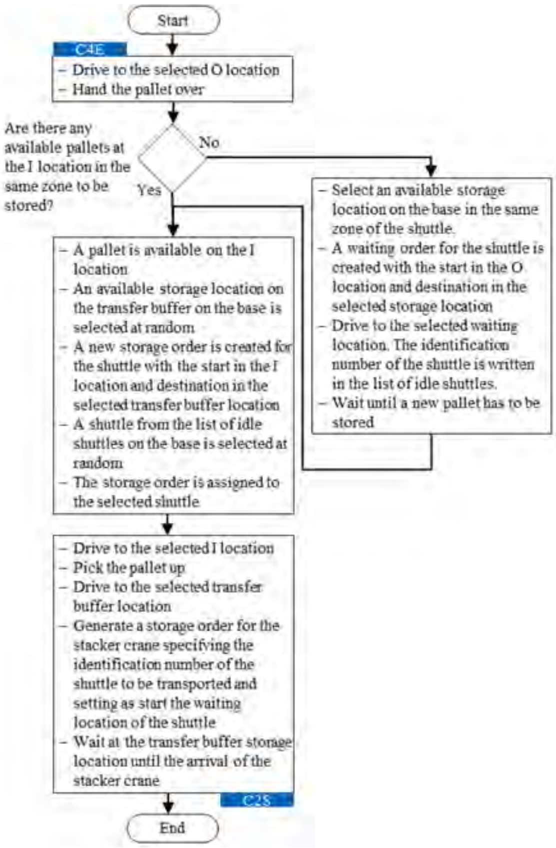

Figure 6: Control Logic – Layout 3, Double Cycles, Shuttles on Base

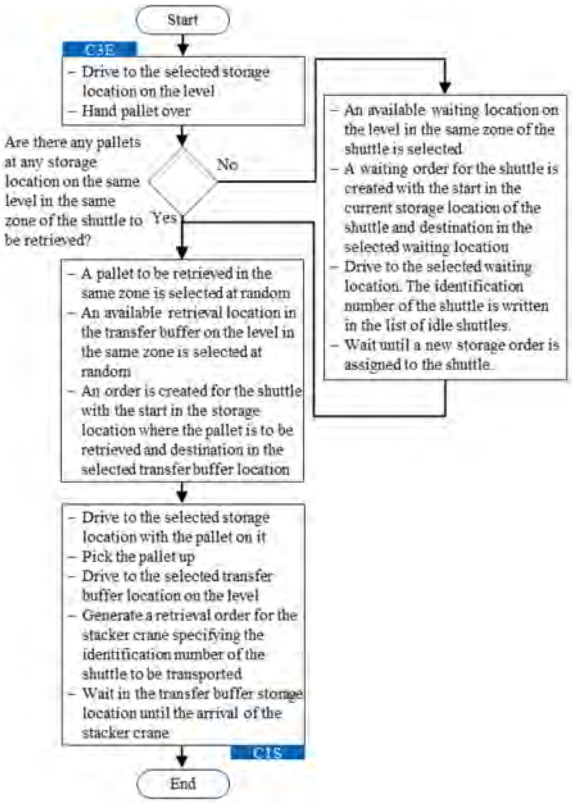

Figure 7: Control Logic – Layout 3, Double Cycles, Shuttles on Level

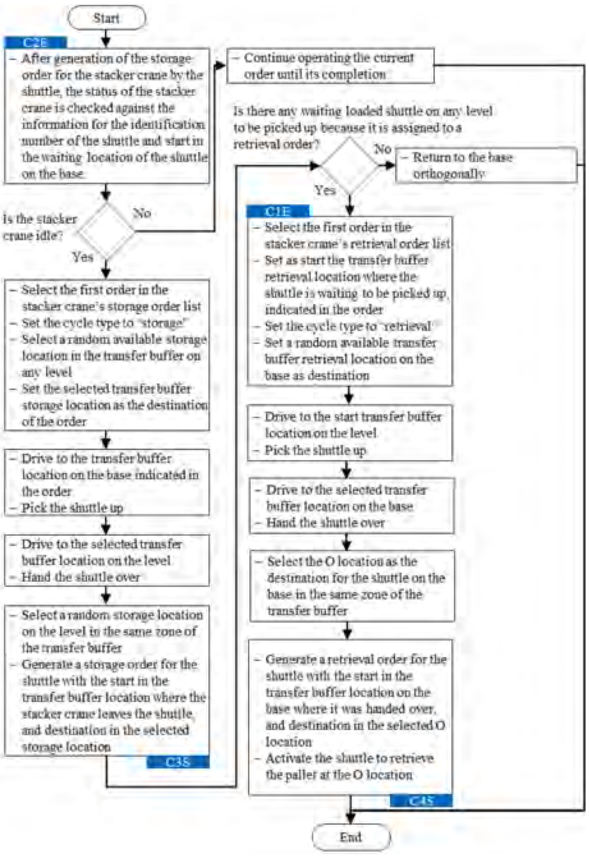

Figure 8: Control Logic – Layout 3, Double Cycles, Stacker Cranes

shuttles themselves. In fact, transportation orders should be created for not only loaded but also empty shuttles that have to be brought back from base to levels; motion orders should also be generated when an empty shuttle has to move, even if no pallet is to be picked or delivered. If the stacker cranes prove to be the bottleneck in the system, the shuttles without orders can wait directly on the transfer buffer. This saves travel time, when the stacker cranes are finally ready to exchange pallets, and energy, compared to having to drive to a waiting position in the storage locations as in layout 2.

SIMULATION STUDY

We implemented the model for layout 2 and layout 3 using the discrete event simulation environment Plant Simulation. To avoid deadlocks, the route of the shuttles on the different levels is based on the reservation of time windows, exactly like the shuttles on the base tier for layout 1 (Siciliano et al., 2020). This concept was initially introduced by (Kim and Tanchoco, 1991) and then further developed for shuttle fleets by (Lienert and Fottner, 2017a). An extensive description of the routing algorithm used for the shuttles on the levels can be found in (Lienert and Fottner, 2017b) (Lienert et al. 2020).

Parameters

The system we consider for layout 2 and layout 3 has two stacker cranes in a single aisle. We define a section as the area of the base or of a level comprised of two cross aisles. The different lengths of the aisle under consideration are two (38 m), three (54 m), four (68 m), five (83m) or ten (159 m) sections. There are three shuttle tier levels above the base. Both sides of the base have I/O area for pallets entering and leaving the warehouse. Each I/O area has two I/O locations, as shown in Fig. 2. The arrangement of cross aisles and storage aisles on the base is the same as in layout 1, see (Siciliano and Fottner, 2021), except for the I/O area. In fact, we discovered through experiments that the I/O area proposed in (Siciliano et al., 2020) creates an asymmetry in the dynamics of the shuttles for the right side of the warehouse compared to the left side for layouts 2 and 3. We therefore modified this as shown in Fig. 2 to guarantee symmetry, in other words the same performance for the right and left side of the warehouse, which resulted in an increased throughput.

The parameters used for the stacker crane in Tab. 1 and for the shuttles in Tab. 2 are provided by a manufacturer. Each experiment lasts 24 hours. We verified the model by comparing the analytically obtained travel time of individual vehicles with the simulated values (Siciliano et al., 2020). We then validated the travel time of the stacker crane and shuttles by comparing them with the values measured on the real subsystems, calculating the test positions of shuttles by the method in (Siciliano et al., 2021).

In the evaluation, we compare the throughput of layout 2 and layout 3 with following systems:

- Layout 1 with three channel storage levels above the base.

- Stacker crane-based warehouses whose throughput values are provided by a manufacturer.
- Shuttle-based warehouses, which we simulated in Plant Simulation. To make this comparable with DHPWs, we used the same shuttle tiers as for layout 2 and layout 3. The system has a total of four lifts i.e. two for each side of the warehouse, these being located at one third and two thirds of the length of the aisle.

The abbreviations used for the different systems examined from Fig. 9 to Fig. 14 are explained in the list of abbreviations at the end of this article.

Table 1: Stacker Crane 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: Shuttle 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
Time of pallet handover	6.0 s
Time for positioning before channel	1.0 s

Evaluation

We first studied the throughput of layout 2 by varying the length of the aisle. For both of the processes of retrieval (Fig. 9) and of double cycles (Fig. 10), reducing the length of the aisle reduces the travel distance for the shuttles, resulting in an increase in throughput. However, this increase is not particularly high, so we can conclude that the length of the warehouse does not have a great influence on the throughput. It is significant for the scalability of the system, that up to a total of 64 shuttles, the shuttles remain the bottleneck in terms of the performance of the system for retrieval and double cycles. This means that simply increasing the number of shuttles would result in a further increase in throughput.

We now consider the behaviour of layout 3 as the length of the aisle changes. For the process of retrieval in Fig. 11, as for that of double cycles in Fig. 12, the length of the aisle has less influence on the throughput than in layout 2. Moreover, layout 3 allows a higher throughput than in layout 2 with a smaller number of shuttles. However, in the case of retrieval, layout 3 is limited by the bottleneck due to the stacker cranes, indicated by the plateaux in the curves, with a smaller number of shuttles than layout 2. Once the bottleneck of the stacker cranes is reached in layout 3, additional shuttles do not increase the throughput. Therefore, layout 3 is less scalable than layout 2. In Fig. 11 and Fig, 12 the results for 48 or more shuttles by two sections of layout 3 are not reported, because we do not recommend to use such a high number of shuttles in this case. The reason is that, when shuttles are able to change their levels, 48 or more shuttles are too many for the short layout of two sections and this causes congestions of shuttles near the transfer buffer of the base. As a consequence, throughput is reduced. This is a further demonstration of the lower scalability of layout 3 compared to layout 2. Not only do we compare layout 2 and layout 3 with each other, but also with other warehouses, as in Fig. 13 for retrieval and in Fig. 14 for double cycles. Layout 3 with four shuttles per level has a

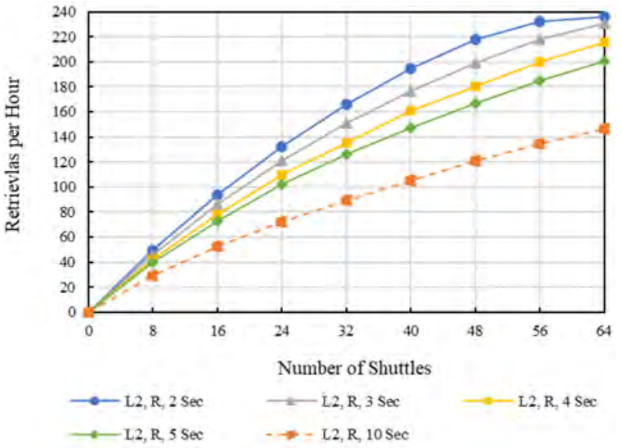

Figure 9: Retrieval Performance of Layout 2 Varying the Length of the Aisle from 2 Sections to 10 Sections

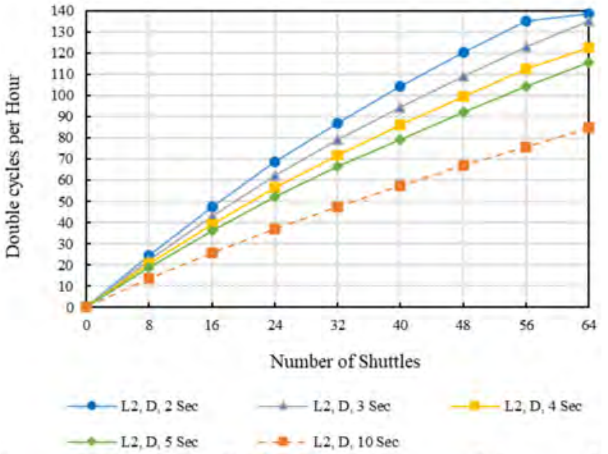

Figure 10: Double Cycles Performance of Layout 2 Varying the Length of the Aisle from 2 Sections to 10 Sections

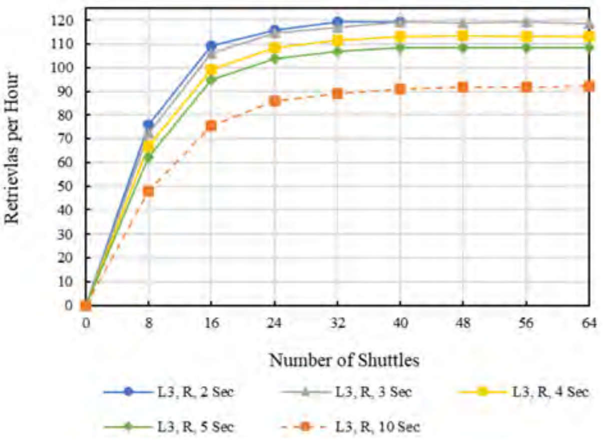

Figure 11: Retrieval Performance of Layout 3 Varying the Length of the Aisle from 2 Sections to 10 Sections

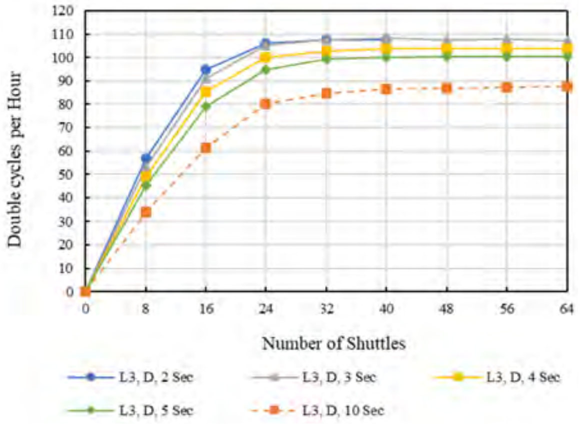

Figure 12: Double Cycles Performance of Layout 3 Varying the Length of the Aisle from 2 Sections to 10 Sections

throughput that is already higher than those of the other systems, in the case of both retrieval and double cycles.

By comparison, layout 2 needs up to 6 shuttles per level to provide a throughput that is not only higher than that of conventional stacker cranes but also of that of the shuttle-based warehouse with four lifts, which has comparable costs. Layout 1 achieves a higher throughput than that of conventional stacker crane-based warehouses, but one that is inferior to that of layout 2 and layout 3. The reason using stacker cranes, as in layouts 2 and 3, improves performance compared to using lifts is that the interface between lifts and shuttle tiers is made up of a reduced number of locations on the transfer buffer. Therefore, shuttles wait longer for a location or a pallet to become available than in the case of stacker cranes, which have locations on the transfer buffer all along the aisle.

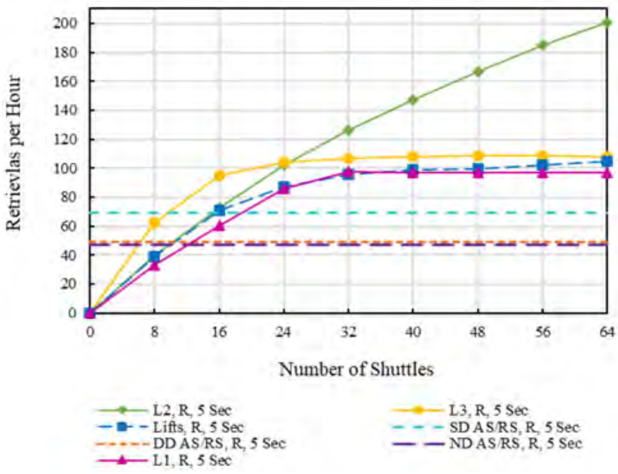

Figure 13: Comparison of Retrieval Performance between Different Warehouse Systems

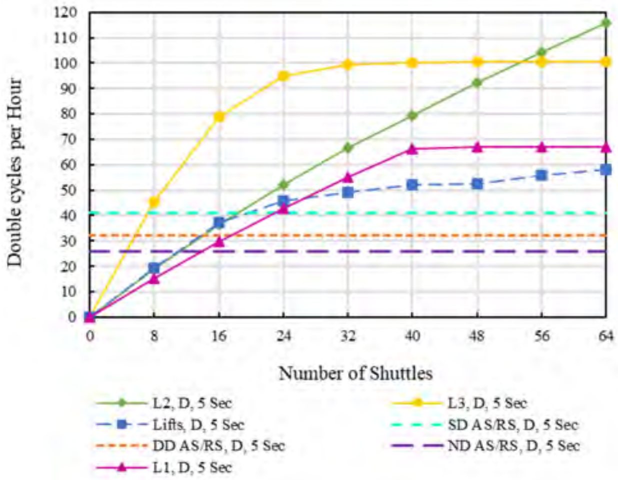

Figure 14: Comparison of Double Cycles Performance between Different Warehouse Systems

CONCLUSION AND OUTLOOK

In this article, we described the design and advantages of two warehouses, classifiable as DHPWs, which we call layout 2 and layout 3 respectively. We then proposed control strategies for each of these. Through a discrete event simulation study, we demonstrated that the length of the stacker cranes' aisle has no great influence on the throughput for either of them. With a small number of shuttles, layout 3 should be given preference over layout 2 because its poorer scalability is not yet dominant: moving shuttles to the levels where they are needed more urgently then overcompensates the additional orders for the stacker cranes. When using many shuttles, these additional orders lead to an earlier bottleneck, so that layout 2 is then preferable. All in all, the results of this paper are decision support in warehouse management for pallets insofar as they illustrate the performance benefits of substituting layout 1 to multi-depth stacker crane-based warehouses applications and of replacing the connection to lifts in shuttle-based warehouses with a connection between shuttles and stacker cranes such as layouts 2 and 3. For future research, different coordination algorithms between shuttles and stacker cranes have to be investigated to further improve the throughput without having to increase the number of shuttles.

ACKNOWLEDGEMENTS

We are very grateful to Thomas Klopfenstein from the firm of Gebhardt Fördertechnik GmbH for providing us with the throughput values for conventional stacker crane-based warehouses.
Moreover, we would like to thank Joerg Eder, also from the firm of Gebhardt Fördertechnik GmbH, for the fruitful collaboration.

REFERENCES

Eder, J., Klopfenstein, T., & Gebhardt, M., 2019. *Patent*: Lagersystem zur Speicherung und Abgabe von Ladungsträgern. DE102019211804, German Patent and Trade Mark Office (DPMA).

Kim, C. W., & Tanchoco, J. M. A., 1991. Conflict-free shortest-time bi-directional AGV routing. International Journal of Production Research 29 (12): 2377-2391.

Lienert, T., & Fottner, J., 2017. No more deadlocks—applying the time window routing method to shuttle systems. Proceedings of the 31st European Conference on Modelling and Simulation (ECMS), 169–175.

Lienert, T., & Fottner, J., 2017. Development of a generic simulation method for the time window routing of automated guided vehicles. Logistics Journal: Proceedings, Vol. 2017.

Lienert, T., Wenzler, F., & Fottner, J., 2020. Simulation-based evaluation of reservation mechanisms for the time window routing method. Proceedings of the 33st European Conference on Modelling and Simulation (ECMS).

Malik, O., 2014. *Patent Application Publication*: Automated warehousing systems and method. US20140086714A1, US Patent and Trademark Office (USPTO).

Siciliano, G., Lienert, T., Fottner, J., 2020. Design, Simulation and Performance of a Highly-Dynamic, Hybrid Pallet Storage and Retrieval System. Proceedings of the 19th International Conference on Modeling and Applied Simulation (MAS).

Siciliano, G. & Fottner, J., 2021. Concept development and evaluation of order assignment strategies in a highly dynamic, hybrid pallet storage and retrieval system. Proceedings of the 11th International Conference on Simulation and Modeling Methodologies (SIMULTECH), ISBN 978-989-758-528-9, ISSN 2184-2841, pp. 360-368.

Siciliano, G., Durek-Linn, A., Fottner, J., 2022. Development and Evaluation of Configurations and Control Strategies to Coordinate Several Stacker Cranes on a Single Aisle for a New Dynamic Hybrid Pallet Warehouse. In: Shi X., Bohács G., Ma Y., Gong D., Shang X. (eds) LISS 2021. Lecture Notes in Operations Research. Springer, Singapore. https://doi.org/10.1007/978-981-16-8656-6_54

Siciliano, G., Schuster, C. U., Fottner, J., 2021. Analytical method to determine the test positions for validation of a two-dimensional shuttle system model. Proceedings of the 20th International Conference on Modeling & Applied Simulation (MAS 2021), pp. 21-28. https://doi.org/10.46354/i3m.2021.mas.003

Wang, Y., Man, R., Zhao, X., Liu, H., 2020. Modeling of parallel movement for deep-lane unit load autonomous shuttle and stacker crane warehousing systems. Processes 8(1)

LIST OF ABBREVIATIONS

- L1 = Layout 1; L2 = Layout 2; L3 = Layout 3
- R = Retrieval process; D = Double cycles process
- Sec = Sections
- SD AS/RS = Single-deep storage stacker crane with telescopic forks
- DD AS/RS = Double-deep storage stacker crane with telescopic forks with relocations
- ND AS/RS = Nine-deep storage stacker crane with satellite without relocations

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