Optimization of the Bottleneck Caused by Stacker Cranes in Dynamic Hybrid Pallet Warehouses and Investigation of the Influence of the Input/Output Area on Performance

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Abstract: The need for ever-higher performance in pallet storage systems has led to the development of Dynamic Hybrid Pallet Warehouses (DHPW). DHPWs are created by either hybridizing a stacker crane-based warehouse with shuttles, or by hybridizing a shuttle-based warehouse with stacker cranes. One limiting factor in both categories is the bottleneck caused by having multiple stacker cranes in a single aisle. In this paper, we demonstrate that, by using the proper control algorithms, the stacker crane bottleneck can be alleviated in relation to the second DHPW category – almost to the point of reaching the performance that would be obtained by introducing an additional stacker crane. Finally, we illustrate how the design of the loop on the base tier has an increasing influence on the range of bottleneck improvement as the number of shuttles increases.

1 INTRODUCTION

DHPWs are new systems which make it possible to take advantage of the flexibility in the connection between shuttles and stacker cranes in order to achieve higher throughputs of the non-hybridized base models on which they are based. The type called Layout 1 is obtained by hybridizing an automated storage and retrieval system (AS/RS) composed of channel storage and stacker cranes with a shuttle base tier (Eder, Klopfenstein, and Gebhardt 2019; Siciliano, Lienert, and Fottner 2020). The types called Layout 2 and Layout 3 are obtained by hybridizing a warehouse based on shuttles with stacker cranes used to connect the different levels (Malik 2014; Siciliano, Yu, and Fottner 2022), as in Figure 1. The structure of their base tier is shown in Figure 2. The difference between Layout 2 and Layout 3 is that, in the latter, the shuttles are free to move among the levels, which strongly affects the performance of the warehouse as the number of shuttles varies (Siciliano, Yu, and Fottner 2022).

Layout 1, having a single base of shuttles, is much more economical than Layouts 2 and 3, but it cannot achieve as high a throughput as these (Siciliano, Yu, and Fottner 2022). In Layout 1, it is possible to increase the performance by using appropriate order assignment strategies (Siciliano and Fottner 2021), or through particular configurations and control algorithms aimed at improving the impact of the stacker crane bottleneck on performance (Siciliano, Durek-Linn, and Fottner 2022).

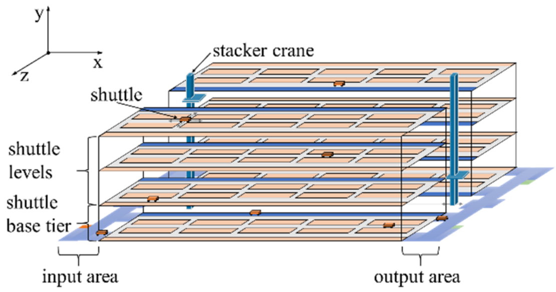

Figure 1: Structure of Layouts 2 and 3 (Siciliano, Yu, and Fottner 2022).

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In the following sections, we will conduct a brief literature review of methodologies for improving the performance of stacker cranes and then propose several configurations and control algorithms for optimizing multiple stacker cranes in a single aisle in Layouts 2 and 3.

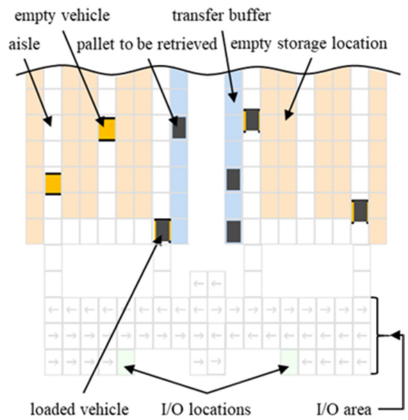

Figure 2: Structure of the base tier for Layouts 2 and 3 (Siciliano, Yu, and Fottner 2022).

2 LITERATURE REVIEW

Unlike DHPWs in which stacker cranes can exchange pallets at transfer buffer locations along the entire aisle, conventional AS/RSs include an input and an output location only at the ends of the aisle. The length of the aisle can be shortened in order to increase the throughput of such systems (Lantschner 2015). Alternatively, a second stacker crane can be introduced on separate rails (Hino, et al. 2009; Kung, et al. 2012; Kung, et al. 2014). Another option for improving performance is to coordinate more than two stacker cranes on the same common rail, doing which requires a specific control strategy (Kung, et al. 2014). In addition, the development of analytical methods (e.g., genetic coding for optimizing stacker crane routes) can also provide an increase in terms of throughput (Zhang and Zheng 1995). In (Siciliano, Durek-Linn, and Fottner 2022) as regards Layout 1, we developed several strategies for improving the stacker crane bottleneck not only for the basic configuration of Layout 1 having one satellite per stacker crane, but also for the case in which more satellites are assigned to each stacker crane, and in which each stacker crane has two satellite positions instead of one. In the following section, we illustrate the optimization strategies applicable to Layouts 2 and 3.

3 OPTIMIZATION ALGORITHMS

We apply the same stacker crane optimization strategies to Layouts 2 and 3. In each layout, however, it is necessary to employ adaptations of varying extent when implementing these strategies.

In the event that the stacker cranes are equipped with one pallet- or shuttle-position, we denote as One Direction the algorithm we propose for improving the stacker crane bottleneck. The purpose of this algorithm is to reduce the time needed for a stacker crane to serve shuttles by requiring that as many orders as possible - up to a maximum of n - be executed in the same aisle direction. For sake of simplicity, the retrieval case is illustrated in Figure 3. P2 denotes the location on the transfer buffer of one of the levels where the stacker crane picks up the pallet for Layout 2 or the shuttle for Layout 3 to be retrieved to the transfer buffer of the base tier. The control logic for the storage process is easily deduced from that for the retrieval, so it is omitted here for the sake of brevity. In the double cycle process, retrieval and storage orders are chosen alternately up to a maximum of 2n, i.e., n double cycles in the same direction. In fact, a double cycle is defined as the combination of a storage and a retrieval carried out by the stacker crane. It is important to note that, in the algorithm, the |x| coordinate of P2 must be greater than and not equal to that of the last selected location on the transfer buffer, because the stacker crane might otherwise get stuck satisfying orders all having the same x coordinate, but on different levels.

If the stacker cranes are equipped with two pallet- or shuttle-positions, then we used the Double algorithm to improve the throughput. We introduced this algorithm for Layout 1 in an earlier contribution (Siciliano, Durek-Linn, and Fottner 2022), and the aim of this strategy is to combine two orders together in order to reduce the total time taken by the stacker crane to execute them. We then modified and further developed the algorithm so as to fit Layouts 2 and 3. In fact, each action is accomplished for each pallet or shuttle, transported by the stacker crane, before executing the next action.

As always in the case of stacker cranes comprising two pallet- or shuttle-positions, an alternative to Double is the Succession algorithm. We have proposed this algorithm for Layout 1 in an earlier paper (Siciliano, Durek-Linn, and Fottner 2022). Its purpose is to find the order of operations allowing the stacker crane to minimize its cycle time after evaluating all of the possible combinations of operations thereby. We then adapted it to be applica-

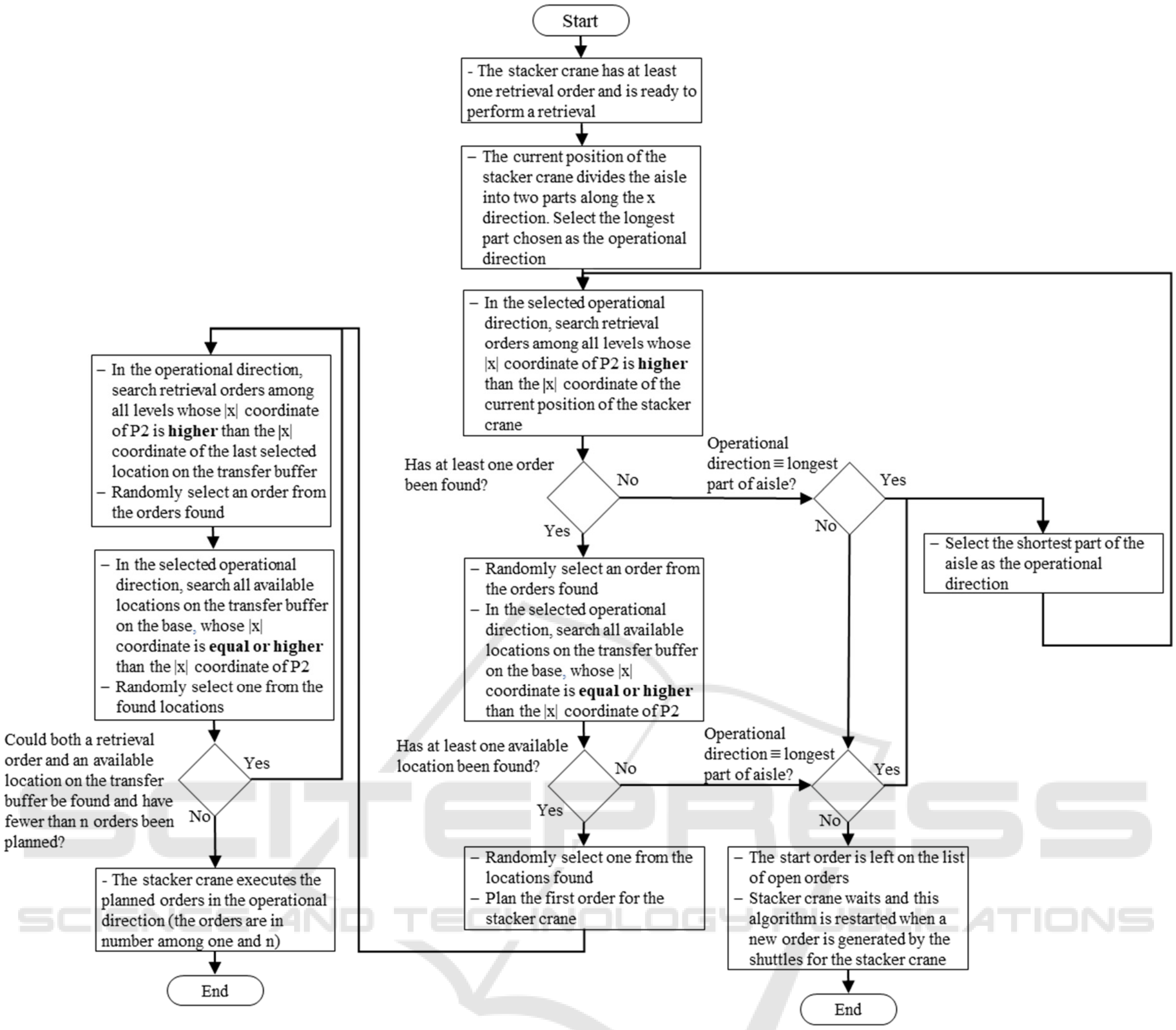

Figure 3: *One Direction* control strategy: Control logic for the stacker crane in Layouts 2 and 3.

ble for Layout 2 and 3 as well. In contrast to Layout 1, the presence of shuttles on all levels in Layouts 2 and 3 introduces additional boundary conditions regarding coordination of the stacker crane. As a result, in the process of double cycles, it is often impossible for at least one retrieval or storage order to be found. In such a case, in order to avoid reducing the throughput of the warehouse, it becomes necessary to perform two single cycles of the same type, thus optimizing the succession of operations in this case as well.

The following sections illustrate the experiments performed and evaluate the effectiveness of each of the algorithms described in Layouts 2 and 3.

4 SIMULATION STUDY

The purpose of this section is to identify which control algorithms most improved the throughput bottleneck caused by stacker cranes, and to demonstrate the strong influence of loop or I/O area design on throughput as the number of shuttles increases. To this end, we performed experiments in the discrete event simulation environment Plant Simulation Tecnomatix. Given the small level of variance, five repetitions of 24 hours each per experiment were sufficient. We compared the analytically calculated single shuttle cycle time with the simulated cycle time to verify the model (Siciliano, Lienert, and Fottner 2020). For validation, we compared the simulated times for the shuttles and stacker crane with those of the real subsystem prototypes (Siciliano, Schuster, and Fottner 2021). The warehouse under consideration had 56 locations distributed along the aisle for each of the transfer buffers on the right and on the left. Every level was similar to the base of Figure 2, except for the absence of the I/O areas, and was equipped with 512 storage locations. These storage locations were divided by three storage aisles on each side of the warehouse and two cross aisles used to ensure the movement of the shuttles. There were three levels in addition to the base. The base had one I/O area for each of the extremes of the aisle. Every I/O area was equipped with two I/O locations, which were used both for the pallet entering from an extreme of the aisle as well as those exiting from the other. The parameters we used were provided by the manufacturer and are provided in Tables 1 and 2. The maximum number of orders for the strategy One Direction is set at four, because the simulation experiments we executed have shown that this number is rarely reached. Therefore, it would not be efficient to set a higher maximum number of orders. The abbreviations used in the experiments are provided in Appendix.

Table 1: Stacker crane parameters.

Parameter	Value
Travel speed x	4.0 $\frac{m}{s}$
Travel acceleration x	0.5 $\frac{m}{s^2}$
Lifting speed y	1.0 $\frac{m}{s}$
Lifting acceleration y	1.0 $\frac{m}{s^2}$
Time of pallet handover	6.0 s
Time for positioning before channel	1.0 s

Table 2: Shuttle parameters.

Parameter	Value
Speed (loaded)	0.6 $\frac{m}{s}$
Speed (empty)	1.0 $\frac{m}{s}$
Acceleration (loaded)	0.3 $\frac{m}{s^2}$
Acceleration (empty)	0.6 $\frac{m}{s^2}$
Turning time	6.6 s
Handover time	10.0 s

4.1 Advantages of Optimization Algorithms for Layout 2

We first evaluated the effectiveness of the optimization strategies on Layout 2 in the case of

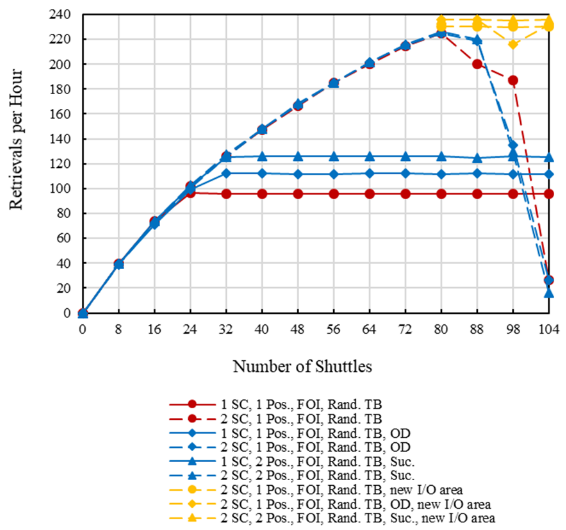

Figure 4: Effects of optimization strategies on the throughput of Layout 2 for retrieval process.

retrieval. Figure 4 shows that, if only one stacker crane is used, it is possible to achieve a significant increase in throughput by applying the One Direction strategy (blue solid line with rhombus), as compared to the non-optimized base case (red solid line with circles), in which the stacker cranes are bottle-necking the system (i.e., for 32 or more shuttles). Double strategy does not result in any throughput improvement in comparison to the non-optimized base case for Layout 2. Figure 4 demonstrates that the Succession strategy (blue solid line with triangles) provides a very high throughput improvement against the non-optimized base case when the stacker crane bottleneck occurs. This improvement amounts to nearly 20 additional retrievals per hour. It should be noted that, in the case of two stacker cranes, the stacker crane bottleneck does not occur until at least 80 shuttles. Therefore, none of the strategies for bottleneck improvement provided results better than the non-optimized base case for two stacker cranes.

Figure 4 reveals the strong influence of the design of the I/O area on performance when a high number of shuttles is used. In fact, in the case of more than 80 shuttles, it is clear from the sudden decrease in performance that deadlocks occur and, observing the simulation, the reason is that they are creating congestion in the I/O area. To avoid deadlocks, we developed a new I/O area in Figure 5. The performance achieved using the new loop is represented in Figure 4 for 88 or more shuttles by the yellow lines, which show that, even in the bottleneck with two stacker cranes, the One Direction and Succession strategies provided a slight throughput improvement compared to the non-optimized base case. However, this improvement was limited by a new bottleneck, i.e., the one caused by the number of I/O locations present in the area.

Figure 6 shows the results of the optimization strategies for Layout 2 in the case of double cycles. For one stacker crane, the Succession strategy (blue solid line with triangles) provided a very high throughput improvement compared to the non-optimized base case (red solid line with circles). For 48 shuttles, this amounted to about 40 additional pallets retrieved and 40 additional pallets stored per hour. It is important to note that this brought the performance of the system quite near to that obtained when using two stacker cranes in the non-optimized base case (red dotted line with circles). This allowed a very high level of throughput to be obtained without the investment of an additional stacker crane, thus reducing investment and operating costs. In addition to improving throughput, the Succession strategy improved the throughput, but it also postponed the bottleneck of the stacker cranes from 24 to 48 shuttles, which represented a significant contribution to the improvement of the systems scalability.

In case of two stacker cranes, the Succession control algorithm (blue dotted line with triangles) guaranteed an even higher throughput improvement, which amounted to about 50 additional pallets retrieved and 50 additional pallets stored per hour compared to the non-optimized base case. Moreover, the stacker crane bottleneck was postponed from 64 to at least 104 shuttles.

We were surprised to see that no relevant improvement was provided by the One Direction and Double strategies. It should be noted that, in Layout 1, the Double strategy was good at enabling bottleneck improvement in the double cycles (Siciliano, Durek-Linn, and Fottner 2022).

4.2 Advantages of Optimization Algorithms for Layout 3

Figure 7 illustrates the behaviour of Layout 3 when applying retrieval process optimization strategies. Regarding the cases of both one and two stacker cranes in the aisle, the Succession control algorithm (blue solid and dotted lines with triangles) was the only one that increased throughput against the non-optimized base case (red solid and dotted lines with circles). However, this was an increase of only about 5 retrievals per hour.

The One Direction strategy (blue solid and dotted lines with rhombus) interfered with the rigid co-ordination of the stacker crane, which has to move shuttles between levels in Layout 3, and caused a decrease of throughput when using a low or medium number of shuttles compared to the non-optimized base case.

The Double strategy did not provide any relevant increase or decrease of throughput against the non-optimized base case.

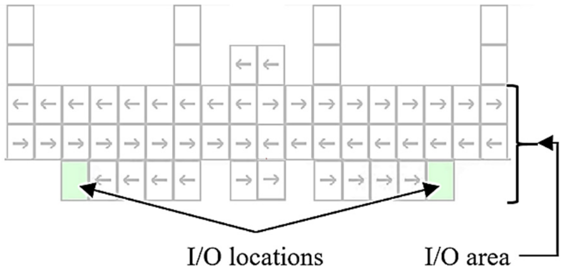

Figure 5: New design for the I/O area.

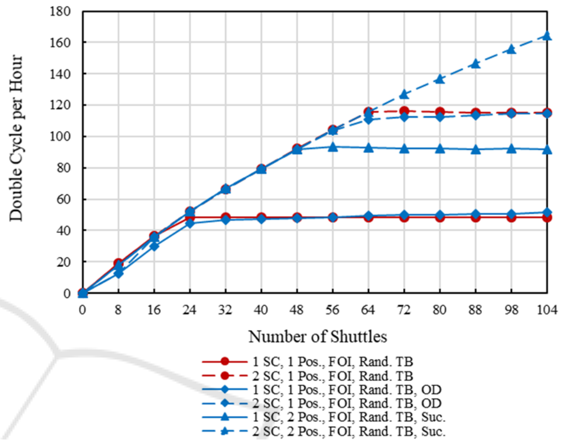

Figure 6: Effects of optimization strategies on the throughput of Layout 2 for the double cycles process.

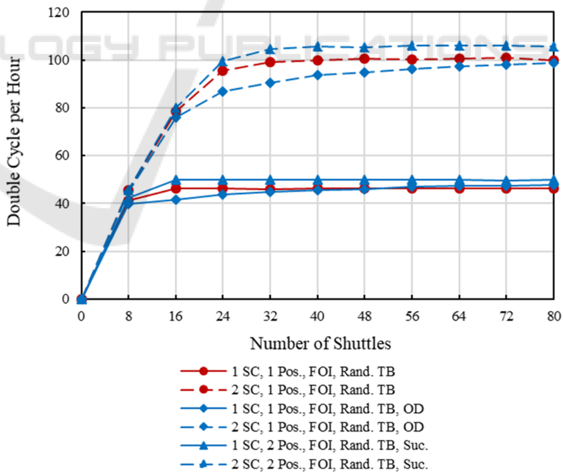

Figure 7: Effects of optimization strategies on the throughput of Layout 3 in the retrieval process.

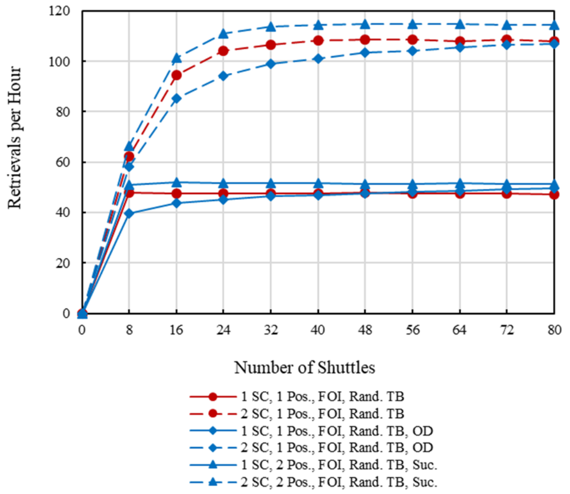

Figure 8: Effects of optimization strategies on the throughput of Layout 3 for the double cycles process.

Figure 8 represents the results obtained when simulating the double cycles process using optimization strategies for Layout 3. In this case, as was true of the retrieval process, only the Succession control algorithm (blue solid and dotted lines with triangles) provided, for both one and two stacker cranes in the aisle, a slight improvement in throughput compared to the non-optimized base case (red solid and dotted lines with circles). In the One Direction and Double strategies, like the retrieval process, brought no improvement in performance. The reason why the optimization strategies were more effective for Layout 2 than for Layout 3 was that the stacker crane bottleneck in the latter had a very strong impact, because the stacker cranes were serving many more order types than in Layout 2 in order to be able to move the shuttles between levels.

4.3 Influence of I/O Area Design on Performance

As illustrated in section 4.1, we noticed while studying the behaviour of Layout 2 that a small change in I/O area design led to an increasing influence on performance, along with the increase of the number of shuttles and stacker cranes. In our previous article (Siciliano, Durek-Linn, and Fottner, 2022), we investigated the influence of several strategies used to optimize the bottleneck caused by the stacker crane in Layout 1. The results discussed in this section are shown in Figure 9. The Double strategy, in the case of retrieval for three stacker cranes (blue small dotted line with squares), reached a throughput level even lower than those for the non-optimized base case (red small dotted line with circles). After studying Layout 2, we concluded that this effect was caused by the design of the I/O area. Therefore, we applied the new I/O area design (see Figure 5) to Layout 1 for the retrieval process. We then noticed that, in addition to the non-optimized base case for two and three stacker cranes (yellow dotted lines with circles) reaching a higher throughput using the new I/O area, the Double control algorithm for three stacker cranes (violet small dotted line with squares) also thus achieved a throughput about 10 retrievals per hour higher than that of the non-optimized base case for 12 or more shuttles. We then decided to also adapt the Succession strategy to the retrieval process in Layout 1 with the old I/O area

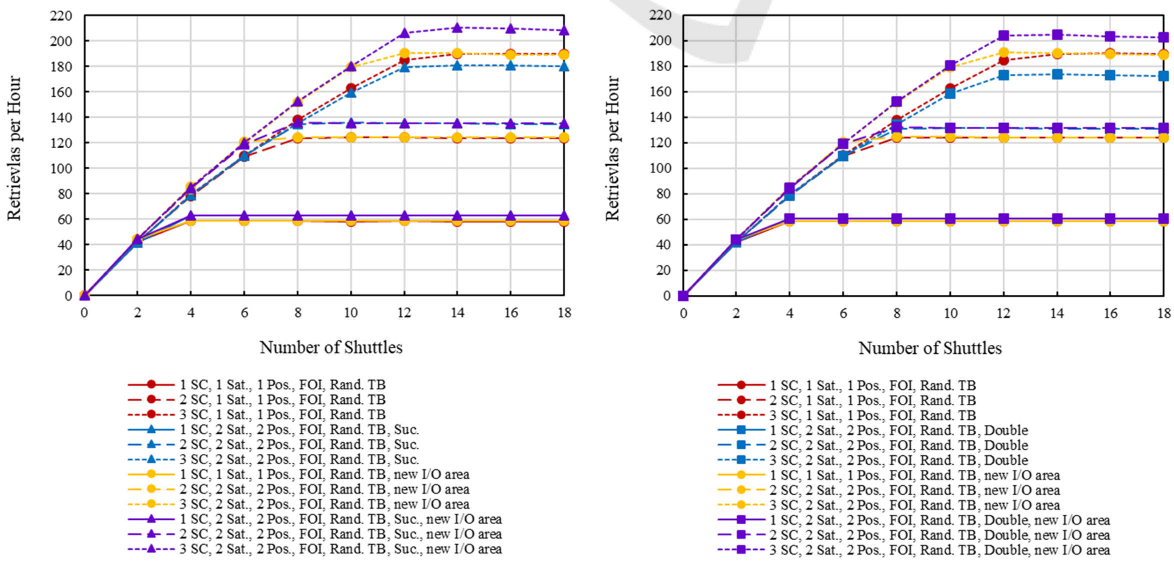

Figure 9: Effects of optimization strategies on the throughput of Layout 3 for the double cycles process.

used in (Siciliano, Durek-Linn, and Fottner, 2022). As a result, we obtained a similar behaviour to that of Double: For three stacker cranes, the throughput obtained by Succession (blue small dotted line with triangles) was lower than that of the non-optimized base case (red small dotted line with circles). However, also in this case, when using the new I/O area of Figure 5, for three stacker cranes, the throughput of Succession (violet small dotted line with triangles) became almost 20 retrievals per hour higher than those of the non-optimized base case for 12 or more shuttles. This outcome demonstrated the strong influence of the I/O area on the behaviour of DHPWs.

5 CONCLUSIONS

In this article, we examined how to improve the bottleneck caused by stacker cranes for DHPWs obtained by hybridizing a shuttle-based warehouse with stacker cranes. The obtained results are valid for DHPWs of Layout 2 and Layout 3. We demonstrated through discrete event simulation that the One Direction algorithm makes it possible to improve the performance of Layout 2 for the retrieval case of one stacker crane having just one pallet position. However, if two pallet positions are used, Succession provided the highest throughput for retrieval and double cycles. Specifically, the improvement in performance obtained using Succession for one stacker crane was close to that which would be obtained using an additional stacker crane in the absence of any optimization strategy. As a result, Succession makes it possible to achieve a high level of throughput while keeping costs low. For Layout 3, only the Succession strategy provided a slight alleviation of the bottleneck caused by stacker cranes because the latter bottleneck was stronger than in Layouts 1 and 2. Finally, we demonstrated the strong influence of I/O area design when the warehouse is operating within the realm of high dynamics, i.e., for a high number of shuttles, and for more than one stacker crane per aisle.

Future research should work on developing control algorithms able to significantly improve the bottleneck caused by stacker cranes for Layout 3 as well. Moreover, a systematic method should be developed which is able to determine the optimal configuration of the I/O area.

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REFERENCES

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

Hino, H., Kobayashi, Y., Higashi, T., Ota, J., 2009. “Control methodology of stacker cranes for collision avoidance considering dynamics in a warehouse”. In *Proceedings of the IEEE International Conference on Robotics and Biomimetics*, pp. 983–988. Piscataway, New Jersey, Institute of Electrical and Electronics Engineers, et al.

Kung, Y., Kobayashi, Y., Higashi, T., Ota, J., 2012. “Motion planning of two stacker cranes in a large-scale automated storage/ retrieval system”. In *Journal of Mechanical Systems for Transportation and Logistics* 5 (1): 71 –85.

Kung, Y., Kobayashi, Y., Higashi, T., Sugi, M., Ota, J., 2014. “Order scheduling of multiple stacker cranes on common rails in an automated storage/retrieval system”. In *International Journal of Production Research*, Jg. 52 (2014) Nr. 4, pp. 1171–1187.

Lantschner, D., 2015. “Spielzeit automatischer Lagersysteme mit mehreren Übergabepunkten”. *Dissertation*, Lehrstuhl für Fördertechnik Materialfluss Logistik, Technische Universität München, Garching.

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”. In *Proceedings of the 19th International Conference on Modeling & Applied Simulation (MAS 2020)*, pp. 68-75, https://doi.org/10.46354/i3m.2020.mas.009

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

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

Siciliano, G., Durek-Linn, A., Fottner, J., 2022. “Development and Evaluation of Configurations and Control Strategies to Coordinate Several Stacker Cranes in 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., Yu, Y., Fottner, J., 2022. “Synergy between Shuttles and Stacker Cranes in Dynamic Hybrid Pallet Warehouses: Control Strategies and Performance Evaluation”. In *Proceedings of the 36th International ECMS Conference on Modelling and Simulation (ECMS 2022)*. In Press.

Zhang, L., Zheng, W., 1995. “Genetic coding for solving both the stacker crane problem and its k-variant”. In *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics. Intelligent Systems for the 21st Century*, pp. 1061–1066.

APPENDIX

List of abbreviations used in the graphs containing the results of simulation:
SC = stacker crane;
Pos. = pallet- or shuttle-position, on each stacker crane in Layouts 2 and 3, respectively;
FOI = fixed operating intervals for each stacker crane;
Rand. TB = locations on transfer buffer are randomly chosen among available ones;
OD = optimization strategy One Direction;
Double = optimization strategy Double;
Suc. = optimization strategy Succession;
New I/O area = use for experiments of the model with I/O area as in Figure 5 instead of as in Figure 2.