19th International Conference on Modelling and Applied Simulation
7th International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0037 ISBN 978-88-85741-48-5 © 2020 The Authors.
DOI: 10.46354/i3m.2020.mas.009

Design, Simulation and Performance of a Highly-Dynamic, Hybrid Pallet Storage and Retrieval System

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Abstract

In this contribution, we consider a new, highly-dynamic hybrid pallet storage and retrieval system comprising a stacker-crane-based automated storage and retrieval system (AS/RS) and an autonomous vehicle storage and retrieval system (AVS/RS). Firstly, we present the design and advantages of the considered system. We then propose control strategies for the connection and coordination of its components. Subsequently, we introduce how to model the whole system in a discrete event simulation. In conclusion, we demonstrate the great advantages in terms of throughput and capability to respond to short-term fluctuations in demand created by the use of intermediate buffering in the shuttle base of the new compact warehouse.

Keywords: stacker–crane-based warehouse; shuttle system; discrete event simulation.

1. Introduction

AS/RSs are warehousing systems that are used to store and retrieve products in distribution as well as in production and dispatching. They have many advantages over non-automated systems, such as savings in labor costs and floor space, improved reliability and reduced error rates (Roodbergen and Vis 2009). The two main pallet storage systems are as follows:

1.1. Stacker-crane-based warehouse system

Stacker-crane-based AS/RSs comprise the following main elements: stacker cranes, storage racks, input/output (I/O) locations, pre-zone (Atz, 2016) (see Fig. 1). Specifically, one or more stacker cranes run along an aisle that has racks along its sides. These racks can have one or more rows of storage locations, in which case they constitute a multiple-depth

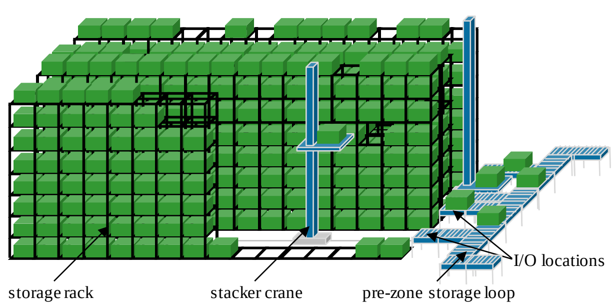

Figure 1. Stacker-crane-based warehouse

channel storage that is served by so-called satellites. A satellite is a vehicle allocated to a stacker crane. The vehicle picks the pallets and stays on the stacker crane, while the stacker crane lifts a load vertically – i.e. parallel to the warehouse height – or travels along its own aisle. The stacker crane delivers the pallets to the I/O locations that are usually situated at one or both extremes of the stacker crane aisle. From here, the pallet is taken up by roller conveyors, loop conveyors, fork stackers or other pre-zone systems. The pallets are buffered and sequenced in the pre-zone before being delivered to the destination where they are needed, which could be a certain production phase or trucks for transportation to customers. Stacker-crane-based AS/RSs have a high storage space density thanks to the multiple-depth channel storage system, though their performance and ability to respond to short-term fluctuations in demand are restricted due to the limitations in the throughput of stacker cranes and connections with pre-zone through I/O locations. In addition, if dispatching orders require a strict sequence, the pallets are sequenced in the pre-zone, where they will be buffered on conveyors to be sequenced through automatic loops (Geinitz, 1998) or on the floor to be sequenced manually by operators. This kind of sequencing operation takes up a lot of space, reducing the space utilization ratio of the warehouse and hindering a smooth and fast management of sequenced retrieval orders.

1.2. Shuttle-based warehouse system

In addition to stacker-crane-based AS/RSs, AVS/RSs are used for storing unit loads (VDI Guideline, 2692). These systems, also known as shuttle systems, are characterized by horizontally operating vehicles, which move on a rail system on every storage tier, performing storage and retrieval tasks (Malmborg, 2002). In the course of recent developments, various shuttle system configurations have emerged that can be classified according to the vehicles' range of motion, mainly into configurations with captive vehicles and those with roaming vehicles (Heragu, Cai, Krishnamurthy, & Malmborg, 2011).

In the most common configuration, the vehicles are restricted to a single storage aisle and tier. A lift transports storage units from the I/O location to the various tiers, where they are transferred to a buffer location. The vehicles load the storage unit from here and bring it to the designated storage location. Retrieval takes place in reverse order. In contrast, roaming vehicles operate on different storage tiers within the same aisle using a lift for the vertical movements. Another configuration allows vehicles to not only change the storage tier but also the aisle. Therefore, the vehicles use a rectangular grid of paths defined by the storage and cross-aisles on each storage tier. Fig. 2 shows an overview of the four system configurations resulting from the vehicles' movement space. The x-axis coincides with the storage aisle, the y-axis with the lifts, and the z-axis with the cross-aisles. Systems with tier- and aisle-captive vehicles - configuration 1 - have the greatest throughput, as the vertical and horizontal movements are completely autonomous and resources do not have to be shared among the shuttles.

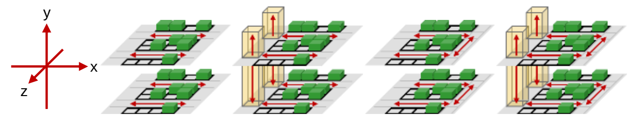

Figure 2. Configurations for shuttle systems

In contrast, several vehicles move within the same rail system in configurations that use tier-to-tier and aisle-to-aisle vehicles. On the one hand, these systems require a more complex control strategy to run smoothly and efficiently. On the other hand, they are easy scalable with regard to the throughput, provide a higher redundancy in case a single vehicle fails and enable a retrieval in sequence. In systems with aisle-to-aisle vehicles - configuration 3 and 4 -, every storage unit can be transported to every connected lift and therefore be provided at every I/O location. A desired sequence can be established directly from the storage system. No additional conveyor technology is needed within the pre-storage area.

Compared to stacker-crane-based AS/RSs, shuttle systems enable a higher performance, are more energy-efficient and flexible (Kriehn, Schloz, Wehking, & Fittinghoff, 2018). On the other hand, they require higher investments and an increasingly complex storage management (Kartnig, Grösel, & Zrnic, 2012).

2. Storage system under consideration

The objective of the new, automated hybrid pallet warehouse system is to combine the advantages of both stacker-crane-based and shuttle-based warehouses. In the following section, we first describe the structure of the system under consideration, then its advantages and finally the challenges it poses.

2.1. Structure of a highly dynamic pallet storage system

In order to meet the demand for ever higher throughput rates in pallet conveyor technology, the solution approach is to develop for the first time a highly dynamic, hybrid pallet retrieval and storage system or dynamic hybrid pallet warehouse (DHPW) for storing, outsourcing and sequencing the delivery of pallets (Eder, Klopfenstein, & Gebhardt, 2019). A shuttle system of configuration 3 (see Fig. 2), and a stacker-crane-based channel warehouse are combined for this purpose. The shuttle system is the base tier with the channel storage system being built above this. Note one peculiarity of the shuttle system: an empty shuttle can move through storage locations which are occupied by a pallet. The base tier and the channel storage system are connected by a transfer buffer served by stacker cranes. The stacker cranes take the pallets from the channel storage and bring them to the transfer buffer on the base tier. A shuttle then comes and takes the pallet to the I/O point. Having shuttles on the base tier that can work in parallel and almost independently to the stacker cranes and their satellites allows the decoupling of the x, y and z directions (see Fig. 3), thus enabling higher dynamics.

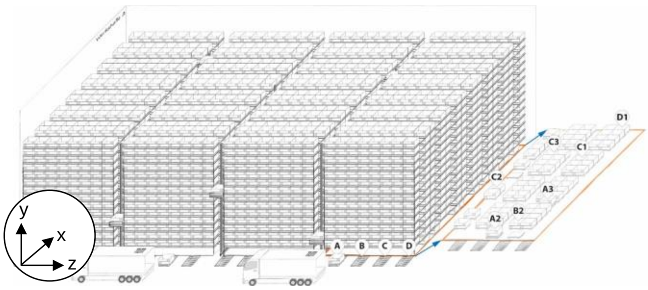

Figure 3. Highly dynamic, hybrid pallet storage and retrieval system

The following advantages can be realized by combining the stacker-crane-based system and the shuttle-based system into the DHPW:

- No space-intensive storage pre-zone needed for sequencing because buffering and sequencing take place in the shuttle base. This makes also possible to react to short-term, high pick fluctuations.
- High dynamics because stacker crane bottlenecks are eliminated by an optimized layout of the delivery area in the shuttle base; the stacker cranes serve transfer locations located along the whole x length of the shuttle base.
- High space utilization ratio due to multiple deep storage options in the channel storage system.
- Low investment and operating costs (electricity, maintenance) compared to the high dynamics and high space utilization ratio available.
- The performance is easily scalable as the number of shuttles can be gradually increased to achieve a higher throughput as necessary.

2.2. Challenges for designing, modeling and controlling a highly–dynamic, hybrid pallet storage and retrieval system

The main challenge is to develop control strategies for connecting and coordinating the components.

In fact, the transfer area between stacker crane and shuttle base is extended along the entire length of the x side of the shuttle base (see Fig. 3) and the stacker crane can deliver pallets to any transfer buffer location. The question thus arises as to which transfer buffer location should be served first by the stacker crane. Moreover, it has to be decided when to create a retrieval order for the shuttles in the base to retrieve the pallets left in the transfer buffer by the stacker crane. And when to create a storing order for the stacker crane, so that it can pick up the pallets left on the transfer buffer by the shuttles. Furthermore, one has to model the behavior to be adopted by the system in case the stacker crane or the shuttles are a bottleneck.

Another challenge lies in the complex control strategies that are necessary to run the base tier in a smooth and efficient way. Because every single shuttle can reach every single storage position within the system, the question arises as to which shuttle should execute which storage or retrieval request. On the other hand, a position can be reached by different routing options. It thus has to be decided which path to take. And finally, since the shuttles share the same rail system, collisions have to be avoided so that there are no deadlocks between the shuttles – situations where the shuttles block each other.

Finally, the analytical prediction of the system's performance is a challenge due to the dynamic interaction between the shuttle base and stacker crane. Simulations are therefore needed. The remainder of this paper is organized as follows. The next section describes the modelling and implementation before a simulation study focuses on the retrieval of pallets. The work is closed by our conclusions.

3. Modelling and implementation

The model– like the real system – consists of two subsystems that are connected by the transfer buffers. In this section, we describe the modeling as well as the implementation of the base tier and the stacker crane system.

We use a generic simulation framework for the modeling and implementation that was developed for the throughput analysis of order picking systems operated by a fleet of vehicles (Lienert & Fottner, 2020). This framework is implemented using the Tecnomatix Plant Simulation discrete event simulation environment and comprises six different modules: the *parameter module* serves an interface for the user and allows the adjustment of numerous parameters such as vehicles' speed and acceleration. The *layout module* contains the formal description of the storage system's layout. The *dispatching module* manages the job assignment and contains the warehouse management system. The *routing module* takes care of the time window routing of the vehicles and manages the reserved and free-time windows for each node. Performance indicators such as the number of fulfilled storage and retrieval jobs or the utilization of the vehicles are gathered by the *evaluation module*. The simulation of the movements of goods and vehicles take place within a module that contains the storage system (Lienert & Fottner, 2020). For our purposes, we extended this module to incorporate the stacker crane system and the connection with the base tier.

3.1. Shuttle base tier

Shuttles use a common rectangular network of paths to move between I/O locations, transfer buffers and storage locations on the base tier. Therefore, routing and deadlock handling need to be addressed. One way to avoid deadlocks is routing on the basis of time windows. This approach avoids deadlocks by reserving the route for a vehicle from its current situation to its destination in advance. A time window is blocked on each segment of the layout that has to be travelled along this path during which the segment can only be used by one vehicle and is not available for the movement of other vehicles. Since the time windows of adjacent segments of a route overlap, the vehicles can move safely through the layout. As soon as a vehicle has to be routed from its current position to a given destination, the method searches for a conflict-free route through the free time windows on the nodes using an A*-algorithm.

The idea of this method was first introduced by Kim and Tanchocco (Kim & Tanchocco, 1991) and has been applied in different logistic contexts – including operating a fleet of shuttles within a storage system (Lienert & Fottner, 2017a). For more detailed insights into the routing algorithm used for the base tier, please refer to (Lienert & Fottner, 2017b) and to (Lienert, Wenzler, & Fottner, 2020).

To apply the time window routing method, the layout of the tier has to be modelled as a graph. We thus define different types of nodes that represent different types of layout segments on the base tier. *Transfer buffer nodes* connect the stacker crane system to the base tier. *Storage nodes* represent the storage locations for the intermediate buffering of pallets on the base tier. *IO-location nodes* are the places where pallets enter or leave the system. The network of paths is represented by *aisles nodes*. All of the nodes are of the same size and can be travelled along in the four cardinal directions. Each rectangle in Fig. 4 represents a node in the underlying layout graph that is used for time window routing. The transfer buffer nodes are served by a single stacker crane. The fleet of vehicles retrieve the pallets from these transfer buffers and transport them towards an I/O location. Storage requests are executed the other way around. Note that vehicles loaded with a pallet are only allowed to move using aisle nodes, whereas empty vehicles are allowed to use storage nodes for movements as well. We also integrated two different movement profiles for the vehicles within the simulation model: empty vehicles have a higher traveling speed and acceleration than full vehicles.

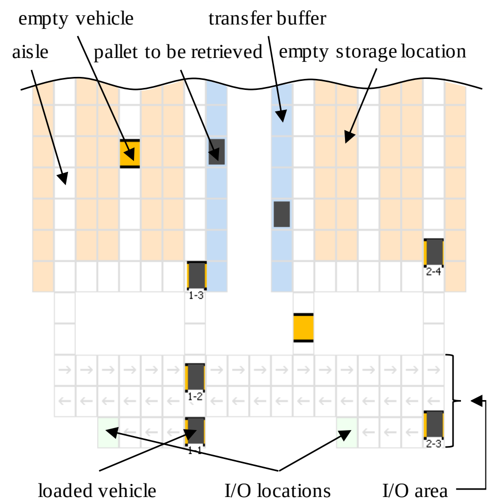

Figure 4. Screenshot of the base tier model

Finally, we used the routing-based sequencing approach to establish a desired sequence of pallets to be retrieved at every IO location (Lienert & Fottner, 2018). In Fig. 4, each pallet transported by a vehicle is identified by two numbers. The first indicates the I/O location where the pallet needs to be handed over, the second defines the position within the corresponding sequence.

3.2. Stacker crane and channel warehouse

We considered one stacker crane, to which one satellite is allocated. The satellite has two different movement profiles within the simulation model: The empty satellite has a higher traveling acceleration than the loaded satellite. The stacker crane can access each storage location in the channel warehouse in the x, y and z directions. The depth and width of the channel warehouse are equal to those of the shuttle base to optimize the space utilization. The coordinates x, y, and z of the first tier of the channel warehouse are associated with the nodes of the transfer buffer of the shuttle tier, so that the stacker crane can bring the pallets exactly to the transfer buffer node for which the retrieval and storing cycle times were calculated. The transfer buffers are alternated: one retrieval position is between two storing positions and vice versa. The stacker crane is modeled as a state machine. One retrieval order will be automatically created after a constant time interval while the storing orders will only be created when a shuttle brings a storing pallet to a transfer buffer location. A new cycle can start if the stacker crane has at least one order and is not currently running another order. If there is at least one retrieval order, but no storing orders, a retrieval cycle will start. If, on the contrary, there is at least one storing order but no retrieval orders, a storing cycle can start. If there is at least one retrieval order and one storing order, a double cycle can start.

The flowchart in Fig. 5 shows the process, that mainly comprises the load of pallet, the storage process and retrieval process that ends with a handover of the retrieved pallet to a transfer buffer.

3.3. Connection and coordination

We first consider the storing process (see Fig. 6). Note that each vehicle is dedicated to an I/O location and hence to a storage area.

If the stacker crane has a lower throughput per hour than the shuttles, the transfer buffer locations for storage may all be occupied by pallets at a certain time. If so, the shuttles wait at the free places in the buffer of the shuttle base. When the stacker crane takes another pallet, the shuttle with the longest waiting time is activated. The system checks whether it can find a storing order in its area. If not, all of the other shuttles in the waiting list will be checked to find a storing order in their area and the shuttle with the longest waiting time that can find a storing order in its area will be activated. The case may also arise whereby all of the shuttles together have a lower throughput per hour than the stacker crane and the transfer buffer locations for retrieval are empty at a certain time.

In this case, the stacker cannot find orders to store and if there are no retrieval orders either, it stops. It will awaken when a shuttle leaves a pallet on the transfer buffer for storage and will create a storing order for the stacker crane. In the simulation, we implemented two possible operating modes for the shuttles of the base, namely *store to transfer buffer* and *store to storage of the shuttle base*. Note that *store to transfer buffer* means not only the process of bringing pallets from I/O locations to the transfer buffer, but also the process of bringing pallets from storage locations to the transfer buffer, that have been stored in advance by the shuttles. This last modality is not described in Fig. 6 for the sake of simplicity.

We now consider the retrieval process (see Fig. 7). If the stacker crane has a lower throughput per hour than the shuttles, the buffer transfer locations for the retrieval may all be empty at a certain time. In this case, the shuttles wait at the I/O trucks for storing the shuttle base. When the stacker crane retrieves a further pallet, the shuttle with the longest waiting time is activated. The system checks whether it can find a retrieval order in its area. If not, all of the other shuttles in the waiting list will be checked to find a retrieval order in their area and the shuttle with the longest waiting time that can find a retrieval order in its area will be activated. The case may also arise whereby all of the shuttles together have a lower throughput per hour than the stacker crane and all of the transfer buffer locations for retrieval are occupied at a certain time. In this case, the stacker cannot find any more space to place the retrieval orders and it stops. It will awaken when a shuttle takes a pallet from the transfer buffer for retrieval and leaves the transfer buffer location empty. Note that we combine a vehicle-initiated dispatching strategy and a retrieval–task-initiated dispatching strategy for dispatching in the shuttle base (Egbelu & Tanchoco, 1984).

In the simulation, we implemented two possible operating modes for the shuttles of the base, namely *retrieve to I/O locations* and *retrieve to storage of the shuttle base*.

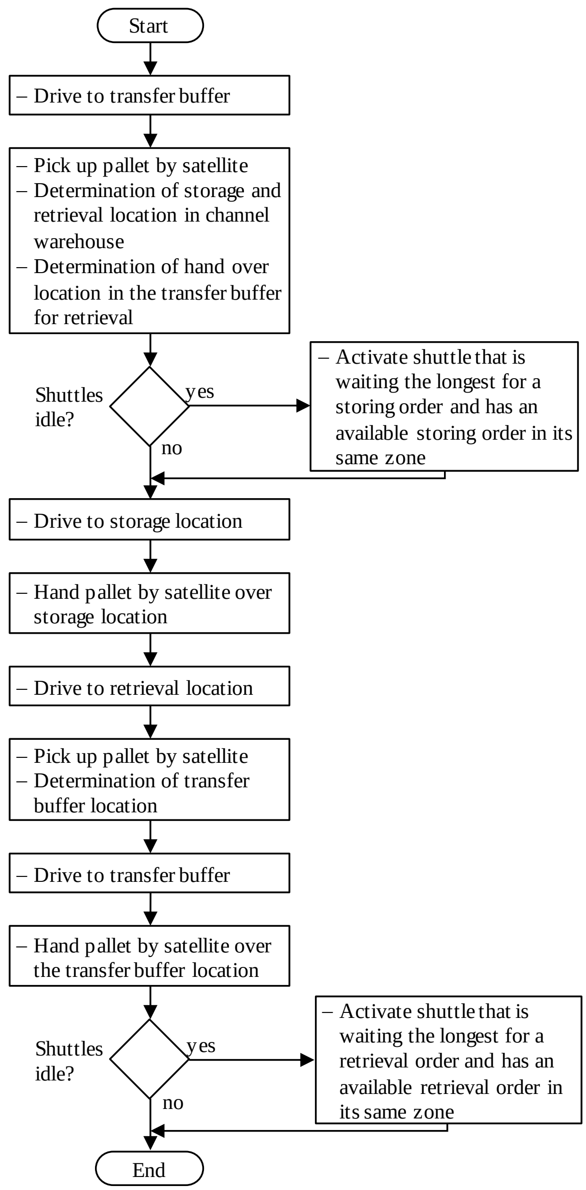

Figure 5. Description of a double cycle for the stacker crane in the event that a transfer buffer location is available for retrieval

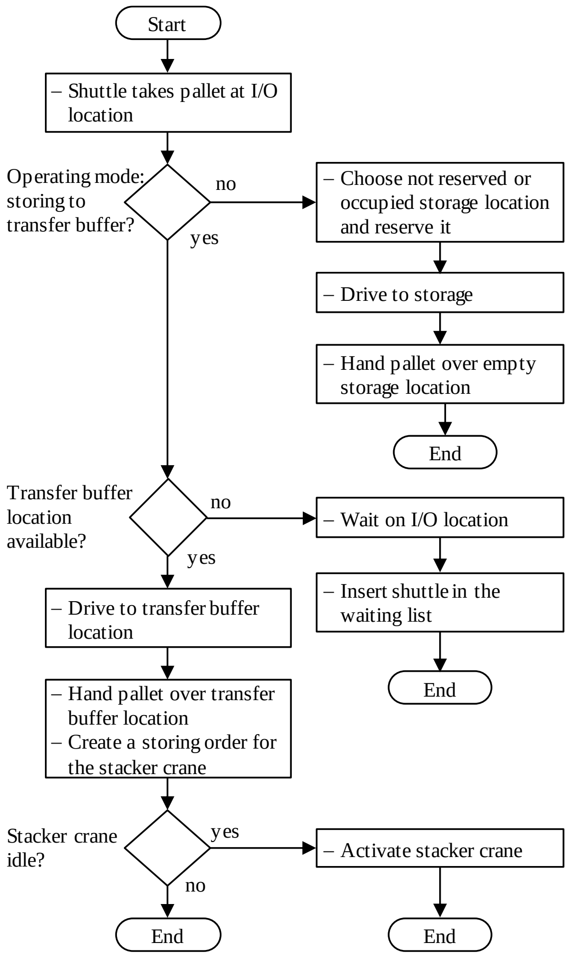

Figure 6. Description of storing process

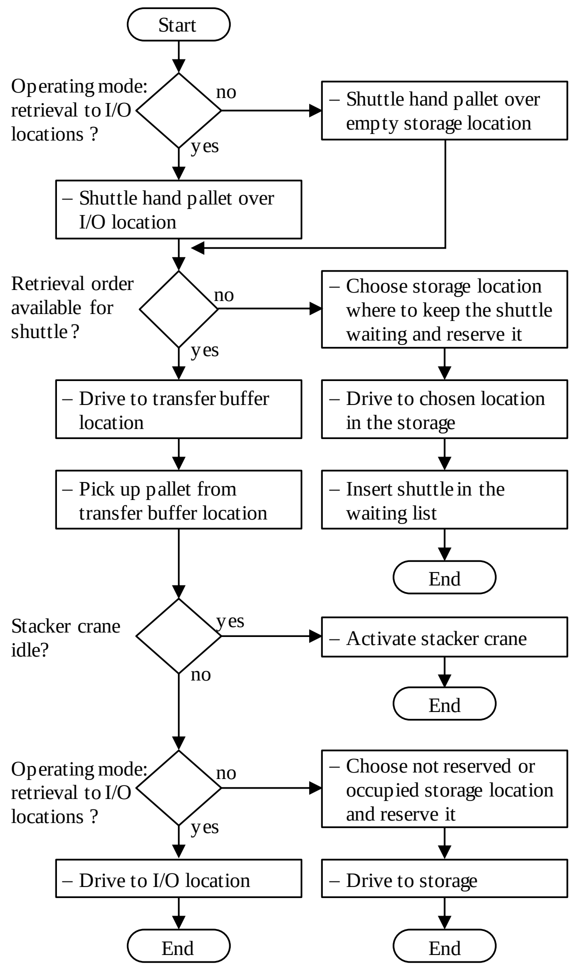

Figure 7. Description of retrieval process

Note that *retrieve to I/O locations* means not only the process of bringing pallets from the transfer buffer to I/O locations, but also the process of bringing pallets from storage locations to I/O locations, that have been retrieved in advance by the stacker crane. This last modality is not described in Fig. 7 for the sake of simplicity.

4. Simulation study

We consider a system with a single stacker crane that serves 34 transfer buffers arranged in two rows alongside the stacker crane (see Fig. 4). The base tier provides 308 storage locations for intermediate buffering. There are three storage aisles in each half of the base tier as well as two cross aisles positioned within the storage area. There are two I/O areas located on both sides of the system that are connected by two bidirectional lanes. One I/O area is used for incoming pallets, the other for outgoing pallets. Furthermore, there are two I/O locations within each I/O area (see Fig. 4).

The channel warehouse system provides 44 storage channels on each of the 8 tiers, each of them having a capacity for 8 pallets. For the following experiments, we focus on the retrieval process since the results of the storing process and of storing and retrieving simultaneously are very similar to the retrieval case. 5 replications are performed with the same parameters for each simulation experiment. Due to low influence of randomness, 5 replications are considered enough to have a little variance. Each replication lasts 24 hours. In order to validate the model, we calculated the travel times for individual vehicles analytically and compared them with the simulation.
All the parameters are provided by the manufacturer.

4.1. Retrieval without intermediate buffering

In a first experiment, we evaluate the throughput of the stacker crane system using the parameters shown in Tab.1

Table 1. Stacker crane parameters.

Parameter	Value
Travel speed x	4.0 m/s
Travel acceleration x	1.0 m/s^2
Lifting speed y	1.5 m/s^2
Lifting acceleration y	1.0 m/s
Satellite speed z	1.2 m/s^2
Satellite acceleration loaded z	0.5 m/s^2
Satellite acceleration unloaded z	1.0 s
Time of pallet handover	1.0 s
Time of satellite handover	4.0 s
Time for positioning in channel	1.0 s
Time for positioning before channel	0.5 s

Given a random choice of the transfer buffers and of the retrieval locations in the channel warehouse, 82.9 retrievals per hour can be achieved. In a second step, we analyze how many vehicles are needed to handle the maximum throughput reached with the stacker crane, taking into account the desired sequence of the pallets. For this purpose, we used the parameters shown in Tab.2.

Table 2. Vehicle 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	6.0 s
Handover time	10.0 s

Using two vehicles - one for each I/O location -, we achieve a throughput of 41 retrievals per hour; using 4 vehicles, we achieve 77.7 retrievals per hour; using 6 vehicles, we reach the throughput of 82.1 retrievals per hour given by the stacker crane. The further increase in vehicles number do not lead to a greater throughput.

4.2. Retrieval with intermediate buffering

In a third experiment we analyze the throughput capacity of the system using the intermediate buffer (see Fig. 8) to show the benefits of the system. The idea is that pallets are retrieved from the storage system by the stacker crane prior to the arrival of an outgoing truck and are then stored on the base tier. The retrieval process by the vehicles is triggered as soon as the truck can be loaded. 5 replications are performed with the same parameters for each simulation experiment once again.

Retrieving directly from the storage locations in the shuttle base avoids bottlenecks in the stacker crane. The maximal throughput is thus greatly increased. Note that the maximum throughput is limited by the handover of the pallets at the I/O locations to 250.5 pallets per hour.

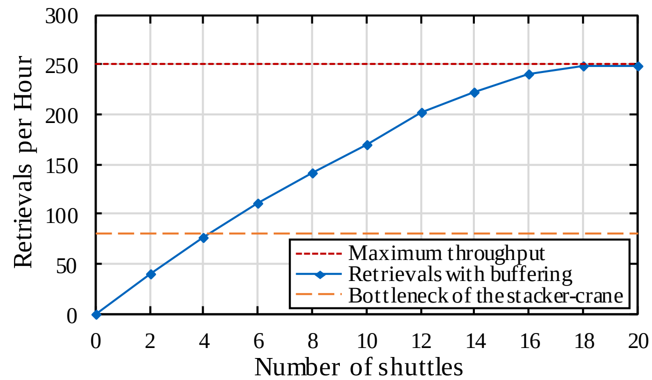

Figure 8. Warehouse performance: retrieval with intermediate buffering

5. Conclusion

In this contribution, we have presented the design and advantages of a DHPW. We then proposed control strategies for the connection and coordination of its components and explained how to model the whole system in a simulation. In conclusion, we have demonstrated the advantages in terms of throughput and ability to respond to short-term fluctuations in demand resulting from the use of intermediate buffering in the shuttle base of the warehouse.
For further research, we suggest investigating how to improve the bottleneck caused by the stacker crane, how to maintain a high space utilization ratio as well as sequencing and affordable investment and operating costs.

Funding

The Chair of Materials Handling, Material Flow, Logistics at the Technical University of Munich gave the funding for the research, which resulted in this contribution.

Acknowledgements

We would like to thank Joerg Eder and Thomas Klopfenstein from the firm of Gebhardt Fördertechnik GmbH for the fruitful collaboration.

The authors wish it to be known that, in their opinion, the first two authors should be regarded as joint first authors. In this contribution, G. Siciliano focused on the modelling of the shuttle base - operating modes of shuttles, order creation and assignment strategy for shuttles -, on the modeling of the stacker crane, on the connection and coordination between shuttles base and stacker crane, on the execution of the experiments. T. Lienert focused on the modelling of the shuttle base.

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