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# Dynamic Hybrid Pallet Warehouses: Synergies Between Shuttles and Stacker Cranes

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# Vorwort

*This dissertation resulted from my activity at Chair of Materials Handling, Material Flow, Logistics at the Technical University of Munich.*

***"Pectus est enim quod disertos facit"[1] (Marcus Fabius Quintilianus)***

First of all, I thank Prof. Dr.-Ing. Johannes Fottner. I am well aware that the time spent working at his Chair has been for me a unique possibility of professional and personal growth: Herzlichen Dank! Further, I thank Prof. Dr.-Ing. Alice Kirchheim and Prof. Dr.-Ing. Veit St. Senner for having agreed to be second examiner of this dissertation and chairman of my oral doctoral examination respectively. Also, I thank the colleagues of the Chair for the great years spent together. Among them, I am particularly grateful to Dr.- Ing. Thomas Lienert, Dr.-Ing. Christian Lieb and Dr.-Ing. Florian Wenzler for having supported me with their experience in the simulation environment Tecnomatix Plant Simulation in the initial phase of the implementation of the simulation model. Moreover, I thank Florian Spiegel, Dr.-Ing. Andreas Rücker and Maximilian Schöberl for having reviewed this dissertation. I thank engineers Dipl.-Wirtsch.-Ing. Jörg Eder and Thomas Klopfenstein for having provided me with the point of view of industry and some data for the purposes of this work. Also, I thank all the students that I supervised, especially Anna Durek-Linn and Yue Yu for their engagement back then and for their valuable friendship now. Further, I heartfully thank my closest friends for their loving support.

Sono infinitamente grata ai miei carissimi genitori ed ai miei carissimi nonni per sostenermi sempre, incondizionatamente e illimitatamente.

Meine unendliche Dankbarkeit für dich, mein liebster C., ist zu tief und zu groß, um sie in Worte zu fassen: Semper et in aeternum!

Giulia Siciliano, October 2024

[1] "For it is the heart that makes the eloquent"

# Kurzzusammenfassung

**Dynamische Hybrid-Palettenlager:**

**Synergien zwischen Shuttles und Regalbediengeräten**

In den letzten zehn Jahren mussten automatisierte Lager aufgrund der Einführung der Just-in-Time-Philosophie, des Omni-Channel-Vertriebs und der Massenanpassung immer höhere Durchsätze bieten. In der Palettenlogistik besteht eine mögliche Lösung darin, die Vorteile herkömmlicher Shuttle- und Regalbediengerät-basierter Lagersysteme zu kombinieren. Umfangreiche Literaturrecherchen haben gezeigt, dass es keine Studien gibt, die die Verbindung, Koordination und Synergien zwischen Gang-zu-Gang-Shuttles und Regalbediengeräten innerhalb desselben automatischen Palettenlagers untersuchen.

Das Ziel dieser Dissertation ist es daher diese innovativen Lagersysteme zu untersuchen, welche als dynamische Hybrid-Palettenlager bezeichnet werden, und deren Eigenschaften zu bestimmen. Dabei zeigen sich Vorteile wie beispielsweise ein höherer Durchsatz als bei den betrachteten konventionellen Systemen, eine hohe Skalierbarkeit, eine hohe Kapazität zur Deckung von Nachfragespitzen, während die Kosten und die Flächennutzung mit denen der jeweiligen konventionellen Lagerhäuser vergleichbar sind. Im Rahmen dieser Arbeit wird die Forschungslücke in Bezug auf Strategien für das Steuerungssystem, die Designoptimierung und die Leistungsanalyse dieser Lagersystemen geschlossen.

Die zentrale Methode dieser Arbeit ist die diskrete Ereignissimulation. Dabei wird diese verwendet, um verschiedene Layouts dynamischer Hybrid-Palettenlager zu bestimmen und zu untersuchen, ob diese herkömmlichen Palettenlager in ihren Anwendungsbereichen ersetzen können. Es werden optimale Strategien für die Steuerung verschiedener Komponenten in verschiedenen Konfigurationen und Situationen vorgestellt und quantitativ die deutlichen Verbesserungen des erreichbaren Durchsatzes demonstriert. Am Ende wird aufgezeigt, dass dynamische Hybrid-Palettenlager gegenüber repräsentativ eingeschätzten herkömmlichen automatisierten Lager höhere Durchsätze erzielen und dass sie eine hohe Skalierbarkeit und eine hohe Kapazität haben, um Bedarfsspitzen abzudecken.

In Anbetracht der Ergebnisse dieser Dissertation erweisen sich Dynamic Hybrid Pallet Warehouses als eines der derzeit leistungsfähigsten Palettenlager und -bereitstellungssysteme.

# Abstract

**Dynamic Hybrid Pallet Warehouses:**

**Synergies Between Shuttles and Stacker Cranes**

In the last decade, automated warehouses have been required to provide ever higher throughputs, as a consequence of the adoption of just-in-time philosophy, omnichannel distribution and mass customisation. In the logistics for pallets, a possible solution is to combine the advantages offered by conventional shuttle-based and stacker crane-based warehouses by using stacker cranes and aisle-to-aisle shuttles in the same warehouse. Extensive literature research has shown that there are no studies investigating the connection, coordination, and the synergies between aisle-to-aisle shuttles and stacker cranes within the same automated pallet warehouse.

Thus, objective of this dissertation is to investigate these innovative warehouses, which are denoted as Dynamic Hybrid Pallet Warehouses, and to demonstrate their advantages. These advantages are higher throughputs than the considered conventional systems, high scalability, high capacity to meet peaks in demand, while maintaining costs and space utilisation comparable to those of the respective conventional warehouses. With this work, the research gap is filled in terms of control system strategies, design optimisation and performance analysis of these warehouses.

The central tool of this work is discrete-event simulation. This tool is used to devise and investigate different layouts of Dynamic Hybrid Pallet Warehouses, able to replace conventional pallet warehouses in their fields of application. Optimal strategies for the control of different components in various configurations and situations are presented, demonstrating quantitatively the high improvement in throughput achievable. In the end, it is demonstrated that Dynamic Hybrid Pallet Warehouses achieve higher throughputs than representative considered conventional automated warehouses, that they have high scalability and high capacity to satisfy peaks in demand.

In view of the outcomes of this dissertation, Dynamic Hybrid Pallet Warehouses prove to be one of the current most performant pallet storage and retrieval systems.

# Table of Contents

# List of Abbreviations

| Abbreviation | Meaning |
|---|---|
| AVS/RS | Autonomous Vehicle-based Storage and Retrieval Systems |
| DHPW | Dynamic Hybrid Pallet Warehouse |
| AS/RS | Automated Storage and Retrieval Systems |
| I/O | Input/Output |
| LIFO | Last In First Out |
| AGV | Automated Guided Vehicle |
| FCFS | First Come First Served |
| L/U | Load/Unload |
| IP | Idle Position |
| DP | Delivery Position |
| PU | Pickup Position |
| OMS | Operating Mode for Shuttles |
| OMSC | Operating Mode for Stacker Cranes |
| OOM | Overall Operating Mode |
| SLTB | Storage Locations Transfer Buffer |
| RLTB | Retrieval Locations Transfer Buffer |
| SC | Stacker Crane |
| ST | Satellite |
| STP | Satellite Position |
| SP | Shuttle Position |
| PP | Pallet Position |
| OC | Overlapping Case |

| | |
|---|---|
| FOI | Fixed Operational Intervals |
| RTB | Random Transfer Buffer Location |
| NTB | Nearest Transfer Buffer Location |
| TC | Time Comparison |
| LSTIT | Longest Satellite Idle Time |
| NST | Nearest Satellite |
| SCC | Succession |
| WD | Wait or Drive |
| DB | Double |
| OD | One Direction |

# 1 Introduction

In this introduction, firstly the initial situation, in the context of which this research takes place, is explained. Next, the problem arising from this initial situation and the research objectives for solving this problem are defined. Finally, the approach followed to reach these objectives is shown, as well as the structure of this dissertation.

## 1.1 Initial Situation

In Europe automated pallet warehouses for storing and retrieving goods are nowadays widespread in distribution, production and shipping processes. Compared to non-automated pallet systems, these warehouses have numerous advantages, such as considerable savings in costs of employment, better space utilisation, high reliability and smaller error rates [Roo-2009]. The two main classes of automated pallet warehouses are using shuttles or using stacker cranes. These systems have very different characteristics and areas of application.

On the one hand, shuttled-based warehouses reach very high throughputs and are very flexible [Kri-2018]. On the other hand, not only do they have a low space utilisation ratio due to the presence of numerous shuttle aisles, but they also require very high operating costs and investments, and the development of complex control systems [Kar-2012].

Stacker crane-based warehouses, thanks to the presence of multiple-deep racks, i.e. racks having more than one row of storage positions orthogonally to the aisle of the stacker crane, allow instead a very high utilisation of space. Furthermore, as they are composed exclusively of one or more stacker cranes and of racks, they involve lower investment and operating costs compared to shuttle-based warehouses. However, stacker crane-based warehouses are not able to reach the same high throughputs as shuttle-based ones, as the stacker cranes have very few locations along the aisle where to exchange pallets. In addition, they are not flexible enough to satisfactorily cope with peaks in demand. Furthermore, if it is required to sequence the goods during retrieval, in the common praxis, this is done in a pre-zone, to avoid the low throughput caused if the sequence would be created directly in the warehouse. On such a pre-zone pallets are either placed on the floor and sequenced by hand or placed on conveyors and sequenced through an automatic loop [Gei-1998]. In both cases, the sequencing process is time-consuming, and the presence of the pre-zone causes a reduction in space utilisation and a significant increase in costs.

## 1.2 Problem Statement and Research Objective

The adoption of just-in-time philosophy, omnichannel distribution and mass customisation deeply impacted the logistics market [Cus-2020]. In the last decade the demand for ever-higher performance caused an acceleration in the development of automated warehouses, i.e. the launch of shuttle-based warehouses or autonomous vehicle-based storage and retrieval systems (AVS/R) [Aza-2019]. While automated warehouses for small load carriers have developed faster to reach higher performance, those for pallets have lagged behind due to their slower dynamics. Specifically, the need for higher performances in terms of throughput, space utilization ratio, flexibility and scalability in pallet warehousing systems and, at the same time, the need to keep the operating costs and the necessary investment of these systems low, creates a problem in the current technological landscape. As discussed in the previous section the current automated pallet storage systems are either very expensive or do not offer high flexibility and efficiency. This technical problem is matched by a gap in the scientific literature. In previous research, as will be shown in Chapter 3 addressing the state of science and research, there are numerous studies on the concepts of shuttle-based and stacker crane-based warehouses, but not on warehouse concepts that allow the division between these two classes to be crossed and thus combine the advantages of both.

To solve the technical problem one possible idea is to use shuttles and stacker cranes within the same pallet warehouse. An initial technical solution was a patent attempt in the USA by *Malik* [Mal-2014]. A further technical solution was subsequently envisioned and filed as patent application by Gebhardt Fördertechnik GmbH [Ede-2019], that undertook a cooperation with the Chair of Materials Handling, Material Flow, Logistics at the Technical University of Munich (TUM) in the form of the research project PALSA (2019-2021) led by the author of this dissertation. This project, with funding number ZF4492103SS8, was funded by the German Federal Ministry of Economics and Energy (BMWi) in the context of the German Central Innovation Program for Small and Medium-Sized Enterprises (ZIM).

However, the scientific gap remains open, as there are still no studies in the literature on the synergies between shuttles moving in both directions of the plane and stacker cranes. Therefore, the aim of this dissertation is to investigate hybrid pallet warehouses and to demonstrate their advantages by filling this scientific gap. The three main aspects for conventional automated pallet warehouses, on which also existing literature focuses, are:

- strategies for control system
- design optimization
- performance analysis.

In fact, to define the model of a certain kind of automated warehouse it is necessary to specify its characteristics in all these three fields. Thus, the research objective in this contribution is to fill the scientific gap regarding hybrid systems synergizing shuttles and stacker cranes in the three fields mentioned above. In particular, it is aim to exploit the advantages offered by the connection and coordination between shuttles and stacker cranes in the form of an innovative class of warehouses, which in this dissertation are denoted as Dynamic Hybrid Pallet Warehouses (DHPWs). This class must provide valid alternatives to warehouses using only shuttles or only stacker cranes in order to be able to replace them in their typical applications. To this end, DHPWs must meet requirements such as

- higher throughputs than the considered conventional systems
- high scalability of performance
- high capacity to meet peak demand
- costs and space utilisation comparable to those of the respective conventional warehouses.

## 1.3 Approach and Structure of the Dissertation

To fill the three fields of the research gap, the approach is to first identify promising DHPW layouts, i.e. different types of connections between shuttles and stacker cranes which allow to create different synergies between the two sub-systems, in order to investigate DHPWs.  On the base of these layouts the material- and information flow is determined and strategies for the control system are defined. Then optimization strategies for the control system regarding order assignment strategies and coordination of multiple stacker cranes in a single aisle are defined, filling the research gap regarding strategies for the control system. A model of the system is implemented in a discrete-event simulation environment, analytically verified and validated against real sub-systems. At this point an analytical method including closed formulas for the base of DHPWs is developed to calculate the test positions necessary for the comparison with real sub-systems. Afterwards, the research gap of performance analysis is filled by studying the behaviour of DHPWs under different conditions in the discrete-event simulation. The simulation study includes also the investigation of the influence of design features on performance, enabling to fill the research gap regarding the design optimization. To demonstrate the usefulness of DHPWs their throughput is compared through discrete-event simulation to conventional systems and properties such as scalability and capacity to satisfy high peaks in demand are investigated.

Parts of the method and results shown in this dissertation were developed from the knowledge gained during the PALSA research project. Elements beyond these initial results were obtained in the widening and deepening of the research on hybrid automated pallet warehouses carried out by the author during her time at the Chair of Materials Handling, Material Flow, Logistics at TUM on the base of the research results from the PALSA project.

This dissertation consists of eight chapters. In Chapters 2 and 3 the basics and the state of science regarding automated pallet storage systems are illustrated. From this state of science, the research gap is derived, which shall be elaborated in several research questions and sub-questions.

Next, Chapter 4 begins with the illustration of the DHPW layouts considered promising for research. It is then proposed how to model the material flow within DHPWs. A systematic approach is shown next for the realisation of strategies for the control system for the connection and coordination of shuttles and stacker cranes in each of the different layouts, i.e. the different types of synergies desired between shuttles and stacker cranes. After that different order assignment strategies that can be used to increase the synergies between shuttles and stacker cranes are described. Configurations and coordination strategies that can be adopted to optimise several stacker cranes within an aisle are illustrated based on different configurations.

In Chapter 5, after having shown the different elements that must be defined for the realisation of a DHPW, some particularities are illustrated to pay attention to for modelling such systems in a discrete-event simulation environment. Given the complexity of the interactions within DHPWs it is not recommended using analytical methods for their design and investigation. When the DHPW model has been realised in the simulation environment, it is necessary to validate it with a prototype. In this regard, an analytical method is proposed which identifies the test positions to enable the validation of the specific base of DHPW shuttles against the prototype.

Once the description of design, control and modelling of DHPWs is completed, the performance analysis of the factors that most influence DHPWs in Chapter 6 is done. The investigation, which consists of the quantitative impact of strategies regarding design and control system, is carried out in the discrete-event simulation environment Tecnomatix Plant Simulation.

Subsequently, Chapter 7 consists in the critical discussion of the proposed method and in the demonstration of the thesis that DHPWs satisfies the requirements. Specifically, it is demonstrated through a quantitative comparison that the performance of DHPWs is considerably higher than representative considered conventional automated pallet warehouses under the same boundary conditions. Then, the high scalability and high capacity of DHPWs to meet peak demand are evidenced through quantitative analysis. Finally, recommendations for the use of DHPWs are elaborated and the adequacy of the elaborated approach in answering the research questions is shown through a final summary evaluation.

Finally, Chapter 8 contains the conclusion and the outlook.

# 2 Basics of Automated Warehouses

## 2.1 Use of Automated Warehouses and Delimitation to Pallet Systems

Nowadays, automated warehouses are used for material handling in numerous fields of application such as production, automotive factories, pharmacy, car parking and libraries. Their optimization is of main importance, because of their high impact on the costs of products. For example, in a manufacturing process, only the material handling represents 15-70 % of the production cost of goods [Mir-2009]. [Cin-2022]

Automated warehouses were introduced in the 1950s in the form of Automated Storage and Retrieval Systems (AS/RSs). AS/RS can store and retrieve goods without intervention of operators in production and distribution. The most basic configuration consists of a crane driving along an aisle to serve the racks arranged on the sides of that aisle. Compared to non-automated warehouses, AS/RS enable to save labour expenses, decrease the frequency of errors committed, augment the reliability of the system, and reach high space utilization ratios. [Roo-2009]

Specifically, being a crane able to achieve higher racks than a forklift driven by an operator, AS/RSs can be significantly higher than non-automated warehouses.

On the other hand, AS/RS require higher investments than non-automated warehouses, are less flexible and necessitate complex, thus expensive, control systems. [Roo-2009]

New performance challenges were opened up in the logistics market by the spread of just-in-time philosophy, omnichannel distribution and mass customisation [Cus-2020]. To cope with them, a large variety of automated warehouses was developed. While systems for small load carriers have developed faster to reach higher performance and flexibility, systems for pallets have lagged behind due to the complexity in improving their slower dynamics caused by high pallet weights. In this dissertation, the analysis is restricted to automatic pallet storage systems, because the dynamics of and available technical solutions for small load carriers are vastly different, making their treatment an independent problem. For example, current warehouses for small load carriers are very rarely deeper than four storage locations[1], while multi-deep channel storages are widespread for pallets. However, regarding the basics and state of science and research illustrated in Chapters 2 and 3, also literature for small load carriers will be cited because for some considerations and information it is not relevant whether the warehouse is for pallets or small load carriers. Among automated pallet warehouses, this contribution is focused on shuttle-based and stacker crane-based systems. The reason is that they are the most widespread systems in pallet logistics and, as a consequence, they are the main competitors for Dynamic Hybrid Pallet Warehouses (DHPWs). Furthermore, they are the two sub-systems, the hybridization of which generates DHPWs.

## 2.2 Stacker Crane-Based Warehouses

The warehouses studied in this thesis rely on stacker cranes for transporting pallets in the vertical plane. To become acquainted with this technology, the structure and functioning of a basic stacker crane-based warehouse are illustrated in the following and existing variants with different characteristics are discussed.

### 2.2.1 Description

Key elements of a stacker crane-based warehouse are stacker cranes, input/output (I/O) locations, storage racks [Atz-2013] and pre-zone as shown in Figure 2-1:

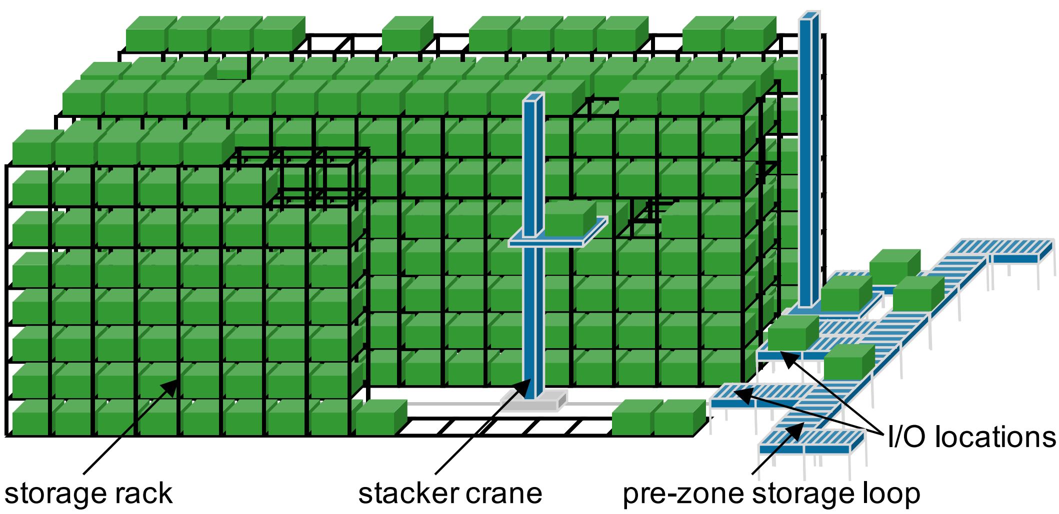



*Figure 2-1: Example of stacker crane-based warehouse [Sic-2020]*

[1] The author of this dissertation is grateful to her former colleague Dr.-Ing. Andreas Rücker for having shared this information with her.

Each aisle can contain one or more stacker cranes. To perform a storage, the stacker crane drives to the I/O locations, generally installed at one or both ends of the aisle and picks up a pallet, for example using telescopic forks or a satellite. A satellite denotes a vehicle positioned on the stacker crane which is able to load a pallet and then returns to its position on the stacker crane. The stacker crane then simultaneously lifts its load handling attachment vertically and drives horizontally along its rail in the aisle. When the target level and position in the aisle are reached, the stacker crane, again using for example its telescopic forks or satellite, delivers the pallet. The retrieval process works in reverse order. If pallets need to be delivered in a certain sequence during retrieval, in general the sequencing takes part in the pre-zone. [Sic-2020]

The pre-zone may include loop conveyors − such as for example roller conveyors −, forklifts or other systems to transport pallets. Usually pallets are sequenced by the automatic loops of the conveyors where they are buffered [Gei-1998]. However, in some applications they are just buffered on the floors and operators sequence them manually. The pre-zone is usually also used to buffer pallets, before e.g. transporting them to the trucks that will dispatch them to customers or delivering them to the successive production phase. The presence of the pre-zone requires a large amount of space in the warehouse, thus it decreases the space utilization ratio and constitutes a high cost. [Sic-2020]

As regards material- and information flows, the stacker crane can execute a *single* or *double cycle*. In the first case, a single retrieval or storage order is executed. For example, a *storage cycle time* is obtained by adding the time to pick a pallet up from the I location, to travel to the target storage location, to store the pallet there, and to travel back to the I location. To reduce the total time of performing storage and retrieval orders, a double cycle is executed. In this case, the cycle time is calculated by adding the time to pick a pallet up from the I location, to travel to the target storage location, to store the pallet there, to travel from the storage to the retrieval location i.e. *interleaving time*, to pick the pallet up, to bring it to the O location. The sequence of single or double cycles is defined as *tour* of the stacker crane. [Roo-2009]

### 2.2.2 Existing variants

The basic configuration of a stacker crane-based warehouse consists in a single crane confined to an aisle, i.e. aisle-captive stacker crane, and being able to transport just a pallet at a time, i.e. *single shuttle*. In this case, such a *single unit-load aisle-captive* stacker crane moves along a stationary single-deep rack. As a consequence, the stacker crane can directly access any pallet stored in the racks. A variant of the basic configuration includes the possibility for stacker cranes to change their aisle, i.e. *aisle-roaming* stacker cranes [Aza-2019]. [Roo-2009]

The advantage in this case is that less stacker cranes than aisles are required, thus the costs are lower than in the basic configuration and the utilization ratio of each stacker crane is higher. Another variant consists in the stacker crane being able to carry two or even more pallets at a time, i.e. *multi-shuttle cranes*. However, stacker cranes that can transport more than two pallets at a time are rare in industrial applications. A *dual-shuttle crane* denotes a stacker crane able to carry two pallets at a time. Such systems are used to combine operations e.g. to first perform the retrieval of a pallet in a certain location and the execute a storage of another pallet in the same location. In this way it is not necessary to drive to the I/O locations to retrieve and take the new pallet to be stored, so the travel path is shorter and time is saved. [Roo-2009]

If a higher space utilization ratio is needed, *double-deep racks* can be used instead of single-deep ones. Double deep-racks can store two pallets, one in a front position and one in a rear position. It is possible to retrieve the pallet in the rear position if there is no pallet in the front position. In order to exchange pallets with the rear position, the stacker cranes are provided with double-deep telescopic forks [Aza-2019]. Specifically, in case there is a low variety of products and a high turnover rate, double-deep storage may be favourable [Tom-2003].

If the priority is to minimise storage space, e.g. in the fresh products industry or for cold storage warehouses, a popular solution is to use *multi-deep racks*. Such racks can store more than two pallets per storage lane. The depth of lanes depends on the technology adopted and the kind of products. While the vertical movements are still performed by the stacker cranes, horizontal movements along the positions of the lanes are executed by a conveying mechanism. Multi-deep stacker crane-based warehouses are classified into the following three configurations according to the conveying mechanism used. [Aza-2019]

*Push-Back Rack:* in this configuration, pallets are mechanically pushed along the depth of lanes by the stacker cranes. Pallets are stored according to the Last In First Out (LIFO) policy. Lanes are slightly sloped to ensure that a pallet is always easily accessible in the front position due to gravity. In general, the depth of a push-back rack has a maximum of five pallets locations.[Aza-2019]

*Conveyor-Based:* in this configuration, conveyors are inserted in the racks. If pallets can be moved along the lane forwards and backwards, then LIFO is performed and the movements are similar to those of push-back racks. If a non-automated gravity conveyor is used, an elevating mechanism is mounted in the backward of each rack to lift pallets from the inbound conveyor to the upper outbound one. Because the vertical movement of the lift is the slowest component of the transportation of pallets in the racks, it regulates the rotation velocity. A minimum of empty slot is necessary in the inbound and outbound conveyors to be able to retrieve a load [Kos-2008]. If automated conveyors are used, no lift is necessary. However, automated conveyors have high investment costs and are costly to repair in case of a malfunction. The advantage of using automated conveyors is that they enable to build deeper racks than gravity conveyors, thus they contribute to the increase of the space utilization ratio. [Aza-2019]

*Satellite[2]-Based:* in this configuration, a satellite transports pallets along the depth of lanes, as previously described. The satellite is dedicated to a lane or, if the number of lanes is higher than those of satellites, is moved by the stacker crane from a lane to another [Sta-1996]. [Aza-2019]

Multi-deep racks enable to reach a high space utilization ratio. However, they slow down the dynamics. Their main disadvantage is the low accessibility of pallets since a product can be reached only from one side of the racks. As a consequence, if no LIFO policy is applied, pallets are subjected to relocations or reshuffles, to enable the retrieval of the target pallet. [Aza-2019]

## 2.3 Shuttle-Based Warehouses

The warehouses studied in this thesis rely on shuttles for transporting pallets in the horizontal plane. To introduce this technology, the structure, the functioning and the properties of a basic shuttle-based warehouse are described, and existing variants with their characteristics are discussed.

[2] As mentioned previously in this contribution, a satellite denotes a vehicle positioned on the stacker crane which is able to load or unload a pallet and then return to its position on the stacker crane. In general, a satellite not only has simpler components than a shuttle, but also moves just forward and backward a lane.

### 2.3.1 Description

Main elements of a shuttle-based warehouse are lifts, storage racks and vehicles [Mal-2003b] as shown in Figure 2-2.

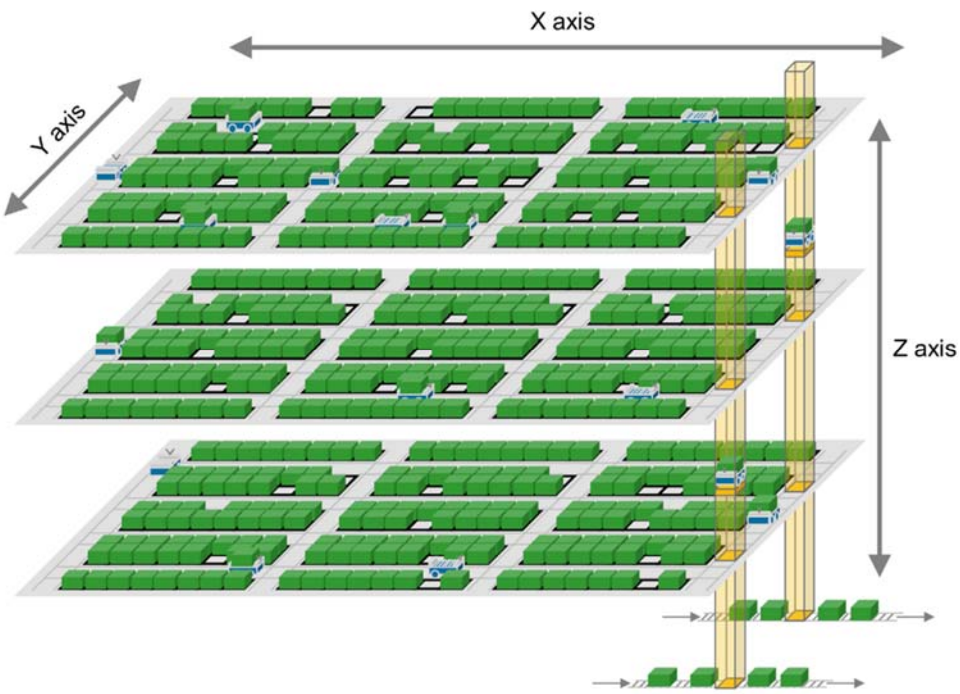



*Figure 2-2: Example of shuttle based-warehouse [Lie-2021, p.142]*

The racks contain aisles on each level, along which shuttles drive to store and retrieve goods on the horizontal plane; in the meanwhile lifts transport goods between the levels along the vertical direction. [Ziz-2000; Mal-2002]

Commonly, shuttles are confined to one level and one single aisle on it. To perform the storage, a pallet is transported from the I/O location by a lift to a target floor, where it is moved to a buffer location. Afterwards, a shuttle picks up the pallet and brings it to the target storage location. To perform a retrieval, the inversed order of operations will be executed. [Sic-2020]

Shuttles represent the main cost component in this type of warehouse. While the costs for lifts are estimated to be only about 25 % of those for shuttles, the lifts usually have a higher influence on performance because the vertical transport of a load requires in general more time than a horizontal transport. [Ekr-2010]

Material and information flows are represented through retrieval and storage transactions, that arrive at or leave a certain lift or a certain shuttle. Each transaction corresponds to a single transport order and can be virtual, i.e. an information, or physical, i.e. a pallet. If, for example, a pallet needs to be transported from its storage location in the racks to the output location of the lifts, this generates a retrieval transaction, that arrives in the warehouse as information and leaves as pallet. [Epp-2018, p.5]

Furthermore, if before the beginning of a cycle at least one storage and one retrieval transaction are available, these can be combined together. Their combination is defined as dual command transaction, i.e. double cycle, or interleaving and allows for performing load movement patterns that reduce the total travel path, fastening the material flow. [Mal-1998; Mal-1997; Mal-2002]

### 2.3.2 Existing variants

A recent review of shuttle-based warehouses can be found in [Aza-2019], which distinguishes them into aisle-based and grid-based systems. In the first case, storage locations and aisles for the movement of shuttles are clearly distinguished. In the second case, shuttles do not move in aisles but on a grid, that can have dynamic or static storage locations. Grid-based systems also include warehouses that do not strictly use shuttles on rails, but also automated guided vehicles (AGVs) such as the GridFlow System [Fur-2011]. Also grid-based warehouses can have more levels connected with lifts as in the case of the Live-Cube storage system [Zae-2017]. [Aza-2019]

The class of grid-based systems is constituted by a variety of warehouses, that are not actually strictly either shuttle-based or compact and are not as common as aisle-based warehouses. Therefore, from now on only aisle-based warehouses are considered and the term “shuttle-based warehouses” is used as synonym for them. Moreover, in accordance with the scientific literature illustrated in the following, the term “tier” is used as synonym of level of a warehouse; the term “lane” is used to denote an aisle for shuttles that lies on a level and is orthogonal to the edge of the level through which transport units, such as for example pallets, or shuttles can exit or enter the level, for example using lifts; the term “cross-aisle” is used to indicate an aisle for shuttles lying on a level and orthogonal to a lane.

These shuttle-based warehouses can be classified into two categories depending if the shuttles are confined to a tier, i.e. tier-captive vehicles, or if shuttles can move from a tier to the other on lifts, i.e. tier-to-tier vehicles. In case of tier-captive vehicles, operations to be executed by shuttles are different if the target storage location is positioned on another level. Shuttles on the base tier deliver pallets to the lift, which transports them to the target level. Shuttles on the target level then pick up pallets from the lift and bring them to the target storage location. [Her-2011b]

Another classification of shuttle-based warehouses differentiates between shuttles that can move between aisles, i.e. aisle-to-aisle vehicles, and shuttles that are confined to a single aisle, i.e. aisle-captive vehicles. As a result, shuttle-based warehouses can be distinguished into four different configurations as in Figure 2-3. [Lie-2017b; Sic-2020]

| Configuration | aisle-captive tier-captive | aisle-to-aisle tier-captive | aisle-captive tier-to-tier | aisle-to-aisle tier-to-tier |
|---|---|---|---|---|
| Movement Axes | x | x/z | x/y | x/y/z |

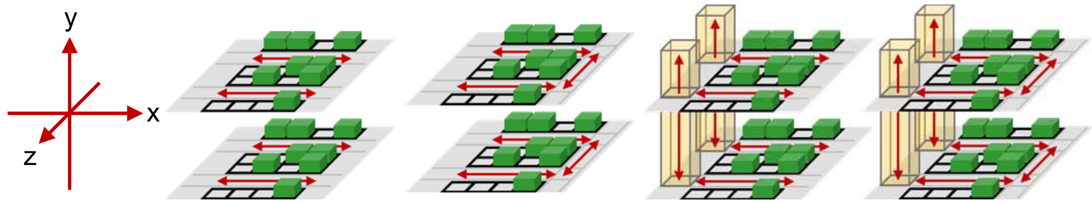



*Figure 2-3: Classification of shuttle-based warehouses based on possible movement axes of shuttles [Lie-2017b; Sic-2020]*

The highest throughput is reached by the configurations with tier-captive shuttles, because vertical and horizontal movements are independent [Mar-2013; Epp-2018, p.10]. As a consequence, shuttles deliver pallets directly to the buffer locations in front of the lift, without having to wait for its arrival. However, if the number of allowed movement axes for shuttles increases, the system becomes more flexible. For example, in the configuration with aisle-to-aisle and tier-to-tier shuttles, every shuttle can drive to any location in the warehouse. As a result, this configuration provides a high scalability in terms of throughput, a high modularity, a high availability and the possibility to easily perform retrieval in sequence. This configuration needs a more complex control system. [Lie-2017b; Sic-2020]

As to warehouses having aisle-captive shuttles, usually each lane stores a certain type of items and the retrieval is performed just from one side according to the Last In First Out (LIFO) policy. In general, in a storage lane, empty shuttles are able to drive underneath stored pallets. Turning now to shuttle-based warehouses enabling transportations between lanes, either transfer cars mounted on shuttles or shuttles able to drive in both directions of the plane can be used. [Tap-2017; Aza-2019]

Specifically, if shuttles are used that can move in both directions on the plane, the travel path for each pallet is shorter than with shuttles using transfer cars for movements between lanes, because there is no need to move empty shuttles in the cross-aisles. However, this operational advantage comes with an economic disadvantage, because a shuttle able to move on both directions of the plane costs about twice as much as a shuttle with a transfer car. [Tap-2017]

As regards the lifts, it can be chosen between continuous and discrete lifts. The first type is able to transport multiple pallets at the same time, e.g. through a helix system. The second type moves just one pallet at a time. [Tap-2017]

## 2.4 Advantages and Disadvantages of Shuttle-Based Warehouses Compared to Stacker Crane-Based Warehouses

In the following, first the main advantages of shuttle-based warehouses are explained as compared to stacker crane-based ones, which can be summarized as:

- Higher scalable throughputs and higher flexibility
- Higher redundancy and higher availability
- Higher modularity
- No pre-zone is needed.

Afterwards, the main disadvantages of shuttles-based warehouses are illustrated as compared to stacker crane-based ones, which are:

- Complex storage management system
- Higher investment costs
- Lower space utilization ratio.

The main advantages of shuttle-based warehouses over stacker crane-based ones include the possibility to reach **higher throughputs** and **higher flexibility** [Kri-2018]. Main causes for higher throughput and higher flexibility lie in the load movement patterns and in the buffering, which constitute the main differences.

In a stacker crane-based warehouse, to reach the I/O locations at the extremes of the aisle, an aisle-captive stacker crane transports pallets simultaneously in horizontal and vertical directions. To the contrary, in shuttle-based warehouses, pallets are moved first horizontally through shuttles and then vertically through lifts. This decoupling of horizontal and vertical load pattern movements causes longer travel paths for pallets.

But, it enables shuttles and lifts to have relatively flexible pattern movements. Specifically, shuttles move independently from lifts and, in aisle-to-aisle and tier-to-tier configurations, reach all locations of the storage racks. As a consequence, since shuttles are not assigned to a specific aisle, by adding or removing lifts or shuttles, the throughput can be increased much more easily than in stacker crane-based systems, providing a high scalability of the throughput of shuttle-based warehouses. [Mal-2002; Her-2011b]

Another reason for higher throughputs and higher flexibility in shuttle-based warehouses lies in the differences between shuttle-based and stacker crane-based warehouses regarding buffering, caused by the strategies for dispatching transactions and the storage policies used.

A third cause for higher reachable throughputs in shuttle-based warehouses regards divergences arising from the use of different strategies for dispatching transactions. Specifically, retrieval transactions create a queue per aisle in stacker crane-based warehouses. In reverse, virtual and physical retrieval transactions generate a single queue in shuttle-based warehouses. Consequently, the opportunity to perform dual command transactions, i.e. double cycles, increase with respect to single command transactions, i.e. single cycles. Therefore, given a certain level of demand in the warehouse, shuttle-based warehouses are able to reach a higher ratio of double cycles than stacker crane-based warehouses. However, this higher opportunity to execute double cycles in shuttle-based warehouses could be reduced by the high probability that retrieval and storage transactions regard different tiers, if the First Come First Served (FCFS) operating policy is applied. With FCFS, the movement patterns of shuttles lessen advantages of possible shorter routes provided by double cycles. As a result, shuttle-based warehouses with FCFS operating policy have smaller potential for improvement than stacker crane-based warehouses, when double cycles are performed. [Mal-2002]

In aisle-to-aisle and tier-to-tier shuttle-based warehouses, the fact that shuttles can reach any position of the storage racks, provides the system with **higher redundancy**. This leads to **higher availability** [Sch-2010; Epp-2018, pp. 10 et seqq.], compared to stacker crane-based warehouses [Kar-2012]. As demonstrated by *Lienert et al.* [Lie-2019], if some shuttles go out of service, with the appropriate failure-handling strategies it is possible for the remaining shuttles to continue to execute orders and avoid a significant reduction in throughput.

The possibility to add shuttles and lifts, provides to shuttle-based warehouses not only scalability and high redundancy, but also **high modularity**. If it is necessary to enlarge the warehouse, for example because more storage capacity is needed, in stacker crane-based warehouses for each new aisle also an additional stacker crane is needed. As a result, little modifications in a stacker-crane based warehouse require generally high costs for redesigning the whole system. To the contrary, with shuttle-based warehouses the number of lifts or shuttles can be modified at least in specific ranges without having to change other parameters. Therefore, usually, if the redesign of certain areas happens to be necessary, only major changes will have an impact on the other parts of the warehouse. [Her-2011b]

Another advantage of shuttle-based warehouses is that they can sequence pallets directly in the storage system, thus they do not need a **pre-zone** to sequence or buffer pallets as stacker crane-based warehouses [Kar-2012; Sic-2020].

Turning now to the disadvantages of shuttle-based warehouses, first of all, due to the presence of many components such as shuttles and lifts, the **storage management system** is more complex for a shuttle-based warehouse than for a stacker crane-based one. This leads to higher costs for the control system. Not only for the control system do shuttle-based warehouses require **high investment**, but also for the power rails, the lifts and the racks. [Kar-2012]

Another disadvantage of shuttle based-warehouses is that shuttles require aisles and cross-aisles on each level to be able to move, thus reducing the **space utilization ratio** when compared to a multiple-deep stacker crane-based warehouse.

# 3 State of Science and Research

The scientific literature has dealt extensively with the investigation of shuttle-based and stacker crane-based warehouses. Research specifically studied the long-term and short-term levels of decision making, necessary to plan and design a warehouse according to [Aza-2019].

Long-term planning means designing and optimizing the hardware of the warehouse. Main objective of this decision level is to reach the maximum possible space utilization ratio and throughput. A main decision variable in such optimization problems is for example the physical layout. The physical layout is defined for example by the number of levels, the number of aisles, the number of cross-aisles on each level, the number of depths per lane. Other significant parameters are the number of components, e.g. number of lifts or robots, and the number and positioning of I/O positions and of workstations. Once these decisions are made and implemented, it becomes complex and expensive to change them. [Aza-2019]

Short-term planning consists of the definition of control system and organization of operations. The aim of such planning is to minimize the duration of processes, the time resources for staying idle, the waiting times for the components, the response time. For example, at this decision level it is determined the dwell point policy of idle components, the policy to assign a certain component to a certain job, the storage policy, the scheduling of resources and the transactions used for sequencing. [Aza-2019]

During the last decades, many reviews of the scientific literature regarding automated warehouses were produced. The first literature review regarding automated storage and retrieval systems is that of *Roodbergen and Vis* [Roo-2009]. A review of simulation models is provided by *Gagliardi, Renaud, and Ruiz* [Gag-2012] and a review of literature classified by the type of scheduling problem for the stacker cranes is given by *Boysen and Stephan* [Boy-2016]. *Azadeh, de Koster, and Roy* [Aza-2019] furnish an comprehensive classification and literature review of different kinds of automated warehouses according to their system analysis, design optimization and operations planning and control. *Cinar and Zeeshan* [Cin-2022] is the most recent literature review on automated warehouses found in the context of this dissertation. It classifies papers on automated warehouses according to their objectives, to modelling assumptions, to optimization and methodologies used, i.e. analytical or simulation-based models, and to applications. In the following chapters sources are selected and discussed, which are relevant for shuttle-based and stacker-crane based warehouses, from the different existing reviews. These sources are then be integrated with other literature that appears significant for the topic of this dissertation. In particular, selected literature is illustrated regarding long-and short-term planning for stacker crane-based and shuttle-based warehouses. Specifically, the focus is on the state of science and research regarding design optimization, the control system and the operation policies, the modelling and the validation.

## 3.1 Strategies for the Control System

The methods determining the operations executed by AS/RSs are denoted as control policies. All control policies together form a coherent set that governs the control system of the AS/RS. Each control policy regulates a specific aspect or set of operations [Roo-2009]. These sets appear to be applicable to both stacker crane-based and shuttle-based warehouses and are as follows:

- *Storage assignment policy* defines which pallet should be allocated in which position. Specifically, not only the method for the storage assignment, but also the number and positioning of storage classes are chosen.
- *Dwell-point policy* determines in which position should an idle stacker crane should wait. In addition, the type of positioning is selected i.e. static or dynamic.
- *Sequencing rules* generate tours to reduce the sum of the time to execute all orders is minimized or to minimize the violations of the due time. Together with the sequencing method, the scheduling approach must be defined as either block or dynamic. Moreover, it must be defined if the operation is of single or double cycle and what the restrictions are i.e. due date.
- *Batching policy* regulates the combination of different orders in a single tour of the stacker crane. Particularly, the type of batching and its size should be selected, together with the selection rule used to assign orders to a batch. [Roo-2009]
- *Order Assignment Strategies* regulate which order should be assigned to which resource. As subsets of order assignment strategies, in the context of this dissertation, policies are defined that regulate the following decisions: which order to assign to a certain resource that just became available; which idle resource to execute a certain available order i.e. *resource assignment policies*; to which I/O location or spatial resource should an order be assigned i.e. *transfer point assignment policies*.
- *Routing:* it defines which path should be followed by a resource to complete orders.

The first four subsets of control policies for AS/RS or stacker crane-based warehouses were indentified by *Roodbergen and Vis* [Roo-2009]. Afterwards, *Epp* [Epp-2018, pp. 22 et seqq.] expanded them for shuttle-based warehouses. Specifically, *Epp* [Epp-2018, pp. 22 et seqq.] stated that control policies for shuttle-based warehouses are classifiable according to the following subjects: storage assignment strategy, dwell point strategies, sequencing rules, resource assignment policies, and routing, not considering batching. While sequencing, dwell point strategies and storage assignment were already widely studied, routing strategies and resource assignment are less frequently investigated. The reason for considering them in case of shuttle-based warehouses is the complexity of a shuttle level. This is due to aisles and cross-aisles, where many resources can move in parallel and various paths can be selected. Consequently, it is necessary to make additional control choices in comparison to standard AS/RSs. As described above, for sake of completeness, it appears that resource assignment policies should be regarded as a type of order assignment strategies, together with transfer point assignment policies.

Each control policy and the scientific investigations on them present in the literature is illustrated in detail in the following.

### 3.1.1 Storage Assignment Policy

Most common storage assignment policies are: random, dedicated, closest open location, full-turnover-based and class-based [Hau-1976; Gra-1977; Roo-2009]. The first two policies were already introduced in Section 2.4. The *closest open location* storage assignment policy requires that the items are always stored in empty storage locations which are the first to be run across. As a consequence, in case of oversized racks capacity, the distribution of products becomes higher near the I/O location and gradually decreases for the storage locations furthest away from it. To guarantee a more balanced distribution of items in the warehouse, the *full-turnover* storage assignment policy can be used. This policy assigns the products to the storage locations depending on the frequency they are demanded. Subsequently, most frequently demanded items are stored in the most accessible positions, i.e. in general near the I/O location. However, to apply this policy, it is necessary to know the turnover frequencies a priori. This is often a problem, because turnover frequencies change over time, together with the assortment of products to continue following the full-turnover policy, it is necessary to reposition the pallets stored each time a new type of product is introduced or the turnover frequency of an existing product changes. In praxis, full-turnover and dedicated storage assignment policies are combined and, to avoid frequent repositions of products, the storage locations are reassigned to the products in each period. The *class-based* storage assignment policy can be seen as a development of the full-turnover storage assignment policy. It offers a high efficiency while reducing the number of necessary repositions over time and decreasing the space required to store the pallets. This policy divides the warehouse in areas, reserved for products belonging to a certain class, i.e. range of turnover frequency. Within an area, products are randomly stored, so that a high space utilization can be reached. Commonly, if three classes are used, the denomination ABC storage is used, being A-products those with the highest turnover frequency, B-products those with the second highest turnover frequency and so on. [Roo-2009]

### 3.1.2 Dwell-Point Policy

There are four types of basic static dwell-point policies:

- *Input station policy:* the stacker crane returns always to the input station i.e. I location when it remains idle.
- *Midpoint policy:* the stacker crane goes back to the position of the racks which is allocated in correspondence of the midpoint.
- *Input/ Output policy:* after completion of a single storage order, the idle stacker crane should wait on the I location. Likewise, it waits on the O location if the just concluded order is a single retrieval.
- *Last location policy:* in case a single storage order has been completed, the idle stacker crane should wait on the last storage location it came across. To the contrary, if the order was a single retrieval, then the stacker crane should go to the O location. [Boz-1984; Roo-2009]

### 3.1.3 Sequencing Rules

It is often assumed that storage orders have no due dates, therefore they are not time-critical and are executed following the FCFS rule. To the contrary, retrieval orders are commonly required to meet due times, therefore more complex sequencing rules are usually applied. In addition, an efficient sequencing of retrieval orders can increase the throughput of the whole warehouse. Creating an efficient sequence of retrieval orders is made complex by the fact that the amount of these orders varies continuously with time. They are continuously inserted or deleted from the list of retrieval orders. [Roo-2009]

*Block sequencing* is a method to sequence retrieval orders in an efficient way. It consists in the selection of a certain number, i.e. block, of orders with highest priority, organize them in sequence and execute them. Afterwards, the next block is selected. Another method is *dynamic sequencing*, which suggests resequencing the list of orders each time a new one comes. [Han-1987; Roo-2009]

While block sequencing provides transparency, dynamic sequencing is preferable in case the environment is non-deterministic [Ebe-1992]. There are many literature sources investigating the scheduling of single and double cycles for stacker crane-based warehouses having just one I/O location and one stacker crane per aisle. Specifically, double cycles improve travel times in comparison to single cycles [Gra-1977]. Not only, if both retrieval and storage orders are available, performing as many double cycles, as possible can reduce the number of necessary stacker cranes to reach a certain throughput [Ebe-1996; Ebe-1997]. [Roo-2009]

According to *Roodbergen and Vis* [Roo-2009], the following methods can be applied to provide dynamic sequencing of orders:

- *FCFS:* the order of scheduling of retrieval orders is the same as the order of their appearance.
- *Shortest completion time:* retrieval orders with the smallest cycle time are scheduled first.
- *Nearest-neighbour:* pairs constituted by one storage and one retrieval order are formed to minimize the distance between the storage location and the retrieval location. This method enables to obtain smaller average cycle times compared to FCFS. [Han-1987]
- *Shortest leg:* storage locations are chosen to minimize the travel distance to execute the storage order, while the stacker crane is driving to the retrieval location. However, the nearest-neighbour method provides a higher performance over time, when all locations near the I location are occupied and pallets can be stored only in locations far away from the I location. [Han-1987]
- *Online asymmetric Traveling Salesman Problem (TSP):* sequences for the execution of all appeared orders are defined through heuristics and a method of optimal branch-and-bound. [Asc-1999]. [Roo-2009]

### 3.1.4 Batching Policy

The objective of batching policies is to plan a single tour of the stacker crane during which multiple orders are completed so that the travel distance of the single tour results shorter than performing the sum of all tours, if one tour per order would be executed. The maximum dimension of a batch is generally limited by the maximum acceptable response time and by the maximum quantity of items temporarily transportable by the stacker crane. Therefore, a central issue is to define the optimal batch dimension and the orders assigned to the batch to reach the minimum travel distance for the stacker crane. To solve this optimization problem, usually heuristic methods are used consisting of three parts: a first heuristic selects a starting order i.e. *seed selection rule*, a second heuristic determines which orders should be grouped in the same batch i.e. *order addition rule*, a third heuristic defines when a batch is to be considered complete i.e. *stopping rule*. The assumption made by these methods is that an order cannot be divided into several batches, but must be included entirely in one batch. An alternative to select a single seed is to consider all orders contained in the batch i.e. *cumulative seeding rule* [Els-1983]. [Roo-2009]

Another possibility is to use a cluster analysis, that enables to generate a cluster of orders through multiple iterations: a starting order is chosen and merged with the other order most similar to it; the order obtained from such merger is then considered the starting order of the next iteration. [Hwa-1988a; Hwa-1988b; Roo-2009]

### 3.1.5 Order Assignment Strategies

As regards resource assignment policies, in stacker crane-based warehouses all orders are assigned to the stacker crane driving along the aisle. To the contrary, in shuttle-based warehouses it is necessary to choose which shuttle must execute a certain transaction, because different shuttles can access the same storage locations. Based on the type of transaction, location and status of the shuttles, different resource assignment policies enable minimising the travel time of the shuttles. A similar argument applies to the allocation of a certain transaction to one lift rather than another. Analytical methods in the literature for ease of modelling usually assume that resources are allocated randomly or according to the FCFS principle. However, other resource assignment policies can enable the execution of transactions in less time. Such policies could be for example based on the travel time of shuttles when they are empty and not executing orders or the travel time of shuttles to reach lifts. [Epp-2018, p.26]

In the literature, most authors investigate resource assignment policies for AGVs and not for shuttles. The two most adopted policies are to assign the next available transaction to the AGV which is the closest to the pick-up location or to assign it to the AGV that, at the moment of the assignment, executed the smallest number of transactions. [Gru-2007; Sic-2021b]

In recent years, *Habl et al.* [Hab-2020] developed and compared resource assignment policies in a single-tier, double-deep shuttle level in a discrete-event simulation environment. In the policies considered, the next available job is assigned to:

- *Random Vehicle:* a shuttle selected randomly
- *Nearest Vehicle First:* the shuttle having the shortest distance to the job to be executed

- *Least Utilized Vehicle:* the shuttle which has been idle for the longest time since beginning of the simulation
- *Longest Idle Vehicle:* the shuttle which started its idle status the longest time ago
- *Nearest Vehicle First with Idle Priority:* the idle shuttle nearest to the next job
- *Nearest Vehicle First with Task Maximum:* the shuttle nearest to the next job having the minimum value of task maximum at a time

As regards transfer point assignment policies, the literature considers the issue in a stacker crane-based warehouse of deciding to which I/O location should a pallet be delivered. If there is more than one I/O location, then the most immediate solution is to deliver the pallet to a random I/O location [Ara-1993]. In recent years, *Lantschner* [Lan-2015, pp. 41et seqq.] considered a stacker-crane based warehouse with one stacker crane in the aisle having between two and five I/O locations and demonstrated analytically that two alternative strategies guarantee a shorter mean path for the stacker crane. The first strategy is to select the I/O location which is located nearest to the current position of the crane. The second one is to choose the I/O location which is nearest to the next job.

### 3.1.6 Routing

In stacker crane-based warehouses as well as in shuttle-based warehouses where shuttles are not able to change the aisle, the routing problem is usually solved adopting the shortest path, calculated in case of single and double cycles. [Epp-2018, p.26]

However, to obtain a higher throughput in stacker-crane based warehouses, analytical route optimization methods such as genetic coding can be applied [Zha-1995]. [Sic-2022a]

To the contrary, if shuttles can change their aisle and eventually also their level, the routing problem becomes more complex. The literature providing routing algorithms to avoid deadlocks[3] and minimize blockades among shuttles is scarce. [Epp-2018, pp. 26 et seqq.]

One routing method to avoid deadlocks in a fleet of shuttles is the time window routing [Lie-2017b; Lie-2017a; Lie-2018a; Lie-2020]. The idea behind this method was first developed by *Kim and Tanchoco* [Kim-1991] and consists in reserving the route of

[3] A deadlock occurs when one or more parallel processes are permanently blocked due to unmeetable demands of resources [Lie-2017b; Kim-1997]

each vehicle to reach its destination from its current location. On each segment of the path to be travelled, a certain time window is occupied by the vehicle to route and that segment during that time window cannot be used for the motion of other vehicles. When a new route for a vehicle needs to be planned, free time windows are searched by the routing algorithm applying the navigation algorithm A* [Har-1968]. [Sic-2020]

## 3.2 Design Optimization

### 3.2.1 Design of Stacker Crane-Based Warehouses

The physical design of an AS/RS or stacker crane-based warehouse is defined through two choices. The first one is the selection of the AS/RS type i.e. *system choice*. The second one is the configuration of the different parts of the warehouse i.e. *system configuration*. This configuration concerns the definition of following variables: number of aisles, height of racks, length of aisles, storage locations having the same size or not, number and position of I/O locations, buffer capacity at I/O locations, number of stacker cranes per aisle, eventually number of order-pickers per aisle. The criteria on which the choice of these variables is based are for example features of products, maximum acceptable financial costs, target throughput, target storage space, available area on the land, historical or expected data. In general, the required capacity of a warehouse is given. As a consequence, the product of height and length of racks with number of aisles is fixed. Subsequently, if the number of aisles is increased, the length and height of the warehouse decreases and quicker response times are obtained. This not only results in a higher throughput, but also in higher investments. In a conventional stacker crane-based warehouse having one crane per aisle, the number of cranes increases with the number of aisles. If not only the capacity of the warehouse, but also the number of aisles is given, then the optimal proportion between height and length of the system should be identified. The stacker crane reaches the channels of the racks by driving along vertical and horizontal directions. Therefore, the travel time to reach a certain channel is obtainable by the Chebyshev distance metric i.e. it is equal to the maximum of the time required by the stacker crane to cover the horizontal distance and the time required to cover the vertical one. A way to decrease travel times of the stacker crane is to find the optimal proportion between height and length of the warehouse. In general, the warehouse is designed so that the travel time to cover its height is equal to the travel time to cover the length of its aisle. This configuration is denoted as *square-in-time* and, although very widespread, it does not always guarantee the optimal proportion between height and length of the system. Configurations other than square-in-time are called *rectangular.* [Roo-2009]

A main issue in the design of stacker crane-based warehouses is in being able to introduce more than one stacker crane per aisle, to increase throughput, without risking collisions. This is not a pure design concern, it is also a control system issue. One possibility is to introduce *separate rails* for each stacker crane. According to *Hino et al.* and *Kung et al.*[Hin-2009; Kun-2011; Kun-2014], up to two stacker cranes on separate rails per aisle contribute to a performance improvement. In particular, if each crane has its own rails, it is easier to coordinate the different cranes while avoiding collisions between them. Furthermore, a methodology to coordinate more than two stacker cranes per aisle on a *multi-crane common rail* was developed by *Kung et al.* [Kun-2014] to reach an additional increase in throughput.

### 3.2.2 Design of Shuttle-Based Warehouses

In analogy to stacker-based warehouses, also the performance of shuttle-based ones is influenced by the configuration of the basic layout, which was subject of various scientific investigations.

The literature existing on the design criteria for a shuttle-based warehouse can be classified in two categories: literature investigating design through comparison of stacker crane-based and shuttle-based warehouses; literature studying the influence of various configurations of the racks on the performance of the warehouse. [Mar-2013]

#### Design Optimization through Comparison of Stacker Crane-Based and Shuttle-Based Warehouses

*Malmborg* [Mal-2002] presented the first study comparing the design of stacker crane-based and shuttle-based warehouses while varying the elements of the configuration such as storage rack shape, the number of lifts and of shuttles. Then, the comparison was extended to economic factors by *Fukunari and Malmborg* [Fuk-2008]. The analysis comprised 15 different scenarios. The storage capacities were varied between 10,000 and 30,000 while the level of demand ranged between 100 and 300 orders per hour. The analysis was performed for each scenario confronting the cheapest configurations of stacker crane-based and shuttle-based warehouses, where the utilization ratio for the vehicles or the stacker cranes was lower than 90 %. Based on the optimal solution found, the optimal configurations of stacker crane-based warehouses in general have a smaller number of aisles but longer aisles to reduce the number of stacker cranes. To the contrary, shuttle-based warehouses should have more aisles but shorter in order to provide optimal travel paths for the shuttles. Moreover, according to [Ekr-2012] shuttle-based warehouses reach a better performance than stacker crane-based warehouses under numerous circumstances. [Mar-2013]

### Design Optimization through Investigation of Performance for Various Configurations

As regards the investigation of different configurations for shuttle-based warehouses, *Ekren and Heragu* [Ekr-2010] realized a regression analysis based on simulation, having the average cycle time as output variable and the number of levels and of aisles among the input variables. The outcome was that the cycle time has a positive regression relation to the number of levels and of aisles respectively, but has a negative regression relation to the product of the number of levels and aisles. [Aza-2019]

Afterwards, *Ekren* [Ekr-2011] compared not only the average cycle time and average utilization of shuttles and lifts but also the costs for 55 layout configurations. As a result, the optimal configuration varies with the required performance and, thus, the selection of a certain configuration should be determined depending on the priorities of the customer. [Mar-2013]

Roy et al. [Roy-2012] modelled a semi-open queuing network to examine the optimal layout configuration, defined as the one achieving the best performance of the system. The optimal configuration resulted to be the one with the depth twice the size of the width. Later, *Marchet et al.* [Mar-2013] modelled a tier-captive shuttle-based warehouse in a simulation environment to identify the optimal configuration. The method applied was to observe the behaviour of the throughput of the system, while the configuration had been varied. With respect to multi-deep shuttle-based warehouses, *Manzini et al.* [Man-2016] determined not only the optimal shape ratio and position of the load/unload (L/U) location but also the number and length of the lanes, which maximize the space utilization and minimize operative costs.[Aza-2019]

### Allocation and Configuration of Lanes and Cross-Aisles

Two important issues in the design of shuttle-based warehouses are represented by the allocation and the detail configuration of lanes and cross-aisles on levels.

A significant study on the position of cross-aisles was performed by *Roy et al.* [Roy-2015], that developed the previous model [Roy-2012] further and demonstrated that the optimal position for a cross-aisle is the end of the aisle. [Aza-2019]

As regards the detail configuration of lanes in a shuttle tier, it is already known through the investigations of *Le-Anh and de Koster* [Le--2006], that within systems containing autonomous vehicles, the freedom of movement of these vehicles within the system, whether unidirectional or bidirectional, affects the size of the fleet of vehicles required to reach a certain throughput. In reality, the only advantage of unidirectional vehicle movement is greater ease in generating warehouse design and controlling material flow traffic. It is through the possibility of bidirectional vehicle movements that greater efficiencies can be reached, particularly if the fleet is small [Egb-1986]. [Lie-2018b]

*Lienert et al.* [Lie-2018b] investigated, through simulation, three different configurations of lanes and cross-aisles of a robotic mobile fulfilment system with AGVs, where the vehicles were able to move in both directions of the plane, but not diagonally. Therefore, actually similar to a shuttle level, where shuttles can move in both directions of the plane on rails. The first configuration considered had two unidirectional lanes per aisle, the second one had one bidirectional lane per aisle, the third one had one unidirectional lane per aisle. Moreover, for each of the three configurations, a variant without cross-aisles and a variant with two cross-aisles respectively at one third and two thirds of the aisles was contemplated. The results showed that in case the number of AGVs is small, the configuration with one single bidirectional lane per aisle is recommended. Although the configuration with two unidirectional lanes per aisle enables to reach the highest throughput, it also demands more space, decreasing the storage capacity of the system. Finally, higher throughputs are reached by the introduction of cross-aisles.

As regards the optimal length of lanes, it is a subject that was widely investigated. The block relocation problem was the main focus of various studies in the last decade. Particularly, *Yang and Kim,* and *Jang et al.* [Yan-2006; Jan-2013] considered port yards applications, while *Meneghetti* [Men-2009] focused on warehousing. Recently, *Goetschalckx, de Koster, and Bartholdi and Hackman* [Goe-2003; Kos-2010; Bar-2014] examined the state of art to obtain the optimal length of lanes. [Man-2016]

## 3.3 Performance Analysis

To evaluate the performance of a stacker crane-based warehouse, measurements in the literature are, according to *Roodbergen and Vis* [Roo-2009], at least:

- Travel time per order
- Number of orders executed per time unit [Aza-1986; Fol-2002]
- Time necessary to execute a certain number of orders
- Duration of the idle time of stacker cranes
- Time interval waited by an item to be retrieved or stored
- Number of orders waiting to be executed [Hur-2004]

However, the most widespread performance measurement in the literature for stacker cranes is by far the travel time per order. Given the rich literature on travel models for stacker crane-based warehouses, many reviews on the methods used were published. *Lantschner* [Lan-2015, p.7] already identified different review works, among which those of *Sarker and Babu*, *Johnson and Brandeau*, *Roodbergen and Vis*, *Gu et al., Gag et al., Vasili et al.* [Sar-1995; Joh-1996; Roo-2009; Gu-2010; Gag-2012; Vas-2012] appear to be the most exhaustive.

Throughput being the inverse of expected travel time, various performance models in literature consider throughput for performance analysis [Roo-2009].

Regarding shuttle-based warehouses, the performance measurements are according to *Epp* [Epp-2018, pp. 28 et seqq.]:

- “Utilization of secondary resources”
- “Retrieval transaction time”
- “Number of transactions waiting to be stored/ picked”
- “Inter-departure time of leaving transactions”

In the following models are illustrated regarding different performance measurements for shuttle-based warehouses.

**Single Tier Shuttle-Based Warehouses**

There is only a restricted number of studies in the literature investigating the performance measures of a single tier shuttle-based warehouses. *Roy et al.* [Roy-2012] focused on the analysis of the influence on performance of shuttle locations, shuttle assignment policies and zoning. For this purpose, a semi-open queuing network model was developed. Successively, the model was expanded by *Roy et al.* [Roy-2015] to include the analysis of the influence of dwell-point policies and of the placement of the cross-aisle on performance measures. However, in both studies of *Roy at al.* [Roy-2012; Roy-2015], shuttles blocking effects were not considered. To take this phenomenon into account, *Roy et al.* [Roy-2014; Roy-2016] developed protocols to represent delays in the movements of shuttles in aisles and cross-aisles caused by blockades. [Roy-2017]

**Multi-Tier Tier-to-Tier Shuttle-Based Warehouses**

The first study analysing a shuttle-based warehouse was accomplished by *Malmborg* [Mal-2002]. In this study, a state equation model is realized to calculate not only the cycle time, but also the utilization of shuttles. Specifically, the average cycle time of a shuttle is modelled as $(1-\alpha)t_{SC}+\alpha t_{DC}/2$, being $t_{SC}$ the expected cycle time of a single cycle, $t_{DC}$ that of a double cycle, and $\alpha$ the proportion of double cycles. The successive study [Mal-2003a] focused on the adaptation of the fleet size of shuttles to satisfy the demand in terms of transactions. Subsequently, *Malmborg* [Mal-2003b] included in the state equation model also the number of waiting transactions in order to determine $\alpha$. Opportunistic interleaving is executed only if there are both storage and retrieval transactions in the waiting queue, when the stacker crane starts its cycle. This kind of approach loses its computational efficiency when a larger system is considered. Subsequently, a model that enables to deal efficiently also with large systems was developed by *Kuo et al.*, and *Fukunari and Malmborg* [Kuo-2007; Fuk-2008]. This model considers the lift and the shuttles in the form of closed queuing networks. The network of lifts is within that of shuttles. The disadvantage of this approach is that it is not possible to model the case of a cycle of the stacker crane starting outside the racks, which means the case of pallets transferred to the stacker crane from outside the racks. To solve this problem, a novel queuing network was modelled by *Fukunari and Malmborg* [Fuk-2009]. This network is able to foresee the utilization of resources with acceptable accuracy. However, it cannot foresee the waiting time of transactions. To be able to foresee the time a transaction has to wait to be executed, *Zhang et al.* [Zha-2009] considers a series of queuing approximations and selects dynamically among three of them, depending on the variance in the interarrival times of transactions. Recent studies applied semi-open queuing networks instead of closed networks to obtain an even better accuracy in the forecast of waiting time of transactions and the performance of the system. [Aza-2019]

A tier-to-tier shuttle-based warehouse was then modelled as a semi-open queueing network by *Ekren et al.* [Ekr-2013] for forecasting performance measures. To further improve the determination of the number of transactions in the queue of the vehicles, *Ekren et al.* [Ekr-2014] introduced a matrix-geometric method in the semi-open queueing network. Again a tier-to-tier shuttle based-warehouse was investigated by *Cai et al.* [Cai-2014] using matrix-geometric methods and a multi-class multi-stage semi-open queueing network. [Aza-2019]

**Multi-Tier Tier-Captive Shuttle-Based Warehouses**

As regards tier-captive shuttle-based warehouses, there is a restricted number of literature sources. Open queueing networks are used by *Heragu et al.*, *Marchet et al.*, and *Epp et al.* [Her-2011b; Mar-2012; Epp-2017] for the forecasting of cycle times. [Aza-2019]

Specifically, *Heragu et al.* [Her-2011b] modelled the warehouse through an open-queueing network where lifts and tiers follow the FCFS policy, ignoring the blocking effects of shuttles in the tiers. However, the use of an open-queueing network could cause an overestimation of the quantity of transactions waiting for shuttles [Her-2011a]. [Roy-2017]

*Lehrer et al.* [Ler-2015] developed an analytical travel time model to compute the cycle time. It considers operating characteristics of the shuttle and of the lifting table, such as maximum speed, acceleration and deceleration. Such method enables the calculation of the mean cycle time in case of single and double cycles.

The model of *Lehrer et al.* [Ler-2015] was developed for single-deep shuttle-based warehouses. Successively, *Lehrer et al.* [Ler-2016] developed this method further for double-deep shuttle-based warehouses. *Ekren* [Ekr-2017] evaluated the performance of the warehouse in terms of cycle time and utilization of lifts for different designs through simulation, obtaining a graph-based solution. *Roy et al.* [Roy-2017] developed an integrated queuing network to model the warehouse and to foresee the utilization of resources and the cycle times. Specifically, a semi-open queuing network is used to represent each of the tiers. Lifts are modelled as multi-class queuing networks having G/G/1 queues. A single load-dependent queue substitutes each tier and embedded Markov chain analyses are applied to represent both inter-departure times. [Aza-2019]

## 3.4 Validation for Simulation Models

When a model of an automated warehouse is created in a simulation environment to develop a new system or to optimize an existing one, the model should be validated to have the guarantee that the simulated behaviour of the warehouse can be trusted. Validating the simulation model of an automated warehouse means that measurements taken on the prototype or on the real system and results of the simulation should be compared. The resulting error between simulation results and measurements should not exceed a certain given maximum limit. In most cases, it is not a feasible option to gather enough measurements on the real system to accurately infer key performance indicators such as the average cycle time. Therefore, test positions are identified in the warehouse and used to obtain representative values of the average performance from a little number of measurements. [Sic-2021a]

In the next sections, it is illustrated how to define test positions and how to use them for validation of stacker crane-based and shuttle-based warehouses.

### 3.4.1 Validation for Stacker Crane-Based Warehouses

The most popular method to validate a stacker crane-based warehouse is the one provided by the European guideline FEM 9.851 [FEM-9851]. It considers a stacker crane serving a single I/O location at the bottom of the beginning of the aisle in a single-deep channel storage. According to this guideline, validation tests can be executed to prove the cycle time of the stacker crane, selecting the storage locations closest to the theoretical reference points $P_1$and $P_2$ as test points $PT_1$ and $PT_2$ as in Figure 3-1. Actual values, calculated as the mean values of measurements on the real system, are then compared with the values obtained through an analytical model or simulation. To accommodate deviations from theoretical values of measurements of loads, operating voltages, mechanical equipment, accelerations, shelf construction, etc., an error of up to 6 % is considered, according to this guideline, acceptable between actual and calculated or simulated values, to consider the system validated.

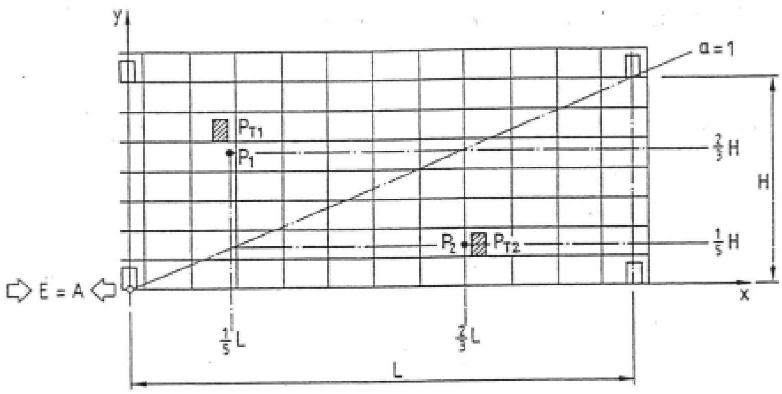



*Figure 3-1: Location of test positions [FEM-9851]*

### 3.4.2 Validation for Shuttle-Based Warehouses

For a shuttle-based warehouse, in which vehicles can move between levels through one or more lifts, the most popular way to calculate the cycle time of the shuttles are provided by the European guideline FEM 9.860 [FEM-9860] and by the German guideline [VDI-4480]. Moreover, the European guideline FEM 9.860 [FEM-9860] contemplates test cycles. It recommends to test not only shuttles and lifts separately, but also storage cycles separately from retrieval cycles. According to this guideline, first the average cycle time of a shuttle is calculated. Then, test positions are determined as the travel distance in the aisle covered by the vehicle during an average cycle time at a given velocity and acceleration. As actual test position, for the shuttles the storage location nearest to the test position calculated analytically is selected. Afterwards, five test cycles are executed. The actual value is calculated as the average of the five measured test cycle times to mitigate errors in the measurements and statistical variations of the cycle time. The actual value is then compared to the value of the cycle time calculated. A maximum error of 5 % is admissible to consider the system validated. The types of shuttle-based warehouses taken into consideration are small load carriers systems as in Figure  and “shuttle on shuttle” systems as in Figure 3-3. As the guideline itself states, for the second system kind, only single and no double cycles are possible, because of the LIFO policy.

As a consequence, the configuration of a warehouse in which *generic shuttles* are able to move in both directions of the plane is not covered by the guideline. Furthermore, the assumption made by the guideline is that the filling degree is uniform in the warehouse, at least on different levels. This norm provides the probability and travel path of vehicles in tabular form for various degrees of filling. In the literature, there are no other relevant analytical methodologies to define test positions in a shuttle-based warehouse. [Sic-2021a]

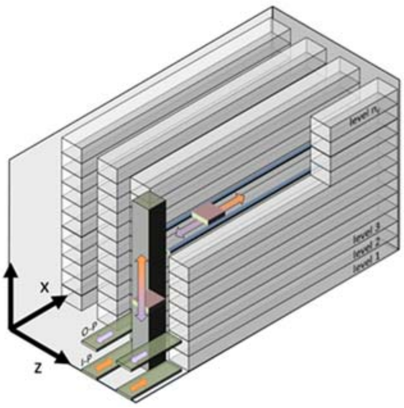



*Figure 3-2:* *Small load carrier’s system [FEM-9860]*

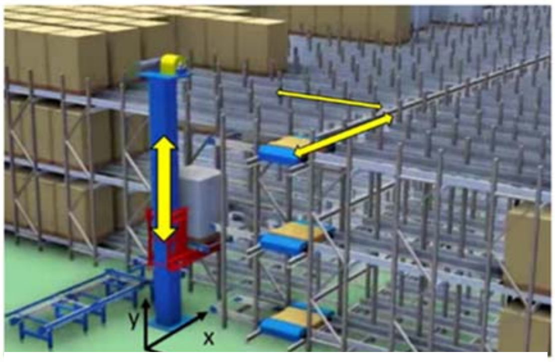



*Figure 3-3:* *“Shuttle on shuttle” system [FEM-9860]*

## 3.5 Definition of Research Gap and Research Questions

As illustrated in Chapter 2, the main pallet automated storage and retrieval systems are either shuttle- or stacker crane-based. To combine the advantages of these conventional systems and obtain high throughput, high scalability, high capacity to satisfy high peaks in demand at contained investment and operational costs, the technical solution of hybrid automated warehouses was envisioned. In the context of this dissertation, this class of hybrid automated storage and retrieval systems is denoted as Dynamic Hybrid Pallet Warehouses (DHPW). Furthermore, DHPWs are classified into two types: those obtained hybridizing a stacker crane-based warehouse through one or more shuttle levels and those obtained hybridizing a shuttle-based warehouse by connecting the levels through stacker cranes. The first type was filed as patent application by the company Gebhardt Fördertechnik GmbH [Ede-2019] and was the subject of the research project PALSA (2019-2021) at Chair of Materials Handling, Material Flow, Logistics at TUM, led by the author of this dissertation. The idea behind the second type was proposed in a US patent application [Mal-2014].

As shown in Chapter 3, research in the field of pallet warehouse systems has so far investigated separately shuttle-based warehouses and stacker crane-based warehouses. Major research fields were strategies for the control system, design optimization and performance analysis. Consequently, the state of research lacks the investigation of hybrid systems, obtained by connecting and coordinating shuttles and stacker cranes within the same warehouse. There are no previous studies which consider the connection and coordination between shuttles moving in both directions of the plane and stacker cranes as regards strategies for the control system, design optimization and performance analysis.

In this dissertation selected research achievements obtained during the research project PALSA (2019-2021) will be illustrated together with research accomplishments gained after the project as result of widening and deepening of the research on DHPWs by the author to fill this research gap. Specifically, the research gap is summarized in the following main research question, formulated into six sub-questions:

- **How to conceive the connection and coordination between shuttles and stacker cranes to exploit their synergies in the form of DHPWs?**

    I. Which **layouts** should be designed to investigate the connection between shuttles and stacker cranes? Which components should these layouts comprise?
    II. How should the **material and information flow** be organized to guarantee a smooth coordination of shuttles and stacker cranes?
    III. Which **strategies for the control system** enable cooperation and coordination between shuttles and stacker cranes for each layout in the different operating processes?
    IV. Which **order assignment strategies** can be applied to the connection between shuttles and stacker cranes in the different operating processes to improve the throughput?
    V. Which **optimization strategies** can be applied to improve the performance obtained with multiple stacker cranes in a single aisle?

VI. Which elements of **the macro- and the micro-layout**[4] have a main influence on the performance of DHPWs?

## 3.6 Approach for Achieving the Research Objectives

In the next chapters the research questions will be addressed. In short, the approach to answer the research questions consists of the following four main steps:

- ***Theoretical development of DHPWs.*** It consists in the determination of the layouts to be investigated including component selection and requirements definition for each of these layouts. Not only does this step comprehend the determination of material and information flow for each component and for the whole warehouse, but also the definition of strategies for the control system, differentiated for each layout. Afterwards, order assignment strategies and coordination strategies associated to different configurations for multiple stacker cranes in a single aisle should be conceived to improve the performance of the warehouse.
- ***Implementation of simulation model of DHPWs, verification and validation against real sub-systems.*** It is constituted by the implementation of the theoretical conception of DHPWs into a model in the discrete-event simulation environment Tecnomatix Plant Simulation. To guarantee the reliability of results of the simulation study in the next step, the simulation model must be analytically verified and then validated against measurements taken on real sub-systems.
- ***Simulation study.*** To investigate design and strategies for the control system of DHPWs quantitatively a simulation study is executed. Consequently, the influence of main design features and of strategies for the control system on throughput is discussed.
- ***Critical discussion.*** To demonstrate the value of DHPWs, their throughput is compared against stacker crane-based and shuttle-based warehouses. Also, their scalability of performance and their capacity to satisfy high peaks in demand are discussed on the basis of the simulation results.

With the completion of these four steps, the research sub-questions will have been answered, and the gap in the scientific literature will have been filled regarding design optimization, strategies for the control system and performance analysis of DHPWs.

[4] In this contribution, the term “macro-layout” denotes the set of design elements determining the dimension of the interface between shuttles and stacker cranes, such as the length and height of the aisle. The term “micro-layout” defines the set of design elements of the base of the warehouse.

# 4 Dynamic Hybrid Pallet Warehouses

The aim of integrating shuttles and stacker cranes into the same automated compacted warehouse is to create a system which exploits the advantages of both technologies while avoiding their weaknesses as much as possible. In the following sections, design of and strategies for the control system of DHPWs are illustrated.

## 4.1 Determination of Layouts, Components Selection and Requirements Definition

In this section, the research sub-question “Which layouts should be designed to investigate the connection between shuttles and stacker cranes? Which components should these layouts comprise?” is answered. For this purpose, in the following, different layouts for DHPWs are considered. Their differences and commonalities are investigated, and how they relate to conventional warehouse concepts. They possess very different characteristics in terms of costs, performance and complexity. Parts of the content of this section were published in reduced form in [Sic-2020; Sic-2022d].

### 4.1.1 Layout 1

The first layout to be considered presents one shuttle level on the base which is connected to a multi-deep channel storage through a transfer buffer served by one or more stacker cranes in a single aisle as in the rendering of Figure 4-1. Layout 1 was

*Figure 4-1: Rendering of Layout 1 (Image courtesy of Gebhardt Fördertechnik GmbH) [Sic-2021b]*

designed and partly investigated in the research project PALSA (2019-2021). Objective of the project was to conceive and study the design and the strategies for the control system with the support of discrete-event simulation to realize a high performing hybrid warehouse on the base of the idea of the patent application in [Ede-2019] and of a first possible layout draft and analytic calculations contained in a student work (Projektarbeit) [Seb-2019]. The final Layout 1 proposed is the result of trial of different concepts in the discrete-event simulation and the discussion of the different concepts proposed by the author of this dissertation with engineers of Gebhardt Fördertechnik GmbH in regular meetings to develop a concept which is not only interesting from a scientific point of view but also applicable for the industry. Regarding the layout, each stacker crane serves both sides of the aisle and to be able to reach all locations of the multi-deep channel storage, it must be equipped with satellites, which can move just along the z-direction as defined in the schematic Figure 4-2. The shuttles on the base on the other hand should be able to move in both x- and z-directions of the plane, to ensure an adequate flexibility of the system, e.g. if it is necessary to deliver the pallets in a certain sequence. Another characteristic which guarantees mobility to the shuttles

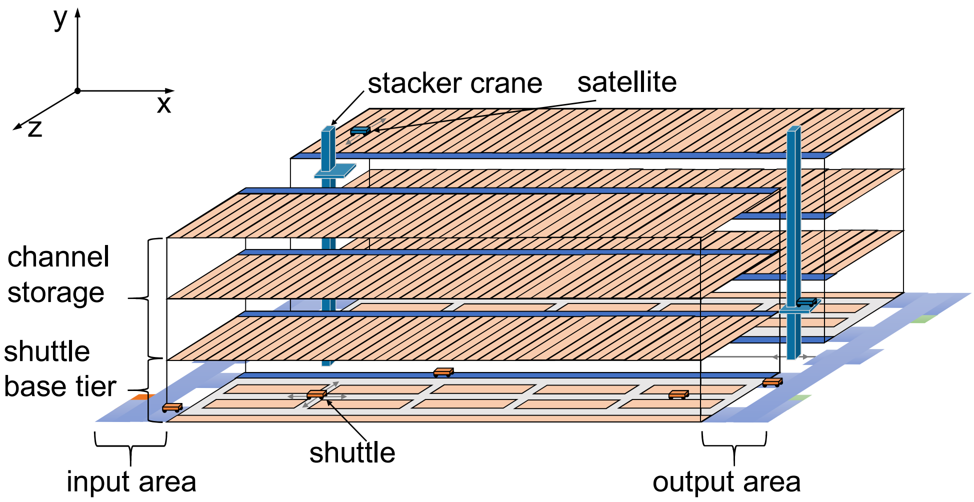



*Figure 4-2: Structure of Layout 1*

of the base level is the possibility for those of them which are not carrying pallets to move under occupied storage locations. The shuttle base level is designed as in Figure 4-3. It presents an input/output (I/O) area on each side, which enable the shuttles to follow a loop to drive to the input (I) or output (O) locations. Pallet conveyors are connected to the I/O locations as in Figure 4-1 and bring pallets to the I locations or pick up pallets from the O locations. Moreover, it is defined as *zone* each of both right and left side of an aisle as in Figure 4-4. The set of both sides forms a *module*. It is denoted as *section* each part along the z-direction of the base level comprised between two

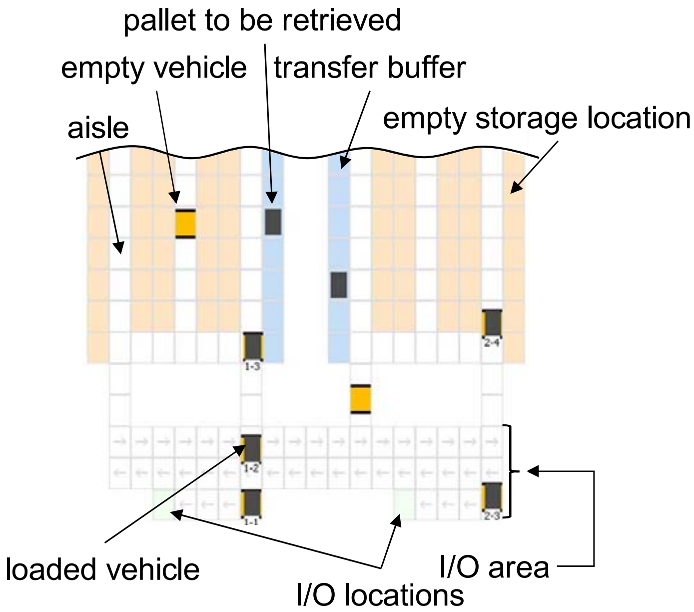



*Figure 4-3: Structure of the base level based on screenshot in Tecnomatix Plant Simulation [Sic-2020]*

cross aisles as in Figure 4-4. This distinction between zones, modules and sections is important, because, while running experiments in the discrete-event simulation environment, it was noticed that the throughput decreases and the computer calculation time increases if the shuttles are allowed to reach every position in the warehouse. Restricting the operating area of the shuttles to a zone improves the performance and the calculation speed of the simulation. The cause of this is that shuttles confined to a zone have shorter routes to travel and have to investigate fewer nodes when searching for the best route than shuttles free to move around the base. The layout of the warehouse is modular and scalable: according to the space and performance requirements, the number of zones and sections can be easily adapted. As a rule of thumb, the probability to have deadlocks increases significantly if the number of shuttles operating in a certain zone is almost as high or higher than the number of positions near the I/O location in that zone, because of the formation of “Kreisschlüsse” as called by [Lie-2021, pp. p.27]. This means that the loop formed by these positions can become completely occupied by shuttles, causing a deadlock. Thus, in the context of this dissertation, the number of positions near the I/O locations was chosen according to the maximal number of shuttles used for the experiments.

The first remarkable advantage provided by Layout 1 is the avoidance of space waste by eliminating the pre-zone, which is needed in stacker crane-based warehouses to sequence and buffer pallets. Sequencing and buffering are instead performed in the


*Figure 4-4: Definition of section, zone and module based on screenshot in Tecnomatix Plant Simulation*

shuttle base level. This also should enable, as further asset, sudden peaks in demand to be met. Furthermore, it is expected that the presence of shuttles enables the system to be scalable: if a higher throughput is needed, further shuttles can be progressively added on the base. Another advantage over traditional stacker crane-based warehouses, in which the stacker crane has only a little number of locations where to exchange pallets, is that the stacker crane serves numerous transfer buffer locations all along its whole operating interval in the aisle. It is presumed this will enable high dynamics and the mitigation of an eventual throughput's bottleneck of the system caused by the stacker cranes. Compared to traditional shuttle-based warehouses, Layout 1 guarantees on the one hand a higher space utilization through the presence of the multi-deep channel storage built above the shuttle base level. On the other hand, the channel storage has the limitation that relocations result in a loss of time for the stacker cranes. Therefore, Layout 1 should be used preferably in case no relocations are needed as for example with single-product channels i.e. each channel of the warehouse stores only one kind of product. This happens for example in the food sector for distribution warehouses of supermarket chains. Yet, not only has Layout 1 a higher space utilization ratio than traditional shuttle-based warehouses, but requires also lower investments and costs. A shuttle level costs more than a channel storage level, because of the need to buy and maintain the fleet of vehicles, and the racks specifically configured to contain rails for vehicles that can move on both directions of the plane.

As a consequence, having a shuttle level only on the base is much more economical than having one on every level of the warehouse.

### 4.1.2 Layout 2

The second layout to be considered has a shuttle tier on every level. This layout was designed by the author of this dissertation on the base of the idea in the patent attempt [Mal-2014] to extend and deepen the synergies between shuttles and stacker cranes started on Layout 1. After the completion of the research project PALSA, in which part of the characteristics of Layout 1 were investigated, contact between the author of this dissertation and engineers of Gebhardt Fördertechnik GmbH continued. Thus, Layout 2 and 3, like Layout 1, are the results of the trial of different concepts in the simulation and the discussion of most promising concepts with some members of the engineering staff of Gebhardt Fördertechnik GmbH to make sure that they are attractive not only for scientific research but also for possible future industrial applications. The shuttle levels are connected through transfer buffers served by stacker cranes as in Figure 4-5.

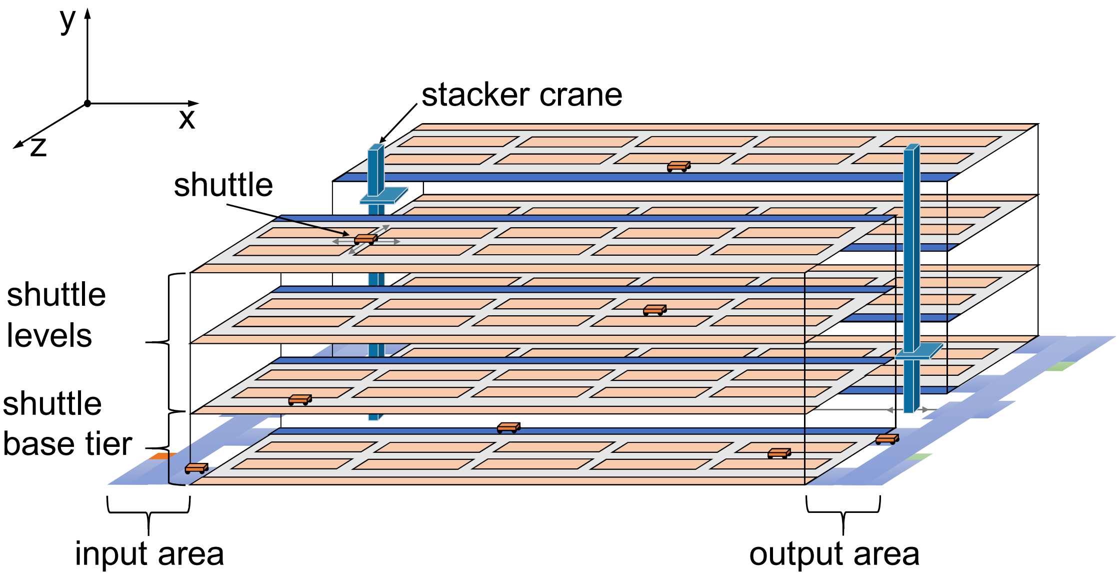



*Figure 4-5: Structure of Layout 2 [Sic-2022b]*

The base level is equal to the one of Layout 1, and the levels above are similar to it, but missing the I/O areas. Each stacker crane serves both sides of the aisle. Instead of stacker cranes with satellites, each stacker crane is equipped with a telescopic fork to exchange pallets. The shuttles move on both x- and z-directions of the plane within their zone and empty shuttles can move under loaded storage locations.

A first advantage of Layout 2, in comparison to Layout 1, is that stacker cranes are not slowed down in case of relocations, because such relocations are performed by the shuttles on the levels. Therefore, Layout 2 can be used also in case of multi-product-channels. Moreover, the shuttles on the levels can bring and take pallets to the transfer buffer locations which are more advantageous for the stacker cranes to exchange pallets with the transfer buffer on the base, e.g. the positions nearest to the I/O locations. The cross- and storage aisles needed for the movement of shuttles use space at the expense of storage locations. As for Layout 1, no pre-zone is needed to buffer and sequence pallets. Over traditional shuttle-based systems, Layout 2 presents the advantage of being able to exchange pallets among transfer buffers along the whole aisle and not only in a few fixed lift positions. Specifically, this flexibility of the stacker cranes is expected to allow them to deliver a pallet to a certain transfer buffer and then execute immediately the next order. A lift would have to wait for a shuttle to pick up the pallet to be able to execute the next orders. Furthermore, stacker cranes can exchange the pallets on the transfer buffer locations where it is more advantageous for the shuttles of the base. As for Layout 1, also Layout 2 is expected to show a readily scalable performance by progressively increasing or reducing the number of vehicles on the base and on the levels. However, if stacker cranes are the bottleneck of the system in terms of throughput, many shuttles can be added and it will not increase throughput.

### 4.1.3 Layout 3

The third layout examined has a shuttle tier on each level like Layout 2 except that the shuttles are now able to change their level. They are transported from the levels to the base level and vice versa by the stacker cranes. These have therefore no telescopic forks but instead have load handling attachments able to transport shuttles. As in the previous case, each stacker crane still serves both sides of the aisle.

According to the expectations, the main advantage provided by Layout 3 in comparison to Layout 2 is the possibility to reach high throughputs for a smaller number of shuttles. Since shuttles can be moved from levels to the base, the throughput bottleneck caused by few shuttles in the base can be delayed to higher throughputs compared with Layout 2 for the same total number of shuttles. Another advantage of Layout 3 over Layout 2 is the high redundancy of the system. If a shuttle on the base of Layout 3 is broken, as opposed to Layout 2, it can be substituted by another one coming from the levels. However, the high flexibility of Layout 3 comes with the price of a higher complexity than in Layout 2. To move shuttles between levels, the stacker cranes have to execute a much higher number of orders than in Layout 2. It is presumed that this will result in a strong limitation of throughput caused by the stacker cranes for large shuttle fleet dimensions.

## 4.2 Material- and Information Flow within the System and between System and Environment

The presence of the shuttle base level in the hybrid warehouses enables the system to have more possible types of material- and information flows in comparison to stacker crane-based warehouses. In this section, an answer is given to the research sub-question "How should the material and information flow be organized to guarantee a smooth coordination of shuttles and stacker cranes?". In this dissertation, each different type of material- and information flow is denoted as *operating mode*. Parts of the content of this section were published in reduced form in [Sic-2020; Sic-2022d].

As shown in Figure 4-6, the operating modes for the shuttles on the base level (OMSs) are identified as follows:

- i. OMS *retrieve to I/O locations*: the shuttles bring pallets from the transfer buffer to the O location or the shuttles bring pallets from the storage location of the base level to the O location.
- ii. OMS *retrieve to storage of the base level*: the shuttles bring the pallets from the transfer buffer to the storage locations on the base level.
- iii. OMS *store to transfer buffer*: the shuttles bring the pallets from the I location to the transfer buffer or the shuttles bring the pallets from the I location to the storage location.
- iv. OMS *store to storage of the base level*: the shuttles bring the pallets from the I location to the storage locations on the base level.

Usually, the retrieval process requires a high throughput, defined as retrieved pallets per hour, so that for example the lorries ordering pallets do not have to wait for a long time. Unfortunately, a peak in the demand of pallets to be retrieved could require for some hours a throughput which is significantly higher than the usual one provided by the warehouse retrieving pallets from the levels through the stacker cranes. To overcome this problem, the solution could be to run the warehouse with the ii. OMS first and then with the i. OMS, in order to temporarily buffer pallets into the storage locations in the base level during the night while there is no lorry waiting to be loaded. When, during the day, retrieval orders are placed to deliver the pallets to waiting lorries, if the required throughput exceeds the one provided by the stacker cranes, the pallets can be retrieved directly from the storage locations on the base level. This enables for some hours to sustain a much higher throughput than in a traditional stacker crane-based system as it is demonstrated in the section of the dissertation regarding the evaluation of hybrid warehouses. The same considerations can be formulated also for the case of the storage process, by applying first iv. OMS and then iii. OMS.

As shown in Figure 4-6, the operating modes for the stacker cranes (OMSCs) are defined as follows:

*i. OMSC* *retrieval:* the stacker crane travels from the idle position (IP) to position P2. There it takes a pallet and then delivers it to the delivery position (DP), within the operating range of the stacker crane.

*ii. OMSC* *storage:* the stacker crane travels from IP to the pickup position (PU), where it takes a pallet and then it stores it in the position P1.

*iii. OMSC* *double cycles:* the stacker crane travels from IP to position PU, where it takes a pallet to store. It then delivers that pallet to P1. Next, it travels to P2 to take a pallet, which it retrieves to DP.

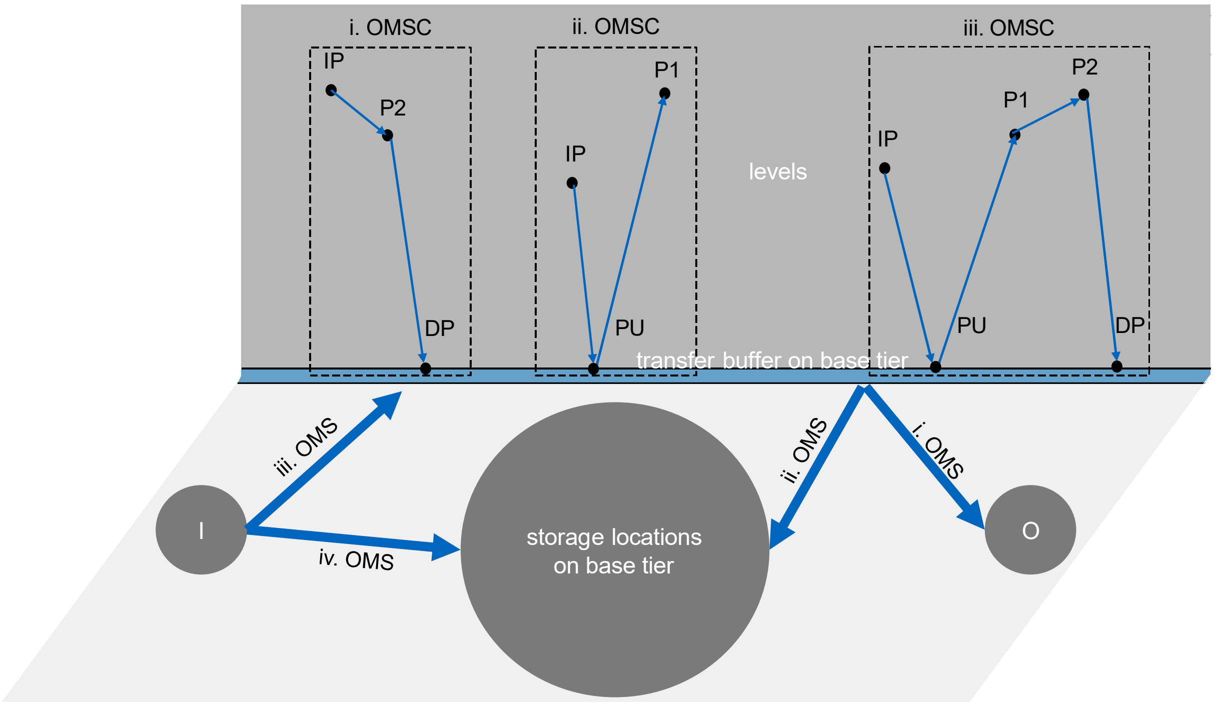



*Figure 4-6: Operating modes for shuttles and stacker cranes in DHPWs*

Moreover, it is defined as *overall operating mode* (OOM) the operating mode which controls the material- and information flow of the set of shuttles and stacker cranes together. There are following possible OOMs for Layouts 1 and 2:

*i. OOM* *retrieval:* stacker cranes perform *retrieval* while shuttles perform *retrieve to I/O locations* or *retrieve to storage of the base level*.

*ii. OOM* *storage:* stacker cranes perform *storage* while shuttles perform *store to transfer buffer* or *store to storage of the base level*.

*iii. OOM* *double cycles:* stacker cranes perform *double cycles* while shuttles perform *retrieve to I/O locations* or *retrieve to storage of the base level* and *store to transfer buffer* simultaneously or *store to storage of the base level*.

For Layout 3, also in case of i. *OOM retrieval* and ii. *OOM storage*, the stacker crane has to perform *double cycles* in order to transport empty shuttles between base and levels.

In contrast to Layout 1, in Layout 2 and 3 there are shuttles also on the levels. For these shuttles it is not necessary to define independent operating modes in the strategies for the control system, because their behaviour is determined completely by the selected operating modes of the shuttles on the base and the stacker cranes.

Now that the overview of material- and information flows in DHPWs is completed, in the next section a systematic approach to develop the strategies for the control system of a DHPWs, that enable to proceed orderly despite the number of components of these hybrid warehouses, is briefly illustrated. Afterwards, strategies are proposed for the control system of Layout 1 in case of storage, retrieval and double cycles. Then, strategies for Layout 2 and 3 are explained by comparison with Layout 1.

## 4.3 Strategies for the Control System for Connection and Coordination of Shuttles with Stacker Cranes

The aim of this section is to answer the research sub-question “Which strategies for the control system enable cooperation and coordination between shuttles and stacker cranes for each layout in the different operating processes?”. The developed control algorithms for a DHPW is reported following the structure of Figure 4-7. To describe these algorithms in a clear and unambiguous way, flow charts are used. For the sake of simplicity, the basic logic of a DHPW is explained considering just one stacker crane per aisle. Once the basic mechanisms are clear, more complex logics for multiple stacker cranes per aisle and optimization strategies are also explained later within this dissertation.

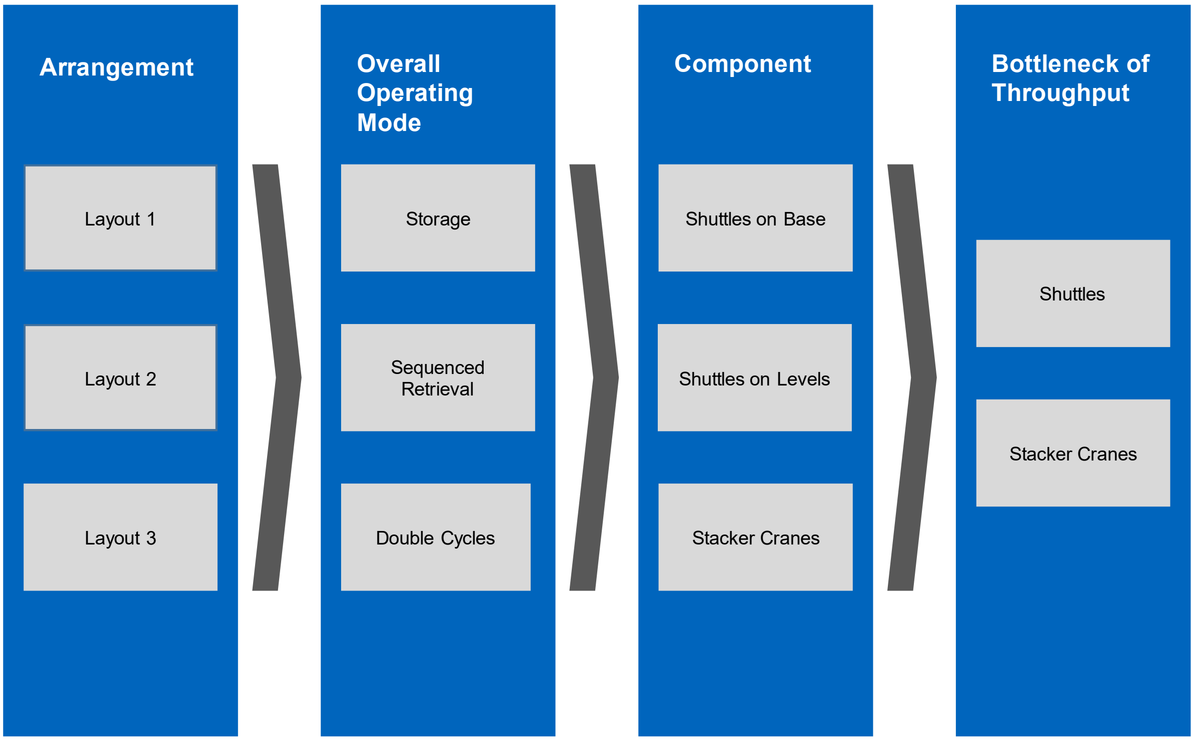



*Figure 4-7: Structure for the development of the control algorithms*

The strategies for the control system of a DHPW can be developed according to the systematic approach shown in Figure 4-7. Specifically, first of all, the strategies are conceived for the control system for a certain layout. Given the layout, only a single OOM is considered at a time. For that OOM, the control algorithms are developed for one of the components considering the cases in which that component is bottleneck of the throughput of the system or not.

Parts of the content of this section were published in reduced form in [Sic-2020; Sic-2022d].

### 4.3.1 Storage Process

Layout 1 and as OOM the storage process are considered. The connection and coordination logic in the storage process is described in Figure 4-8.

If the stacker crane stores in the channel warehouse less pallets per hour than those brought by the shuttles on the transfer buffer, then the stacker crane is the bottleneck of the system's throughput. Therefore, at a certain moment, all the transfer buffer locations are filled up by pallets. As a consequence, shuttles stop bringing further pallets

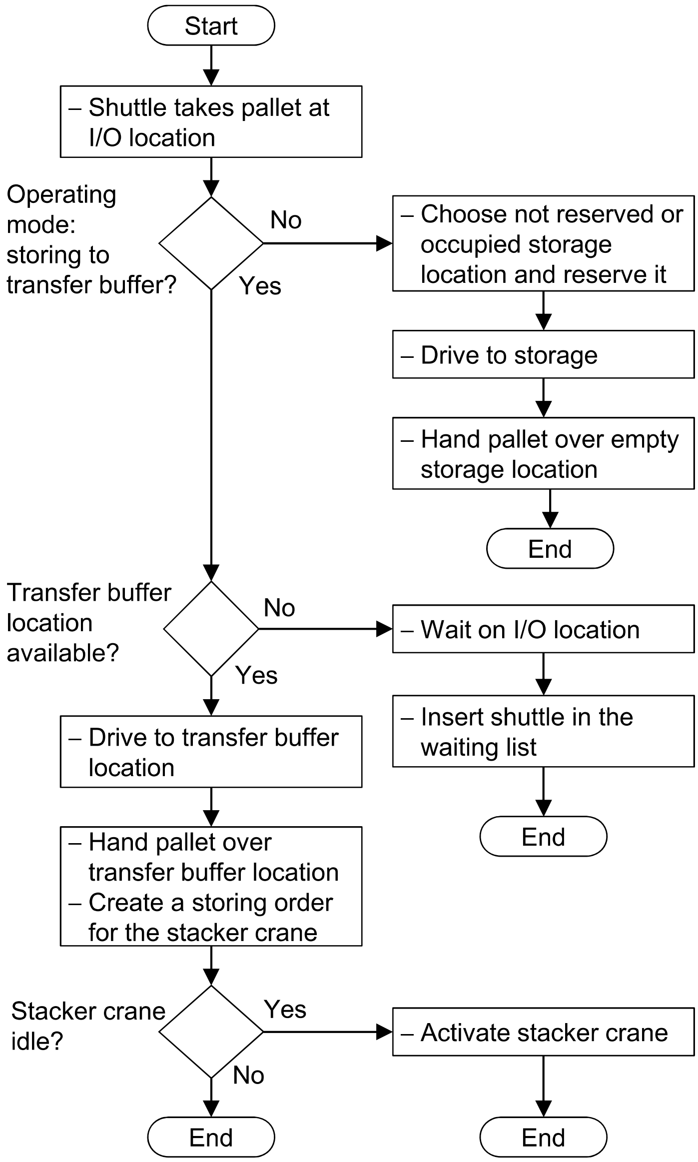



*Figure 4-8: Control Logic – Layout 1, Storage [Sic-2020]*

to the transfer buffer and wait, until a location in the transfer buffer becomes available. At this point the question arises, where to place shuttles while they are waiting. A possible option is moving them to empty storage locations of the base level as near as possible to the transfer buffer and let them wait there. The aim of this strategy is that, when shuttles are required to bring their pallets to the transfer buffer, they have just a short distance to travel from their waiting positions to the transfer buffer. However, while the stacker crane is the bottleneck of the system, the fact that the shuttles reach the transfer buffer in a minor time does not bring any improvement in terms of throughput. Moreover, this option has the disadvantages that more energy is needed for the detour of the shuttles to the storage locations and that less storage locations are available to store pallets in the base level. On that account, the best option is to let the shuttles wait on the loop of the I locations. The shuttle with the longest waiting time is the one loaded which waits exactly on the I location, while others wait on the loop. As soon as the stacker crane picks up a pallet from the transfer buffer, it controls if there are shuttles waiting for an available transfer buffer location in the same zone where it just took the pallet and activates the one with the longest idle time.

If the stacker crane is fast enough to store in the channel warehouse more pallets per hour than the shuttles are able to bring to the transfer buffer, then the shuttles are bottleneck of the system's throughput. This implies that at a certain instant all the locations on the transfer buffer of the base become empty. The stacker crane, not finding any other pallet to pick up on the base, stops in front of the location of the transfer buffer on the level it just served. Then it drives vertically to the base. The reason is that this way, being already on the base, as soon as a new pallet is available on the transfer buffer of the base, the stacker crane has a short way to drive to pick it up.

**Storage for Layout 2**

The OOM storage strategy for the control system of Layout 2 is now illustrated. Being the connection and coordination logic more complex in Layout 2 than in Layout 1, for Layout the logic is described in detail differentiating shuttles of the base as shown in Figure A-1, shuttles on the levels as shown in Figure A-2, and stacker cranes as shown in Figure A-3. In the arrangement of Layout 2 there is between shuttles and stacker cranes not only the interface of the transfer buffer on the base, but also, as opposed to Layout 1, the interfaces of the transfer buffers on the levels. Thus, supposing that the stacker crane is the bottleneck of the system, its low throughput can delay the shuttles in two ways: at a certain moment all the transfer buffer locations on the base are occupied by pallets or all the transfer buffer locations on the levels are empty. In the first case, as soon as a shuttle on the base cannot find an available position of the transfer buffer where to deliver its pallet, it follows the same idle logic described for Layout 1 and will be activated as soon as the stacker crane picks up a pallet on the transfer buffer of the base, making that position available. In the second case, a shuttle on a level which just concluded a storage and finds no additional pallet to store, should go wait to the storage position of the level which is the nearest to the transfer buffer and which is situated as middle as possible in a section along the direction of the aisle. This not only enables the shuttle to have a short way to reach the transfer buffer for the next storage, but also enables to collocate the charging stations in defined and accessible positions where all the shuttles go to wait. So, while a shuttle is waiting it can also recharge.

If the shuttles on the base are the bottleneck of the system, the same logic as for Layout 1 is to be followed when at a certain time all locations of the transfer buffer of the base are empty.

The case that the shuttles on a certain level become the bottleneck of the system is very unlikely. However, it could happen if stacker cranes have a very high throughput, if there are more shuttles on the base than on the level considered and if it is necessary to store almost all the incoming products on the level considered. At a certain moment, all the locations of the transfer buffer of that level are occupied by pallets and the stacker crane thus cannot find any available position where to deliver its pallet. The order to store that specific pallet remains in the list of orders to execute while the stacker crane stops and waits still on the base for a location of the transfer buffer of that level to become available.

**Storage for Layout 3**

The focus is now on the storage process as OOM in case of Layout 3. The connection and coordination logic for the shuttles on the base and on the levels is described in Figure A-4, while that for the stacker crane is in Figure A-5. In these figures, because the shuttles can move between levels and base, as opposed to Layout 2, the logic of shuttles, when they are on levels or on the base, is represented in a single diagram.

In contrast to Layouts 1 and 2, in Layout 3 during the OOM storage, shuttles on the base perform iii. OMS that is *store to transfer buffer* while the stacker crane executes iii. OMSC that is *double cycles*. It picks up a loaded shuttle on the base, delivers it to a level, it picks up an empty shuttle on a level and delivers it to the base.

If the stacker crane is the bottleneck of the system, the shuttles wait on the locations on the transfer buffer to be picked up. It is a very remote possibility that all locations on the transfer buffer of the base are occupied by loaded shuttles or all locations of at least one level are occupied by empty shuttles. Thus, strategies for the control system can leave out the possible reactions of shuttles in case they find no place on the transfer buffer. As a consequence, shuttles always find an available position on the transfer buffers when the stacker crane is the bottleneck of the system.

In case the shuttles of the base are the bottleneck, at a certain moment in time all locations on the transfer buffer of the base are empty. In this situation the stacker crane should continue to move empty shuttles waiting on the transfer buffer of levels down to the base, so that the additional vehicles support the shuttles on the base and mitigate their bottleneck. Only if there are also no more shuttles of levels to be transported to the base, then the stacker crane stops. It is then activated when a loaded shuttle arrives in a location on the transfer buffer on the base or an empty shuttle comes to a location on a transfer buffer on a level.

### 4.3.2 Sequenced Retrieval Process

The focus is again on Layout 1 and the sequenced retrieval process as OOM is examined. The connection and coordination logic in the retrieval process is described in Figure 4-9.

As for the storage process, also for the sequenced retrieval it is necessary to develop different algorithms for the case that the stacker crane is the throughput's bottleneck of the system and for the case that the shuttles are the bottleneck.

The first case happens when the shuttles retrieve more pallets per hour than the stacker crane can bring from the channel storage to the transfer buffer. This causes that, at a particular moment, all the transfer buffer positions are empty. Consequently, the shuttles remain without retrieval orders, i.e. pallets to retrieve from the transfer buffer to O location, and stop. Again, the question arises, where they should wait until a new retrieval order is available. If the inactive shuttles are left waiting on the O locations, not only they get in the way of active shuttles in delivering pallets to lorries but also need to drive a long way to reach the transfer buffer when they are activated again. Hence, unlikely the storage process, in the retrieval process the best option is to drive empty shuttles without an order to an empty location of the storage location as near as possible to the transfer buffer. Consequently, once a pallet reaches the transfer buffer, it is brought faster to the lorries which is waiting for it. When the stacker crane brings a pallet to a transfer buffer location, it checks if there are waiting shuttles in the same zone of that location and activates the one which has the longest idle time.

In the second case, the shuttles on the base are the bottleneck of the system, because they retrieve less pallets per hour than the stacker crane moves from the channel storage to the transfer buffer. Thus, at a particular moment, all the locations of the transfer buffer are full with pallets. As a consequence, the stacker crane that just completed a retrieval cannot find any available position on the base for the next pallet to retrieve. The order to retrieve that specific pallet remains in the list of orders to be executed while the stacker crane stops and waits in front of the position of its last retrieval on the base. It will be activated when a shuttle of the base picks up a pallet from the transfer

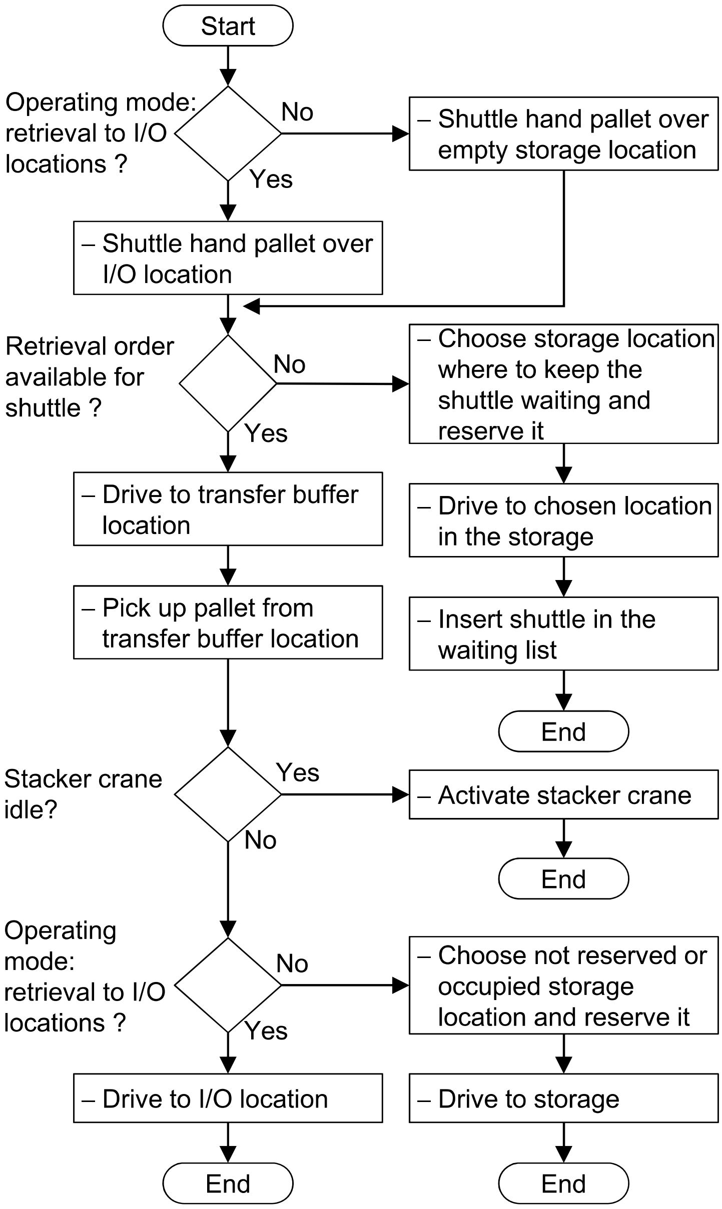



*Figure 4-9: Control Logic – Layout 1, Retrieval [Sic-2020]*

buffer, making a position available. In case the shuttles on the base are the bottleneck of the system one should consider whether to use a decentral or a central control of the shuttles. In the control algorithms a decentral control is proposed, because the shuttles in each zone are independent from those on other zones and the fact that a shuttle is active or idle depends directly only on the situation of the transfer buffer of its zone. A centralized control implies that the state of each shuttle is affected directly by the situation of the transfer buffer of each zone, base included. For example, if the transfer buffer on the base is completely occupied by shuttles, it could make sense to send all the shuttles on the levels for a certain time interval to stand by or to recharge. However, whether a centralized control should be preferred over a decentralized control depends on specific factors such as characteristics of the possible stand by, the type of batteries and charging stations, etc. which vary from case to case and that is not considered here because it is not the focus of the investigation. In this contribution, it was opted for the decentralized control because it can be applied with good results in any case.

**Retrieval for Layout 2**

Keeping the retrieval as OOM, the strategies for the control system in Layout 2 are now examined. The connection and coordination logic for the shuttles of the base in the retrieval process is described in details in Figure A-6, for those on the levels is in Figure A-7, while that for the stacker cranes is described in Figure A-9.

In the retrieval process, like in the storage process, there are two events which cause a slowdown in the dynamics of the shuttle given the stacker crane acts as the bottleneck: At a certain moment all locations on the transfer buffer on the base are empty or, in contrast to Layout 1, all locations on the transfer buffer on the levels are occupied by pallets. In the first case a shuttle that just completed a retrieval order and cannot find any other pallet on the transfer buffer to retrieve should follow the same idle logic described for Layout 1. In the second case a shuttle on a level which just completed a retrieval to the transfer buffer and cannot find an available position on it for the next pallet to retrieve, is going to wait on a storage position which is the nearest to the transfer buffer and which is situated as much in the middle as possible in a section for the same reason as idle shuttles on the levels described previously for the storage as OOM in Layout 2.

If the shuttles on the base are the bottleneck of the system, at a certain moment all the locations of the transfer buffer are full of pallets. At this point the stacker crane, not being able to find an available transfer buffer location for its retrieval order, stops. Following the same logic of retrieval as OOM for Layout 1, the stacker crane is activated again only when a shuttle picks up a pallet from the transfer buffer, making that position available.

Like for the storage process, the case in which the shuttles on a level are the bottleneck is unlikely. This would happen if the stacker cranes are very fast, if there are more shuttles on the base than on the level considered and if almost all the pallets to retrieve are on the level considered. When all the locations of the transfer buffer on the considered level are empty the stacker crane that just completed a retrieval cannot find any other pallet to retrieve from that level. Hence, it stops and waits in front of the location of the transfer buffer on the base where it just delivered the previous pallet. It will be activated as soon as a shuttle on any level brings a new pallet on the transfer buffer.

**Retrieval for Layout 3**

Keeping the retrieval as OOM, Layout 3 is taken into consideration. The connection and coordination logic for the shuttles on the base and on the levels is described in details in Figure A-10, while that for the stacker crane is in Figure A-8.

Unlike Layouts 1 and 2, while the shuttles on the base execute i. OMS that is *retrieve to I/O locations*, the stacker crane effectuates iii. OMSC that is *double cycles*. It picks an empty shuttle on the base, delivers it to a level, it picks a loaded shuttle on a level and delivers it to the base.

When the stacker crane is the bottleneck of the system, as for the storage as OOM, the retrieval shuttles wait directly on the transfer buffer. It is a very unlikely situation that all locations on the transfer buffer of the base are occupied by empty shuttles and all locations on the transfer buffer of at least one level are occupied with loaded shuttles. Thus, this situation can be ignored by the strategies for the control system.

If the shuttles of the base are the bottleneck, at a certain point in time all locations on the transfer buffer on the base are empty. The stacker crane should continue executing transport orders to bring loaded shuttles on the levels to the base. It stops only if there are also no shuttles on the levels waiting to be picked up.

### 4.3.3 Double Cycles Process

The strategies are now illustrated for the control system in double cycles as OOM for Layout 1. In this case, each shuttle performs alternatingly a storage and a retrieval order, while the stacker cranes choose the operating mode according to the orders availability as in Figure 4-10.

Specifically, each shuttle departs from the I location with a pallet and brings it to an available location of the transfer buffer as in iii. OMS, that is *store to transfer buffer*. Then, it takes an available pallet to retrieve from the transfer buffer and brings it to the O location as in i. OMS that is *retrieve to I/O locations*. Afterwards, the empty shuttle comes back to the I location to start another double cycle. In the meantime, the stacker crane performs double cycles if it finds at least one storage order and one retrieval order to combine. If this is not the case, it performs directly the storage order or retrieval order available to continue keeping high the throughput of the warehouse.

To avoid deadlocks, the locations of the transfer buffer reserved for pallets to store or "storage locations transfer buffer" (SLTB) and those for pallets to retrieve or "retrieval locations transfer buffer" (RLTB) are fixed. Consequently, it is not possible that a pallet to store will be temporarily buffered on a location of the transfer buffer intended for pallets to retrieve. That said, if the stacker crane is the bottleneck of the system, at a certain moment in time all the SLTBs are occupied with pallets and all the RLTBs are

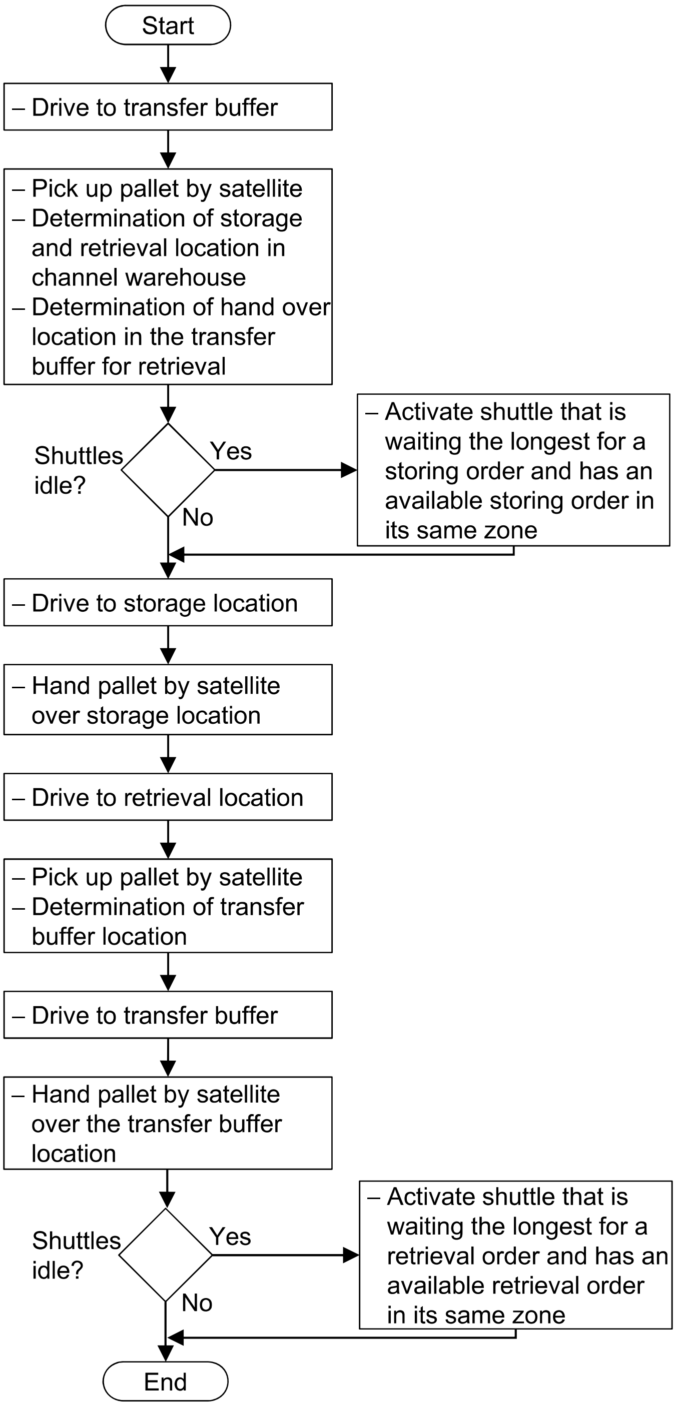



*Figure 4-10: Control Logic – Layout 1, Double Cycles [Sic-2020]*

empty. From that moment on, the shuttles which just finished a storage operation and should hence begin a retrieval but do not find available orders, drive to storage locations as near as possible to the transfer buffer and wait on them for the same reason explained for the retrieval as OOM in Layout 1. In the meantime, the shuttles which just completed a retrieval and should thus begin a storage, even if they do not find available orders, drive to the I location and wait on it or on the queue before it for the same reason explained for the storage as OOM in Layout 2.

If the shuttles on the base are the bottleneck, when on the base all SLTBs are empty or all RLTBs are occupied by pallets, the stacker crane stops and follows the same logic illustrated for Layout 1. Specifically, in the first case the stacker crane just completed a retrieval order and cannot find any pallet to store, therefore it remains waiting in front of the location of the base where it just delivered the previous pallet. In the second case, the stacker crane just finished a storage order and cannot find an available position where to bring the pallet to retrieve. Thus, the retrieval order regarding that specific pallet remains in the list of orders to be executed while the stacker crane stops and drives vertically to the base. It waits on the base, so that it has a short way to reach the next pallet of the base to store. It will be activated when a shuttle respectively brings a pallet to store on the SLTB or picks up a pallet on a RLTB, making that position available.

**Double Cycles for Layout 2**

The focus is now on double cycles as OOM for Layout 2. The connection and coordination logic for the shuttles of the base in the storage process is described in Figure A-11, for those on the levels is in Figure A-12, while that for the stacker cranes is in Figure A-13.

Each shuttle on the base performs the succession of iii. OMS, that is *store to transfer buffer*, followed by i. OMS, that is *retrieve to I/O locations*. Each shuttle on a level executes a retrieval order to the transfer buffer followed by a storage order to a storage location of the level. In the meantime, the stacker crane performs double cycles. The sequence of SLTBs and RLTBs is fixed not only for the base, like in Layout 1, but also for each level.

If the stacker crane is the bottleneck, four events can slowdown the dynamic of the shuttles. At a certain point, like for Layout 1, all SLTBs on the base are occupied by pallets or all RLTBs on the base are empty or, in contrast to Layout 1, all SLTBs on the levels are empty or all RLTBs are occupied by pallets. In the first and second case the shuttles which remain should follow the idle logic described for Layout 1 for double cycles as OOM. In the third case the shuttles on levels which just completed a retrieval order and remain with no storage order should follow the idle logic of Layout 2 for the storage as OOM. In the fourth case the shuttles on levels which just concluded a storage order and find no retrieval order to execute should follow the idle logic of Layout 2 for retrieval.

In case the shuttles on the base are the bottleneck of the system at a certain moment all the SLTBs are empty or all the RLTBs are full. As soon as the stacker crane cannot find any pallet on the SLTBs to store or any available RLTB to retrieve its pallet, it stops and waits, following the same logic described for Layout 1 for double cycles as OOM.

The case in which the shuttles of a level are the bottleneck of the system is very remote. It would happen only if the stacker cranes operate at high speeds and accelerations, if there are more shuttles on the base than on that level and if almost all the pallets to store and retrieve have to be respectively stored at or retrieved from that level. For sake of completeness, the idle logic is described also in this improbable case. Suppose that the shuttles of a certain level are the bottleneck of the system, then it happens that on that level at a certain time all SLTBs are occupied by pallets or all RLTBs are empty. In the first case the stacker crane that just completed a retrieval order cannot find any available position for the pallet to store it on the transfer buffer of the level. Hence, the storage order for that specific pallet remains in the list of storage orders to be executed. The stacker crane stops and follows the idle logic described for storage as OOM in Layout 2. In the second case, the stacker crane which just executed a storage order cannot find any pallet to retrieve from the level. Thus, it stops and follows the idle logic illustrated for retrieval as OOM in Layout 2.

**Double Cycles for Layout 3**

The double cycles process as OOM for Layout 3 is now considered. The connection and coordination logic for the shuttles on the base and on the levels is described in details in Figure A-14, while that for the stacker crane is in Figure A-15.

As opposed to Layouts 1 and 2, in Layout 3 the shuttles on the base execute iii. OMS, that is *store to transfer buffer*, followed by i. OMS, that is *retrieve to I/O locations*. In the time the stacker crane performs "dual *double cycles*". This means that it picks an empty shuttle on the base and delivers it to a level; it picks a loaded shuttle on a level and brings it to the base; it picks a loaded shuttle on the base and transports it to a level; it picks an empty shuttle from a level and brings it to the base. Consequently, there are four different kind of transport orders that the stacker crane should execute. As for Layout 2, SLTBs and RLTBs are fixed for the base and for the levels.

As for storage and retrieval, when the stacker crane is the bottleneck of the system, shuttles wait on the transfer buffer. It is highly unlikely that all the locations in the transfer buffer of the base and of at least one level are occupied, for the same reason explained for storage or retrieval as OOM in Layout 3, considering the case of stacker cranes being the bottleneck of the system. Subsequently, the strategies for the control system can neglect this event.

When the shuttles on the base are the bottleneck, the stacker crane has to wait because it does not find any loaded shuttles for storage or any empty shuttles for retrieval on the transfer buffer of the base to move to the levels. Despite this, it should continue executing orders to bring loaded shuttle for retrieval and empty shuttles for storage from levels to base. It only stops when no order of any type is available.

## 4.4 Order Assignment Strategies for Overall Performance Optimization

In this section it is responded qualitatively to the research sub-question “Which order assignment strategies can be applied to the connection between shuttles and stacker cranes in the different operating processes to improve the throughput?”. The answer to this research sub-question is then completed by quantitative examples in Section 6.4. As shown in Section 6.4, adequate order assignment strategies can optimize the performance of a warehouse. Only by identifying the operations in which a decision needs to be made meaningful order assignment strategies for a DHPW can be determined. For this purpose, the relevant operations for DHPWs are defined in the next sections, considering separately the processes of sequenced retrieval and of storage. Then, from such operations, order assignment strategies that are adequate to DHPWs are derived. This is carried out only for Layout 1, because Layout 2 and 3 have equivalent operations and order assignment strategies. Parts of the content of this section were published in reduced form in [Sic-2021b].

### 4.4.1 Decision-Making Operations

In the process of sequenced retrieval, with regard to the stacker cranes, an available pallet is taken from a predefined position of the channel warehouse and delivered to an available transfer buffer location. Two decisions need to be made: which characteristics should the available transfer buffer location have in order to be chosen? Which attributes should the selected idle shuttle have? In the meantime, from the point of view of activated shuttles, a pallet from the transfer buffer is collected and brought to the O location. The decision to take is: according to which criterion should the pallet be selected?

Ultimately, the three decision-making operations for the sequenced retrieval are denoted as *stacker crane chooses an available position on the transfer buffer*, *stacker crane chooses a shuttle to woken* and *shuttle chooses an available pallet on the transfer buffer*.

In the process of storage, from the perspective of the activated shuttles, a pallet is picked up from the I location and delivered to an available transfer buffer location. The decision concerns the following point: which features should the chosen available transfer buffer location have? From the perspective of the stacker cranes an available pallet is picked up from the transfer buffer and delivered to its final destination in the channel storage. The decision to take is: which requirements should the designated pallet satisfy? The two decision-making operations for the storage are indicated accordingly as *shuttle chooses a free position on the transfer buffer* and *stacker crane chooses an available pallet on the transfer buffer*.

At this point different strategies are presented for each decision-making operation. In the interests of clarity, each strategy is connoted with a name and a number.

### 4.4.2 Sequenced Retrieval Strategies

**Operation *stacker crane chooses an available position on the transfer buffer***

The most direct arrangement is choosing the position randomly (*Strategy Random Position*).

However, to minimize the travel time of the shuttles, their travelling distance from the transfer buffer to the O location should be reduced as much as possible. Therefore, the available transfer buffer position to select it is the one with the shortest distance to the O location (*Strategy Nearest Position to O Location*). Nevertheless, a drawback of this strategy is that confining all the shuttles to a tiny region of the shuttle base level increments interference among them. Consequently, their travel time is increased by the time interval they have to wait until their route is free from shuttles with a higher priority.

Choosing the available position on the transfer buffer in order to minimize the travel time of the shuttles is not the only promising solution to optimize the performance. Another option is to designate a position on the transfer buffer to ensure the minimum cycle distance for the stacker crane effectuating the retrieval (*Strategy Shortest Path* *for the Stacker Crane*). The idle position of the stacker crane is indicated with IP and the position of the pallet to be picked up in the channel warehouse is denoted with P2. Both positions IP and P2 are fixed and independent from the order assignment strategy applied. To accomplish the shortest cycle path for the retrieving stacker crane, the pallet should be brought from P2 to the position with coordinates (P2x, 0) as in Figure 4-11.

Still, the shortest cycle path for the stacker crane does not mean necessarily the shortest cycle time, because it could be that the traction drive and the lift drive do not have the same velocity and acceleration. A possibility to calculate the path that provides the shortest cycle time is to weight the x and y components of the path with the maximal velocity and acceleration of the stacker crane in both directions. This calculation would however not create a significant change in the path, therefore for sake of simplicity the simpler option of minimizing the travelled distance is used. Selecting the position on the transfer buffer to minimize the cycle path of the stacker cranes does not reduce interference among shuttles but at least does not augment it like when choosing the position on the transfer buffer to minimize the travel time of the shuttles.

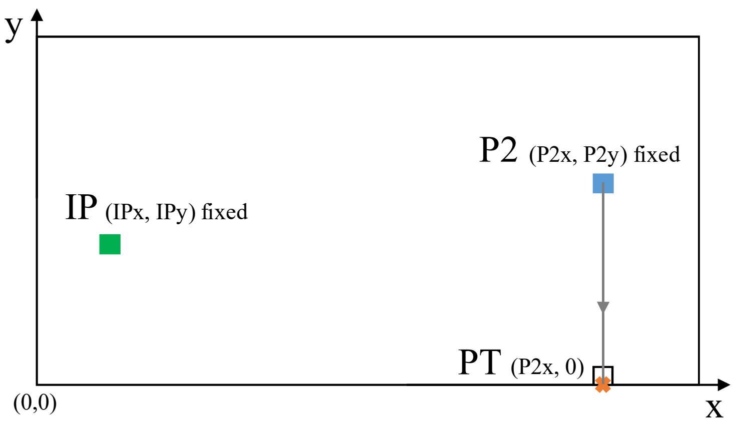



*Figure 4-11: How to determine PT, that is the retrieval location of the transfer buffer ensuring the shortest path for the stacker crane [Sic-2021b]*

To improve the performance through minimization of the interference among shuttles, the position on the transfer buffer should be selected which is available for the longest time (*Strategy Position Available for the Longest Time*). If the orders' distribution is well balanced along the transfer buffer, the shuttles have to drive over a larger region of the shuttle base level to retrieve pallets. Consequently, their travel distance increases, but their routes have less positions in common, thus less interference is generated.

**Operation *stacker crane chooses a shuttle to activate***

As always, the easiest setup is to activate a random shuttle between the available ones waiting on the storage locations (*Strategy Random Shuttle*).

It could however be beneficial to assure that all the shuttles are used to the same extent. If no shuttle is over- or underused, the necessary maintenance interventions are more reliably predictable and must only be carried out at longer intervals. For this aim, orders' distribution can be well balanced among the shuttles if the available shuttle is activated which has been waiting for the longest time (*Strategy Longest Shuttle Idle Time*). This approach cannot improve the number of pallets retrieved per hour by the overall system, but, with equal throughput as other strategies, it could be chosen for the advantages described above.

A different approach which could contribute to the improvement of the overall performance is to activate the idle shuttle nearest to the position on the transfer buffer of the pallet to be retrieved (*Strategy Nearest Shuttle to the Job*). This reduces the distance to the job, consequently the travel time of the shuttle.

Such a strategy can cause that some shuttles execute many more orders than others. If a shuttle has been activated, at the end of its retrieval cycle it is preferred over idle shuttles to take the next order. To promote equal use of all shuttles at least among the idle shuttles, the shuttle, which accomplished the least number of orders from the beginning of the retrieval process, should be activated (*Strategy Least Utilized Shuttle*). As for activating the shuttle with the longest idle time, this approach does not improve the number of pallets retrieved per hour by the overall system, but in case of equal throughput with other strategies, can be preferred over them because of maintenance savings resulting from the balanced use of all the shuttles. At this point one might question the difference between activating the shuttle with the longest idle time and the shuttle which executed the least amount of orders. The difference is that the second option provides indirectly a more equal distribution of the travelled distance among shuttles. Therefore, in case of equal provided throughput, the second one should be favoured.

**Operation *shuttle chooses an available pallet on the transfer buffer***

The simplest approach is that the shuttle simply selects a random pallet from the transfer buffer (*Strategy Random Pallet*).

However, if the shuttle is forced to select the available pallet on the transfer buffer closest to the O location (*Strategy Nearest Position to O Location*), the travel distance of the shuttles is shortened. Therefore, the travel time of the shuttles is reduced. This strategy has the disadvantage that in case more than one stacker crane is used, the stacker-crane which serves the interval of transfer buffer nearest to the O location will have a higher utilization ratio than others.  Malfunctions and break downs are then more probable in a machine and not equally distributed among all stacker cranes. As a result of the need for more frequent interventions, maintenance costs arise.

Another option for performance improvement is to force the shuttle to retrieve the available pallet on the transfer buffer which has the smallest sequence number (*Strategy Smallest Sequence Number*). This means that, while operating sequenced retrieval, a shuttle, that just picked up a pallet from a position of the transfer buffer, can leave that position only after the shuttle loaded with the pallet having the “precedent-sequence-number” has left the transfer buffer. Consequently, the time waited by a loaded shuttle before departure is minimized. With a small number of shuttles in the base level this strategy guarantees the prevention of deadlocks.

### 4.4.3 Storage Strategies

**Operation *shuttle chooses a free position on the transfer buffer***

The easiest option is to select the position randomly among the positions available (*Strategy Random Position*).

The throughput could be improved if the position on the transfer buffer is picked which has the shortest distance to the I location in the same zone (*Strategy Nearest Position to I Location*). The aim is to reduce the cycle path of the shuttle and so its cycle time. The risk is to increase the route overlaps among shuttles. Also, in case there is more than one stacker crane in the same aisle, the risk is that the stacker crane closest to the I locations fulfils most of the orders. This could result in an overuse of such stacker crane, therefore in a frequent required maintenance and high maintenance costs.

Still, to balance the distribution of storing orders on the transfer buffer, the position should be chosen which has been available for the longest (*Strategy Position available for the longest time*). It is started to count the time a position is available from the moment the satellite of the stacker crane leaves the transfer buffer position with its whole chassis, if no other shuttles reserved exactly that position. An enlargement of the operating area of the shuttles and the reduction of the interference time of their routes result from this strategy.

**Operation *stacker crane chooses an available pallet on the transfer buffer***

Choosing the pallet randomly is an easy solution (*Strategy Random Pallet*).

However, as already described above for other cases, the throughput can be improved by picking the available pallet, whose location on the transfer buffer has the shortest distance to the I location in the same zone (*Strategy Nearest Pallet to I Location*). This produces, as always, a reduction of the operating area of shuttles and of their travel time with an increase of the overlaps among the routes. As discussed for the retrieval in sequence, an increase of the performance can be obtained not only by reducing actively the travel time of shuttles but also the travel time of the stacker cranes. For this purpose, the stacker crane should pick the available pallet the position of which on the transfer buffer ensures the shortest cycle path (*Strategy Shortest Path for the Stacker Crane*). Such position is denoted as Position Transfer Buffer (PT). P1 is defined as the position where the stacker crane will store the pallet in the channel warehouse. Both positions IP and P1 are fixed and independent from the order assignment strategy applied. The coordinates of PT are calculated analogously to the determination of the shortest path for the reflection of light described by Fermat's principle. The pallet to be picked is then the available one nearest to the obtained coordinates. The graphical derivation of PT is shown in Figure 4-12. P1 is projected symmetrically with respect to the x axis. The straight-line s connects the projection of P1 with IP. The position PT is the intersection between s and the x axis. The abscissae of PT can be analytically calculated as follows:

$$\frac{PTy - (-P1y)}{PTx - P1x} = \frac{IPy - (-P1y)}{IPx - P1x} \tag{4-1}$$

$$PTx = P1y\,\frac{IPx - P1x}{IPy - P1y} + P1x \tag{4-2}$$

Moreover, to balance the distribution of orders on the transfer buffer, the pallet should be picked, which has been available on the transfer buffer for the longest time (*Strategy*

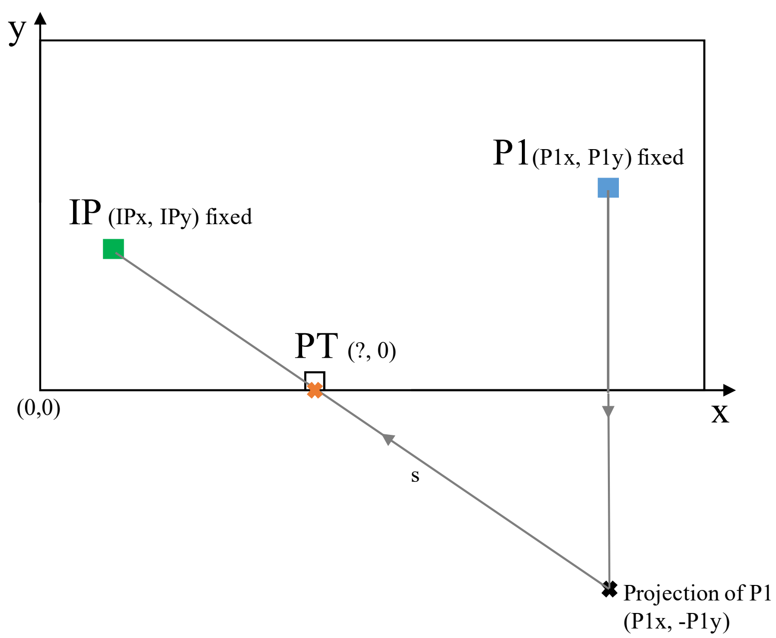
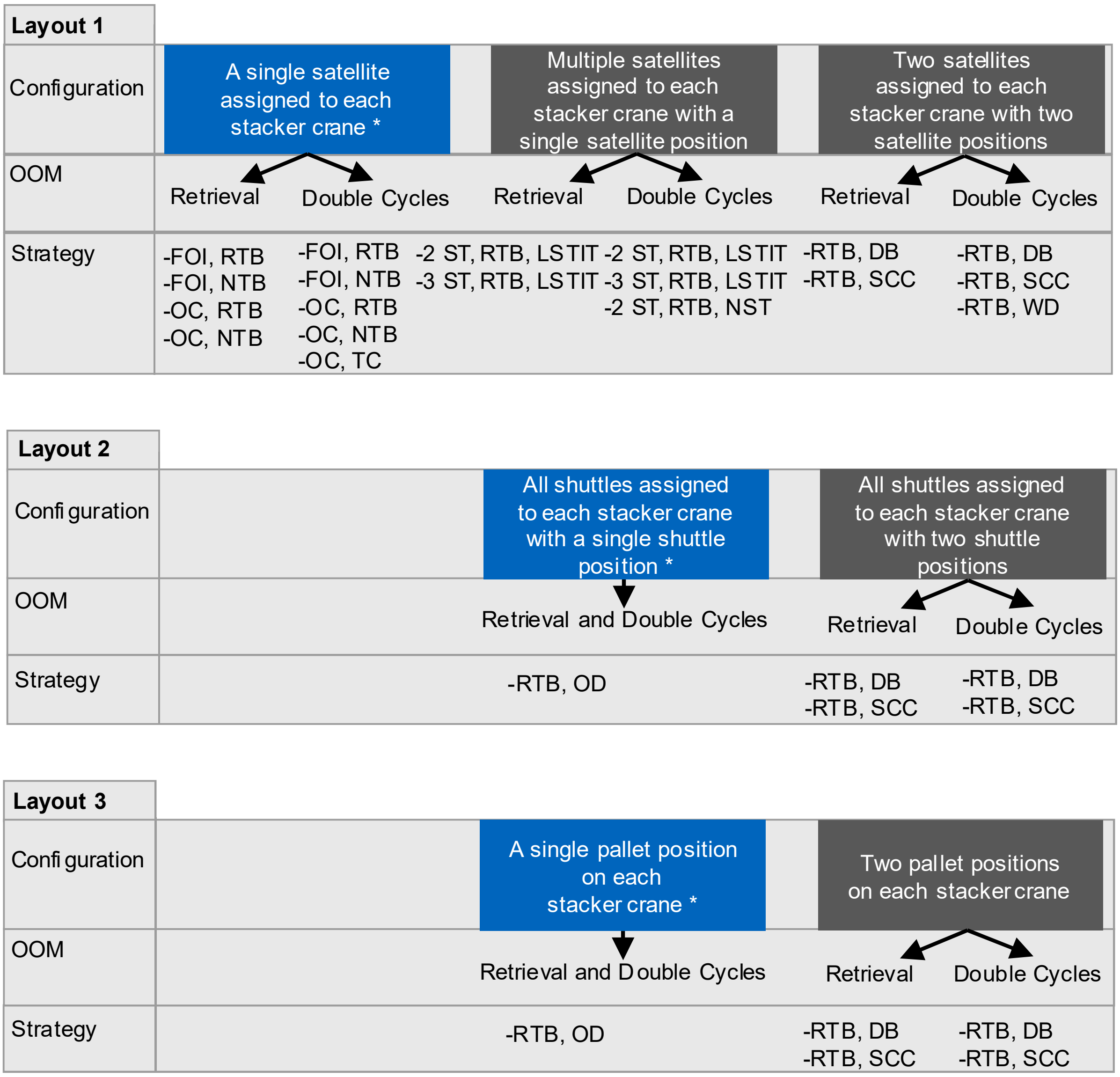



*Figure 4-12: How to determine PT, that is the storage location of the transfer buffer that ensures the shortest path for the stacker crane [Sic-2021b]*

*Position available for the longest time*). Similarly, to the cases described above this results in an expansion of the operation intervals of the shuttles, thus in a pruning of route overlaps.

## 4.5 Configurations and Coordination Strategies for Performance Optimization of Multiple Stacker Cranes

The aim of this section is to answer qualitatively the research sub-question “Which optimization strategies can be applied to improve the performance obtained with multiple stacker cranes in a single aisle?”. This answer is then completed by a quantitative study in Section 6.5. If in a DHPW the number of shuttles in the base level is raised, the throughput also increases until the stacker cranes eventually become the bottleneck of the system. To mitigate this bottleneck, the following systematic structured approach is used. Considering Layouts 1, 2 and 3 separately, different configurations for each of them are developed as in Figure 4-13, starting with the basic configurations. In Figure 4-13 basic configurations are marked in blue and with an asterisk. Non-basic configurations are meant to mitigate the bottleneck of the stacker cranes with respect to basic configurations. For each configuration, including the basic ones, the OOMs are considered individually and specific optimization strategies are elaborated for the control system for each of them. Three variants are investigated: one, two and three stacker cranes per aisle. Four or more stacker cranes per aisle are not investigated, because, to exploit their potential in terms of throughput, it would be necessary to use a number of shuttles per level so high that the system would become too expensive for industrial standards. The configurations and optimization strategies conceived for three stacker cranes can be adapted for more stacker cranes in a single aisle. All in all, the mitigation of the bottleneck of the stacker cranes happens in two steps: realization of an improved configuration and application of optimization strategies. The optimized configurations, because they contain more components than the basic ones, require higher investments and maintenance costs. Later, in Chapter 6, the configurations and their optimization strategies are investigated quantitatively. In the following sections the developed concepts are presented. Figure 4-13 provides a graphical representation of the systematic structured approach described above and it is recommended to keep it in mind while reading next subsections. Parts of the content of this section were published in reduced form in [Sic-2022a; Sic-2022b] .




| | |
|---|---|
| FOI | Fixed Operational Intervals |
| OC | Overlapping Case |
| RTB | Random Transfer Buffer Location |
| NTB | Nearest Transfer Buffer Location |
| TC | Time Comparison |
| ST | Satellite |
| LSTIT | Longest Satellite Idle Time |
| NST | Nearest Satellite |
| DB | Double |
| SCC | Succession |
| WD | Wait or Drive |
| OD | One Direction |

*Figure 4-13: Overview of configurations and optimization strategies for the control system of Layouts 1,2 and 3*

### 4.5.1 Layout 1: Dynamic Operational Interval for Each Stacker Crane

The range along the rails, in which a stacker crane travels, is denoted as operational interval. A first low-cost approach to mitigate the bottleneck of the stacker cranes by utilizing dynamic operational intervals is adapted and further developed from the research on conventional stacker crane-based warehouses. It is demonstrated however, in the simulation study later in this dissertation, that this adapted approach does not bring significant improvement of throughput, thus for sake of simplicity in the control system, fixed operational intervals are preferable for the DHPWs considered. The aim of the adapted approach is to allow stacker cranes to reach a larger range of locations of the transfer buffer and of the channel storage, so that even if a shuttle on a transfer buffer location cannot be served by the stacker crane assigned to that location, another stacker crane can serve it, thus reducing the waiting time of the shuttle. Specifically, a stacker crane is enabled to translate and exchange pallets among channel storage and transfer buffer only along its operational interval, which is defined as a range of the aisle length.  Such a range can be fixed for all times or it can be dynamic and change after the completion of each single retrieval, storage or double cycle operation of each stacker crane. In order to make the logic behind the determination of dynamic intervals clear, the example of two stacker cranes in the aisle for the sequenced retrieval process are considered. In this case the dynamic operational intervals for the two stacker cranes are defined by following algorithm:

<u>Initialization</u>:

The initial operational intervals for stacker crane 1 and for stacker crane 2 are defined (see Figure 4-14).

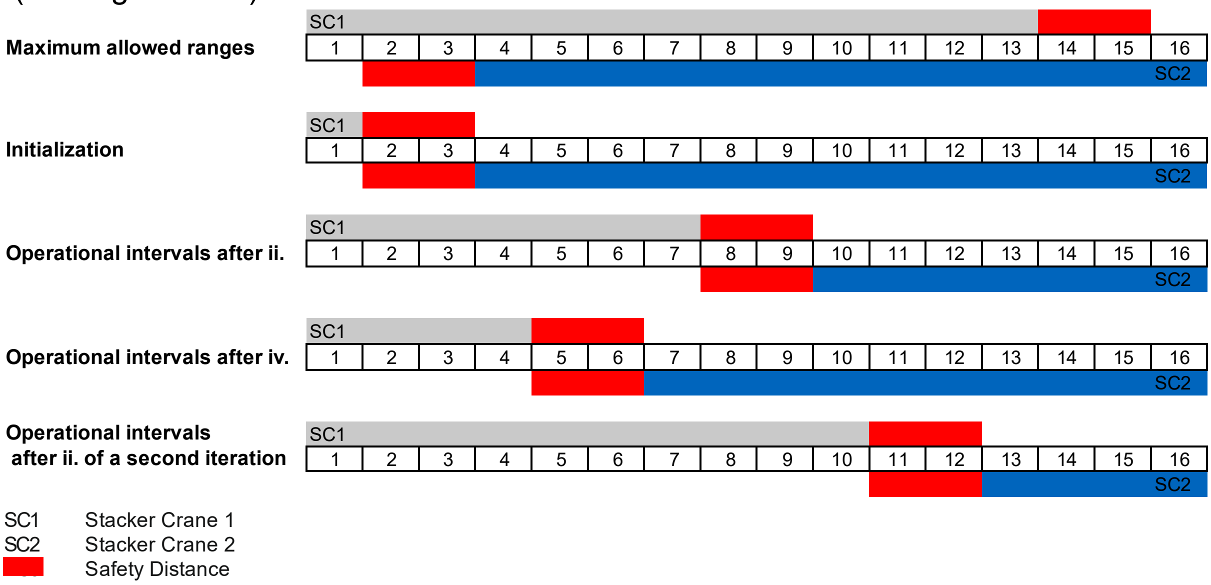



*Figure 4-14: Determination of the dynamic operational intervals in case of two stacker cranes [Sic-2022]*

Iteration:

i. Stacker crane 2 chooses a pallet for retrieval within its operational interval (green interval) and travels to it.
ii. The boundary between the operational intervals of the two stacker cranes is moved to the location of the pallet chosen by stacker crane 2 (considering a certain safety distance). Consequently, stacker crane 1 adapts its operational interval.
iii. Stacker crane 1 choses a pallet for retrieval within its operational interval (blue interval) and travels to it.
iv. The limit between the operational intervals of the two stacker cranes is moved to the location of the pallet chosen by stacker crane 1 (considering a certain safety distance). Consequently, stacker crane 2 adapts its operational interval.

Furthermore, for the logic of the algorithm described above, maximum overlapping ranges must be defined for the dynamic operational intervals. In Figure 4-15 and Figure 4-16, systematically growing maximum overlapping ranges are represented for two and three stacker cranes in the aisle.

Moreover, not only the maximum overlapping ranges but also the strategies for the control system within the maximum range can be determined to try to exploit dynamic operational intervals. Specifically, a stacker crane can select a position or a pallet randomly in its range for its next storage or retrieval (*Random Transfer Buffer Location or RTB*). However, it could select the nearest position or pallet to its current position to reduce its current cycle path as much as possible (*Nearest Transfer Buffer Location or NTB*). In case of storage another strategy can be used, which calculates the time the stacker crane would need to reach a certain random position in the channel warehouse and compares it to the time needed by the other stacker cranes to reach exactly that same position. At the end, the stacker crane drives to the position only if it is the fastest to reach that position (*Time Comparison or TC*). All in all, none of these strategies improves the throughput significantly as the simulation study demonstrates. This is the reason why in the strategies to mitigate the bottleneck of stacker cranes in the next subsections, the operational intervals for the cranes are considered fixed while other aspects of the system to improve the throughput are varied.

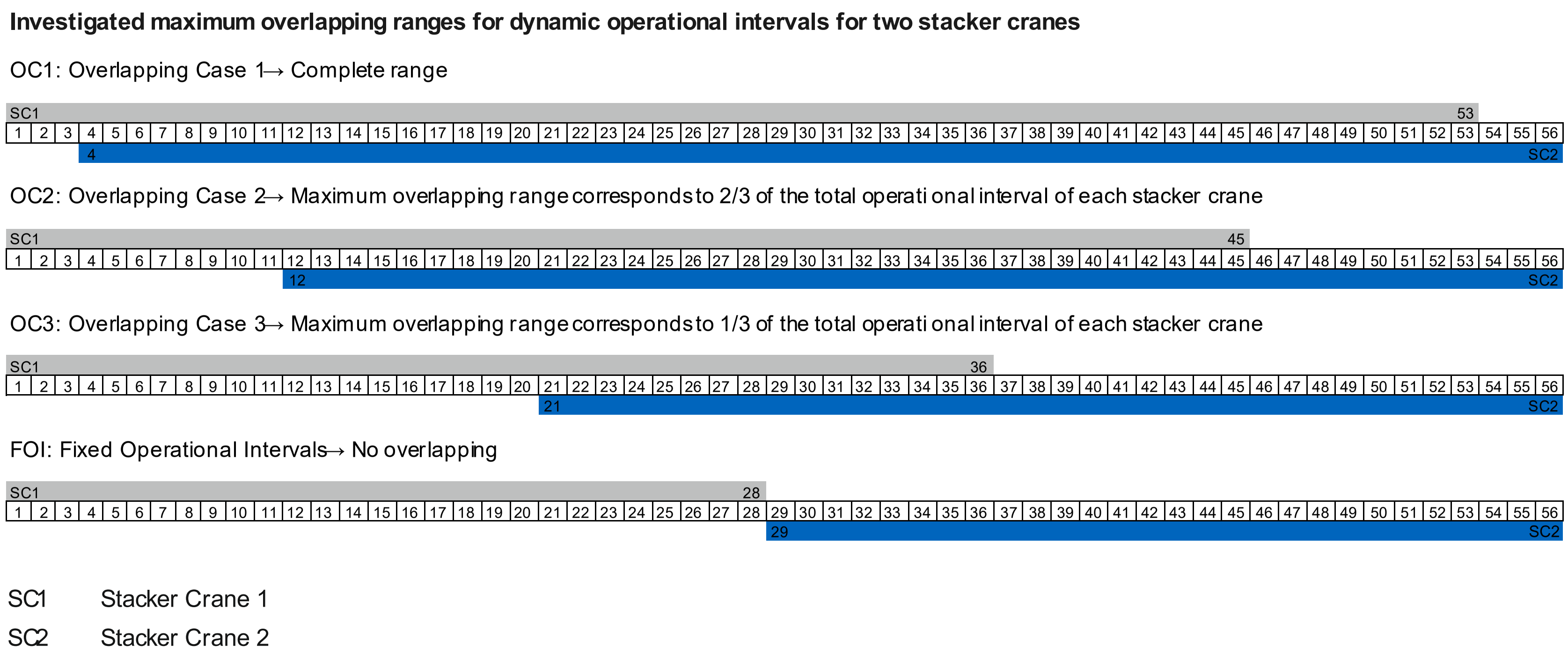
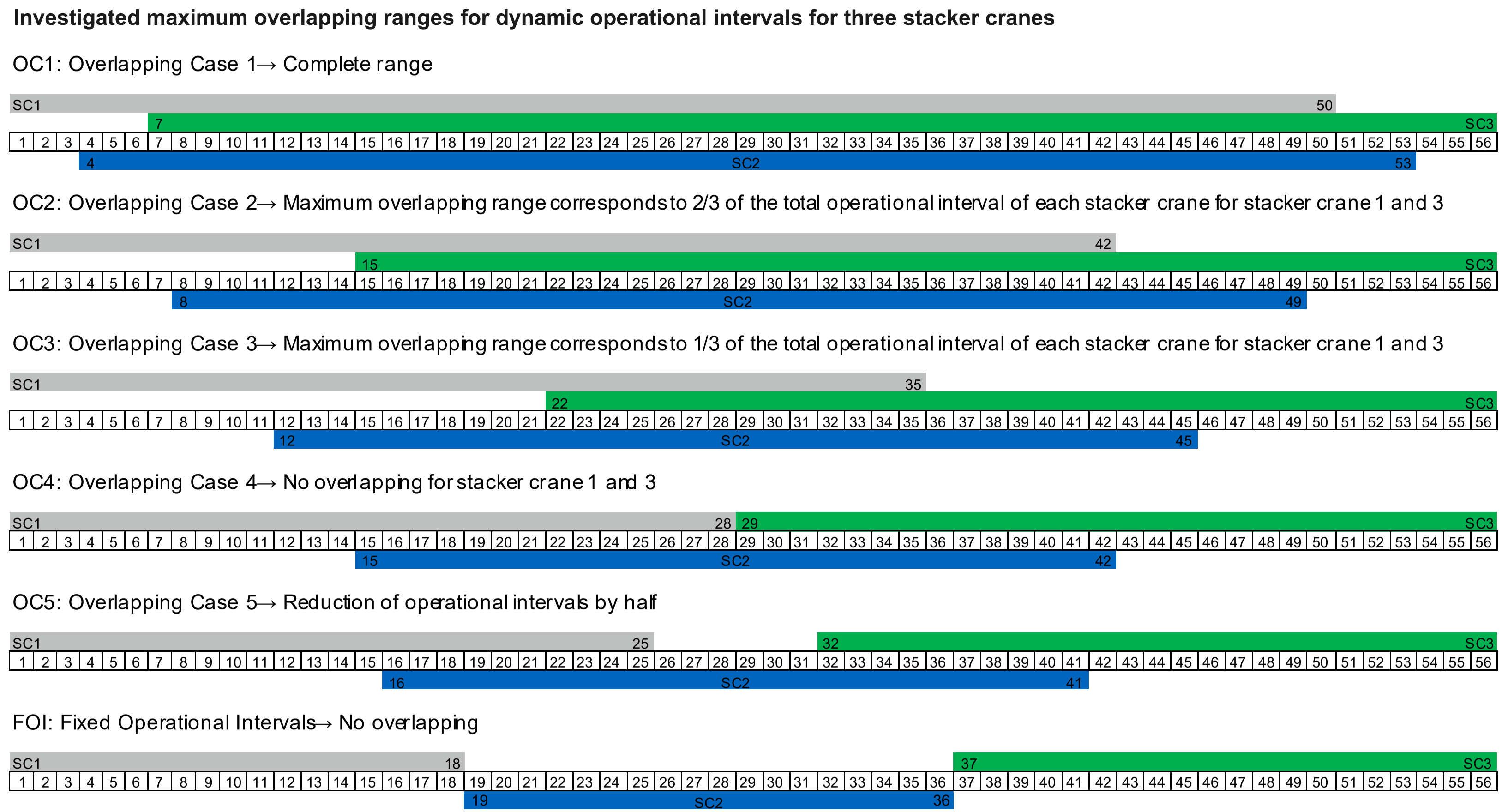



*Figure 4-15:* *Relevant overlapping ranges in case of dynamic operational intervals for two stacker cranes [Sic-2022]*




SC1 Stacker Crane 1
SC2 Stacker Crane 2
SC3 Stacker Crane 3

*Figure 4-16: Relevant overlapping ranges in case of dynamic operational intervals for three stacker cranes [Sic-2022]*

### 4.5.2 Layout 1: Multiple Satellites Assigned to Each Stacker Crane with a Single Satellite Position

A possible configuration to mitigate the bottleneck of stacker cranes in a DHPW is to assign multiple satellites to each stacker crane but maintaining just a single satellite position on each crane. An increase in the number of satellites enables the use of additional strategies for the control system that can be implemented to speed up the time to relocate a pallet from the channel storage to the transfer buffer and vice versa. Specifically, the stacker crane does not have any more to wait in front of a channel storage, where it just left a satellite, that the satellite comes back. It can directly drive to another satellite which is available to take or deliver a pallet. All in all, this configuration enables to decouple the cycle of a stacker crane from the cycle of its satellites.

Before a stacker crane starts its cycle there must be a satellite on it. The channel warehouse locations for storage and retrieval are respectively defined as P1 and P2. Each stacker crane in the aisle should perform the operations illustrated in Figure 4-17. Such strategies depend in part on the type of cycle, i.e. retrieval, storage or double cycle that the stacker crane has to execute. The type of cycle is determined depending on which satellites are available and if the available ones are loaded or empty. The operations to be followed by each satellite are described in detail in Figure A-16.

In addition to the operations described in Figure 4-17, it should also be decided if the next satellite to be picked up by the stacker crane should be selected randomly among the available ones, or if it should be the nearest available one to the stacker crane (*Nearest Shuttle or NST*) in order to shorten the cycle path of the crane. As an alternative the available satellite with the longest idle time (*Longest Satellite Idle Time or LSTIT*) can be chosen with the aim of balancing orders among satellites and avoiding that an order will be picked only after a long time, introducing a delay for the formation of a sequence for the retrieval in the base level.

### 4.5.3 Layout 1: Multiple Satellites Assigned to Each Stacker Crane with Multiple Satellite Positions

In the previous configuration, the stacker crane could serve multiple satellites but could transport just one pallet at a time. In the configuration described in this section, a stacker crane has two satellite positions, which means that it can exchange a maximum of two satellites within the same cycle with the transfer buffer locations. This enables to develop further strategies for the control system to combine two stacker crane cycles into one and so fasten the process. No more than two satellite positions are considered in this contribution for the development of the strategies. The reason is that three or more satellite positions per stacker crane are for an optimized system not relevant

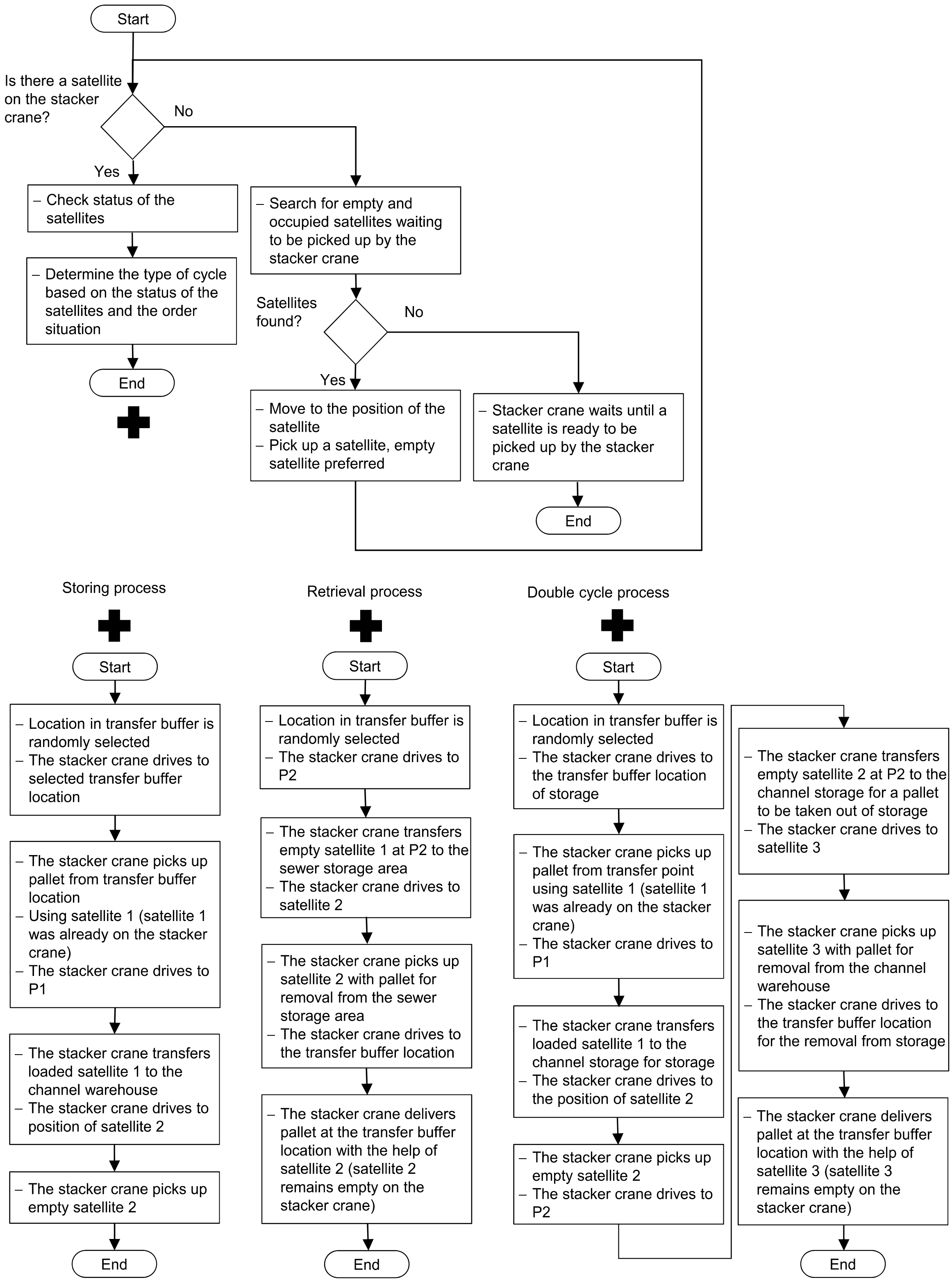



*Figure 4-17: Operations – Layout 1, Stacker Crane (in case multiple satellites are assigned to each stacker crane with a single satellite position) [Sic-2022]*

because they are difficult to build in the praxis and require a large amount of space. Two strategies are developed that are denoted respectively as *Double (DB)* and *Fixed Assignment*.

### Optimization Strategy *Double*

The characteristic of this strategy is that within the same stacker crane cycle both satellite positions are used either for pallets to be stored or for pallets to be retrieved. Therefore, it can be applied not only to the process of double cycles but also to the storage and to the retrieval in sequence. Another specificity of this strategy is that the stacker crane that just delivered a satellite to the channel warehouse always waits for it to come back. This means that each operation is executed for each satellite before performing the next operation. Moreover, the positions of the channel storage where the pallets have to be stored are designated as $P1_1$ and $P1_2$. The positions of the channel storage where the pallets have to be retrieved are indicated as $P2_1$ and $P2_2$. In this case there are multiple P1 and P2 positions because their number is equal to the number of satellite positions on each stacker crane. In order to enable the stacker crane to serve both sides of the aisle, the two satellite positions are arranged next to each other along the length direction of the aisle. For sake of clearness, Figure 4-18 illustrates the operations performed by the stacker cranes in case of double cycles as OOM. Operations for the single cycles storage and retrieval are for the optimization strategy *Double* exactly like respectively the first half and the second half of a double cycle as indicated in Figure 4-18.

### Optimization Strategy *Fixed Assignment*

This strategy is characterized by the fact that one satellite position performs exclusively the storage and the other one exclusively the retrieval. Consequently, only in case of double cycles it is possible to apply this approach. The flexibility offered by the use of two satellites and two satellite positions at the same time for retrieval and storage, enables to develop route optimization policies which each use different criteria to identify the fastest route for each stacker crane. The logical steps of the optimization strategy Fixed Assignment first determine the selection of the transfer buffer locations for the stacker crane to execute the assigned order, then calculate the total travel time for all route options and finally select the route that guarantees the shortest total travel time. Afterwards the stacker crane travels along the chosen route. Depending on the way the different routes are assembled, two different route optimization policies are defined. The first one, which is indicated as *Succession (SCC)*, focuses on the combination of the stations crossed by each stacker crane. Each position of the channel

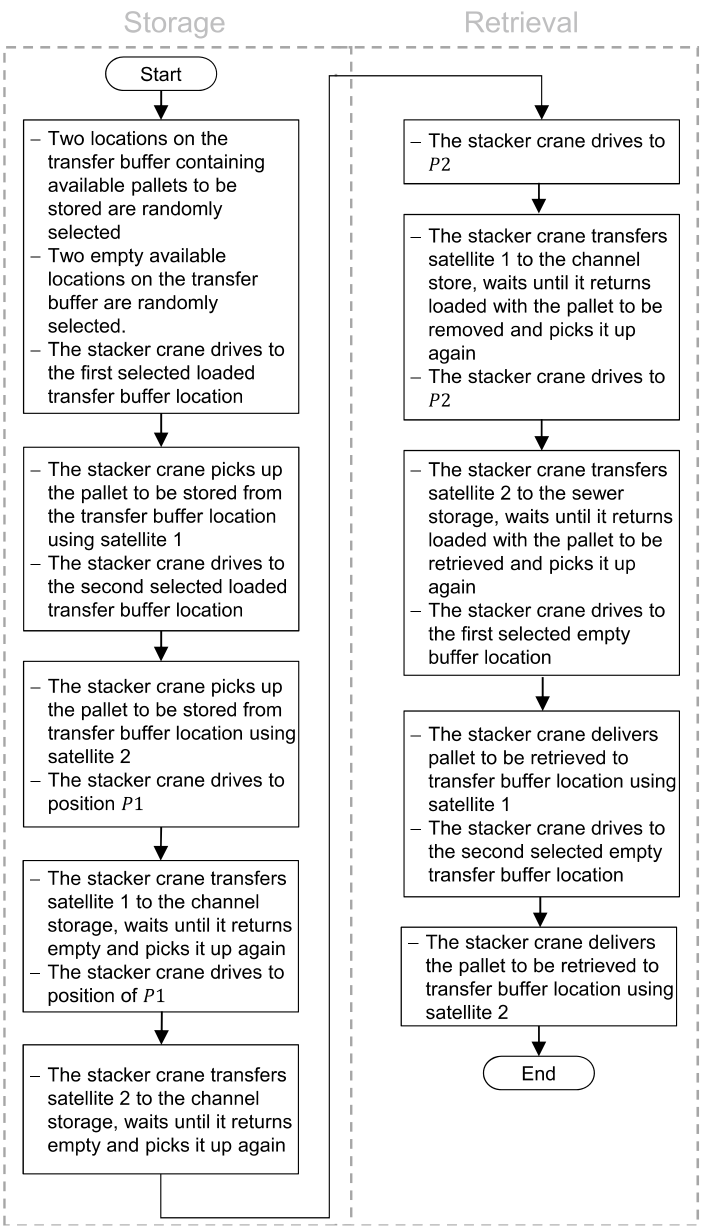



*Figure 4-18: Optimization strategy Double – Layout 1, Stacker crane [Sic-2022]*

warehouse or of the transfer buffer where the driving speed and the lifting speed of the stacker crane are both equal to zero for a finite interval of time is denoted as station. Hence, the stations are defined as follows:

- Stations *P1* and *P2*: exactly as defined above for storage and retrieval in the channel storage;
- Stations *Pick up* and *Hand over*: respectively the locations for storage and retrieval on the transfer buffer;

- Station *Last position*: the final coordinates of the stacker crane in the channel storage at the end of its previous cycle and the start location for the upcoming cycle.

The optimization strategy *Succession* exchanges the sequence of stations of a cycle, calculates the foreseen travel time for each possible combination and communicates to the stacker crane the fastest route as the one to be executed for the upcoming cycle. All the routes investigated by *Succession* for each cycle are represented in Table 4-1.

*Table 4-1: Programmed routes to be calculated by strategy Succession based on [Sic-2022a].*

| Route | Station 1 | Station 2 | Station 3 | Station 4 | Station 5 |
|---|---|---|---|---|---|
| **1** | Last position | Pick up | P1 | P2 | Hand over |
| **2** | Last position | Pick up | P2 | P1 | Hand over |
| **3** | Last position | Pick up | P2 | Hand over | P1 |
| **4** | Last position | P2 | Pick up | P1 | Hand over |
| **5** | Last position | P2 | Pick up | Hand over | P1 |
| **6** | Last position | P2 | Hand over | Pick up | P1 |

The second route optimization strategy is indicated as *Wait or Drive (WD)*, which concentrates on the combinations of operations, and not stations as in *Succession*, executed in a cycle by the stacker cranes. When the stacker crane serves a satellite in the channel storage, it can either wait for that satellite to complete its task and come back or it can drive forward to serve another satellite that may is ready for a pallet exchange. *Wait or Drive*, given a certain stations succession, investigates the possible combinations of operations and suggests to the stacker crane the one which guarantees the fastest route for the upcoming cycle. The routes considered by *Wait or Drive* are described in Table 4-2.

*Table 4-2: Programmed routes to be calculated by strategy Wait or Drive based on [Sic-2022a].*

| Route | Operations |
|---|---|
| **7** | Last position → Pick up → P1 (wait) → P2 (wait) → Hand over |
| **8** | Last position → Pick up → P1 (drive) → P2 (drive) → P1 (drive) → P2 (drive) → Hand over |
| **9** | Last position → Pick up → P1 (drive) → P2 (wait) → P1 (drive) → Hand over |
| **10** | Last position → Pick up → P2 (wait) → P1 (wait) → Hand over |
| **11** | Last position → Pick up → P2 (wait) → P1 (drive) → P2 (drive) → P1 (drive) → Hand over |
| **12** | Last position → Pick up → P2 (drive) → P1 (wait) → P2 (drive) → Hand over |

The routes seven to nine are based on the first stations combination of the strategy *Succession*, while ten to twelve are based on the second stations combination of *Succession*. Figure 4-19 illustrates the logical steps for the stacker crane for routes 8 and 9, that are two significant routes. All other routes follow a logic which is easily deductible from these two.

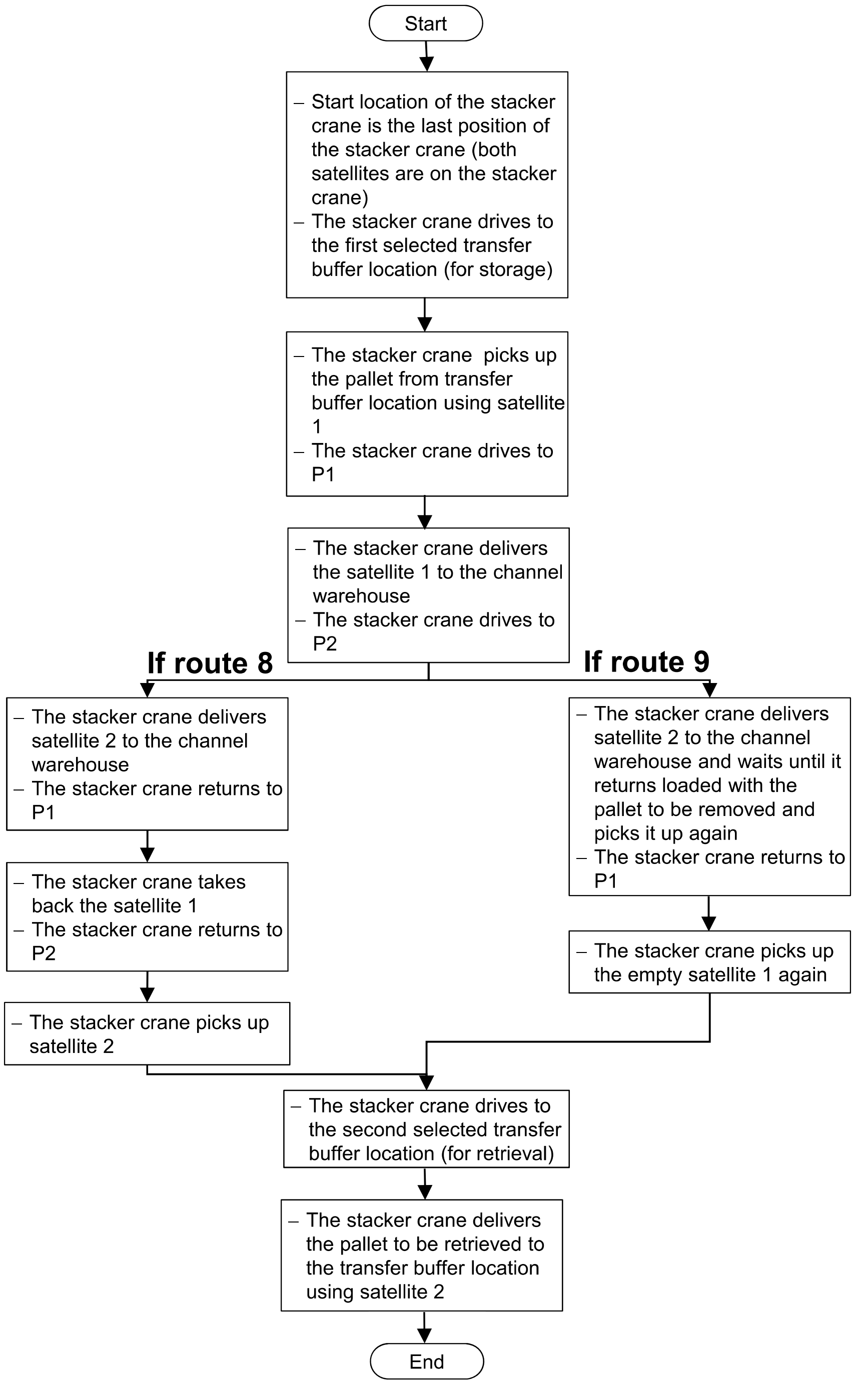



*Figure 4-19: Optimization strategy Wait or Drive – Layout 1, Stacker crane [Sic-2022]*

### 4.5.4 Layout 2: A Single Pallet Position on Each Stacker Crane

The basic configuration of Layout 2 consists of a stacker crane which serves all shuttles and has just one pallet position. To mitigate the bottleneck of the stacker crane in this configuration the optimization strategy *One Direction (OD)* is developed. The aim of this strategy is to reduce the cycle time of the stacker crane by reducing the number of changes in the direction along the aisle of the crane to serve the shuttles on base and on levels. For this purpose, the stacker crane selects and executes only orders which enables it to move along just one direction of the aisle, for a certain maximum number of orders, within its fixed operational interval. For sake of simplicity, first of all, the case having the retrieval as OOM as illustrated in Figure 4-20 is explained. The stacker crane first selects the side along the aisle which is the longest and thus where there is the highest possibility to find more orders, assuming a homogeneous

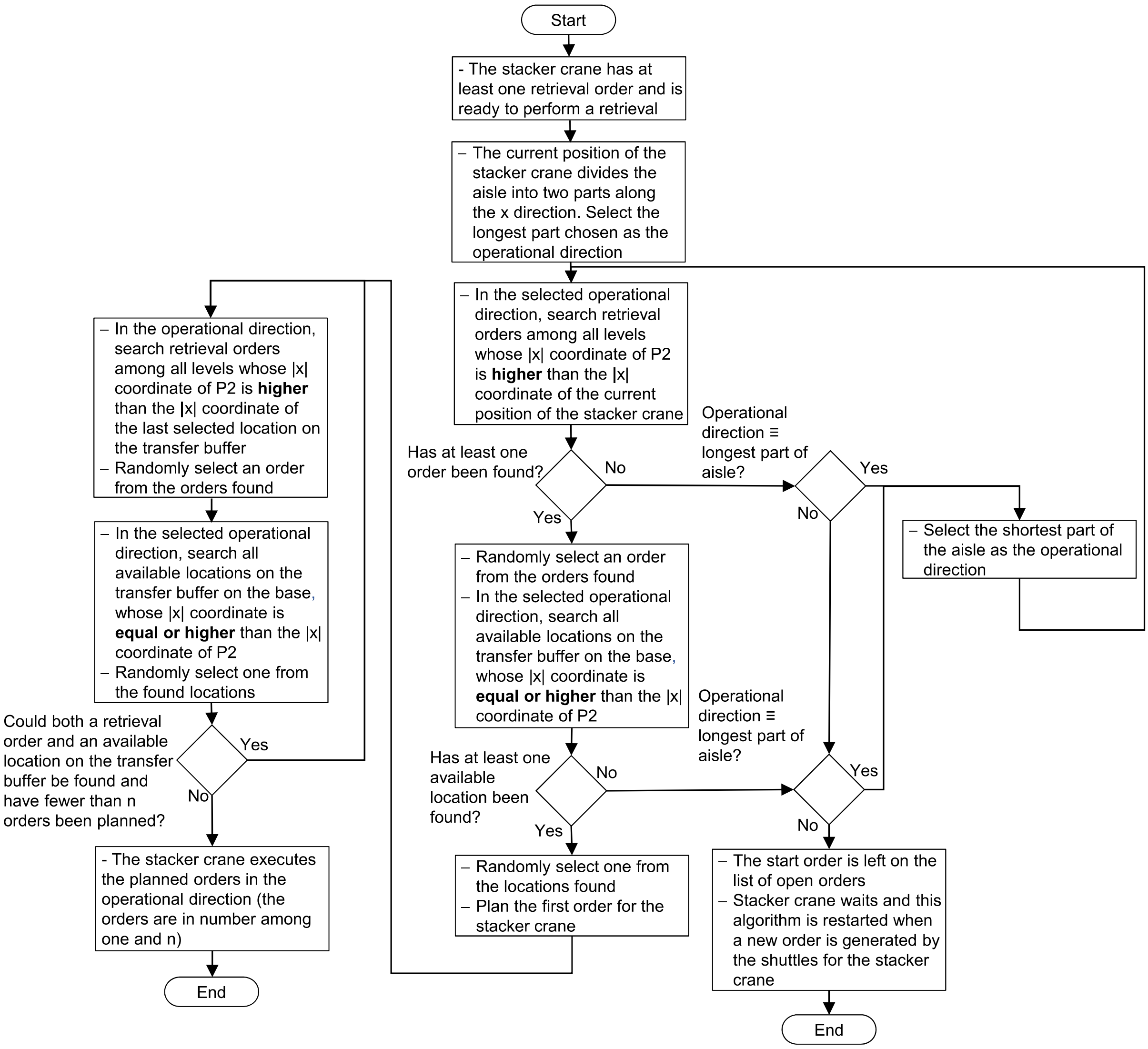



*Figure 4-20: Optimization strategy One Direction – Layout 2, Retrieval, Stacker crane [Sic-2022b]*

distribution of retrieval orders among the levels. Afterwards it selects randomly an available order having P2 in the chosen direction. It then looks for an available transfer buffer location, the x coordinate of which is equal to that of P2 or higher in the chosen direction. Next, the stacker crane looks for a second order having the coordinate of P2 higher than that of the available location of the transfer buffer selected for the first order and so on until a maximum of four orders is reached. It is recommended four as maximum allowed number of orders in a row because in the simulation study it was found that the stacker crane only rarely finds even four available orders in a row. Therefore, looking for more than four orders in a row would just cost more computing time, but it would not bring any significant improvement in the throughput of the system. Moreover, it is important to note that P2 is not allowed to have the same x coordinate as the current position of the stacker crane, because otherwise the stacker crane would be able to serve orders on the levels on transfer buffer locations with the same y coordinate and it would not move along the aisle, guaranteeing a good distribution of orders along the transfer buffer locations of the base.

In case of double cycles as OOM, retrieval and storage orders are selected alternating still according a logic similar to that of the single cycles. Orders are still executed with increasing x coordinates along the chosen direction as described in details in Figure A-17 (the star represented in this figure is a reference that will be explained in the subsection regarding Layout 3). Also, in this case a maximum number of four double cycles is implemented per direction, which means four retrievals alternated to four storages. If the number of selected and executed orders is uneven, then the next double cycle should start with a storage if the last order was a retrieval and vice versa. The reason is to avoid that the number of completed storage orders and that of completed retrieval orders are so different that they introduce an imbalance into the performance of the warehouse.

### 4.5.5 Layout 2: Two Pallet Positions on Each Stacker Crane

The second configuration of Layout 2 includes a stacker crane that serves all shuttles and has two pallet positions on it. As for Layout 1, no more than two pallet positions per stacker crane are examined, because three or more of them would be expensive to build in practice and demand too much space for the optimized system. Like for Layout 1 with multiple satellite positions per stacker crane, having several pallet positions per stacker crane makes it possible to develop strategies for the control system that combine two stacker crane cycles into one with a shorter total driven distance. Fixed operating intervals are imposed for each stacker crane, and the optimization strategy *Double* is adapted also for Layout 2 in this configuration. Figure A-18 contains the detailed description of the adapted strategy *Double* in case of double cycles as

OOM. As for Layout 1, in case of storage or retrieval process as OOM, the operations for the stacker crane are respectively contained in the first and second half of the double cycle diagram.

$P2_1$ and $P2_2$ can belong to different levels, exactly like for the strategy *Double* developed for Layout 1. However, unlike in Layout 1, in Layout 2 there are shuttles on each level. This has considerable influence on the behaviour of the stacker cranes and has to be considered when developing the strategy *Double* for Layout 2. For example, in case of double cycles, each shuttle on the base or on levels alternates between storage and retrieval orders. On the one hand, this rigid behaviour of the shuttles, even in the levels, makes it possible to maintain a balance between the number of storage and retrieval orders executed. On the other hand, it introduces a rigidity in the system, which requires a greater adaptability of the stacker crane in order to keep the throughput of the system high. By this it is meant that while in Layout 1 each stacker crane is able to execute all standard double cycles after a short initialisation phase, in Layout 2 even after the initialization phase it happens often that the stacker crane cannot find any storage or retrieval order to execute a double cycle. So as not to waste time waiting for the shuttles to provide the stacker crane with at least two storage orders and two retrieval orders to execute a double cycle, the stacker crane must be flexible and execute just a double storage or double retrieval cycle, according to the strategy *Double* for single cycles, while being in the OOM of double cycles. For example, if the stacker crane finds no storage orders but at least two retrieval orders, then, it should perform a double retrieval. If there are at least two storage orders and no retrieval order, then it performs a double storage. In Layout 2 it could also be that the stacker crane does not find more than one order of a kind. In that case it should just perform the retrieval or storage of that single pallet, in order to keep the throughput of the system high.

In addition, for the second configuration of Layout 2, the strategy *Succession* can be adapted, which was developed for the second configuration of Layout 1, to determine which order of the stations provides the shortest cycle time for the stacker crane. As described above the rigid behaviour of the shuttles on levels requires for Layout 2 a more flexible behaviour of the stacker crane than in Layout 1 in order to keep the throughput high. Therefore, according to the available kind of orders, the stacker crane optimizes the succession of the stations not only for standard double cycles, but also for double retrievals and double storages. A double cycle is executed only if at least one retrieval and one storage order is available. If at least two retrieval or two storage orders are available, then respectively a double retrieval or a double storage is performed. Therefore, even if the routes of Table 4-1 for Layout 1 are valid also for Layout 2, the algorithm of *Succession* should be adapted to consider also the routes for the double storages as in Table 4-3 and for the double retrievals as in

Table 4-4.

*Table 4-3: Programmed routes to be calculated by strategy Succession in case of double storage [Sic-2022b].*

| Route | Station 1 | Station 2 | Station 3 | Station 4 | Station 5 |
|---|---|---|---|---|---|
| **1S** | Last position | $Pick\ up_1$ | $Pick\ up_2$ | $P1_1$ | $P1_2$ |
| **2S** | Last position | $Pick\ up_1$ | $Pick\ up_2$ | $P1_2$ | $P1_1$ |
| **3S** | Last position | $Pick\ up_1$ | $P1_1$ | $Pick\ up_2$ | $P1_2$ |
| **4S** | Last position | $Pick\ up_2$ | $Pick\ up_1$ | $P1_1$ | $P1_2$ |
| **5S** | Last position | $Pick\ up_2$ | $Pick\ up_1$ | $P1_2$ | $P1_1$ |
| **6S** | Last position | $Pick\ up_2$ | $P1_2$ | $Pick\ up_1$ | $P1_1$ |

*Table 4-4: Programmed routes to be calculated by strategy Succession in case of double retrieval [Sic-2022b].*

| Route | Station 1 | Station 2 | Station 3 | Station 4 | Station 5 |
|---|---|---|---|---|---|
| **1R** | Last position | $P2_1$ | $P2_2$ | $Hand\ Over_1$ | $Hand\ Over_2$ |
| **2R** | Last position | $P2_1$ | $P2_2$ | $Hand\ Over_2$ | $Hand\ Over_1$ |
| **3R** | Last position | $P2_1$ | $Hand\ Over_1$ | $P2_2$ | $Hand\ Over_2$ |
| **4R** | Last position | $P2_2$ | $P2_1$ | $Hand\ Over_1$ | $Hand\ Over_2$ |
| **5R** | Last position | $P2_2$ | $P2_1$ | $Hand\ Over_2$ | $Hand\ Over_1$ |
| **6R** | Last position | $P2_2$ | $Hand\ Over_2$ | $P2_1$ | $Hand\ Over_1$ |

### 4.5.6 Layout 3: All Shuttles Assigned to Each Stacker Crane with a Single Shuttle Position

In the basic configuration of Layout 3 the stacker crane moves pallets between levels and the base and has just one shuttle position on it. The strategy that can be applied in this case is *One Direction*. The control logic in case of retrieval is very similar to that for Layout 2 in case of double cycles. Unlike for Layout 2 the stacker crane searches for both storage and retrieval orders at the beginning of each iteration. For Layout 2 it was necessary to start each search for orders in a certain operative x-direction with a storage to guarantee a balance in the type of orders executed. For Layout 3 however the algorithm should allow both storages and retrievals as first order to reduce the probability that in case only a few shuttles are used, no orders to complete one or more double cycles are found in the selected x-direction and thus the throughput is reduced. The operations to apply in case of double cycles are described in Details in Figure A-19. Specifically, the operations should be followed until the symbol of the “star” and afterwards the operations in Figure A-17 from the symbol of the “star” can be used.

### 4.5.7 Layout 3: All Shuttles Assigned to Each Stacker Crane with Two Shuttle Positions

For Layout 3, in case each stacker crane has two shuttle positions instead of just one, the strategy to mitigate the bottleneck of stacker cranes are, like for Layout 2, *Succession* and *Double*. The logic of both used for Layout 2 can be applied also to Layout 3 with minor modifications. Specifically, the algorithms used for *Double* are those explained in Figure A-18 considering shuttles instead of pallets as marked with "*". Regarding *Succession*, the routes described in Table 4-2 and Table 4-3 respectively for double storage and double retrieval should be applied to increase the throughput also in Layout 3, since often one of the two types of orders cannot be found to perform double cycles.

# 5 Modelling and Validation

In this chapter the modelling of DHPWs in a discrete-event simulation environment, and the verification and validation of the models against the real sub-systems are briefly presented. Verification and validation are necessary to ensure the reliability of the model. Specifically, for the validation of the shuttle base level of DHPWs, an innovative analytical method is proposed.

## 5.1 Model Implementation

Layouts 1, 2 and 3 were modelled using the discrete-event simulation environment Tecnomatix Plant Simulation. On the one hand, each stacker crane is modelled as a state machine[5] and is independent from the others. It can execute a new order only when no other orders are already running on it. In case of Layout 1, each stacker crane can reach all storage locations in z-direction, using their satellite. On the other hand, because shuttles are routed on a rectangular network, to avoid deadlocks caused by the routing, their routes are planned according to the free time windows method. The shuttle level model was developed on the base of the framework illustrated in [Lie-2021, pp. 111 et seqq.] divided into separated modules respectively for layout, for parameters, for orders, for routing and for evaluation. The routing free time windows-based algorithms utilized are those recommended in [Lie-2017b; Lie-2020; Lie-2021, pp. 63 et seqq.][6]. In addition, it was considered useful to use also a further module to impose the OOM and impose the many different combination of specific conditions necessary for the experiments on DHPWs. To apply the routing algorithms, base and levels had to be represented as graphs and the types of nodes, that constitute these graphs, had to be determined. It was therefore defined:

- *Transfer buffer nodes*, that represent the interface between shuttles and stacker cranes for the exchange of pallets for Layouts 1 and 2 or of shuttles for Layout 3

[5] The author is grateful to Florian Wenzler, who gave her the suggestion to represent one stacker crane as state machine.

[6] The author is grateful to Dr.-Ing. Thomas Lienert, who introduced the author to the free time windows method and explained her in details how he implemented it for his own research. Moreover, the author thanks heartfully Dr.- Ing. Thomas Lienert, Dr.-Ing. Christian Lieb and Dr.-Ing. Florian Wenzler for supporting her with their precious experience in the simulation environment Tecnomatix Plant Simulation in the initial phase of the implementation of the simulation model.

- *I/O location nodes*, where pallets enter the warehouse or exit it
- *Storage nodes*, where pallets can be stored on the base or on levels and where in some cases idle shuttles wait
- *Aisles nodes*, along which both empty and loaded shuttles are free to move in x and y direction

All kinds of nodes have the same dimension and can be entered or exited on each of their four sides.

For sake of clearness and simplicity, as concerns the implementation in the simulation, only the main elements characterizing the two sub-systems which constitute DHPWs, i.e. stacker cranes and shuttles, are illustrated.

Each stacker crane is implemented in a separated network unit. Within this network the different *elements*, i.e. methods, tables, variable, etc., can be classified in the main following categories:

- *Order Processing*: elements creating orders for the stacker crane and takes account of them
- *State Machine*: elements that regulate the various operations performed by the stacker crane to execute an order. Within this method there are those determining the type of cycle to be performed and those calculating the time needed by the stacker crane or its eventual satellites.
- *Transfer Buffer Selection*: elements determining which available pallet, available location or available shuttle should be chosen by the stacker crane on the transfer buffer of the base or of levels
- *Strategies*: elements regulating optimization strategies for the stacker crane
- *Parameters*: dynamical parameters of the stacker crane and the geometrical parameters characterizing the structure of the warehouse, such as dimensions of each compartment or number of compartments in each direction
- *Cycle Variables*: variables defined by the state machine in each cycle. These variables are for example the time interval needed by the stacker crane from each station to the successive one, the total cycle time or the coordinates of the stations.

A key element for modelling shuttles in DHPWs is the network of the module which manages orders. This can be divided into following categories:

- *Initialization: includes the elements setting initial variables regarding the orders for shuttles and it creates shuttle elements on base or levels*

- *Locations Accounting: contains tables registering which locations such as transfer buffer locations or storages on levels are reserved or occupied by shuttles or pallets. Moreover, one of the tables represents orders with the initial and final location assigned to them.*
- *Order Processing: elements that generate and account orders for the shuttles. Here also the methods used by the stacker crane to generate warehouse intern orders for the shuttles can be found.*
- *Shuttles Operating Modes: the elements determining which order or orders, according to the current operating mode, are assigned to an available shuttle.*
- *Idle Shuttles: The elements classified in this category are particularly critical to the coordination of satellites and stacker cranes. They regulate the determination of waiting positions for shuttles and they account which shuttles wait to be activated by stacker cranes.*

There are multiple connection points between shuttles and stacker cranes. However, the most important connections are modelled into six methods contained in the network having the objects of the layout. These methods regulate respectively the actions to be taken when following six operations are executed:

- *Arrival of shuttle in an I/O location*
- *Arrival of shuttle on transfer buffer*
- *Arrival of shuttle on storage position*
- *Shuttle just before leaving a node*
- *Shuttle just after leaving an I/O location*
- *I/O location pulling pallet off*

Specifically, in Layout 3, when a shuttle arrives on the transfer buffer to be moved by the stacker crane on another level, its route is newly calculated when it reaches the arrival transfer buffer.

After this brief description of the implementation of the model in Tecnomatix Plant Simulation, in the next section it is described how the model was verified and validated against the real sub-systems.

## 5.2 Verification and Validation of the Model

The focus is now on the verification and validation of the model. For both verification and validation, shuttles and stacker cranes are considered separately. This in analogy with the European guideline FEM 9.860 [FEM-9860], in which shuttles and lifts of a shuttle-based warehouse system are considered independently. For the verification the cycle time of single shuttles and of single stacker cranes were computed analytically to verify the good agreement among the calculated values and the results obtained through simulation [Lie-2018b; Gud-2010; Gro-1984; Rab-2008, pp. 93 et seqq.].

Then, it was proceeded with the validation against real sub-systems provided by the manufacturer. In the next sections, procedures and results of the validation for the stacker crane and for the shuttles are illustrated. Parts of the content of this section were published in reduced form in [Sic-2021a].

### 5.2.1 Validation of Stacker Crane Model

Each modelled stacker crane can exchange pallets with the base level and the other levels along its whole operational interval. No literature was found suggesting how to validate the correct modelling of a stacker crane run according to these strategies for the control system. Therefore, a way was developed to validate the model of a stacker crane using analogies from the European guideline FEM 9.851 [FEM-9851]. It was defined which experiments to perform and Gebhardt Fördertechnik GmbH executed them on a real stacker crane following the author’s instructions. It was asked for two horizontal travels of the stacker crane without load and two with load, two vertical travels without load and two with load, two diagonal travels with load and without load. From the company the author then received the raw data of the measurements in the software PicoScope. This software provides the electric power of the stacker crane in function of time. Based on the trend in power, the following different phases of the cycle of the stacker crane were identified. The example in Figure 5-1 is the representation of the travel of the empty stacker crane, where the red area is between zero and the consumed power. The phases are as follows:

A. Stand-by with all brakes closed
B. Acceleration
C. Travel with constant velocity
D. Braking with load sharing, because lift and traction motors are connected
E. Waiting in front of the shelf

F. Acceleration

G. Travel with constant velocity

H. Braking with load sharing

I. Stand-by with service brakes still on

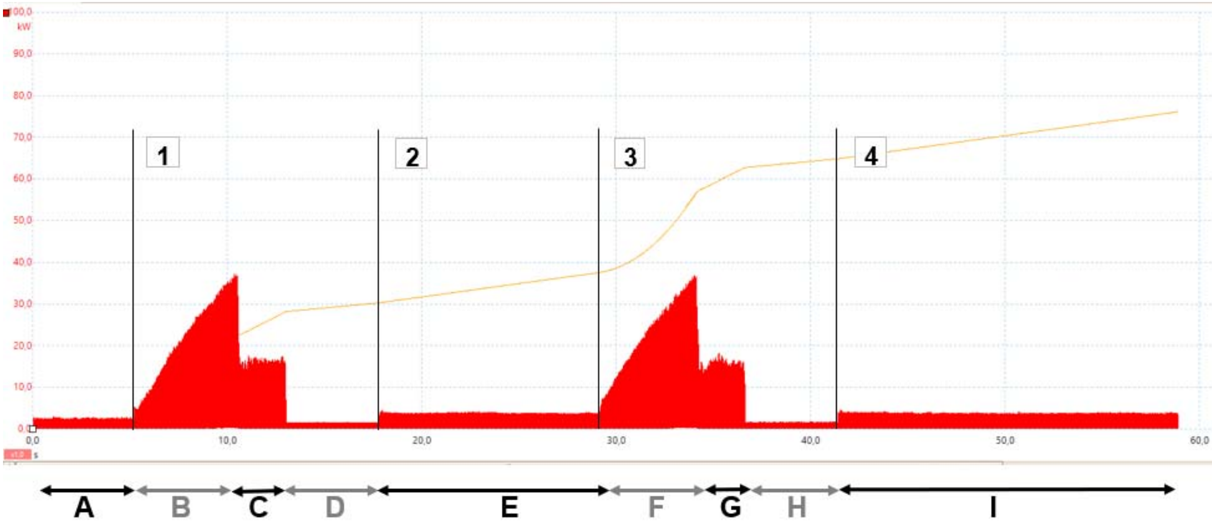



*Figure 5-1: Phases of an example travel (in this case horizontal) of the empty stacker crane*

After identifying the phases of each graph representing the travel of the stacker crane, the time points one to four (see Figure 5-1) were defined for each of the eleven experiments[7] to obtain the time interval to reach the location of the shelf ($\Delta t$ *forward* between positions one and two) and the time interval to go back to the starting position ($\Delta t$ *backward* between positions three and four). The time interval elapsed while waiting in front of the shelf is not relevant for the validation because it is arbitrary. Then, the average time intervals for the horizontal, for the vertical and for the diagonal travels were calculated obtaining Table 5-1.

*Table 5-1: Average time intervals calculated from the measurements.*

| Type of travel | **Δt forward** | **Δt backward** |
|---|---|---|
| **Horizontal** | 12.44 | 12.06 |
| **Vertical** | 7.50 | 7.09 |
| **Diagonal** | 12.42 | 12.13 |

[7] Regarding the diagonal travel with load, one of the planned measurements was not available. Regarding the horizontal travel with load, one of the $\Delta t$ *backward* had to be discarded due to experimental problems.

Then, the distance travelled by the stacker crane was converted in coordinates in the model of the shelf in the simulation model. Specifically, the stacker crane travelled for 18700 mm in the horizontal direction for both horizontal and diagonal travel, while 6000 mm in the vertical direction for both vertical and diagonal travel. These distances correspond to position (20; 3) in the model of the shelf along the aisle, given a compartment height of 2000 mm and a compartment width of 935 mm. After running the simulation with the same dynamical parameters of the real sub-system for horizontal, vertical and diagonal travels, the simulated results were compared with the measured Δt calculated as average between Δt forward and Δt backward. As shown in Table 5-2, for horizontal, vertical and diagonal travels the maximum error of the simulation with respect to the measured values of time is smaller than 6 %, in analogy to the maximum allowed error in the European guideline FEM 9.851 [FEM-9851]. This means that the model of the stacker crane can be considered as validated.

*Table 5-2: Comparison of measured and simulated travel times for stacker crane.*

| Type of travel | **Δt measured** | **Δt simulated** | **Maximum error** | **< 6 %** |
|---|---|---|---|---|
| **Horizontal** | 12.25 s | 7 s | 1.84 % | yes |
| **Vertical** | 12.28 s | 12.48 s | 4.06 % | yes |
| **Diagonal** | 12.28 s | 12.48 s | 1.63 % | yes |

### 5.2.2 Validation of Shuttle Model

In the state of the art for shuttle-based warehouses no relevant analytical method was found to determine the test positions of the real system to validate the shuttle base of a DHPW. Therefore, it was developed in the context of this contribution. The new method is explained in Section 5.3. With the new method it was possible to determine the test positions of the real system and to adapt the layout in the simulation to allow a direct comparison. In the following, the procedure will be explained that was used to validate the shuttle levels model, which is the frame in which the new analytical method is used. As for the stacker crane the author defined the experiments to be performed and Gebhardt Fördertechnik GmbH executed them on a real shuttle level following the author’s instructions. To validate the system, the double cycle as OOM was chosen because it comprises both storage and retrieval combined together.

Given the physical shuttle level, first, it was determined which route the shuttle should follow during the experiment based on the routing policies of the simulation. In analogy with the European guideline FEM 9.860 [FEM-9860], it was decided to perform five repetitions of the double cycle of the shuttle. From the experiments a list of measured raw data was obtained, containing time stamps and the total driven distance at each time stamp. Each time stamp corresponded to the beginning of the next action of the shuttle. From this list the distance and time intervals for each segment of the route and for each operation of the shuttle were calculated, defining as segment the distance travelled by the shuttle without change in direction and without additional operations. With operations it is meant the change of direction by 90 degrees, the drop or the pick of a pallet, the fine positioning before dropping or picking a pallet, the fine positioning before a change of direction by 90 degrees. For each operation the average time of all operations of the same kind within each experiment and the average among the experiments were calculated. Then, the average velocity among all segments of all experiments was calculated. Afterwards, a shuttle level was modelled in the simulation environment having as test positions exactly the positions used in the experiments as transfer buffer for storage and retrieval. This calculation was performed by inverting the closed formulas of the analytical method explained in Section 5.3. The same parameters used for experiments were inserted in the simulation. Next, the simulation was performed with one shuttle, as in the experiments, and it served randomly the whole transfer buffer as in normal operation. Five repetitions were considered as enough to represent the little variance of the simulated system. Each repetition simulated 24 hours. It was then obtained from the simulation the average time interval of double cycles, starting when the shuttle leaves the O location and ending when the shuttle arrives in the I location. The time needed by the shuttle to move from the I location to the O location was not considered, because the distance between I and O locations can be chosen arbitrarily and remains constant. Then, this simulated average time interval was compared with the measured average time interval as in Table 5-3. In analogy with the European guideline FEM 9.860 [FEM-9860], since the error of the simulation is smaller than 5 % with respect to the real sub-system, the model is considered as validated.

Table 5-3: Comparison of measured and simulated travel times for stacker crane.

| Type of travel | $\Delta$t measured | $\Delta$t simulated | Maximum error | < 5 % |
|---|---|---|---|---|
| **O location → I location** | 121.0 s | 118.4 s | 2.48 s | yes |

## 5.3 Analytical Method for Validation of a Bi-Dimensional Non-Uniformly Filled Shuttle Base Level

### 5.3.1 Approach

To validate the simulation model with the prototype, an analytical method is developed to obtain the test positions. Parts of the content of this section were published in reduced form in [Sic-2021a].

First of all, the average distances travelled by shuttles transporting pallets between the different zones are calculated. Then the test positions are set such that they are separated by the same distances. Since the position of pallets in a warehouse is described by probability distributions, the trajectory of a shuttle to take a pallet from one area to another is also described by a probability distribution and can therefore not be calculated exactly in advance. Thus, to calculate the mean cycle time, the cycle times of all possible trajectories must be averaged. If it is also considered that the mean is linear, all possible trajectories can be considered independent of each other as shown in following equation:

$$\bar{\tau} = \langle \sum_i t(\vec{r}_{i-1}, \vec{r}_i) \rangle = \sum_i \langle t(\vec{r}_{i-1}, \vec{r}_i) \rangle, \tag{5-1}$$

With

- $\bar{\tau} =$ mean cycle time
- $t =$ cycle time of a single trajectory

If it is assumed that the shuttles are moving at the effective velocity $V$ and that they take the most direct route between the starting position $r_a$ and the destination $r_b$, with $d$ using the taxicab geometry[8], Equation (5-1) can be expressed as follows:

$$\bar{\tau} = \sum_i \langle \frac{d(\vec{r}_{i-1}, \vec{r}_i)}{V} \rangle = \frac{1}{V} \sum_i \langle d(\vec{r}_{i-1}, \vec{r}_i) \rangle. \tag{5-2}$$

[8] In taxicab geometry, an agent moves on a two-dimensional grid exclusively along orthogonal directions and cannot move diagonally.

Since taxicab geometry is assumed and since the mean is linear, the $x$- and $z$-directions can be assumed to be independent of each other in terms of both displacements and distances. Hence, the mean distance between the start position $r_a$ and the destination $r_b$ can be expressed as follows:

$$\begin{aligned}\langle d(\vec{r}_a, \vec{r}_b)\rangle &= \langle |x_a - x_b| + |z_a - z_b|\rangle \\ &= \langle |x_a - x_b|\rangle + \langle |z_a - z_b|\rangle\,.\end{aligned} \tag{5-3}$$

In order to express Equation (5-3) explicitly, it is necessary to represent the starting position $r_a$ and the destination $r_b$ by means of probability distributions. Although these distributions may be arbitrary, to obtain explicit formulas it is assumed that there are restricted rectangular regions in the warehouse, within which the probability distribution of the pallets can be approximated to a constant. Two of those restricted rectangular regions are denoted as respectively a and b. Such regions are defined by the coordinates in Figure 5-2 and may be overlapping. It is summed over the possible locations of pallets within an area, represented through integer numbers along a coordinate. Without loss of generality the $x$-direction is considered, since for the $z$-direction the approach is exactly the same.

To express the distance in meters, the argument of summation is multiplied by $l_x$, which is the width of a storage location. As a result, the first term of Equation (5-3) can be expressed as follows:

$$\begin{aligned}\langle x_a - x_b\rangle &= \sum_i \sum_j |i-j| P_A(i) P_B(j) \cdot l_x \\ &= \sum_{i=a_{0,x}}^{a_{e,x}} \sum_{j=b_{0,x}}^{b_{0,x}} |i-j| \frac{1}{L_{a_x}} \frac{1}{L_{b_x}} \cdot l_x\,,\end{aligned} \tag{5-4}$$

Where

$$L_{a_x} = a_{e,x} - a_{0,x} + 1 \tag{5-5}$$

$$L_{b_x} = b_{e,x} - b_{o,x} + 1\,. \tag{5-6}$$

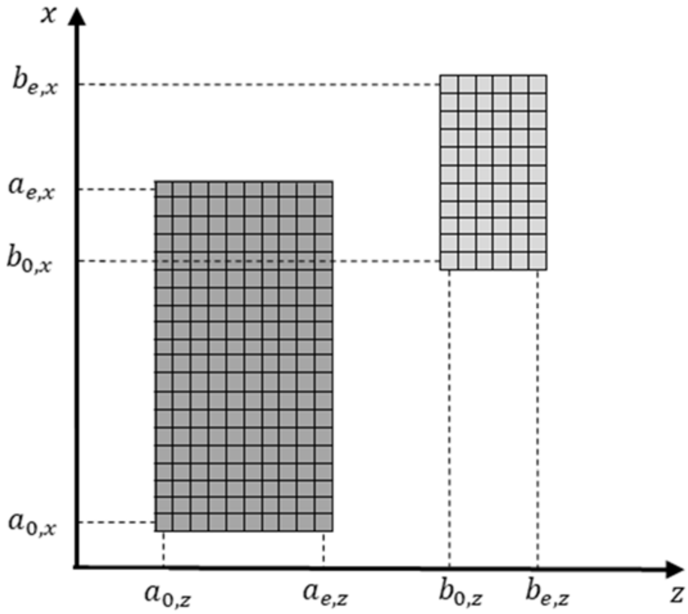



*Figure 5-2: How to define the coordinates of regions on the shuttle level [Sic-2021a]*

To eliminate the absolute value in Equation (5-4), it is necessary to distinguish different possibilities for the positioning of the two regions. The sums are then calculated using the formula for the sum of natural numbers known also as “Gaußsche Summenformel”:

$$\sum_{k=0}^{n} k = \frac{n(n+1)}{2}. \tag{5-7}$$

Since the two dimensions of each region are independent the mean distance of the trajectory of the shuttle is just the sum of the distance along the $x$- and $z$-directions:

$$d = d_x + d_z\,. \tag{5-8}$$

In the following sections, formulas are developed for $d_x$ and $d_z$, explicating Eq. (4) for the different cases. A Monte Carlo Simulation was implemented in Python to numerically verify following the formulas through the determination of the mean distances.

### 5.3.2 Possible Mutual Positions for the One-Dimensional Projections of the Two Regions

Separated Projections

If the one-dimensional projections of the two regions considered do not overlap, as in Figure 5-3, the mean distance can be calculated using the following formula:

$$d = \left| \frac{a_0 - a_e}{2} - \frac{b_0 - b_e}{2} \right| \, l_x. \tag{5-9}$$


*Figure 5-3: The unidimensional projections of two areas if there is no overlap [Sic-2021a]*

Completely Overlapping Projections

If the one-dimensional projections are identical, as in Figure 5-4, then the mean distance is as follows:

$$d = \frac{L_x^2 - 1}{3L_x} \, l_x \tag{5-10}$$

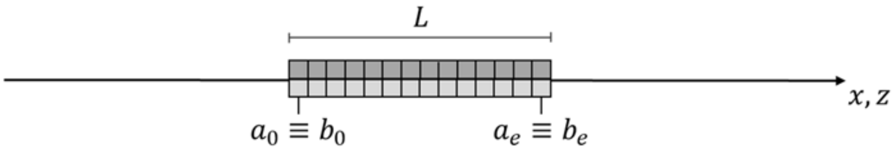



*Figure 5-4: The unidimensional projections of two completely overlapping areas [Sic-2021a]*

One Projection Contained in the Other One

If one of the two one-dimensional projections is contained in the other one, as in Figure 5-5, then the mean distance can be obtained from the following formula:

$$d = \frac{-2 + 2L_a^2 + 3L_{post}^2 + 3L_{pre}^2 + 3L_a(L_{post} + L_{pre})}{6(L_a + L_{post} + L_{pre})}\, l_x \, . \tag{5-11}$$

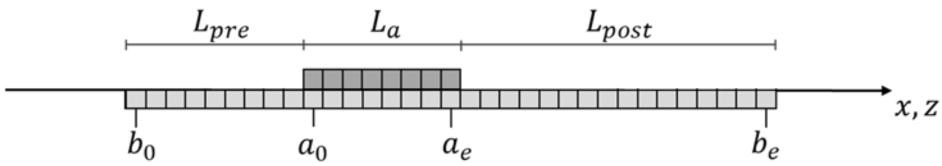



*Figure 5-5: The unidimensional projections of two areas where one projection entirely encloses the other [Sic-2021a]*

Partially Overlapping Projections

If both one-dimensional projections have some positions in common but also other positions which they do not share, as in Figure 5-6, the mean distance is represented by:

$$d = \frac{2L_o(-1 + L_o^2) + 3L_oL_{post}(L_o + L_{post}) + 3L_{pre}(L_o + L_{post})(L_o + L_{post} + L_{pre})}{6(L_o + L_{post})(L_o + L_{pre})}\, l_x \, . \tag{5-12}$$

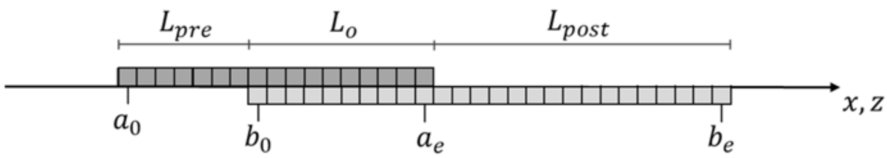



*Figure 5-6: The unidimensional projections of two areas in case projections have a partial overlap [Sic-2021a]*

### 5.3.3 Extension to Non-Rectangular Regions and Determination of the Test Positions

Not necessarily in the real world are the pallets uniformly distributed in a rectangular region. However, also in this case can the developed method be applied. On the one hand Equation (5-4) can be applied to calculate directly the mean distance. On the other hand, a region can always be approximated by one or more rectangular subregions having a uniform distribution. In order to extend the method to non-rectangular regions, it is necessary to substitute to $\boldsymbol{P_A}$ and $\boldsymbol{P_B}$ the sum of the probability distributions corresponding to the subregions as in the following formula:

$$D = \sum_{k=1}^{n} \sum_{l=1}^{m} p_k q_l d_x(k,l)\,, \tag{5-13}$$

With

- $n =$ number of rectangular subregions in zone A
- $m =$ number of rectangular subregions in zone B
- $p_k =$ probability that the pallet is in the rectangular subregion k
- $q_l =$ probability that the pallet is in the rectangular subregion l
- $d_x(k,l) =$ mean travelled distance between the subregions k and l, obtainable through Equations (5-9), (5-10), (5-11) and (5-12).

In case of correlation between $p_k$ and $q_l$, a joint probability distribution should be applied for $k$ and $l$.

To determine the test positions, it is first of all necessary to calculate the mean distances between each of the zones where the shuttle has to exchange a pallet. Afterwards, the test positions for each zone are established so that the distances between them are the same as the calculated mean distances between the zones. One should begin with small zones to determine test positions, ideally from I or O locations, because they just have one possible location, and then choose the test positions in all the other zones. Distances must be calculated in taxicab geometry. In the next section the verification of this analytical method is illustrated.

### 5.3.4 Verification of the Method

The analytical method is using a much simpler model than the discrete event simulation. In this section the analytical method with this simpler model is compared to the more sophisticated model from the discrete-event simulation for verification. Four scenarios are considered as shown in Figure 5-7, when shuttles are performing double

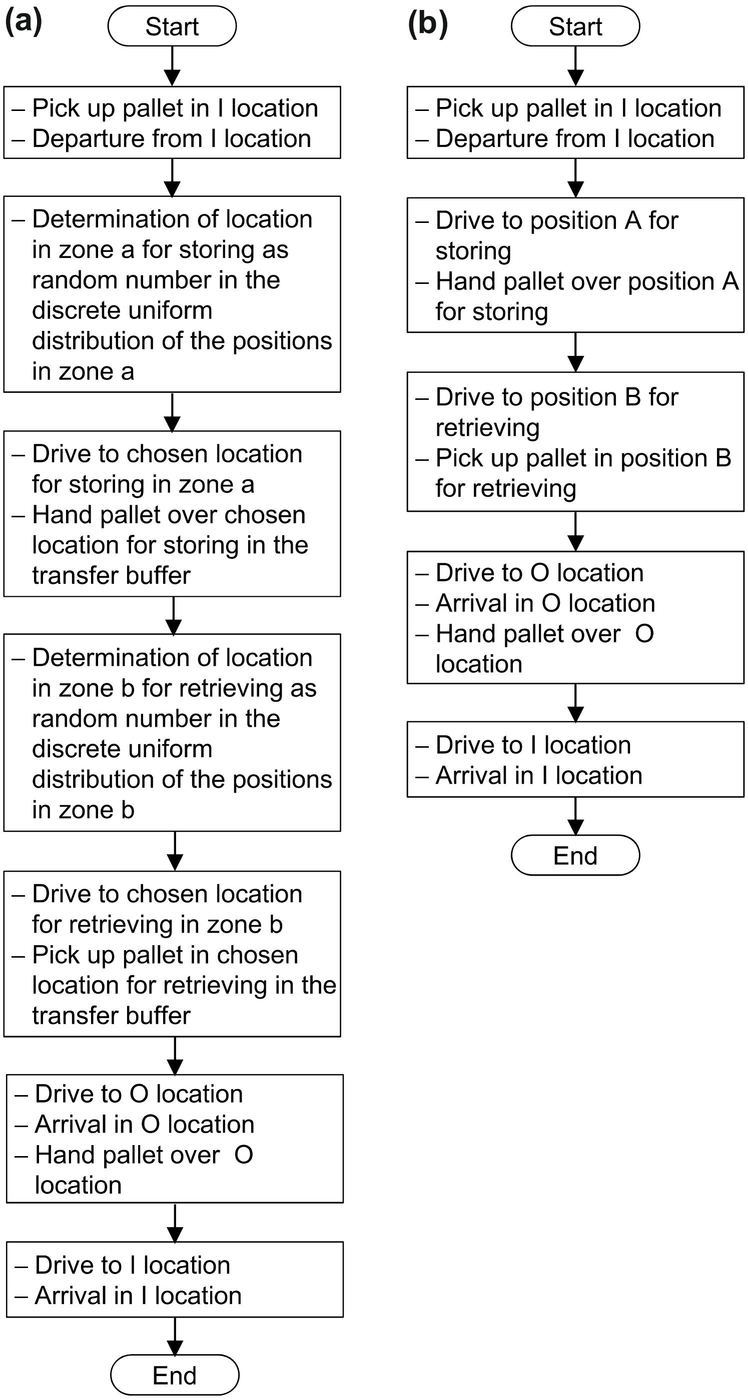



*Figure 5-7: (a) Average cycle, (b) Test cycle [Sic-2021a]*

cycles, in which one of the four different operating modes for shuttles is applied and the relative positions of storage zones to validate all four explicit Equations (5-9), (5-10), (5-11) and (5-12) are varied. If in each of the four scenarios, the error resulting from the difference between the mean cycle time and the test cycle time, both simulated, as in Figure 5-7, is smaller than 5 %, the analytical method is considered as verified because the test cycle is indeed representative for the considered zones. The reference value is chosen to be 5 % in analogy with the validation method. The units of pallets are used as measure for positions and distances. The number of units of pallet width and length is used as unit of measure for distances respectively along $x$- and $z$-direction, as defined in Figure 5-2. Five replications are executed in the simulation, each lasting 24 hours. In the following the verification of the analytical method in all four scenarios is illustrated.

**Scenario 1**

The double cycle is defined as a storage from I location to the transfer buffer plus a retrieval from the transfer buffer to O location. Zone a and b are as shown in Figure 5-8. The cycle times considered are obtained calculating average of mean cycles or of test cycles. To apply the analytical method to determine the test positions, first, the distances $d_{IA}$, $d_{AB}$, $d_{BO}$ are calculated (see Table 5-4 having the formulas used for the distances calculation in the second column). Then, the coordinates of the test positions A (7.5, 19) and B (7.5, 47) are calculated on the base of the obtained distances. In the simulation model, A and B are chosen as the pallet locations as near as possible to these coordinates calculated. In the first scenario, the positions A and B correspond to the central location of the zones. For scenarios from 2 to 4, the identification of A and B is more complicated. Then, simulations are executed and, as results, the mean cycle time amounts to 7:05 min and the test cycle time to 7:08 min. Thus, the error is just 3 s, i.e. 0.7 % of the mean cycle time. Being the error smaller than 5 %, the method is verified for the first scenario.

**Scenario 2**

The double cycle is defined for the second scenario as a storage from I location to storage locations plus a retrieval from transfer buffer to O location. Zone a and b are defined as in Figure 5-8. As for the first scenario, $d_{IA}$, $d_{AB}$, $d_{BO}$ are calculated as in Table 5-4 . Then A (5.0, 25) and B (7.5, 20) are determined. In the second scenario it is more difficult to identify the test positions. It is started from the smallest zones, that are O and I locations. The advantage is that each of them has just one location. Next, a location is selected for A set at the distance $d_{IA}$ from I location and a location for B at $\mathrm{d_{BO}}$ from O location. However, the distance between A and B is smaller than $\mathrm{d_{AB}}$ previously calculated. In order to respect the sum $d_{AB} + d_{BO}$ in the travel path of the shuttle, it is necessary to position B at distance $d_{AB}/2$ from O location. Finally, in the simulation model, A and B are selected as the pallet locations as near as possible to the calculated coordinates. From the simulations, it is obtained the mean cycle time as 7:42 min and the test cycle time as 7:47 min. The error amounts to 5 s, which is 1.1 % of the cycle time. This is smaller than 5 %, thus also the second scenario is verified.

**Scenario 3**

The double cycle is determined as a storage from I location to storage location and a retrieval from transfer buffer to O location. Unlike in the second scenario, in the third scenario the projections of zones a and b show just a partial overlap along the $z$-direction as in Figure 5-8. As in the scenarios above, $d_{IA}$, $d_{AB}, d_{BO}$ are calculated as in Table 5-4. Next, A (5.5, 33) and B (7.5, 19.5) are determined. Resulting values from the simulations are a mean cycle time of 8:22 min and a test cycle time of 8:20 min. The error is 2 s, which is 0.4 % of the mean cycle time. This is smaller than 5 %, hence the method is verified also for the third scenario.

**Scenario 4**

The double cycle includes a storage form I location to a storage location and a retrieval from a storage location located in the same zone to O location. Zone a and b are entirely overlapping as in Figure 5-8. As for the previous scenarios, $d_{IA}$, $d_{AB}, d_{BO}$ are calculated as in Table 5-4 and A (5.0, 38.0) and B (5.0, 32.5) are determined. From the simulations, the results are a mean cycle time of 7:49 min and a test cycle time of 7:51 min. The error is 2 s, corresponding to 0.4 % of the mean cycle time. This is smaller than 5 %, consequently the analytical method is verified also in the fourth scenario.

*Table 5-4: Determination of test positions [Sic-2021a].*

| Distance | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Scenario 1** | $\boldsymbol{x_a}$ | $\boldsymbol{x_b}$ | $\boldsymbol{z_a}$ | $\boldsymbol{z_b}$ | $\boldsymbol{L_x}$ | | | **Value** |
| $d_{IA} = \lvert\langle x_a\rangle - \langle x_b\rangle\rvert + \lvert\langle z_a\rangle - \langle z_b\rangle\rvert$ | 2.5 | 7.5 | 0.5 | 19.0 | - | | | 27.0 |
| $d_{AB} = \lvert\langle z_a\rangle - \langle z_b\rangle\rvert + \frac{L_x^2 - 1}{3L_x}$ | 19.0 | - | 19.0 | 47.0 | 1.0 | | | 14.9 |
| $d_{BO} = \lvert\langle x_a\rangle - \langle x_b\rangle\rvert + \lvert\langle z_a\rangle - \langle z_b\rangle\rvert$ | 47.0 | 2.5 | 47.0 | 65.5 | - | | | 43.5 |
| **Scenario 2** | $\boldsymbol{x_a}$ | $\boldsymbol{x_b}$ | $\boldsymbol{z_a}$ | $\boldsymbol{z_b}$ | $\boldsymbol{L_x}$ | $\boldsymbol{L_z}$ | | **Value** |
| $d_{IA} = \lvert\langle x_a\rangle - \langle x_b\rangle\rvert + \lvert\langle z_a\rangle - \langle z_b\rangle\rvert$ | 2.5 | 5.0 | 0.5 | 38.0 | - | - | | 40.0 |
| $d_{AB} = \frac{-2 + 2L_a^2 + 3L_{post}^2 + 3L_{pre}^2 + 3L_a(L_{post} + L_{pre})}{6(L_a + L_{post} + L_{pre})}$ | - | - | - | - | 2.0 | 32.0 | | 11.2 |
| $d_{BO} = \lvert\langle x_a\rangle - \langle x_b\rangle\rvert + \lvert\langle z_a\rangle - \langle z_b\rangle\rvert$ | 5.0 | 2.5 | 38.0 | 65.5 | - | - | | 30.0 |
| **Scenario 3** | $\boldsymbol{x_a}$ | $\boldsymbol{x_b}$ | $\boldsymbol{z_a}$ | $\boldsymbol{z_b}$ | $\boldsymbol{L_a}$ | $\boldsymbol{L_{post}}$ | $\boldsymbol{L_{pre}}$ | **Value** |
| $d_{IA} = \lvert\langle x_a\rangle - \langle x_b\rangle\rvert + \lvert\langle z_a\rangle - \langle z_b\rangle\rvert$ | 2.5 | 5.0 | 0.5 | 25.0 | - | - | - | 27.0 |
| $d_{AB}$[9] | 5.0 | 7.5 | - | - | 26.0 | 7.0 | 11.0 | 14.9 |
| $d_{BO} = \lvert\langle x_a\rangle - \langle x_b\rangle\rvert + \lvert\langle z_a\rangle - \langle z_b\rangle\rvert$ | 7.5 | 2.5 | 27.0 | 65.5 | - | - | - | 43.5 |
| **Scenario 4** | $\boldsymbol{x_a}$ | $\boldsymbol{x_b}$ | $\boldsymbol{z_a}$ | $\boldsymbol{z_b}$ | $\boldsymbol{L_o}$ | $\boldsymbol{L_{post}}$ | $\boldsymbol{L_{pre}}$ | **Value** |
| $d_{IA} = \lvert\langle x_a\rangle - \langle x_b\rangle\rvert + \lvert\langle z_a\rangle - \langle z_b\rangle\rvert$ | 2.5 | 5.0 | 0.5 | 33.0 | - | - | - | 35.0 |
| $d_{AB} = \frac{L_x^2 - 1}{3L_x} + \frac{L_z^2 - 1}{3L_z}$ | - | - | - | - | 5.0 | 23.0 | 5.0 | 14.1 |
| $d_{BO} = \lvert\langle x_a\rangle - \langle x_b\rangle\rvert + \lvert\langle z_a\rangle - \langle z_b\rangle\rvert$ | 7.5 | 2.5 | 19.0 | 65.5 | - | - | - | 51.5 |

[9] $d_{ab} = \frac{2\mathrm{L_o}(-1+\mathrm{L_o^2})+3\mathrm{L_o}\mathrm{L_{post}}(\mathrm{L_o}+\mathrm{L_{post}})+3\mathrm{L_{pre}}(\mathrm{L_o}+\mathrm{L_{post}})(\mathrm{L_o}+\mathrm{L_{post}}+\mathrm{L_{pre}})}{6(\mathrm{L_o}+\mathrm{L_{post}})(\mathrm{L_o}+\mathrm{L_{pre}})}$

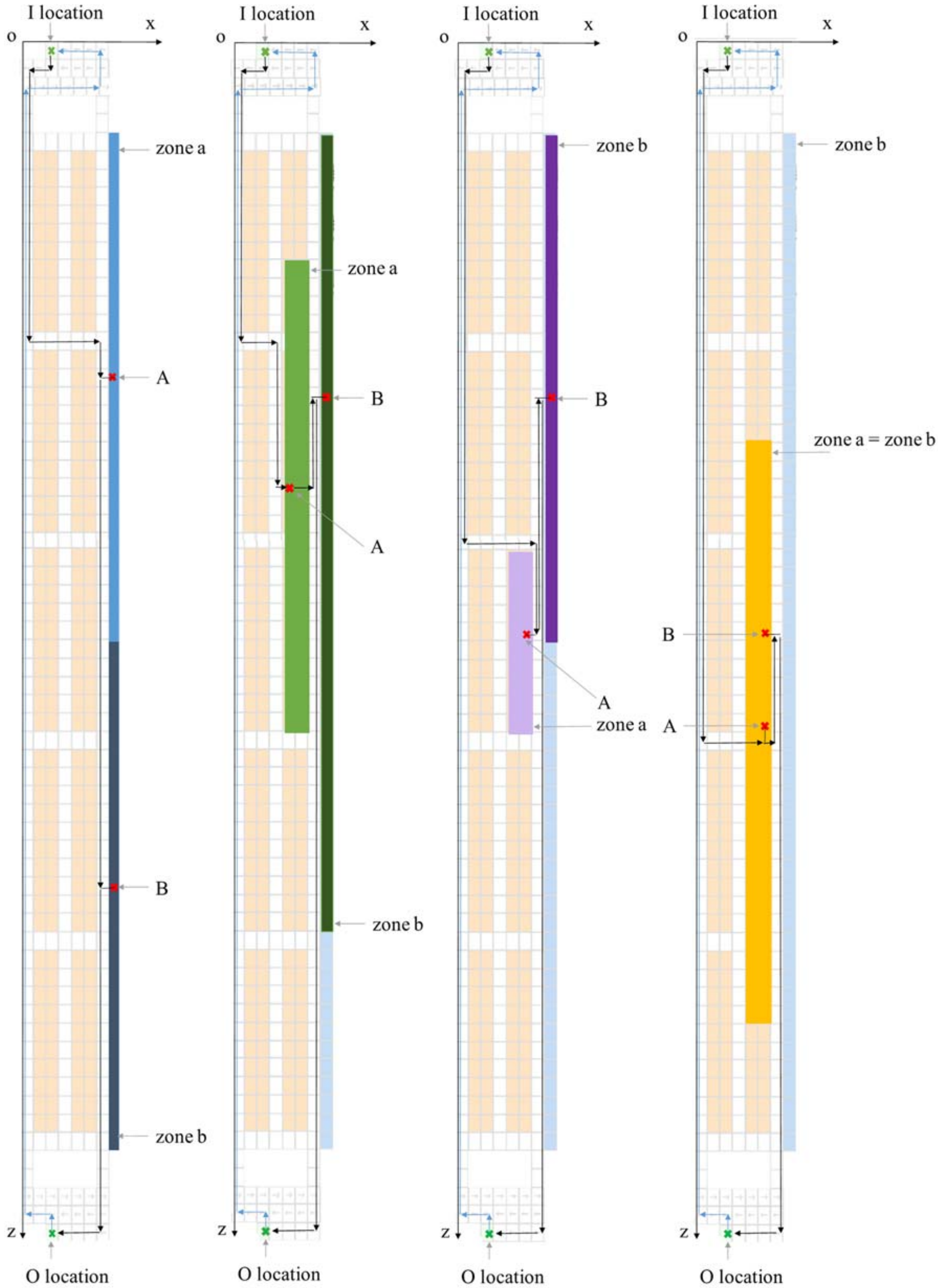



*Figure 5-8: (left to right) Scenario 1; Scenario 2; Scenario 3; Scenario 4 [Sic-2021a]*

# 6 Simulation Study

Objective of this chapter is to study quantitatively the influence of main design factors and strategies for the control system on performance of DHPWs. For this purpose, the investigation of the results obtained through discrete-event simulation is structured as in Figure 6-1. First, the main design factors of DHPWs, that can be grouped into

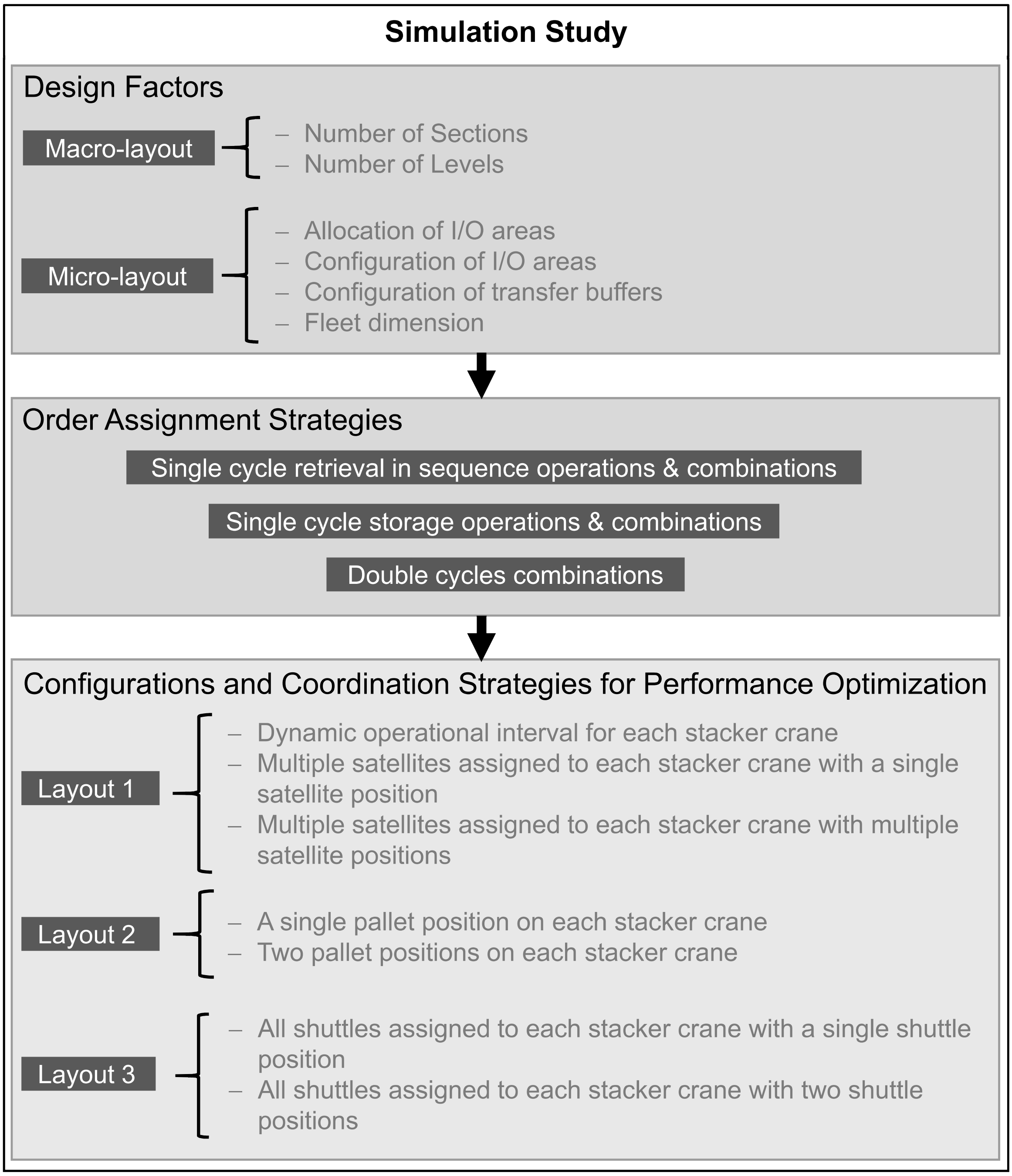



*Figure 6-1: Overview of the simulation study on DHPWs*

parameters of macro- and micro-layout, are examined. Afterwards, the focus is on the investigation of the order assignment strategies illustrated in Chapter 4. The aim is to determine which operations have the highest influence on performance as well as the potential for throughput improvement given by combinations of order assignment strategies. Then, the optimization strategies proposed in Chapter 4 for the different configurations of Layouts 1, 2 and 3 are studied with the aim to determine their potential for throughput improvement.

## 6.1 Description of Experiments

Before illustrating the results of the simulation study, it is explained in this section how the experiments are designed. First, a certain DHPW is defined, which is denoted as basic. Independently from its arrangement, it has five sections, i.e. 56 transfer buffer locations on the base, and its aisle is 83 m long. These dimensions were chosen by the author for the basic DHPW, because they approximate a general medium size warehouse in the industrial practice[10]. Unless otherwise indicated, the basic DHPW is considered to have eight levels if it is of arrangement Layout 1 and to have four levels if it is of arrangement Layout 2 or 3. The reason is that Layout 1 has a channel storage. Thus, it is expected that Layout 1, if used in the industrial practice, would be configured with a higher number of levels than Layout 2 and 3. In fact, in Layout 2 and 3, each additional shuttle level is more expensive than a level of the channel storage of Layout 1. The basic DHPW has just one module, i.e. it can store up to 512 pallets on the storage locations of the base. The shuttles are confined to their zone. This implicates that each module is independent from the others and the throughput of multiple modules can be obtained multiplying the number of modules by the throughput of just one of them. Therefore, only a single module is needed for the simulation. Each zone has one I area for incoming pallets on one end and one O area for outgoing pallets on the other end. There are two stacker cranes in the aisle. The parameters of shuttles (see Table 6-1) and stacker cranes (see

Table 6-2) are provided by the manufacturer.

The experiments show that randomness has only a small influence on the performance of the system in the simulation. Specifically, due to the low variance in performance, five repetitions per experiment have proven to be enough. To reduce the influence of

[10] The author is grateful to the engineers Dipl.-Wirtsch. -Ing. Jörg Eder and Thomas Klopfenstein of Gebhardt Fördertechnik GmbH for the support in the identification of relevant dimensions of warehouses in industrial practice and of the parameters for shuttles and stacker cranes.

transient initialisation phenomena on the model and to prevent deadlocks, each case is simulated for a period of 24 hours.

*Table 6-1: Shuttle parameters.*

| Parameters | Value |
|---|---|
| **Speed (loaded)** | $0.6\ \mathrm{m/s}$ |
| **Speed (empty)** | $1.0\ \mathrm{m/s}$ |
| **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 6-2: Stacker cranes parameters.*

| Parameters | Value |
|---|---|
| **Travel speed x** | $4.0\ m/s$ |
| **Travel acceleration x** | $0.5\ m/s^2$ |
| **Lifting speed y** | $1.0\ m/s$ |
| **Lifting acceleration y** | $1.0\ m/s^2$ |
| **Satellite speed z** | $1.2\ m/s$ |
| **Satellite acceleration loaded z** | $0.5\ m/s^2$ |
| **Satellite acceleration unloaded z** | $1.0\ m/s^2$ |
| **Time of pallet handover** | $2.0\ s$ |
| **Time of satellite handover** | $6.0\ s$ |
| **Time for positioning in channel** | $1.0\ s$ |
| **Time for positioning in front of channel** | $1.0\ s$ |

In the following sections, specific parameters of the basic DHPW are modified to evaluate different properties in each case. These modifications to the parameters are always indicated and justified at the beginning of each of the following sections.

In Table 6-3 the abbreviations used in the graphs of the simulation results are listed.

*Table 6-3: List of abbreviations used in the graphs of the simulation results.*

| Abbreviation | Meaning |
|---|---|
| **SC** | Stacker Crane |
| **STP** | Satellite Position |
| **SP** | Shuttle Position |
| **PP** | Pallet Position |
| **OC** | Overlapping Case |
| **FOI** | Fixed Operational Intervals |
| **RTB** | Random Transfer Buffer Location |
| **NTB** | Nearest Transfer Buffer Location |
| **TC** | Time Comparison |
| **LSTIT** | Longest Satellite Idle Time |
| **NST** | Nearest Satellite |
| **SCC** | Succession |
| **WD** | Wait or Drive |
| **DB** | Double |
| **OD** | One Direction |

## 6.2 Macro-Layout

The aim of this and the following sections is to respond to the research sub-question "Which elements of the macro- and the micro-layout have a main influence on the performance of DHPWs?". As already mentioned in this contribution, the macro-layout denotes the set of design elements determining the dimension of the interface between shuttles and stacker cranes, such as the length and height of the aisle, while the micro-layout defines the set of design elements of the base of the warehouse. Layouts 1, 2 and 3 present different behaviours when changing the macro-layout. Since the influence of macro-layout on performance in case of single cycle storage or double cycles is similar to the retrieval case, just sequenced retrieval as OOM is illustrated. Parts of the content of this section were published in reduced form in [Sic-2022c; Sic-2022d]. First, the variation of performance is studied when varying the length of the aisle as two, three, four, five and ten sections, i.e. respectively 38 m, 53 m, 68 m, 83 m, 159 m. As expected, for Layouts 1, 2 and 3 the travel path of shuttles decreases when the aisle is short. As a consequence, the shorter the aisle, the higher the performance for a given number of shuttles before the bottleneck caused by stacker cranes occurs. The variation in length of the aisle does not have a strong influence on performance. The maximum observable variation is for Layout 1 about 60 retrievals per hour (see Figure 6-2a), what translates to 0.5 retrievals per hour per meter of aisle for six shuttles, for

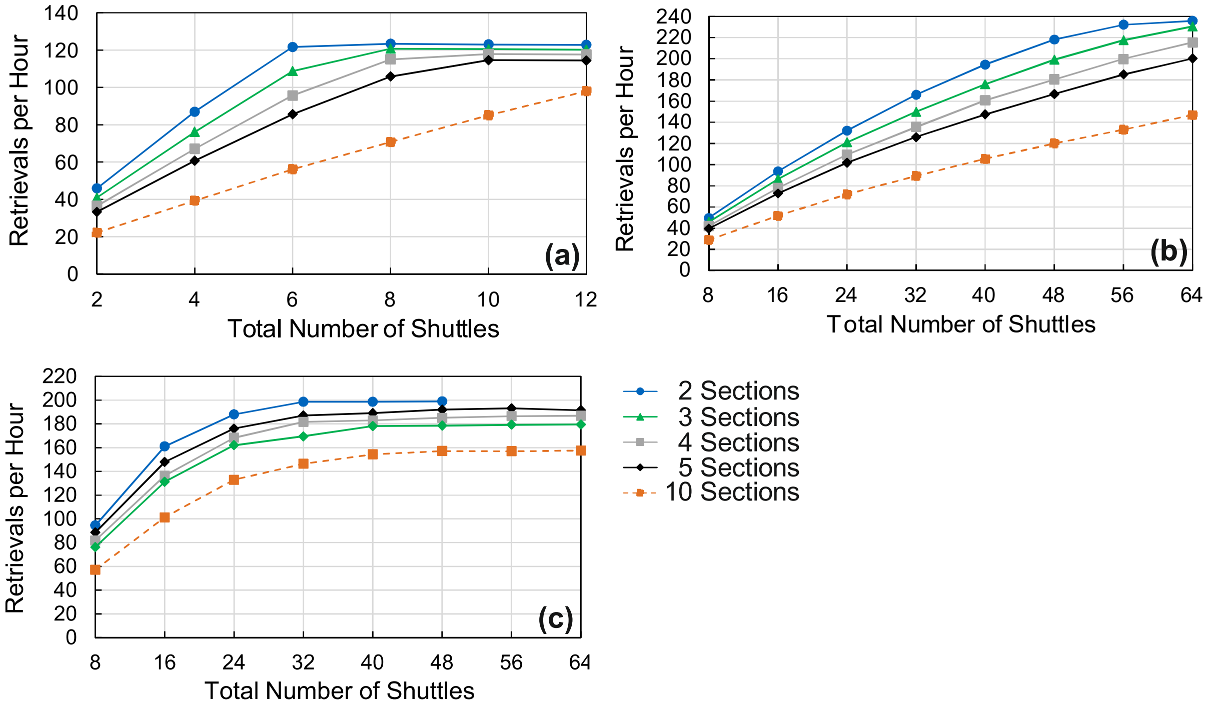



*Figure 6-2: Influence of length of the aisle on throughput for retrieval [Sic-2022c]. Data are shown for Layouts 1 (a), 2 (b) and 3 (c). Different colors and symbols indicate different numbers of sections*

Layout 2 about 0.9 retrievals per hour per meter for 56 shuttles (see Figure 6-2b) and for Layout 3 about 0.5 retrievals per hour per meter for 16 shuttles (see Figure 6-2c). Note that if Layout 3 has just two sections, the throughput for 56 and 64 shuttles is not represented, because it is not recommended using such a high number of shuttles for such a short transfer buffer, since they tend to accumulate on the base, causing congestions and a significant reduction in throughput.

Now, the modification of throughput when varying the height of DHPWs is investigated. Two, four, six and eight levels are considered, as there are 2.1 m between a level and the one above it. The sequenced retrieval and the double cycles as OOM are shown, because the influence of macro-layout on performance in case of double cycles is for Layout 2 different then in case of retrieval as OOM and can be seen as a transition between the behaviour of Layout 1 and that of Layout 3.

As regards Layout 1, for retrieval as OOM (see Figure 6-3a), the difference in the number of levels has a non-negligible influence on throughput only if the stacker cranes become the bottleneck. For ten or more shuttles, the throughput is higher for a smaller number of levels and the maximum throughput is reached by the configuration with two levels. The reason is that a higher number of levels corresponds to a higher vertical

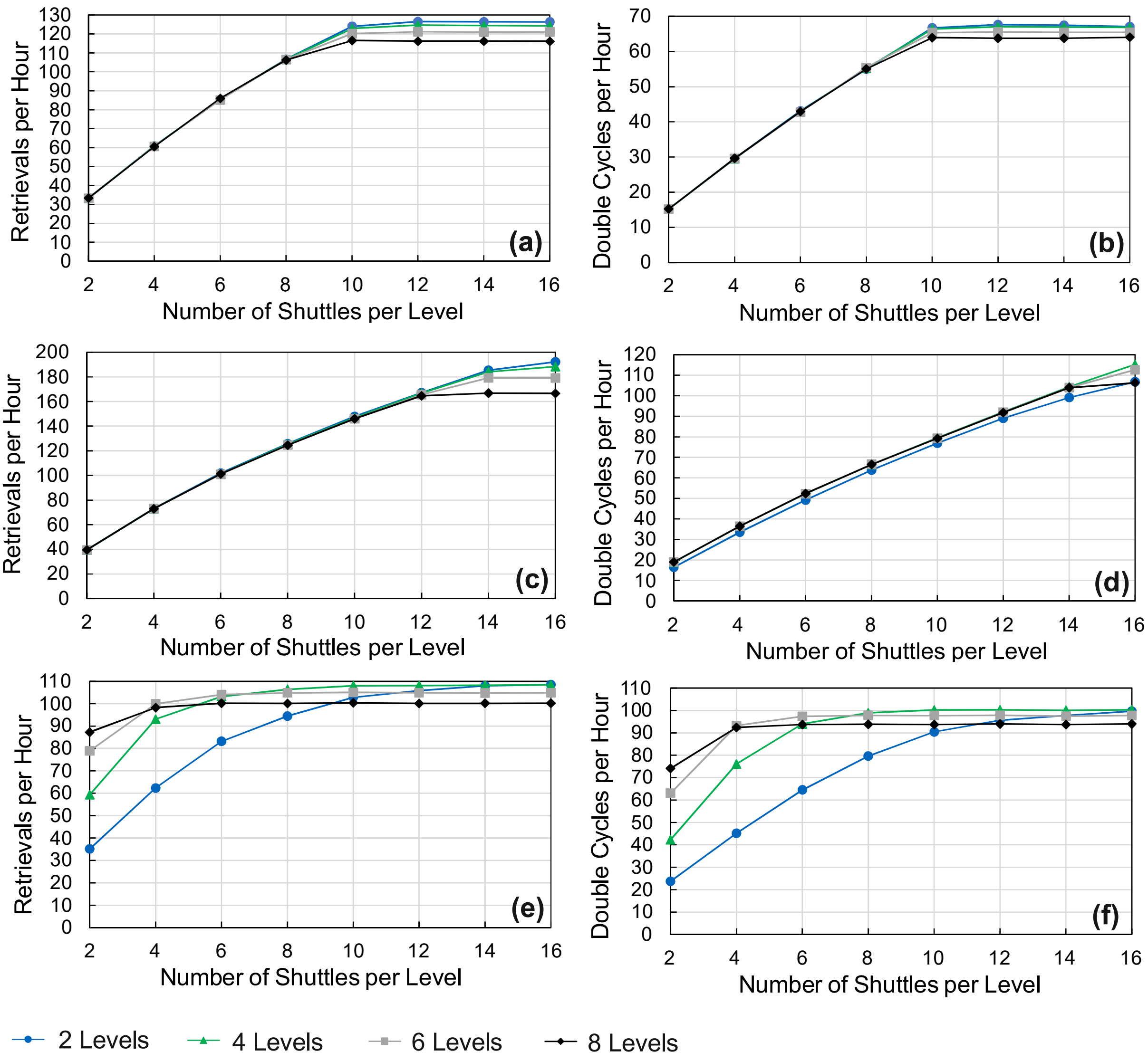



*Figure 6-3:* *Influence of height of the aisle on throughput [Sic-2022b]. The operations per hour are shown both for retrieval (a, c, e) and for double cycles (b, d, f). Layout 1 is considered in (a) and (b), Layout 2 in (c) and (d), and Layout 3 in (e) and (f)*

distance to be travelled by the stacker cranes, which leads to higher cycle times for them. A similar trend can also be found for the double cycles as OOM in Layout 1 (see Figure 6-3b).

As to Layout 2 and 3, because each further level introduces an additional number of shuttles, the throughput is represented as a function of the number of shuttles per level to obtain results comparable with those of Layout 1. In contrast to Layout 1, an increase of the number of levels in Layout 2 for the retrieval as OOM (see Figure 6-3c) causes that the bottleneck of stacker cranes happens for a smaller number of shuttles per level. When the number of levels increases, the stacker crane has to deal with a higher total number of shuttles serving the transfer buffers. As for Layout 1, for the retrieval in

Layout 2, the throughput increases with the decrease of the number of levels and the maximum is reached with two levels. Apart from that, for double cycles as OOM (see Figure 6-3d), the configuration with two levels provides the lowest throughput at least until 16 shuttles per level. The reason is that the small total number of shuttles present in the warehouse with two levels causes a stronger bottleneck, while performing double cycles, than configurations with a higher number of levels. Specifically, for two levels, shuttles are not able to serve the stacker cranes fast enough to reach the bottleneck of the stacker cranes until 16 shuttles per level.

Layout 3 is now considered. In analogy to Layout 2, an increase in the number of levels causes for both retrieval (see Figure 6-3e) and double cycles (see Figure 6-3f) a shift of the bottleneck of stacker cranes to a smaller number of shuttles per level. While shuttles are still bottleneck, the higher the number of levels, the higher the throughput reached. When the bottleneck of the stacker crane is hit, the vertical distance to be travelled by the stacker crane has direct influence on throughput, thus the higher the number of levels, the lower the throughput.

## 6.3 Micro-Layout

After having investigated in the previous section how the performance is depending on the dimensions of the warehouse, it is now investigated how the performance depends on the micro-layout. The focus is on elements of the micro-layout such as the allocation of I/O areas on both sides of the warehouse, the configuration of the I/O area, the arrangement of storage and retrieval locations on the transfer buffer. Parts of the content of this section were published in reduced form in [Sic-2022c; Sic-2022d].

### 6.3.1 Allocation of I/O Areas on One Side or on Both Sides of the Warehouse

The shuttle base of a DHPW can contain I/O areas on both sides or just on one side. If due to the plant structure, the lorries can reach the warehouse only from one side, the latter option should be applied. This does not affect the storage or the sequenced retrieval, but has a non-negligible influence on DHPWs for the double cycles as OOM.

As regards Layout 1 (see Figure 6-4a), the use of just one I/O area causes the bottleneck of stacker cranes to occur for a higher number of shuttles. The cycle distance to be travelled by each shuttle is longer with respect to the case of two I/O areas. As a consequence, the shuttles limit the throughput of the warehouse until 12 shuttles per level are used. In particular, when there are six or more shuttles per level, the difference in terms of throughput between the configurations having one I/O area and two I/O areas increases. After the bottleneck of stacker cranes is reached, the difference in throughput between the two configurations decreases and stays nearly constant. The maximum deviation in throughput between the two configurations amounts to six double cycles per hour and is reached before the bottleneck of stacker cranes for a total number of 32 shuttles.

Analogous to Layout 1, in Layout 2 (see Figure 6-4b) a raise in the number of shuttles corresponds to an increase of the difference in throughput between the configuration with one I/O area and that with two I/O areas. For both configurations, the bottleneck of stacker cranes remains not reached at least until a total number of 64 shuttles. Thus, the maximum deviation in throughput from one configuration to the other is 15 double cycles per hour for a total fleet of 64 shuttles.

In contrast to Layout 1, in Layout 3 the configuration having just one I/O area reaches the bottleneck of stacker cranes for a smaller total number of shuttles (see Figure 6-4c). Moreover, unlike Layouts 1 and 2, Layout 3 present a remarkable difference in throughput between the configuration with one I/O area and that with two I/O areas.

Specifically, the maximum deviation reached is 46 double cycles per hour. The explanation lies in the strategy of the control system of shuttles for double cycles as OOM. Shuttles operating at the side of the warehouse containing the O location perform exclusively retrievals. Meanwhile, shuttles on the other side of the warehouse, where the I location is situated, perform uniquely storage. As a result, empty shuttles that just completed a retrieval need to be transported to a different level than the base to be able to pick another pallet, if there is just one I/O area. To the contrary, if there are two I/O areas, empty shuttles that just completed a retrieval can pick a pallet for storage on the base. Consequently, double cycles are more efficient with two I/O areas and a much higher throughput is reached than in case just one I/O area is used.

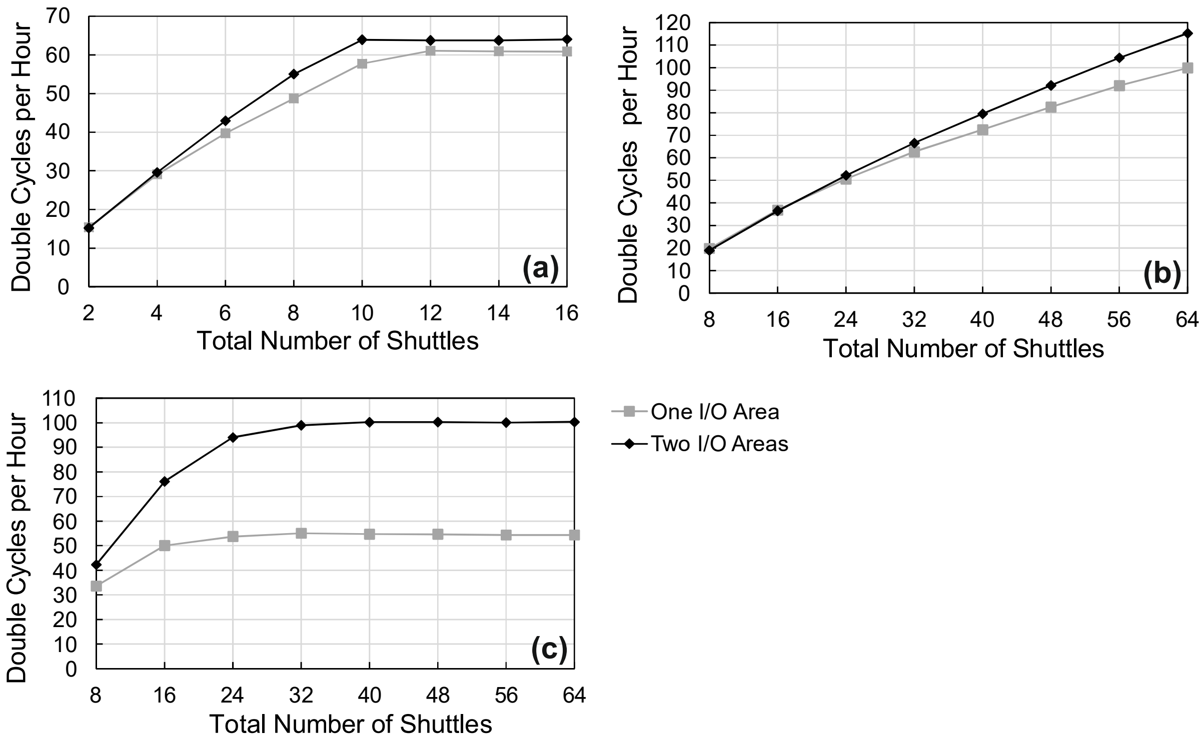



*Figure 6-4:* *Influence of I/O areas allocation on throughput [Sic-2022b]. Data are shown for Layouts 1 (a), 2 (b) and 3 (c). Grey lines with circles show cases with a single I/O area, while blue lines with rhombuses show cases with two I/O areas*

### 6.3.2 Configuration of the I/O Area

Depending on the control strategies used for the shuttles in the automated hybrid warehouse, different configurations of the I/O areas enable to reach high throughputs. Empty storage locations can be driven across by both empty or loaded shuttles. In the investigation it is assumed that empty shuttles are able to move under storage locations even if these locations are loaded. However, this is not always possible due to rail design. In this respect, the shuttles operating in the left zone drive a longer route from the I location to the transfer buffer than the ones in the right zone, because they cannot drive across the storage locations in Figure 6-5 (left). This case was investigated by *Yu* in her master thesis, which the author of this dissertation supervised. *Yu* found that the throughput in the left zone is less than in the right zone. For example, for Layout 2, after 6 hours there are 40 storages per hour of difference between the possible throughputs of the two zones.

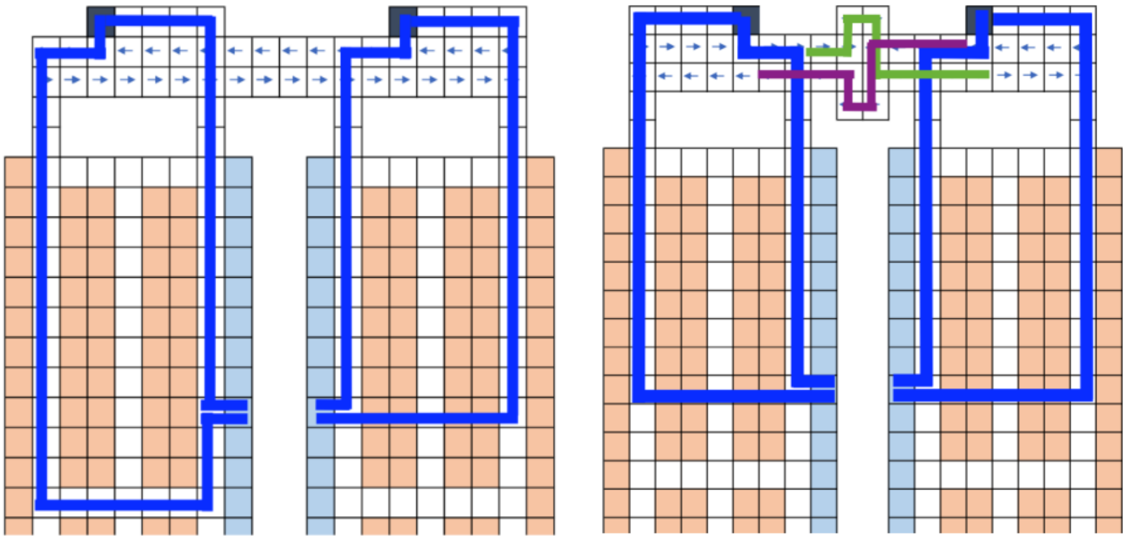


*Figure 6-5: (left) Basic design of I/O area; (right) I/O area designed to balance the throughput in both sides of the warehouse [fml-2021, pp. 45 et seqq.]*

As demonstrated by *Yu*, the configuration in Figure 6-5 (right) solves this problem enabling also the storing shuttles on the left side to drive along a route mirrored to the one on the right side. As a result, both zones provide the same throughput. Yet, the problem of this micro-layout is that, in the event it should be necessary to move some shuttles from one zone to the other, collisions will happen among the shuttles of the zone and the ones migrating in it. A possible solution is to add four more locations in the aisle between the two zones. Thereby, the shuttles migrating from the left zone to the right one should follow the green route and the ones moving in the opposite direction should follow the violet way. [fml-2021, pp. 45 et seqq.]

Moreover, in Section 6.5.3, Section 6.5.4 and Section 6.5.5, it is demonstrated that the design of the I/O area becomes crucial to exploit the performance potential of the warehouse, when very high throughputs are reached using optimization strategies for the control system. In particular, the I/O area design that reaches the highest efficiency is shown in Figure 6-6.

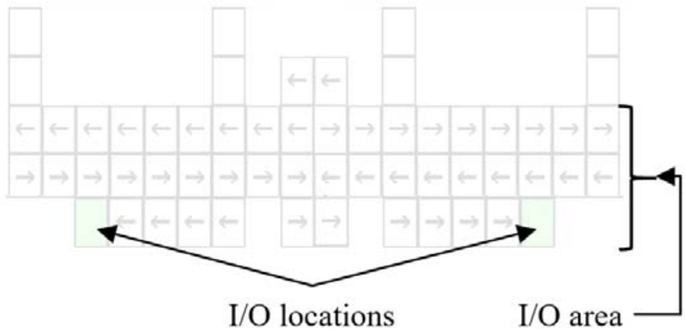



*Figure 6-6: I/O area designed to exploit high dynamics [Sic-2022b]*

### 6.3.3 Configuration of Transfer Buffers

A further micro-layout element affecting the throughput of a DHPW is the design of the transfer buffer. By transfer buffer design it is meant the positioning of SLTBs and RLTBs. The basic Layouts 1, 2 and 3 , i.e. with the transfer buffer having a length of 56 locations, are considered. Both SLTBs and RLTBs are grouped and alternate, i.e. after $n$ SLTBs on the transfer buffer $n$ RLTBs follow, succeeded by $n$ SLTBs, and so on. The transfer buffer design for the operational interval of each stacker crane with $n$ locations being grouped is denoted as TB$n.$ For one stacker crane in the aisle the length of the operational interval is identical to the length of the transfer buffer. Therefore, for example, TB1 means that single SLTB and RLTB alternate on the transfer buffer, while TB28 means that the first half of the operational interval of the crane, located close to the I location, is reserved for SLTBs. For two stacker cranes in the aisle, each operational interval is one half of the transfer buffer. This means that, for example, in TB14 the first half of the operational interval of each crane, located close to the I location, is reserved for SLTBs. These designs of transfer buffers are shown in Figure B-1 for none or one stacker crane and Figure B-2 for two stacker cranes.

If no stacker crane is used, i.e. when considering just the shuttle base, for both retrieval (seeFigure Figure 6-7a) and double cycles (see Figure 6-7b) as OOM, the configuration TB28 (black lines) reaches the highest throughput. This configuration has retrieval and storage positions on the transfer buffer that are positioned closer respectively to the O or I location. Consequently, shuttles travel along short cycle distances, so their cycle times are short. The various configurations show a higher difference in terms of throughput in case of retrieval as OOM compared to double cycles. The reason is that for double cycles the shuttles have to travel to both a SLTB and a RLTB, making it less significant if one position is located better at the cost of the other.

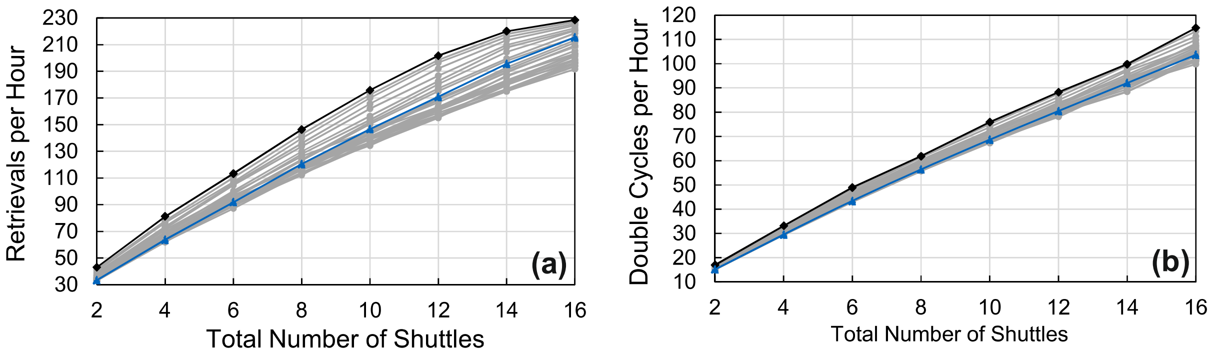



*Figure 6-7: Influence of configurations of transfer buffer on throughput without stacker cranes [Sic-2022c]. Black lines indicate TB28 and blue lines TB19. Grey lines all other configurations.*

Regarding Layout 1, on the one hand there is only a negligible difference in throughput between the various configurations of the transfer buffer, when the bottleneck of stacker cranes, i.e. the plateau of throughput, is reached. This occurs for both retrieval (see Figure a, b) and double cycles (see Figure c, d) as OOM, in case one or two stacker cranes are used. On the other hand, the difference in throughput between configurations is significant when the shuttles are the bottleneck, and increases when the number of shuttles raises, in analogy to the case where only the shuttle base is considered. Configurations TB28 and TB14 (black lines) reach their maximum throughput for one and two stacker cranes respectively, when shuttles are the bottleneck. However, TB19 and TB10 (blue lines), that is the application of TB19 on the operational interval of each stacker crane in case of two cranes, guarantee the maximum throughput when the stacker crane is the bottleneck. The reason is that TB19 has just 18 retrieval locations, which are positioned in the centre of the transfer buffer, compared to 28 retrieval locations of TB28 located at the side of the transfer buffer. As a result, TB19, and similarly TB10, enable the stacker crane to travel an, on average, shorter path and, since the stacker crane is the bottleneck, the distance between transfer buffer of the base and O location has no significant influence on throughput.

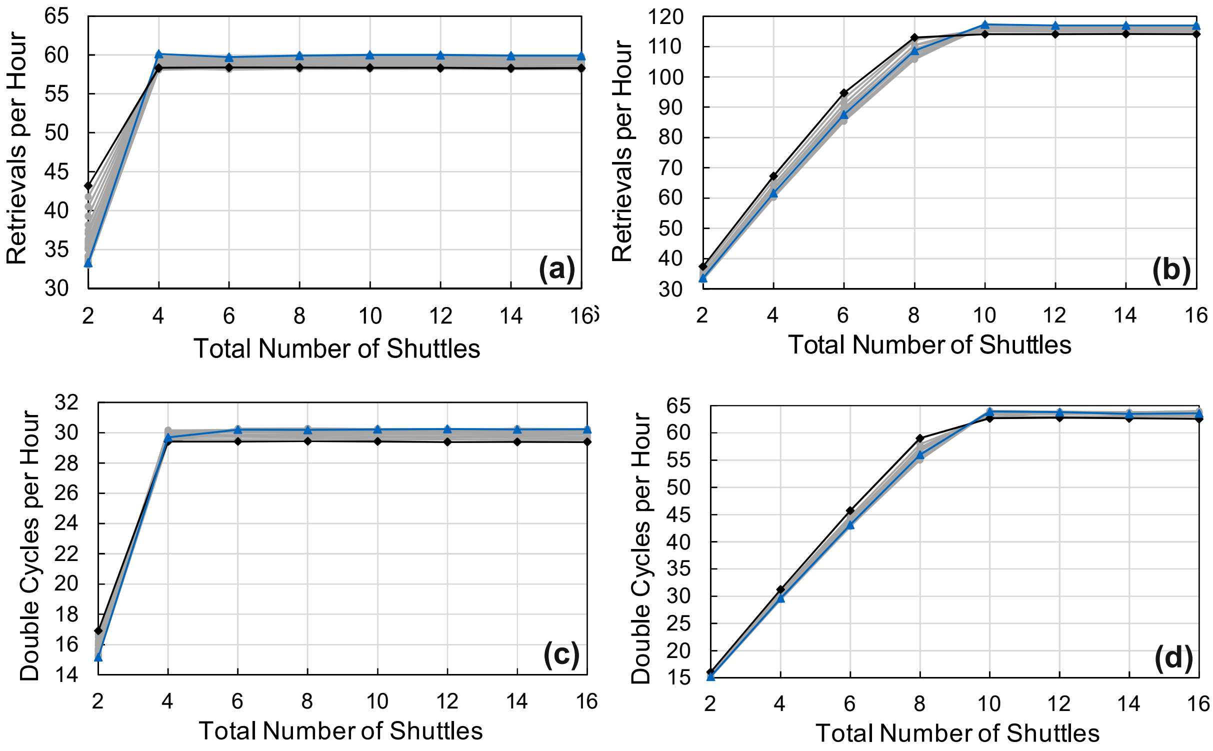



*Figure 6-8:* *Influence of configurations of transfer buffer on throughput for Layout 1 [Sic-2022c]. Black lines indicate TB28 and blue lines TB19 for one stacker crane (a, c). Black lines indicate TB14 and blue lines TB10 for two stacker cranes (b, d). Grey lines indicate all other configurations.*

In Layout 2, unlike Layout 1, for the retrieval as OOM and one crane (see Figure 6-10a) configurations can be divided into two classes when the bottleneck of the crane is reached, i.e. for 24 or more shuttles. The one constituted by TB1 to TB17 is in the lower range of throughput and that constituted by TB18 to TB28 reaches is in the higher range. Between the two classes the minimum difference in throughput is 5 retrievals per hour. In analogy to Layout 1, the maximum throughput is reached by TB28 (black line), when shuttles are the bottleneck of the system, and by TB19 (blue line) when the stacker crane is the bottleneck. The retrieval as OOM with two stacker cranes (see Figure 6-10b) follows a similar behaviour when reaching the bottleneck of stacker cranes by 64 shuttles. To the contrary, when double cycles are performed (see Figure 6-10c, d), the balancing in the distance caused by the alternation of retrieval and storage orders avoid the splitting of configurations into two throughput classes.

For Layout 3 (see Figure 6-10), the bottleneck of stacker cranes is reached already for a small number of shuttles because of the high number of orders to be executed by the cranes to return empty shuttles to levels. In analogy to Layout 1, and Layout 2 for double cycles, the difference between configurations is small when the bottleneck of stacker cranes is reached. Therefore, for Layout 3, to show the behaviour of the different configurations, a larger scale is used in Figure 6-10a, c. However, a non-negligible

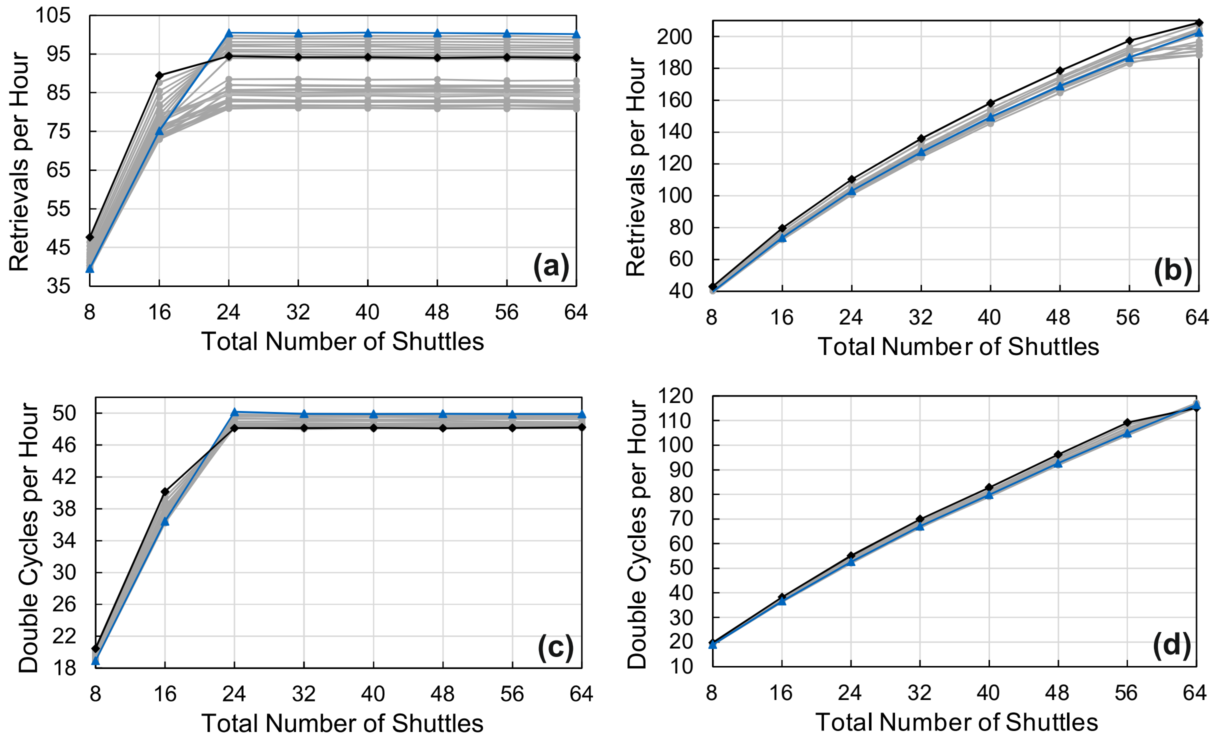



*Figure 6-10: Influence of configurations of transfer buffers on throughput for Layout 2 [Sic-2022c]. Black lines indicate TB28 and blue lines TB19 for one stacker crane (a, c). Black lines indicate TB14 and blue lines TB10 for two stacker cranes (b, d). Grey lines indicate all other configurations.*

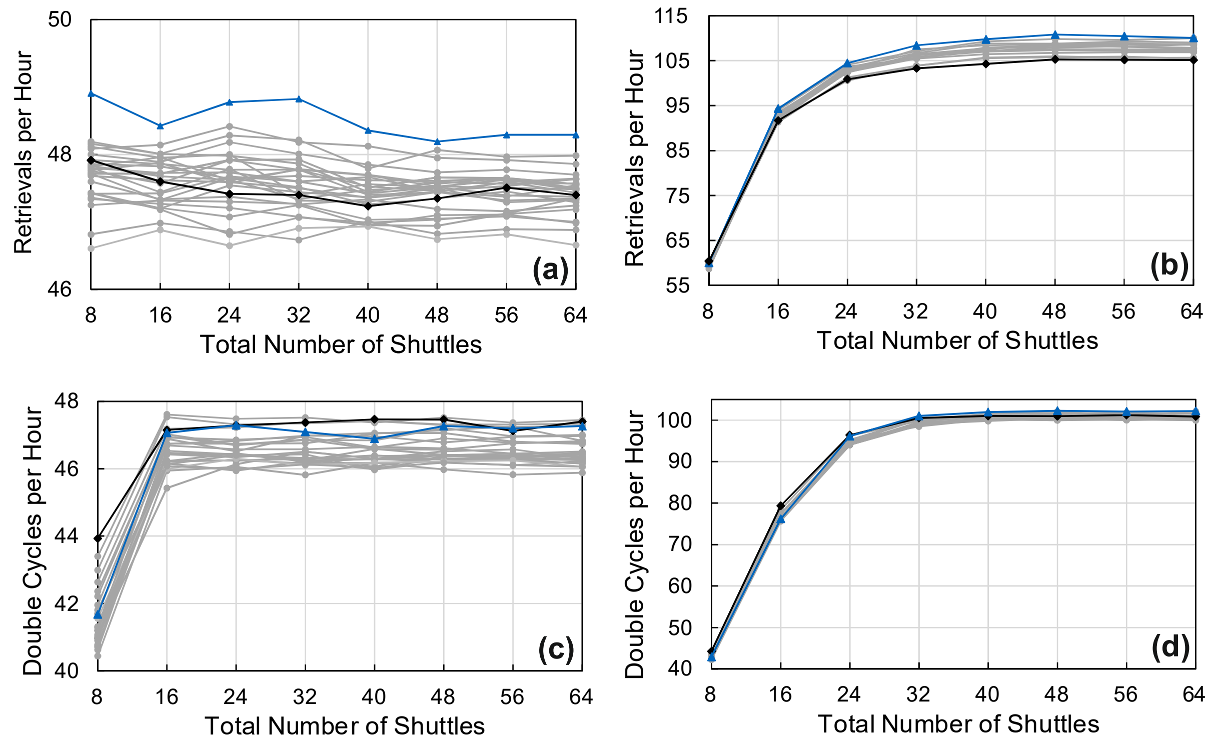



*Figure 6-10: Influence of configurations of transfer buffers on throughput for Layout 3 [Sic-2022c]. Black lines indicate TB28 and blue lines TB19 for one stacker crane (a, c). Black lines indicate TB14 and blue lines TB10 for two stacker cranes (b, d). Grey lines indicate all other configurations.*

difference between configurations occurs for retrieval with two stacker cranes when cranes are the bottleneck as in Figure 6-10b. In this case, the difference in throughput between configurations increases asymptotically and TB10 reaches the maximum throughput. This happens in analogy to Layouts 1 and 2, when the stacker crane is the bottleneck.

### 6.3.4 Fleet Dimension

Specifically, for Layout 2 an optimization of the fleet dimension is possible. As shown in Figure 6-11, the number of shuttles on the base level of Layout 2 has a major influence on throughput. This means that the number of shuttles on levels can be reduced to a certain value without significantly affecting the performance. As for the retrieval as OOM, a reduction of the number of shuttles on levels from eight to two in case one (see Figure 6-11a) or two stacker cranes (see Figure 6-11b) are used do not cause a significant decrease in throughput, as long as the base still has eight shuttles. The same happens starting with six or four shuttles per level. Regarding double cycles as OOM, for one (see Figure 6-11c) or two stacker cranes (see Figure 6-11d) reducing

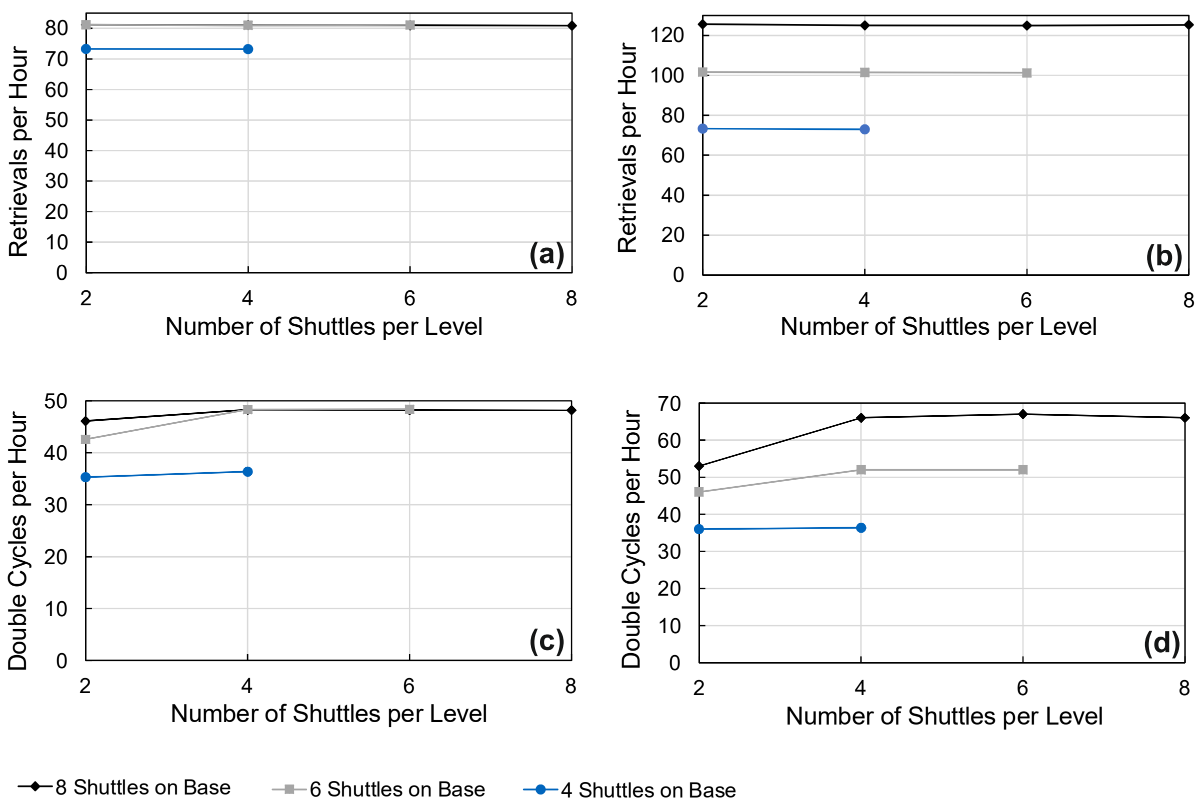



*Figure 6-11: Influence of the fleet size of shuttles of levels on throughput for Layout 2 [Sic-2022c]. The operations per hour are shown both for retrieval (a, c) and for double cycles (b, d). Different colors and symbols indicate different numbers of shuttles on base*

the number of shuttles on each level from eight to four does not cause a remarkable decrease of throughput, provided that the base still has eight shuttles. The same happens starting with six or four shuttles on each level. Twice as many shuttles are required as minimum number of vehicles per level, because shuttles have twice as many orders to execute in case of double cycles as OOM, compared to retrieval as OOM.

## 6.4 Order Assignment Strategies

This section examines the influence of the different order assignment strategies, which were illustrated in Chapter 4, on the throughput of the basic DHPW with Layout 1. The aim is to complete the answer to the research sub-question "Which **order assignment strategies** can be applied to the connection between shuttles and stacker cranes in the different operating processes to improve the throughput?" utilizing simulations. For this purpose, it is necessary to consider separately the cases retrieval in sequence, storage and double cycles. Parts of the content of this section were published in reduced form in [Sic-2021b].

### 6.4.1 Retrieval in Sequence Combinations

Firstly, the influence on throughput of each decision-making operation for retrieval in sequence is analysed.

The graph in Figure 6-12a is obtained requiring the shuttles to choose the pallets available on the transfer buffer at random and the stacker crane to choose the shuttles to activate at random. However, non-random strategies are used when the stacker crane selects the available transfer buffer position to serve. Particularly, for less than 12 shuttles the warehouse reaches the highest throughput if the stacker crane chooses available positions on the transfer buffer as near as possible to the O location (grey line). The explanation for this behaviour is that for less than 12 shuttles the shuttles are the system's bottleneck. Therefore, if the stacker crane serves positions on the transfer buffer as near as possible to the O location, it reduces the travel distance of the shuttles. This results in a mitigation in the bottleneck of shuttles, thus in a throughput increase. For 12 shuttles, the stacker crane should select the position available for the longest time (green line) to maximize the throughput. The reason is that 12 shuttles mark a transition from the shuttles to the stacker crane being the bottleneck. Thus, by improving the distribution of orders, an increase in performance can be reached for both sub-systems. For 14 shuttles or more, the best option to maximize the throughput is for the stacker crane to serve the position which minimizes the length of its travel

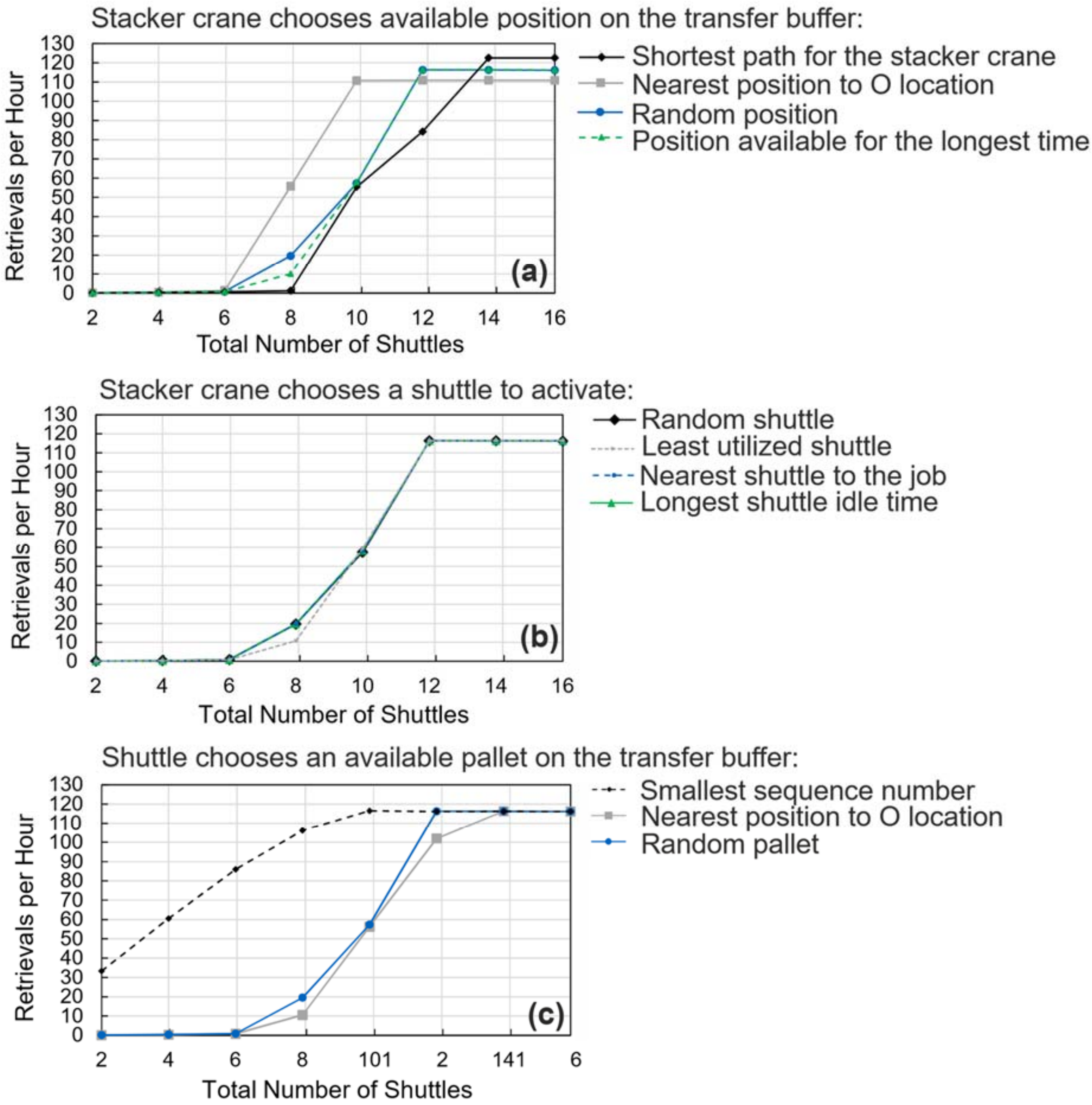


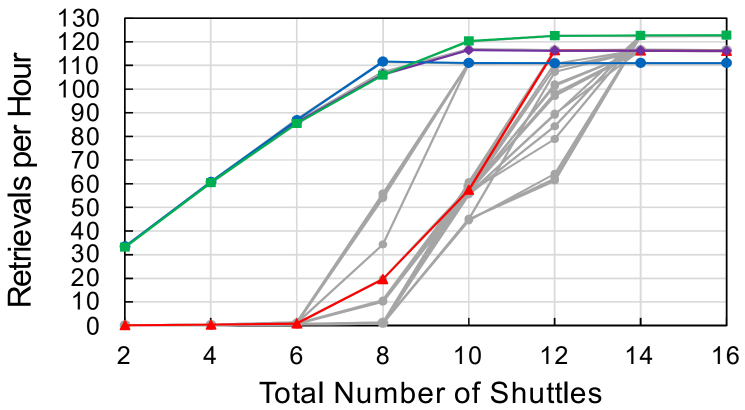

*Figure 6-12: Influence of operations (a) "stacker crane chooses an available position on the transfer buffer", (b) "stacker crane chooses a shuttle to activate", (c) "shuttle chooses an available pallet on the transfer buffer on throughput [Sic-2021b]*

path (black line). In fact, minimizing the travel path of the stacker crane not only delays reaching the bottleneck caused by the stacker cranes, but also mitigates it.

Now, the graph in Figure 6-12b is considered. In this case, the stacker crane chooses the positions on the transfer buffer randomly and the shuttles select the pallets to retrieve randomly. Yet, the stacker crane decides which of the shuttles to activate according to a non-random strategy, e.g. it activates the shuttle nearest to the pallet to be retrieved. However, none of such non-random strategies provides an increase in throughput compared to the random strategy (black line). The explanation is that all idle shuttles have the same distance in the z-direction to the transfer buffer. Therefore, choosing for example to activate the shuttle which is nearest to the pallet to be retrieved only brings a negligible saving of travel distance for this shuttle.

The graph in Figure 6-12c results by requiring that the stacker cranes choose randomly not only the shuttles to activate, but also the positions on the transfer buffer to serve, while shuttles choose the pallets to retrieve from the transfer buffer according also to non-random strategies. Neither choosing the pallets which are nearer to the O location (grey line) nor choosing them randomly (blue line) leads to a high throughput. Since the warehouse is performing sequenced retrieval as OOM, the only way to have a high throughput is for the shuttles to first pick the pallet with the smallest sequence number (black line). As a result, for cases with less than 12 shuttles, the shuttles have to wait so long at the transfer buffer that the performance results are strongly compromised. However, 12 or more shuttles are so fast in serving the transfer buffer, that there is an evident reduction of the waiting time, with consequent increase of the throughput.

In Figure 6-13 there are the results obtained by simulation of all 48 combinations of order assignment strategies for the three decision-making operations of OOM retrieval in sequence.




| | Stacker crane chooses available position on the transfer buffer: | Stacker crane chooses a shuttle to activate: | Shuttle chooses an available pallet on the transfer buffer: |
|---|---|---|---|
| red | Random position | Random shuttle | Random pallet |
| purple | Random position | Random shuttle | Smallest sequence number |
| blue | Nearest position to O location | Least utilized shuttle | Smallest sequence number |
| green | Shortest path for the stacker crane | Least utilized shuttle | Smallest sequence number |

*Figure 6-13: Throughput provided by 48 combinations of order assignment strategies for retrieval in sequence [Sic-2021b]. The table shows which combination of operations are used for the colored lines in the graph*

The most significant combinations are represented by the four coloured lines. The best throughput is reached by the combination depicted by the green line. In this case, the stacker cranes choose the location on the transfer buffer minimizing their path and activate the shuttles waiting for the longest time, while the shuttles pick up the pallets with the smallest sequence number. This combination is very similar in throughput with less than ten shuttles to other combinations in which the shuttles choose the pallet with the smallest sequence number. However, it reaches the highest throughput in case of 10 or more shuttles, when the bottleneck of the stacker crane is hit.

In the combination represented by the violet line the shuttles select the pallet with the smallest sequence number, but the stacker cranes take always random decisions. In comparison with the green combination, this results in a decrease in throughput, when the stacker cranes are the bottleneck. This is also visible from the time components for the shuttles in Figure 6-14. There, the green combination corresponds to Figure 6-14a and the violet combination to Figure 6-14b. The latter shows that when the bottleneck of stacker cranes is reached (i.e. for 10 or more shuttles), the shuttles spend more time waiting for an available pallet to be delivered to the transfer buffer by the stacker cranes than in Figure 6-14a.

The combination represented by the blue line is similar to the green one, except for the fact that the stacker crane brings pallets to the locations on the transfer buffer which are nearer to O. This, when the stacker cranes are the bottleneck, has the effect of reducing the throughput even more than in the violet combination. This is demonstrated also by Figure 6-14c, in which the shuttles wait for an available pallet longer than in Figure 6-14a and Figure 6-14b.

In the end, the red line is the one representing the combination of all random decisions for both the stacker cranes and the shuttles. From the low throughput of this combination, one more time the strong influence on performance of not picking the pallets with the smallest sequence number is shown. This is clear also from Figure 6-14d, that reveals how much impact the time component of shuttles waiting for the previous pallet number to be retrieved has in this combination.

### 6.4.2 Storage Combinations

As for the sequenced retrieval, the effect of each of the decision-making operations on throughput for the storage operation is now examined.

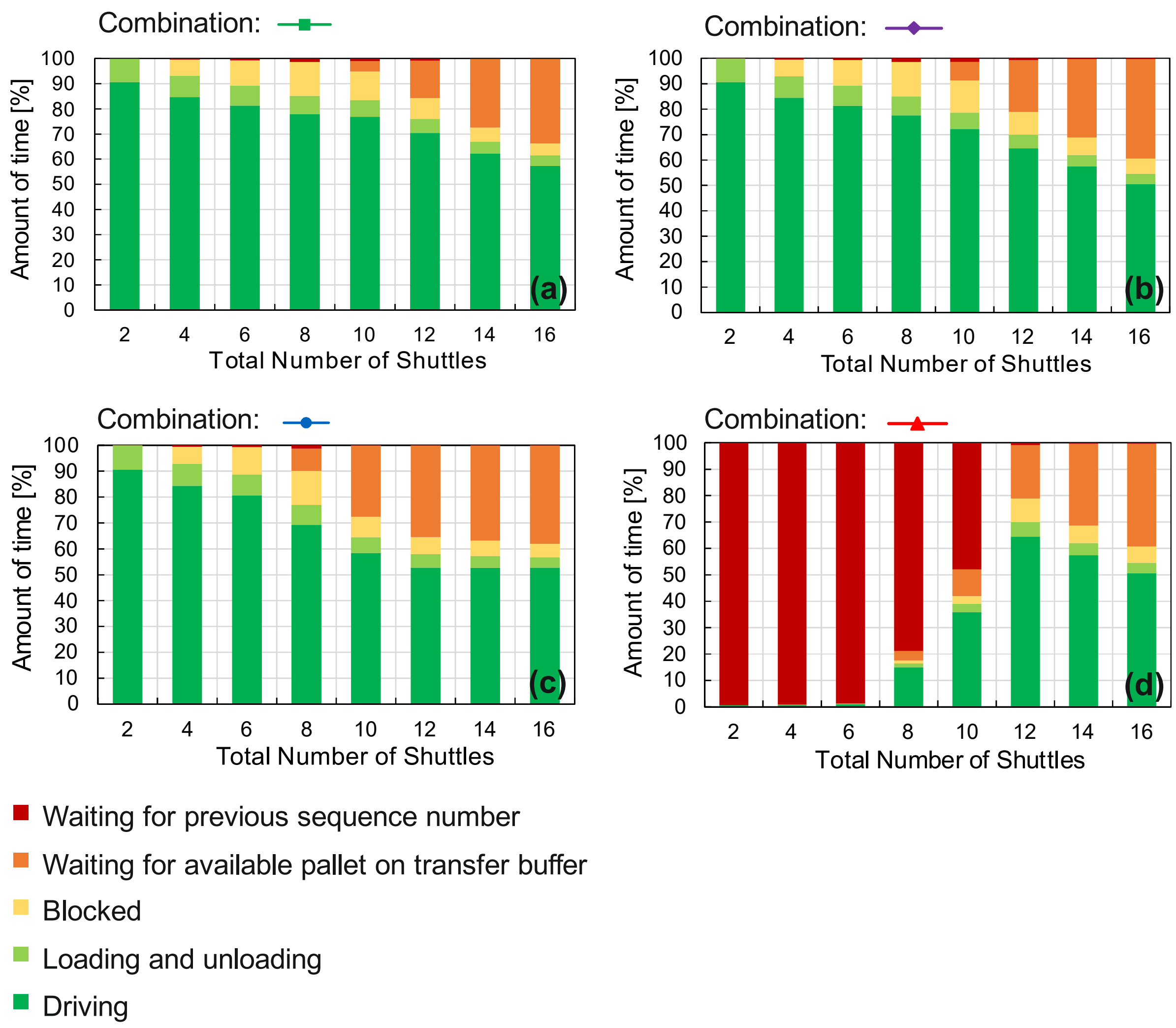
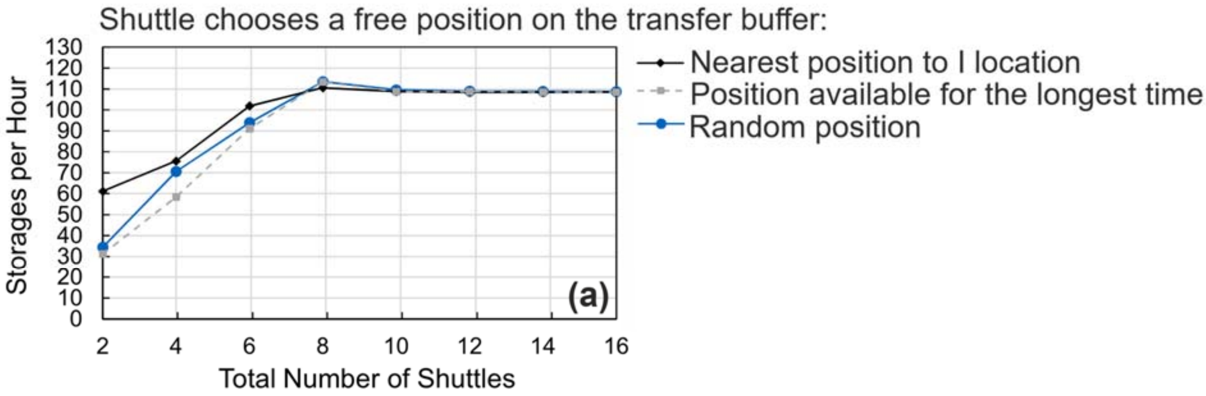



*Figure 6-14: Time components of combinations for retrieval in sequence [Sic-2021b]. In the title of each figure the corresponding line in Figure 6-13 is shown*

For Figure 6-15a the assumption was made that the stacker cranes choose pallets to store randomly, while shuttles adopt also non-random strategies to select locations on the transfer buffer. The results show that the order assignment strategy adopted by the shuttles has influence on throughput only when the shuttles are the bottleneck of the throughput i.e. for less than 10 shuttles. To reach the highest throughput, the shuttles should choose the location on the transfer buffer which is the nearest to the I location (black line). This enables them to drive a shorter path and therefore save time in the execution of each order. As visible from the graph, this effect is stronger for a smaller number of shuttles, because in this case the saved time per shuttle per order has more weight.

Figure 6-15b is obtained requiring that the shuttles choose the location on the transfer buffer randomly, while the stacker cranes select the pallets to store by non-random



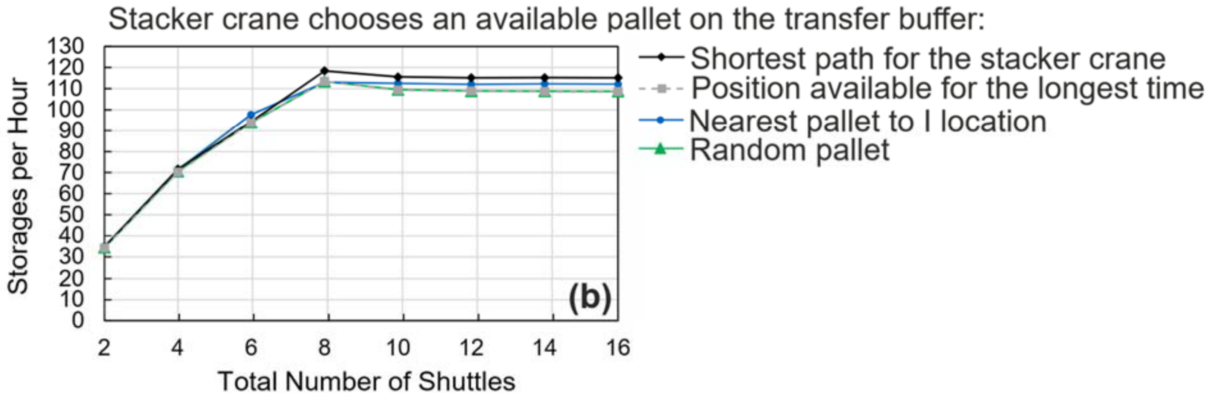




*Figure 6-15: Influence of operations (a) "shuttle chooses a free position on the transfer buffer", (b) "stacker crane chooses an available pallet on the transfer buffer" on throughput [Sic-2021b]*

strategies. From the experiments it is clear that for the OOM storage, unlike the retrieval, order assignment strategies for the stacker cranes have influence only when the stacker cranes are bottleneck. The highest throughput is reached when the stacker crane chooses the pallet in the location that minimizes its travel path (black line). However, the improvement in throughput is not as high for any of the non-random strategies for the stacker cranes. The reason is that in case of OOM storage, too many shuttles lead to disturbances of the stacker cranes on the transfer buffer, since they tend to cluster near the I location.

The results in Figure 6-16 derived by simulation of the 11 combinations of order assignment strategies for the OOM storage are now investigated. Combinations represented by the three coloured lines are the most relevant. When the shuttles are bottleneck i.e. for less than 8 shuttles, the highest throughput is guaranteed if shuttles and stacker cranes select respectively the available position on the transfer buffer and the available pallet which is the nearest to the I location (blue line). The motivation is that by doing so, the shuttles are confined in a smaller area than in case shuttles and stacker cranes choose positions and pallets randomly (green line). Therefore, their travel distance is shorter which leads to reduced travel times and finally to a higher

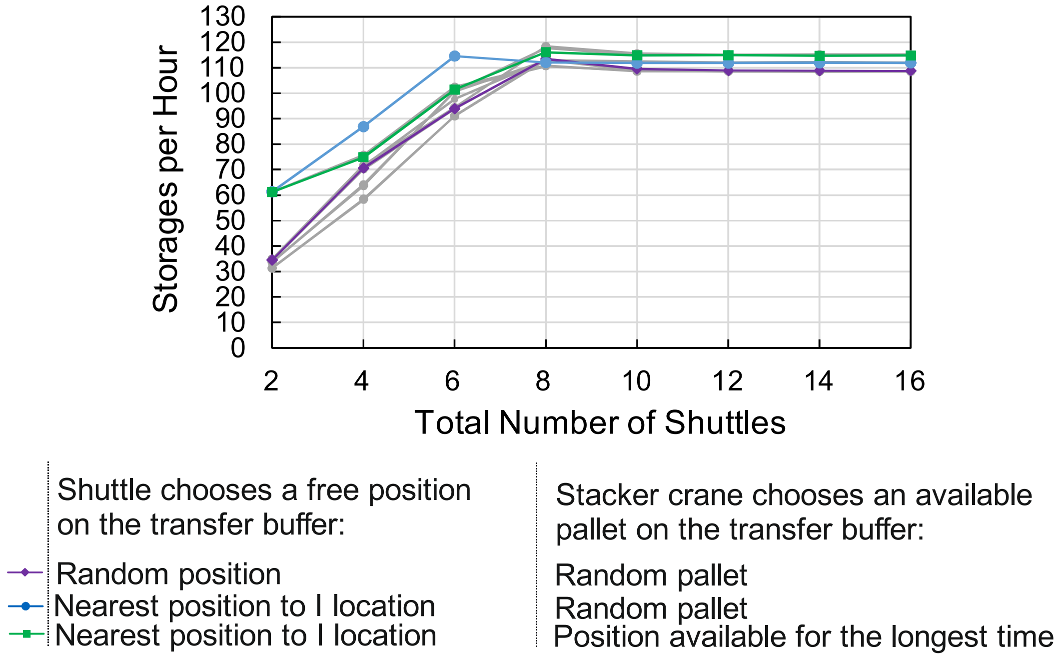



*Figure 6-16: Throughput reached by eleven combinations of order assignment strategies for storage [Sic-2021b]. The table shows which combination of operations are used for the colored lines in the graph*

throughput. When the stacker cranes are the bottleneck of the system, the highest throughput is reached if the stacker cranes pick the pallet in the position with the shortest travel path, while the shuttles should choose the location nearest to I (black line). In fact, this combination enables each stacker crane to reduce its cycle time, thus it improves the limit in terms of throughput caused by the cranes. Figure 6-16b represents the time components of the shuttles when the stacker cranes choose the pallet nearest to the I location, while Figure 6-17c shows the time components when the stacker cranes select the pallet on the location which minimizes their path. On the one hand, before the bottleneck of the stacker cranes is reached, i.e. for less than eight shuttles, Figure 6-17b shows smaller times compared to Figure 6-17c. This is due to the fact, that the shuttles have to wait for a free location on the transfer buffer. On the other hand, after the bottleneck of stacker cranes is exceeded, i.e. for more than eight shuttles, Figure 6-17c shows smaller times than in Figure 6-17b. In this case, the shuttles are blocked.

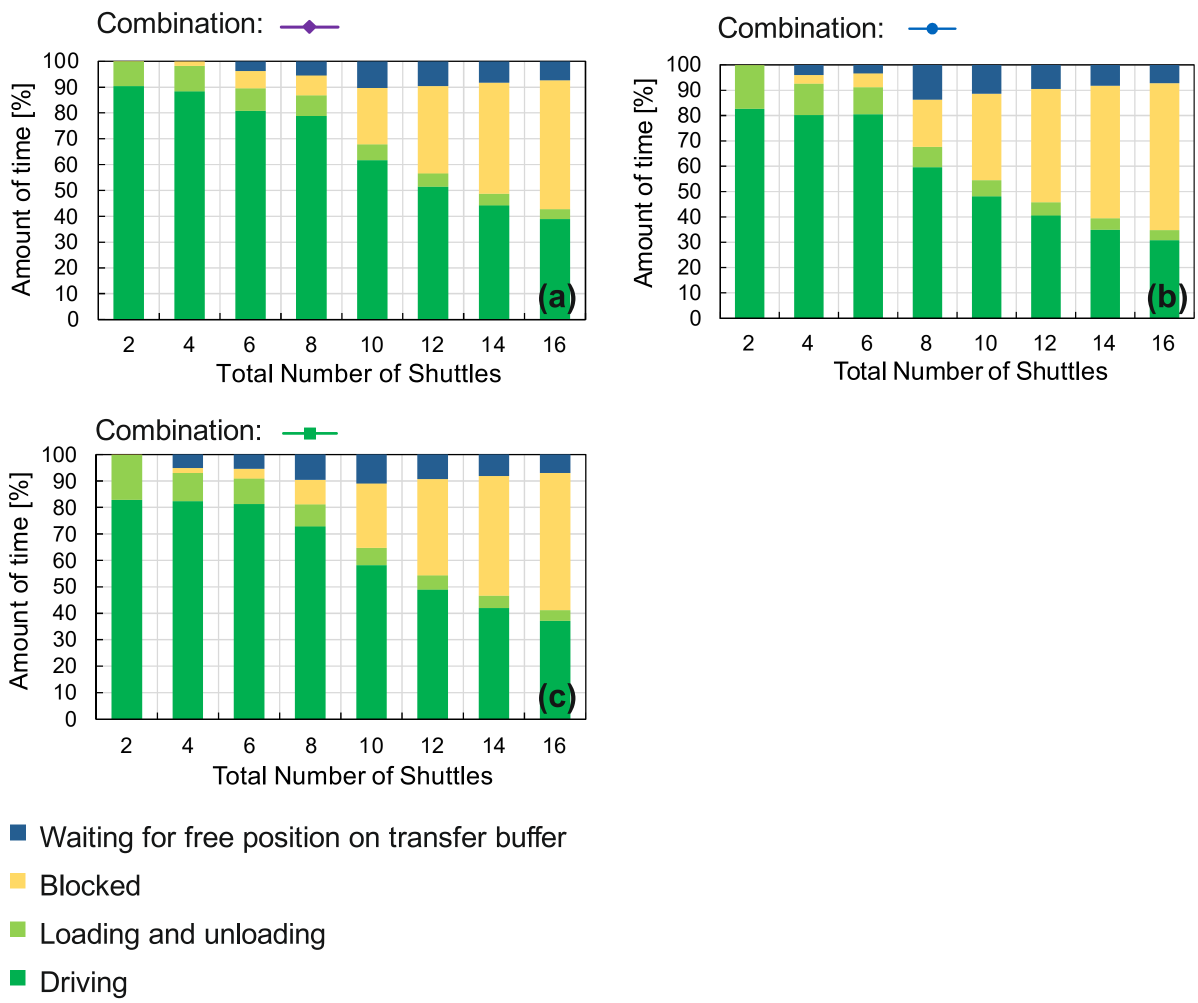


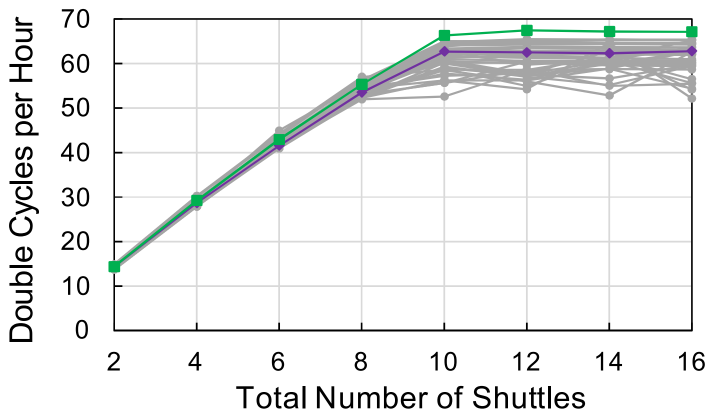

*Figure 6-17: Time components of significant combinations for storage [Sic-2021b]. In the title of each figure the corresponding line in Figure 6-16 is shown*

### 6.4.3 Double Cycles Combinations

The order assignment strategies in case of double cycles as OOM are the same proposed for both retrieval in sequence and storage. In Figure 6-18 the results obtained simulating 48 combinations of such strategies are examined. For each of these combinations it is always imposed that shuttles pick up the pallet with the smallest sequence number on the transfer buffer. The reason is that if, as demonstrated in Section 6.4.1, the shuttles use another strategy to pick up the pallets from the transfer buffer, the throughput is much reduced. Thus, the strategies which are already known to have a negative influence on the performance also using double cycles are excluded a priori from the study. Moreover, for each of the 48 combinations it is required that the stacker cranes activate idle shuttles at random. In fact, again in Section 6.4.1, it is demonstrated that whether the stacker cranes choose the shuttles to activate randomly or using other strategies has almost no influence on the throughput of the system.

The analysis of the 48 combinations for double cycles show results that are consistent with those obtained for retrieval in sequence and storage. When stacker cranes are the bottleneck of the system, i.e. for 10 or more shuttles, the highest throughput (green line with squares) is reached if the stacker cranes pick up the pallet for storage from the transfer buffer whose position minimizes their travel path. Then they transfer pallets for retrieval to the locations on the transfer buffer that minimize their travel path. In the meanwhile, shuttles deliver pallets for storage to the location on the transfer buffer nearest to I location. The reason is that this enables the stacker crane to be fast in serving the transfer buffer, thus it reduces the time the shuttles wait for an available pallet on the transfer buffer (see Figure 6-19a) in comparison with the combination where the same operations are done randomly (see Figure 6-19b). However, the combination where operations are done at random (violet line) already reaches a relatively high throughput in comparison to most other possible combinations (grey lines). This results from a balanced distribution of orders on the transfer buffer.

When the shuttles are the bottleneck of the system i.e. for less than 10 shuttles, all combinations provide about the same throughput. This is because for the double cycles the times saved or lost in the strategies used for retrieval in sequence and storage balance out each other.




| *Retrieval*<br>Stacker crane chooses available position on the transfer buffer: | Stacker crane chooses a shuttle to activate: | Shuttle chooses an available pallet on the transfer buffer: |
|---|---|---|
| Random position | Random shuttle | Smallest sequence number |
| Shortest path for the stacker crane | Random pallet | Smallest sequence number |
| *Storage*<br>Shuttle chooses a free position on the transfer buffer: | Stacker crane chooses an available pallet on the transfer buffer: | |
| Random position | Random pallet | |
| Nearest position to I location | Shortest path for the stacker crane | |

*Figure 6-18: Throughput reached by 48 combinations of order assignment strategies for double cycles [Sic-2021b]. The table shows which combination of operations are used for the colored lines in the graph*

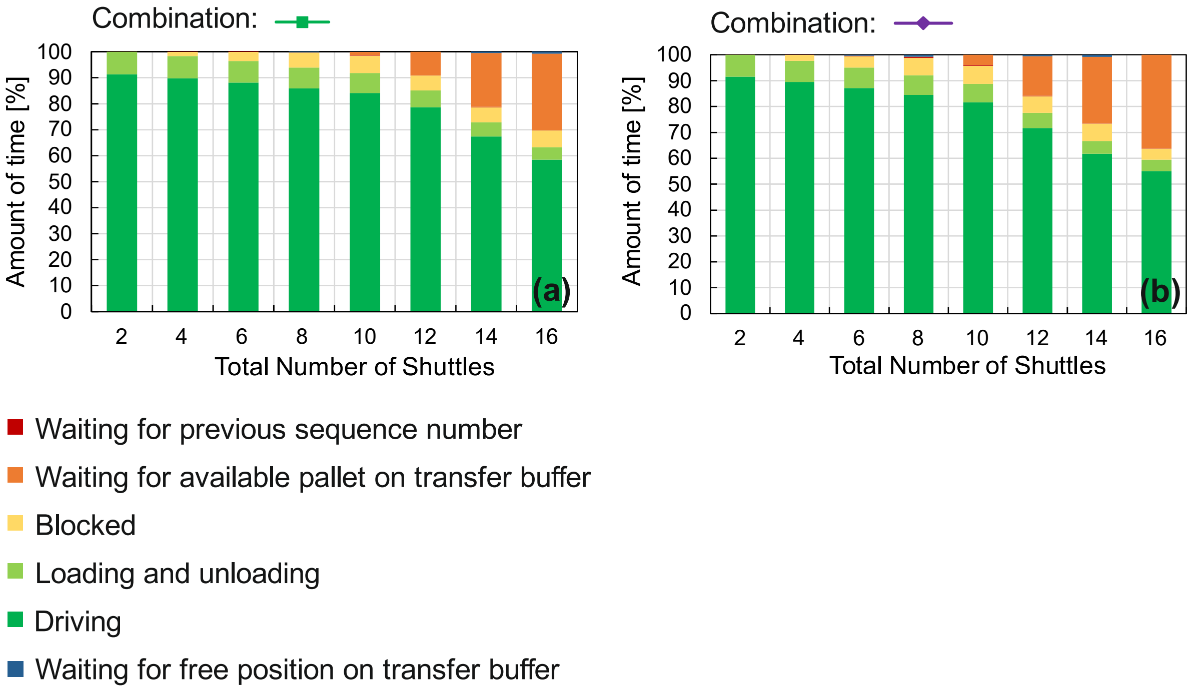



*Figure 6-19: Time components of significant combinations for double cycles [Sic-2021b]. In the title of each figure the corresponding line in Figure 6-18 is shown*

## 6.5 Configurations and Coordination Strategies for Performance Optimization of Multiple Stacker Cranes

In Chapter 4 different configurations and optimization strategies for the control system to mitigate the bottleneck of the stacker cranes are proposed. The purpose of this section is to complete the answer to the research sub-question “Which **optimization strategies** can be applied to improve the performance obtained with multiple stacker cranes in a single aisle?”. The optimization strategies developed for each configuration of Layouts 1, 2 and 3 are investigated quantitatively. Parts of the content of this section were published in reduced form in [Sic-2022a; Sic-2022b].

### 6.5.1 Layout 1: Dynamic Operational Intervals

First, the behaviour of the basic configuration of Layout 1 is evaluated when dynamic operational intervals are applied to each stacker crane in the aisle. The investigated maximum overlapping ranges along the aisle are shown in Figure 4-15.

The results in Figure 6-20 and in Figure 6-21 show that, in case of retrieval or double cycles as OOM, dynamic operational intervals do not provide any improvement on the throughput. To the contrary, when the stacker cranes are the bottleneck of the system, the highest throughput is reached for two and three stacker cranes using fixed operational intervals. An explanation of this effect is that, by making the operational interval of each stacker crane variable, each stacker crane on average must drive a longer cycle route than by fixed operational intervals. This phenomenon prevails over the desired effect of reducing the waiting time of shuttles by increasing the number of stacker cranes which are able to serve a certain location of the transfer buffer.

Moreover, as shown in Figure 6-20 and Figure 6-21, by increasing the number of stacker cranes, also the difference in throughput between system runs with dynamic operational intervals and with fixed operational intervals increases. The cause is that in case of fixed operational intervals the length of each interval is inversely proportional to the number of stacker cranes, while in case of dynamic operational intervals the length is not reduced. Therefore, in the latter case the average cycle route of the stacker crane is proportionally longer than in the case of fixed intervals as the number of stacker cranes increases.

In addition, like for fixed operational intervals, also for dynamic ones the use of the policy *Nearest Transfer Buffer Location* for retrieval and double cycles brings a little improvement in throughput. However, it is so small that it can be ignored. Similarly, the improvement in throughput provided by the policy *TC* for double cycles is too small to be significant. It can be deducted that the effect of increasing the average cycle route of the stacker cranes caused by the use of dynamic operational intervals significantly outweighs the effects of the other applied strategies. Therefore, it is advised against the use of dynamic intervals in DHPWs.

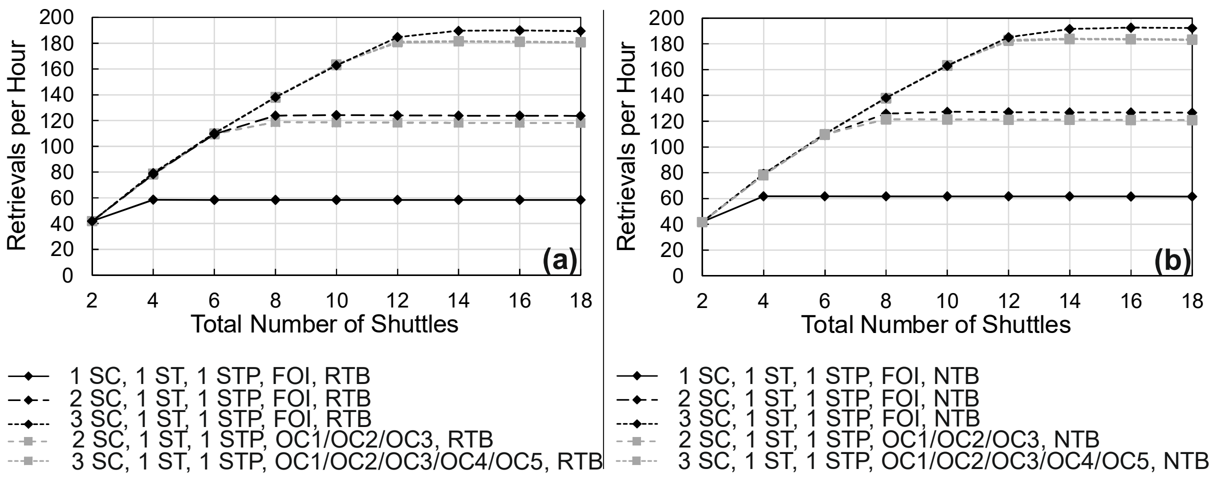



*Figure 6-20: Influence of dynamic operational intervals on throughput for retrieval [Sic-2022a]. Different colors and symbols indicate different strategies for the control system*

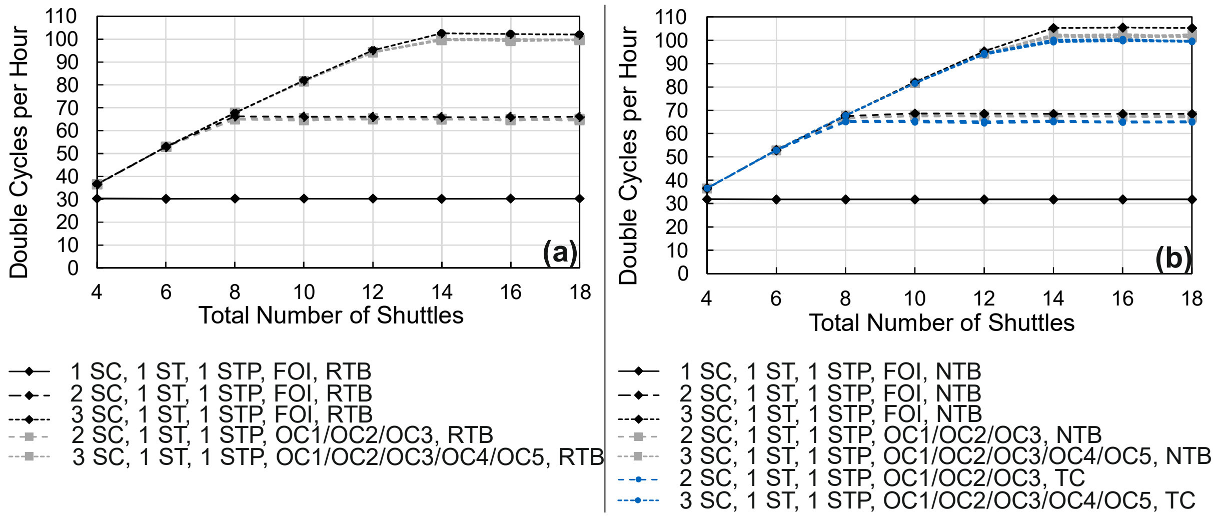



*Figure 6-21: Influence of dynamic operational intervals on throughput for double cycles [Sic-2022a]. Different colors and symbols indicate different strategies for the control system*

### 6.5.2 Layout 1: Multiple Satellites Assigned to Each Stacker Crane with a Single Satellite Position

The analysis now focuses on the behaviour of the second configuration of Layout 1, which is the one that has more than one satellite assigned per stacker crane and one satellite position on each stacker crane, and which is run by the policy *Longest Satellite Idle Time*.

If two satellites per stacker crane are assigned, this configuration (blue lines in Figure 6-22 and in Figure 6-23) provides a significant higher throughput than the basic configuration (black lines in Figure 6-22 and in Figure 6-23) of Layout 1, for both retrieval and double cycles. The reason is that decoupling the cycle of the stacker cranes and those of the satellites enables each stacker crane to avoid waiting for its satellite to come back from the channel storage and to be ready to be served.

Moreover, the throughput improvement increases with the number of stacker cranes in both retrieval and double cycles. An explanation is that the contribution in the improvement of throughput for each additional stacker crane adds up, because each stacker crane works within its own fixed operational interval, thus it does not interact with the other stacker cranes.

In addition, as the number of stacker cranes increases, the new configuration with two satellites makes it possible to shift the bottleneck of stacker cranes to a higher number of shuttles for both retrieval and double cycles. For example the retrieval in Figure 6-22 is considered: for one stacker crane this configuration, like the basic configuration, presents a plateau in throughput already for 4 shuttles; for two stacker cranes this configuration shifts the plateau from 8 shuttles of the basic configuration to 10 shuttles; for three stacker cranes the plateau is shifted from 14 shuttles to more than 18.

Increasing the number of satellites assigned to each stacker crane from two to three, does not bring any improvement. To the contrary, it reduces the throughput. Specifically, in case of retrieval, three satellites (grey lines in Figure 6-22) provide a similar throughput as two satellites (blue lines in Figure 6-22). In case of double cycles, the throughput provided by three satellites (grey lines in Figure 6-23) is even lower than those provided by the basic configuration (black lines in Figure 6-23). An explanation is that when a stacker crane has to serve more than one satellite, on the one hand it saves time because it can move while some satellites are working, on the other hand it wastes time in driving a longer way to reach all the satellites to be served. In case of two satellites, the time-saving effect prevails over the time-wasting one. If there are three satellites, the way that the stacker crane has to drive to serve all three is so long, that the time-wasting effect prevails over the time-saving one. In addition, in double cycles, combining retrieval and storage aggravates the time-wasting effect when using three satellites.

### 6.5.3 Layout 1: Multiple Satellites Assigned to Each Stacker Crane with Two Satellite Positions

The focus is now on performance of the third configuration of Layout 1. It uses more than one satellite assigned to each stacker crane, of which each one has more than one satellite position. Two satellites and two satellite positions per stacker crane are considered for the evaluation, because using stacker cranes having three satellites with three satellite positions is not as common in the praxis.

When the strategy *Double* is applied (grey lines in Figure ) for retrieval as OOM, a significant improvement in throughput is obtained for two stacker cranes, compared to the basic configuration (black lines in Figure 6-24). Also applying the strategy *Succession* to two stacker cranes enable a relevant increase in throughput for the retrieval as OOM. However, when the strategies *Double* (grey small dotted line in Figure 6-24) or *Succession (*grey small dotted line in Figure 6-25) are applied to three stacker cranes per aisle, the throughput becomes lower than in the basic configuration (black small dotted line in Figure 6-24 or Figure 6-25) when the bottleneck of stacker cranes is reached. For strategies that enable very high dynamics, the configuration of the I/O area plays a crucial role in limiting throughput, because depending on its design it facilitates or prevents congestions of shuttles. Thus, the configuration of I/O area represented in Figure 6-6 is designed and applied to obtain an improvement of throughput with

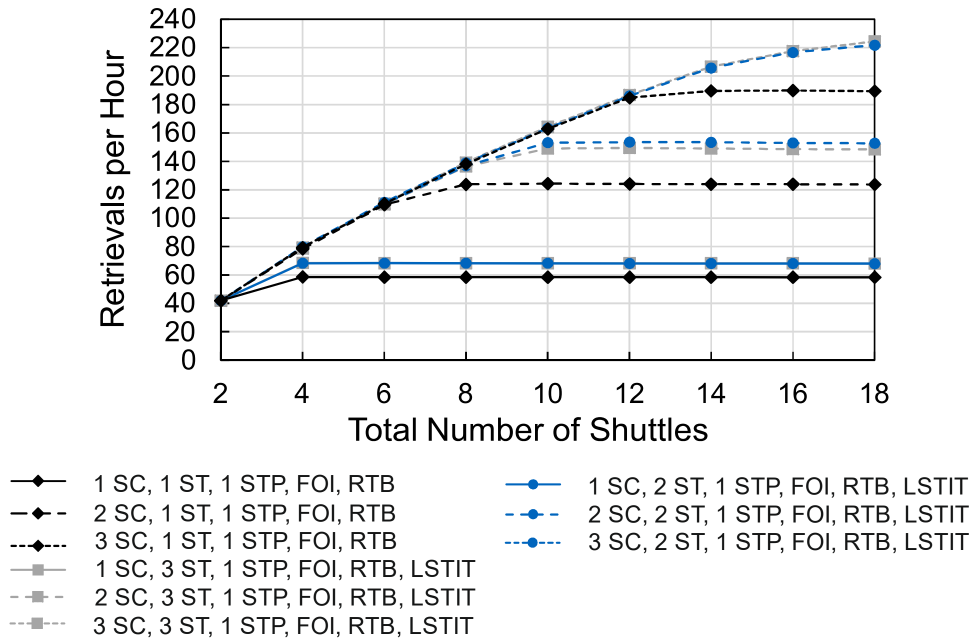



*Figure 6-22:* *Multiple satellites assigned to each stacker crane with a single satellite position for retrieval [Sic-2022a]. Different colors and symbols indicate different strategies for the control system*

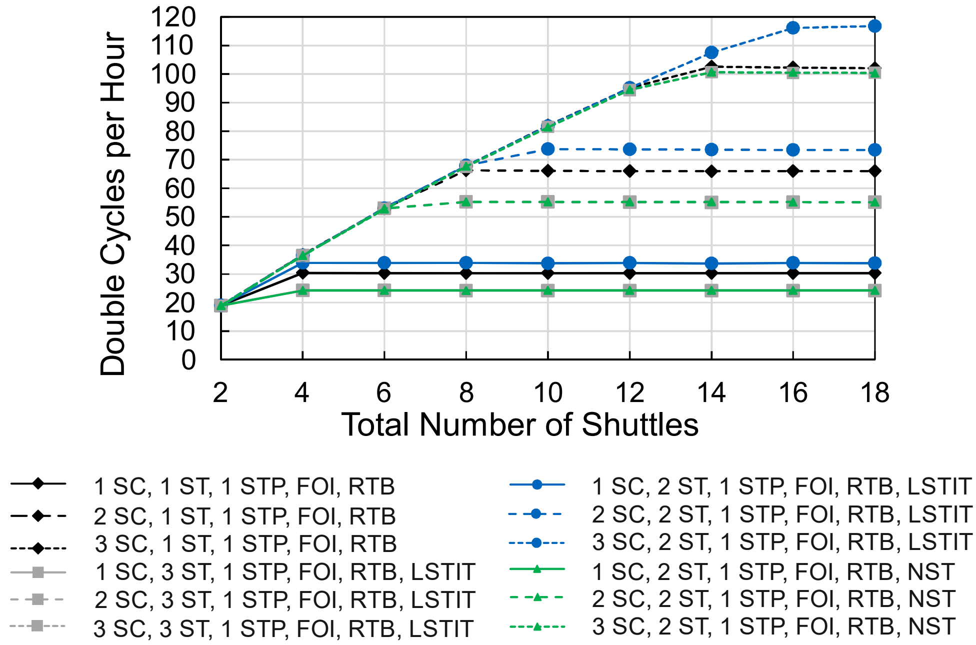



*Figure 6-23:* *Multiple satellites assigned to each stacker crane with a single satellite position for double cycles [Sic-2022a]. Different colors and symbols indicate different strategies for the control system*

the strategies *Double* (green small dotted line in Figure 6-24) and *Succession* (green small dotted line with triangles in Figure 6-25) for three stacker cranes in case of retrieval as OOM, when the stacker cranes are the bottleneck. It is interesting to note that this configuration of the I/O area, when the bottleneck of stacker cranes is reached, does not provide any improvement compared to the use of the I/O area configuration in Figure 6-5 (right) when one or two stacker cranes are used with strategy *Double* (green solid and long dotted lines in Figure 6-24). This is true also for the strategy *Succession* (green solid and long dotted lines in Figure 6-25) and for the basic configuration for three stacker cranes (blue small dotted lines in Figure 6-24 and Figure 6-25). This is a further demonstration of the importance of the configuration of the I/O area in the range of high dynamics of the warehouse.

When using the strategy *Succession* (blue lines in Figure 6-26), an impressive improvement in throughput is obtained for two and three stacker cranes in double cycles as OOM in comparison to the basic configuration (black lines in Figure 6-26). The improvement is so outstanding that the performance with two stacker crane succession is very close to that of the basic configuration but with three stacker cranes. In addition, the strategy *Succession* enables a remarkable shift of the plateau of the throughput from 8 shuttles of the basic configuration to 12 shuttles for two stacker cranes and from 14 shuttles to more than 18 for three stacker cranes. Furthermore, the results in Figure 6-27 show that route 6, followed shortly by routes 5 and 1, is the one which in most cases allows for a minimal cycle time for the stacker crane, since it

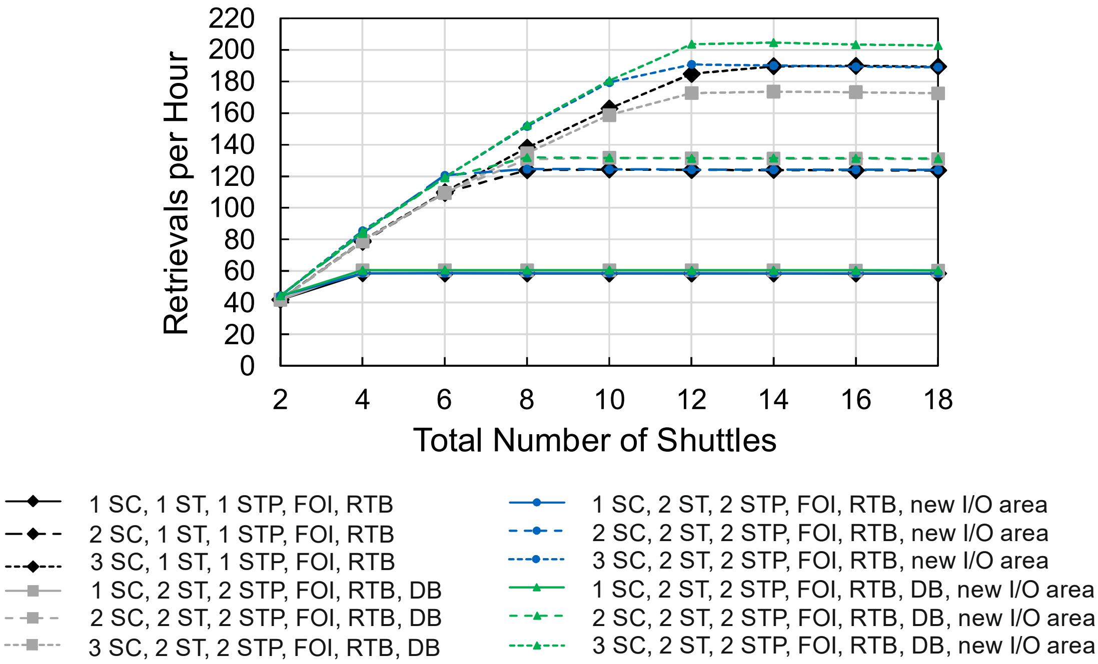



*Figure 6-24: Multiple satellites assigned to each stacker crane with multiple satellite positions for retrieval applying the strategy Double [Sic-2022b]. Different colors and symbols indicate different strategies for the control system*

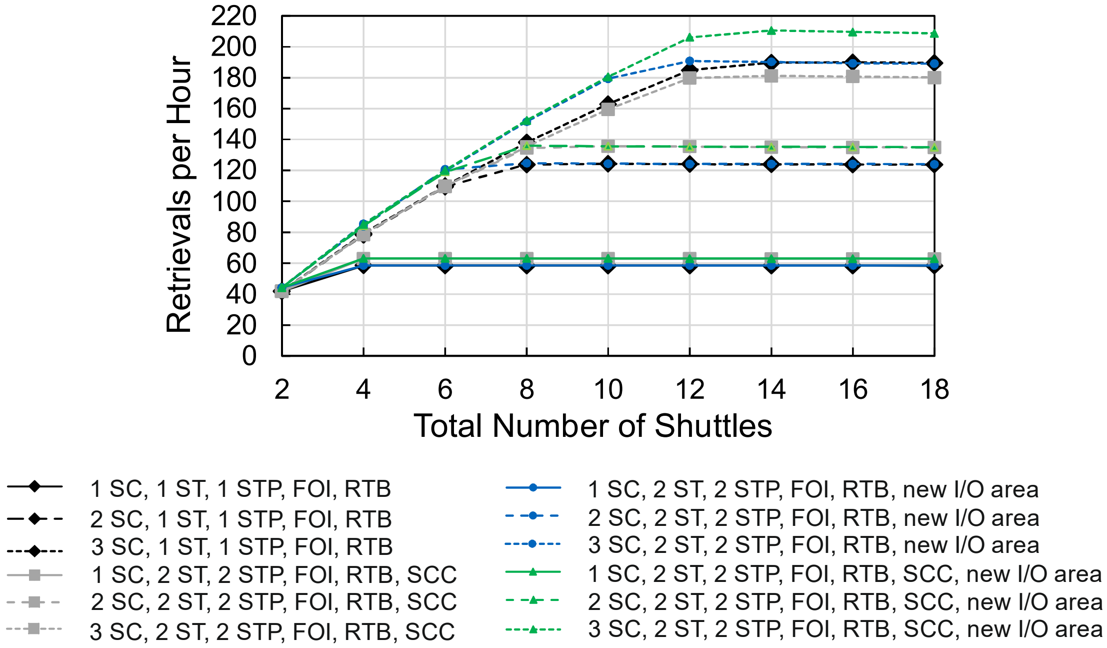



*Figure 6-25:* *Multiple satellites assigned to each stacker crane with multiple satellite positions for retrieval applying the strategy Succession [Sic-2022b]. Different colors and symbols indicate different strategies for the control system*

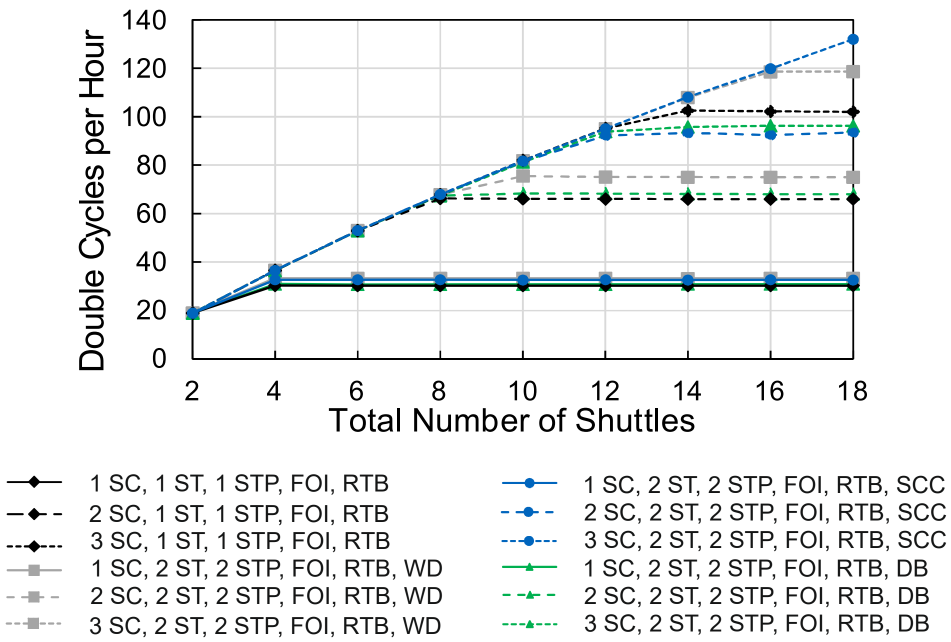



*Figure 6-26:* *Multiple satellites assigned to each stacker crane with multiple satellite positions for double cycles [Sic-2022a]. Different colors and symbols indicate different strategies for the control system*

is chosen by the *Succession* algorithm in most cases, independently from the number of stacker cranes or shuttles.

For the double cycles, a good improvement of the throughput is provided also by the strategy *Wait or Drive* (grey lines in Figure 6-26) against the basic configuration (black lines in Figure 6-26). The gain in retrievals per hour is not as high as for the strategy *Succession* but is still very high. The experiments in Figure 6-28 show that route 12, immediately followed by route 9, is the one chosen most often by the *Wait or Drive* algorithm. On the one hand for the strategy *Succession*, there is only a small difference in the frequency of choice of the different routes, with the exception of routes 3 and 4. On the other hand, in the strategy *Wait or Drive*, routes 9 or 12 are almost always selected.

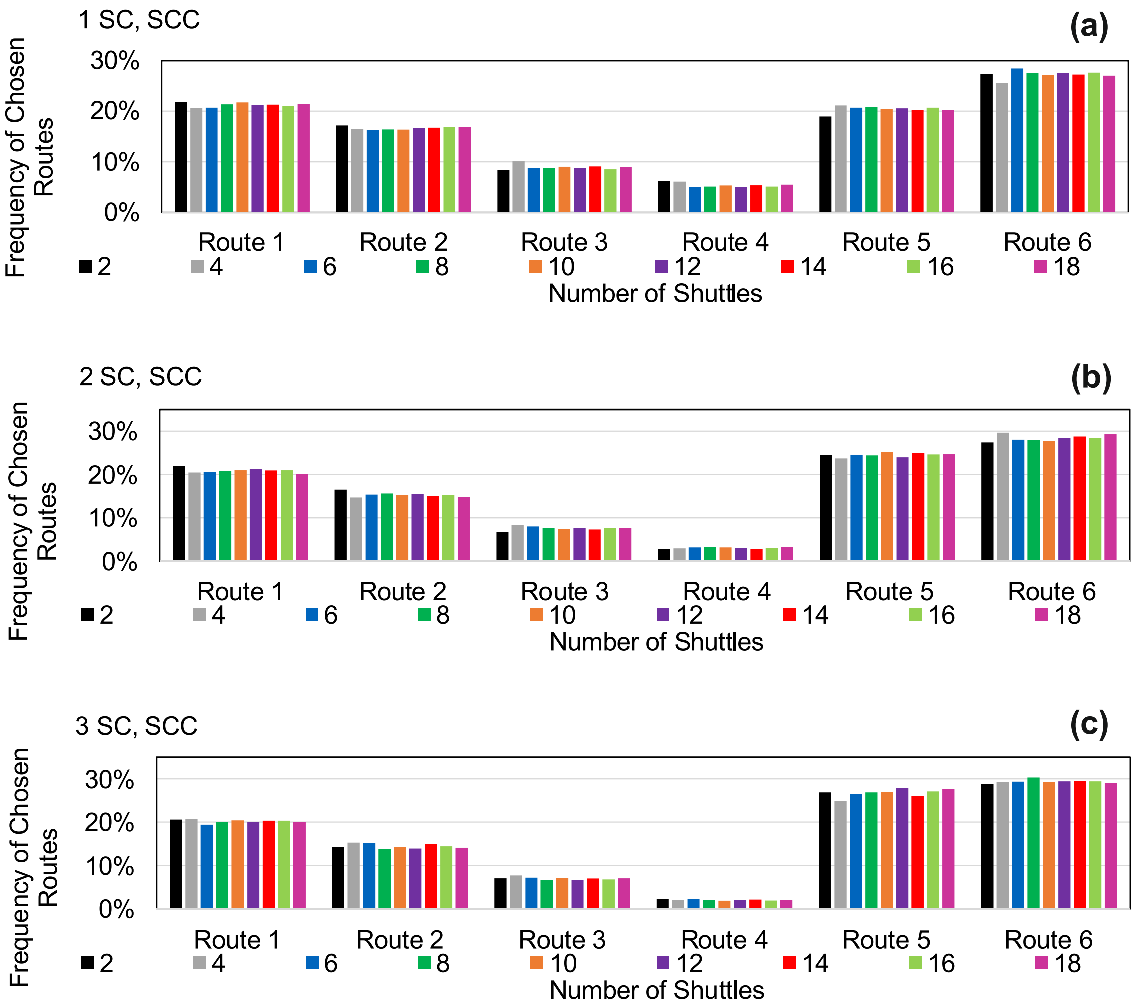



Figure 6-27: *Frequency of choice for routes in strategy Succession for double cycles [Sic-2022a]. Data for one (a), two (b) and three (c) stacker cranes are shown. Different colors indicate different numbers of shuttles*

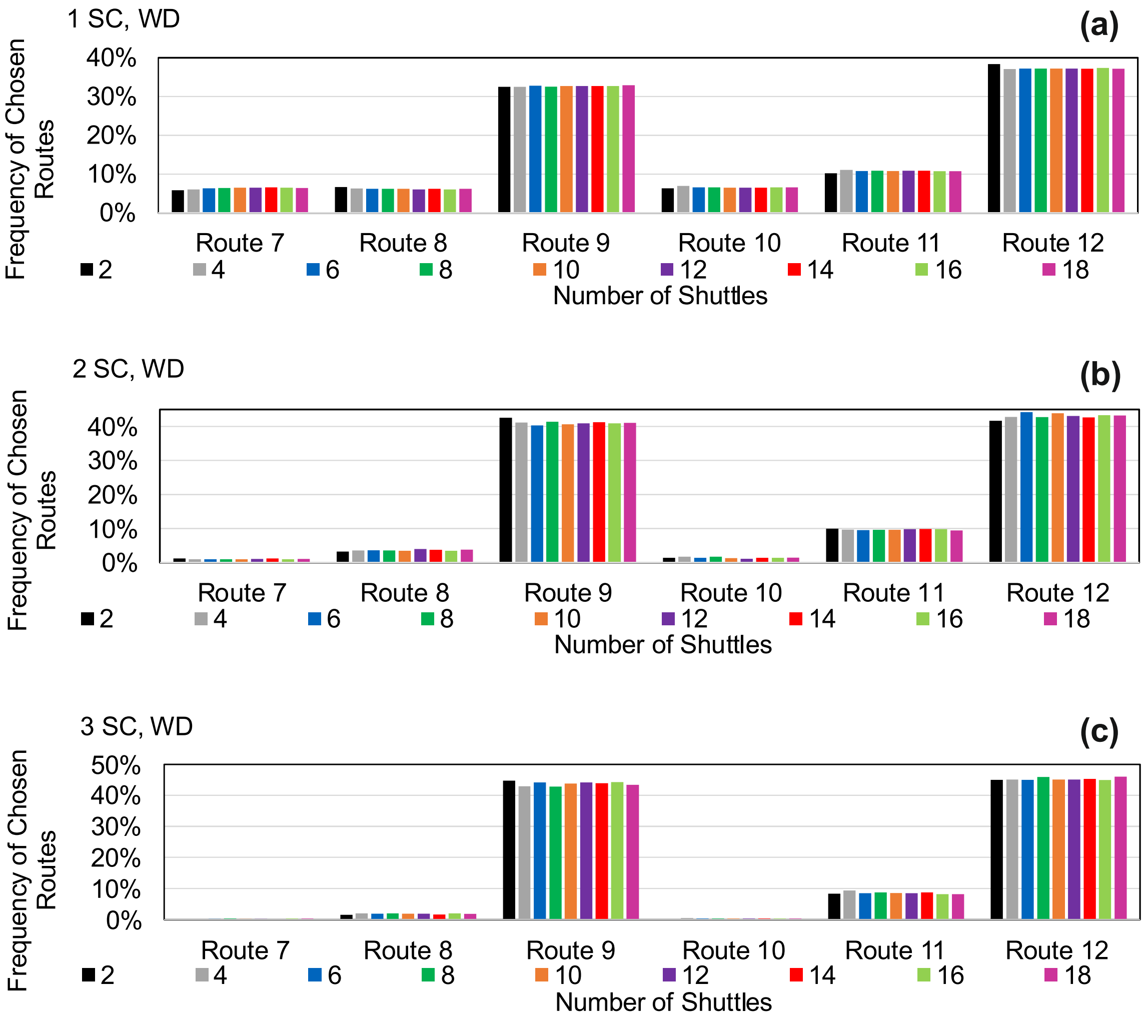



*Figure 6-28:* *Frequency of choice for routes in strategy Wait or Drive for double cycles [Sic-2022a]. Data for one (a), two (b) and three (c) stacker cranes are shown. Different colors indicate different numbers of shuttles*

For both strategies *Wait or Drive* and *Succession* the distance between stations is a crucial point for the cycle time of the stacker crane and there are no other side effects which could cause a time loss as in *Double*. Therefore, for both *Wait or Drive* and *Succession*, when a stacker crane is added, the reduction of the fixed operational intervals results directly in a decrease of the distance between stations, thus a reduction of the cycle time. This effect causes an increase in throughput which is added to the increase already caused by adding a further stacker crane run by *Succession* or *Wait or Drive*.

### 6.5.4 Layout 2: Single Pallet Position on Each Stacker Crane with Forks

The results obtained simulating Layout 2 when applying the strategy *One Direction* are examined.

First, the retrieval case as in Figure 6-29 is considered. For one stacker crane in the aisle, if it is the bottleneck of the system i.e. for 32 or more shuttles, the algorithm *One Direction* (grey solid line) provides a significant increase in throughput in comparison to the configuration in which no optimization strategy is used (black solid line). To the contrary, two stacker cranes in the aisle do not cause a bottleneck in throughput at least until 80 shuttles. Thus, *One Direction* (grey dotted line) in this case leads to no improvement with respect to the non-optimized configuration (black dotted line). The deadlocks happening for 88 or more shuttles again demonstrate the high impact of the design of the I/O area on throughput when very high dynamics occur as for DHPWs. To avoid these deadlocks, the I/O area shown in Figure 6-6 can be applied. The new throughput reached (blue and green dotted lines) is however limited by the presence of just one O location per zone.

The focus is now on the double cycles as OOM (see Figure 6-30). For one stacker crane, *One Direction* slightly reduces the throughput of the system for less than 40 shuttles and it slightly increases it for more than 72 shuttles (grey solid line) compared to the non-optimized configuration (black solid line). *One Direction* requires for the double cycles not only that each order has higher $x$-coordinates than the preceding one,

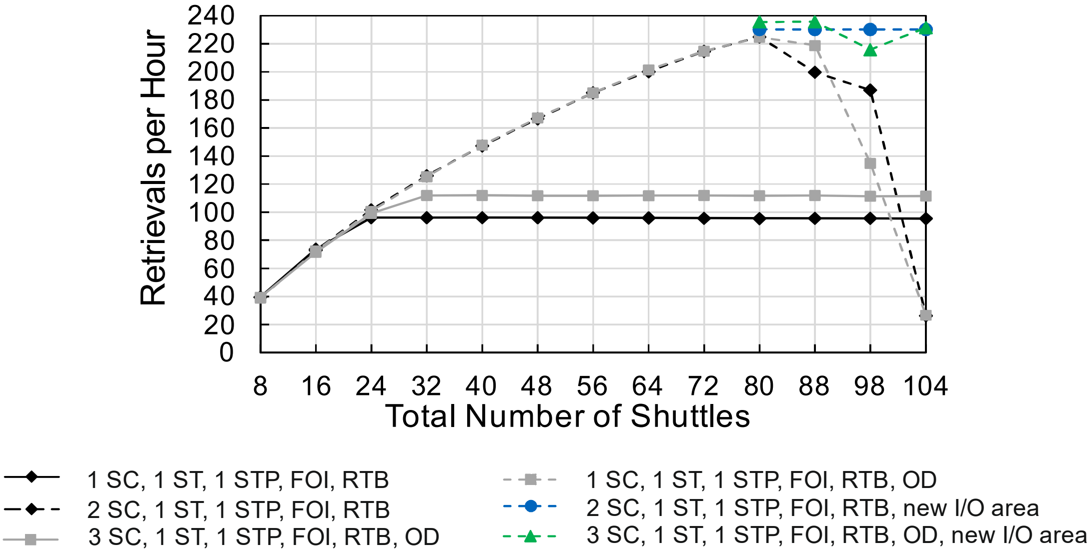



*Figure 6-29: Single pallet position on each stacker crane with forks for retrieval [Sic-2022b]. Different colors and symbols indicate different strategies for the control system or different configurations of the I/O area*

but also the alternation between retrieval and storage orders. The probability to find orders which satisfy these conditions is higher when the number of shuttles on each level increases. A similar behaviour of the system also occurs when there are two stacker cranes in the aisle.

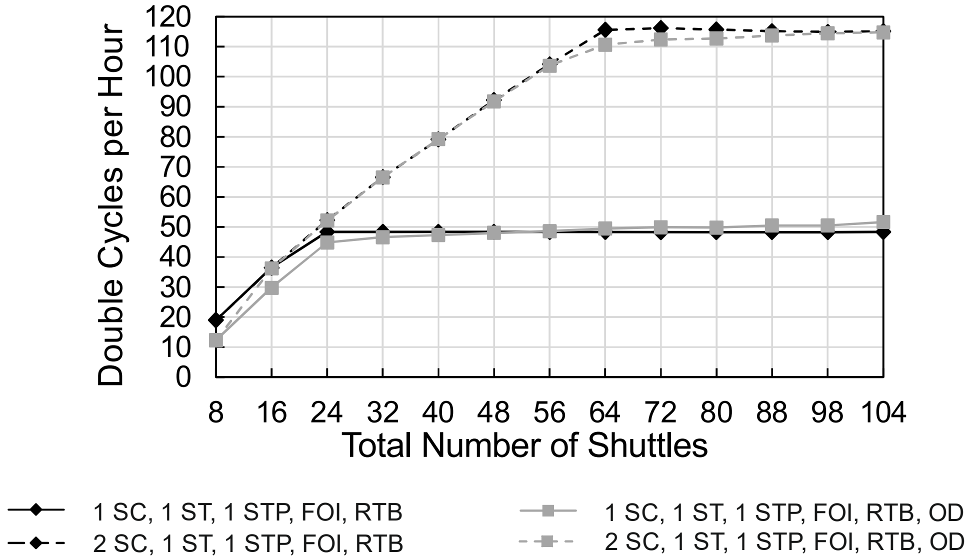



*Figure 6-30: Single pallet position on each stacker crane with forks for double cycles [Sic-2022b]. Different colors and symbols indicate different strategies for the control system*

### 6.5.5 Layout 2: Two Pallet Positions on Each Stacker Crane with Forks

If a second pallet position on each stacker crane with forks is introduced, it is possible to reach a much higher throughput through the *Succession* algorithm than with *One Direction*. In fact, as depicted in Figure 6-31 for the retrieval, *Succession* (grey solid line) reaches a throughput increased by more than 20 retrievals per hour for one stacker crane per aisle for 32 shuttles in comparison to the basic configuration (black solid line). If there are two stacker cranes in the aisle the behaviour of the system is similar to those of *One Direction.*

For double cycles (see Figure 6-32), *Succession* (grey solid line) provides a significant throughput increase of more than 40 double cycles i.e. 40 retrievals and 40 storages performed per hour for 48 shuttles against the basic configuration (black solid line). This increase brings the performance near to those obtained with two stacker cranes in the aisle for the basic configuration (black dotted line). If *Succession* (grey dotted line) is applied using two stacker cranes in the aisle, the reached throughput is also at least more than 40 double cycles higher than those of the basic configuration with 104 shuttles. In case of double cycles, like for Layout 1, also for Layout 2, *Succession*

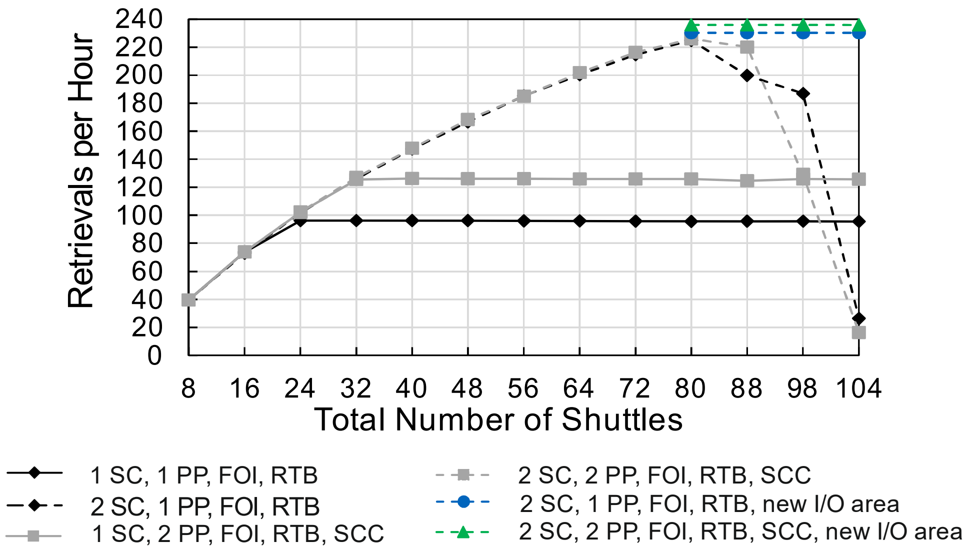



*Figure 6-31:* *Two pallet positions on each stacker crane with forks for retrieval [Sic-2022b]. Different colors and symbols indicate different strategies for the control system*

allows for an outstanding shift of the bottleneck of stacker cranes, making the system more scalable. For example, for one stacker crane with *Succession* the bottleneck occurs at 48 shuttles instead of 24 shuttles as with the basic configuration.

In contrast to Layout 1, the strategy *Double* does not provide any throughput increase for retrievals and double cycles with respect to the basic configuration. Specifically, the strategy *Double* delivers, within numerical accuracy, an identical throughput to that of the basic configuration. Therefore, it is not discussed separately.

### 6.5.6 Layout 3: All Shuttles Assigned to Each Stacker Crane with Forks with a Single Shuttle Position

In this section and in the following one it is shown that the improvement of the bottleneck caused by stacker cranes is not so high for Layout 3 as it is for Layout 1 and 2. The explanation is that in Layout 3 the control logic is more complex and rigid than in Layout 1 and 2, because the stacker cranes must move shuttles between levels. Thus, in Layout 3 cranes have more different order types to coordinate with respect to Layout 1 and 2. Consequently, the optimization potential or Layout 3 is smaller than for Layout 1 and 2.

For both OOMs retrieval (see Figure 6-33) and double cycles (see Figure 6-34), the algorithm *One Direction* causes a behaviour of the system similar to the one of the OOM double cycles for Layout 2, thus no throughput improvement. This was predictable, because as also illustrated above, the stacker cranes perform double cycles for Layout 3 also if retrieval is the OOM.

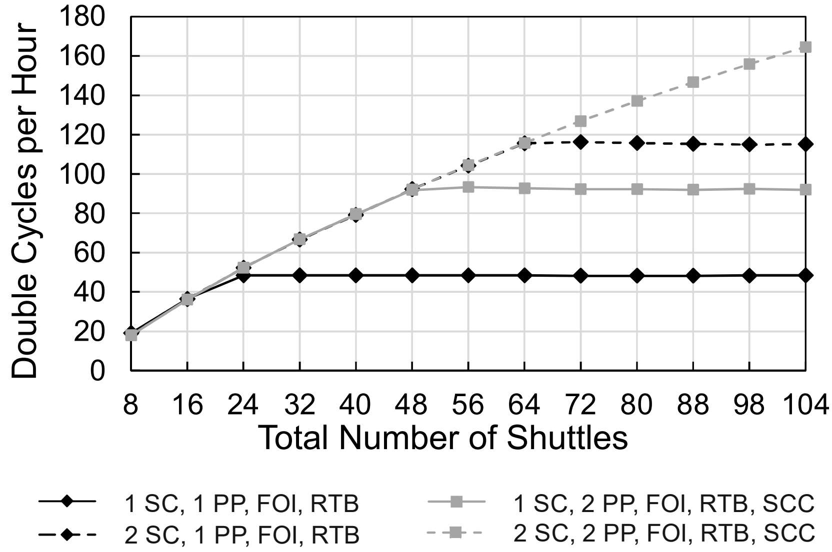



*Figure 6-32: Two pallet positions on each stacker crane with forks for double cycles [Sic-2022b]. Different colors and symbols indicate different strategies for the control system*

### 6.5.7 Layout 3: All Shuttles Assigned to Each Stacker Crane with Forks with Two Shuttle Positions

Introducing an additional shuttle position on each stacker crane allows for a slight performance improvement against the basic configuration through application of the *Succession* algorithm. However, Figure 6-35 for retrieval and Figure 6-36 for double cycles show that this increase in throughput is negligible for one stacker crane in the aisle (grey solid lines) against the basic configuration (black solid lines). For two stacker cranes, the performance improvement obtained through *Succession* (grey dotted lines) is not negligible but still small for both retrieval and double cycles compared to the basic configuration (black dotted lines).

Like for Layout 2, the strategy *Double* does not provide any improvement in case of OOM retrieval or OOM double cycles and its throughput is again identical, within numerical accuracy, with that of the basic configuration.

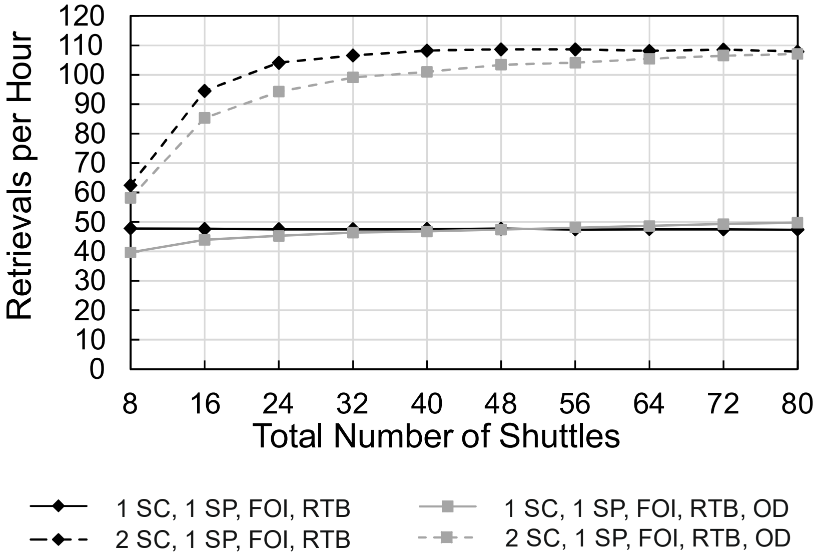



*Figure 6-33:* *All shuttles assigned to each stacker crane with forks with a single shuttle position for retrieval [Sic-2022b]. Different colors and symbols indicate different strategies for the control system*

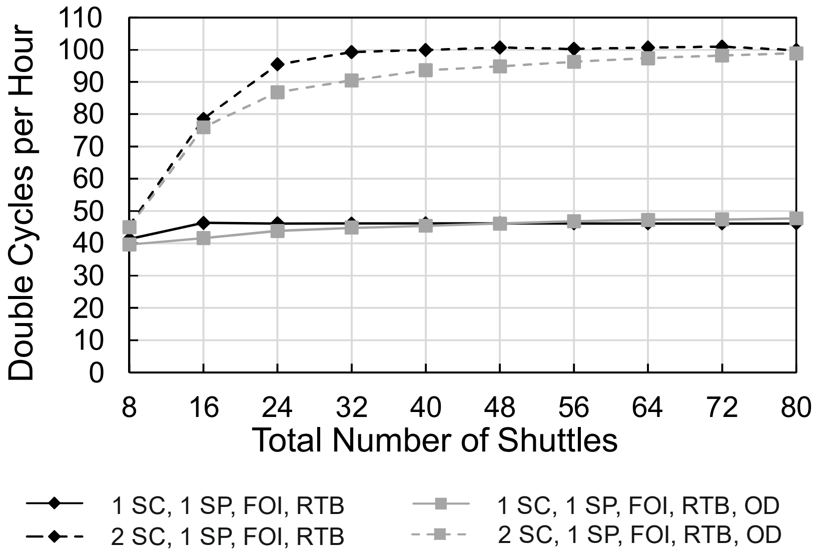



*Figure 6-34:* *All shuttles assigned to each stacker crane with forks with a single shuttle position for double cycles [Sic-2022b]. Different colors and symbols indicate different strategies for the control system*

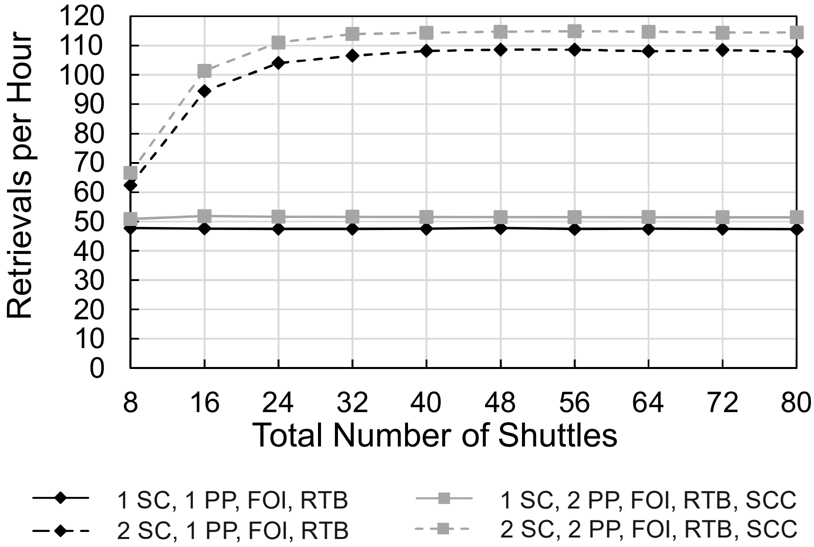



*Figure 6-35:* *All shuttles assigned to each stacker crane with forks with a single shuttle position for retrieval [Sic-2022b]. Different colors and symbols indicate different strategies for the control system*

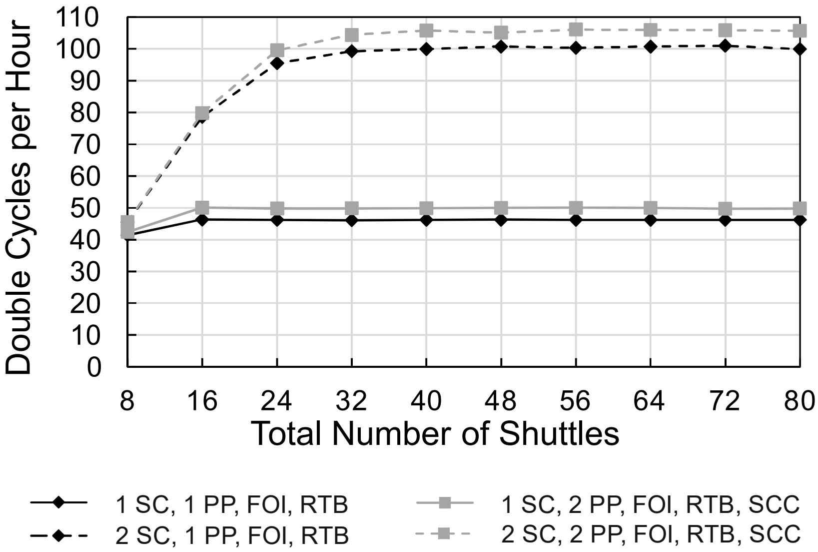



*Figure 6-36:* *All shuttles assigned to each stacker crane with forks with a single shuttle position for double cycles [Sic-2022b]. Different colors and symbols indicate different strategies for the control system*

# 7 Critical Discussion

The aim of this chapter is first of all to demonstrate that the connection between shuttles and stacker cranes in DHPWs enables achieving a much higher performance than existing conventional technologies. Then, the scalability of performance, the capacity to satisfy high peaks in demand and the fields of application of DHPWs are identified and recommendations for their use are formulated. Parts of the content of this chapter were published in reduced form in [Sic-2020; Sic-2022d].

## 7.1 Performance Comparison

### 7.1.1 Description and Modelling of Other Technologies Considered for Comparison

In the description of the state of research the stacker crane-based warehouses and shuttles-based warehouses were identified as the technologies that the DHPWs aim to outperform. Therefore, the different types of DHPWs are compared precisely against these systems.

As stacker crane-based warehouses those are considered that have been the subject of the most research studies, namely the following types: the single-deep storage stacker crane with telescopic forks, the double-deep storage stacker crane with telescopic forks with relocations, and the nine-deep storage stacker crane with satellite without relocations. For the latter nine depths and no relocations are considered to make the comparison with Layout 1 more direct. In Layout 1 the channel storage levels have exactly nine depths and the satellites do not relocate the pallets. The information on the throughput of these systems was provided us by the manufacturer[11].

In the case of shuttle-based warehouses it is more complex to identify which configurations are most widely studied in the research. In fact, these systems differ considerably from each other in the arrangement of storage locations and aisles for shuttles, in the arrangement of lifts, and in the positioning and design of loops. Therefore, in order

[11] The author is grateful for this information to the engineers Thomas Klopfenstein and Dipl.-Wirtsch. -Ing. Jörg Eder of Gebhardt Fördertechnik GmbH. Specifically, Thomas Klopfenstein performed the calculations for the throughput of the considered conventional stacker crane based-warehouses.

to be able to compare such systems with DHPWs, a shuttle-based warehouse having base and levels like that of Layout 2 and 3 was modelled in Tecnomatix Plant Simulation, but with lifts instead of stacker cranes[12]. There are four lifts in the aisle. Two of them serve the left half of the warehouse and the other two the right one. On each side of the aisle the stacker cranes are positioned respectively at one third and two thirds in the x-direction. The comparison of the throughput of this system with that of Layout 2 provides us a direct quantification of the advantage obtained by using stacker cranes with transfer buffer locations along the entire aisle compared to the use of lifts.

### 7.1.2 Results

Figure 7-1 shows the performance in terms of throughput for DHPWs in their basic configurations and relevant conventional technologies in case of retrieval as OOM.

First, the different DHPWs layouts are compared with each other. Layout 3 provides for two and four shuttles per level a throughput that is about 20 retrievals per hour higher than that of Layout 2. The reason is that in Layout 3, even if the fleet size is small on each level, shuttles can move to the base and constitute there a fleet size higher than that of levels. This enables Layout 3 to mitigate the bottleneck of shuttles compared to Layout 2, where shuttles are fixed on each level. However, for six or more shuttles per level, Layout 2 guarantees the highest throughput and best scalability. The explanation is that in Layout 3 the stacker cranes have to perform twice as many orders as in Layout 2 to move shuttles between levels, thus the bottleneck of stacker cranes is reached already for 8 shuttles per level. To the contrary, for Layout 2 at least up to 16 shuttles per level the throughput can be increased by adding more shuttles, as the stacker crane bottleneck is not reached. In the investigation the highest difference in throughput between Layout 2 and 3 is reached for 16 shuttles per level. It amounts to more than 90 retrievals per hour. Layout 1 delivers a lower throughput than Layout 2 and 3 because the time taken by each stacker crane to execute an order also includes the time taken by the satellite assigned to it to enter and exit channels, which slows the dynamics down. However, Layout 1 is significantly cheaper and has a higher space utilization ratio than Layout 2 and 3.

[12] The author is grateful to Dipl.-Wirtsch. -Ing. Jörg Eder of Gebhardt Fördertechnik GmbH for the fruitful discussions about how to perform the comparison of DHPWs with conventional shuttle-based warehouses.

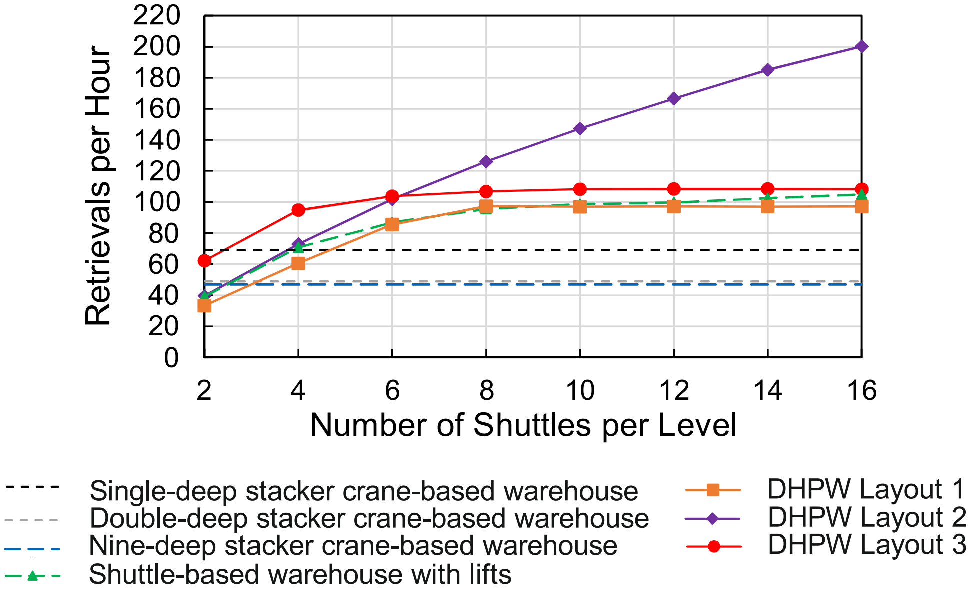



*Figure 7-1:* *Comparison of retrieval performance between DHPWs and existing conventional technologies [Sic-2022b]. Different colors and symbols indicate different technologies*

The DHPWs are now compared against existing conventional technologies. Layout 1 should be examined with respect to stacker-crane based warehouses because it is obtained by hybridizing them with a shuttle level. For six or more shuttles per level the throughput of Layout 1 becomes higher, not only of that of double- and nine-deep storage stacker cranes, but also of that of a single-deep storage stacker crane with telescopic forks. The maximum difference in performance between Layout 1 and the nine-deep storage stacker crane with satellite without relocations is more than 50 retrievals per hour. Such a difference is a direct quantification of the advantage provided by utilizing a transfer buffer along the whole length of the aisle instead of the conventional I/O locations at the ends of it. Regarding Layout 2 the throughput is higher than that of the shuttle-based warehouse for six or more shuttles per level. The reason is that while the throughput of Layout 2 increases when adding further shuttles, that of the shuttle-based system reaches a bottleneck caused by the lifts. Unlike stacker cranes, lifts have a limited number of transfer buffer locations along the way. So, if, for example, a lift carries a pallet from one level to the base, it will have to wait long before a shuttle picks up that pallet and makes that position available for a new pallet carried by the lift. Layout 3 provides for two and four shuttles per level, i.e. before the bottleneck of stacker cranes, a throughput that is about 20 retrievals per hour higher than that of the shuttle-based warehouse.

In case of double cycles as OOM (see Figure 7-2), the behaviour of the systems considered is similar to the case of retrievals as OOM. However, due to the more severe bottleneck of shuttles caused by having to execute double cycles, the throughput of

Layout 3 is higher than that of Layout 2 for a larger range of fleet size, i.e. between two shuttles per level and 12 shuttles per level, with a maximum difference of more than 40 double cycles per hour. Moreover, the high amount of orders to be executed by stacker cranes for double cycles causes that, when the stacker cranes are the bottleneck, Layout 1 reaches a higher throughput even than the shuttle-based warehouse. This is a further demonstration of the efficacy of stacker cranes compared to lifts in providing high dynamics on the transfer buffer, compared to lifts.

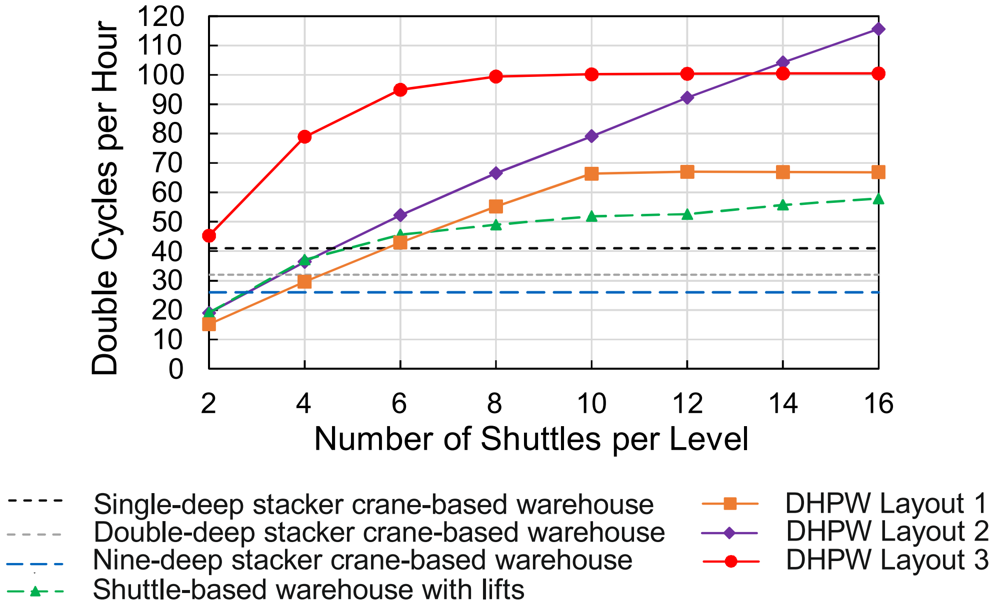



*Figure 7-2: Comparison of double cycles performance between DHPWs and existing conventional technologies [Sic-2022b]. Different colors and symbols indicate different technologies*

## 7.2 Capacity to Satisfy High Peaks in Demand Bypassing the Stacker Cranes Bottleneck

In this section it is demonstrated that the presence of a shuttle base is essential for DHPWs to meet much higher peaks in demand than can be met by channel storage systems served by a stacker crane, even assuming the stacker crane can exchange pallets on all locations along the aisle.

For this purpose, a basic DHPW having arrangement Layout 1 is considered. The same conclusions can be extended to Layout 2 and 3 because they also have a shuttle base. The performance of the system is discussed in case of sequenced retrieval as OOM, because the behaviour of the warehouse for storage or double cycles as OOM in case of retrieval from the storage of the base level is similar. To prove that the capacity of a DHPW to satisfy high peaks in demand is superior than that of the channel

storage independently from the velocity of the stacker crane, faster parameters are considered for the stacker crane (see Table C-1) than those in the basic DHPW. Moreover, to show more clearly that the limit to the high peak in demand is caused by the bottleneck from the limited number of I/O locations per module, just three sections are considered, i.e. aisle 53 m long, instead of the five of the basic DHPW. The reason is that for three sections the travel path of shuttles is shorter, thus a higher throughput is reached for a smaller number of shuttles compared to five sections. As a consequence, the bottleneck caused by the I/O locations is reached for a smaller number of shuttles per zone with respect to five sections. Even with three sections it is necessary to simulate up to 20 shuttles on the base level to investigate the bottleneck. Five sections would require even more shuttles in the simulation, causing technical difficulties.
First, the throughput of a single stacker crane in the aisle is assessed to determine the throughput bottleneck it causes on the whole warehouse. No order assignment strategies are applied, therefore, the stacker crane performs a random selection of the locations on the transfer buffer and of the removal locations in the channel storage. The stacker crane retrieves 83 pallets per hour (orange dotted line in Figure 7-3). Afterwards, it is considered to store the pallets during the night with ii. OMS that is *retrieve to storage of the base level* and then to pick them up in the morning by i. OMS that is *retrieve to I/O locations*, bypassing the stacker crane. As the number of shuttles per module increases, the throughput during i. OMS also increases (blue solid line with squares in Figure 7-3). Specifically, already for 6 shuttles per module, the throughput is higher than that of the channel storage. Once the stacker crane is no more a bottleneck, increasing the number of shuttles make sense only until the bottleneck imposed by the number of I/O locations per module is reached (red dotted line in Figure 7-3). Afterwards, a performance plateau is reached and it is not possible anymore to increase the throughput, even if the number of shuttles is increased. The bottleneck caused by I/O locations is calculated as:

$$Bottleneck_{I/O} = \frac{N}{t} \tag{7-1}$$

Where

- $N =$ number of I/O locations per module
- $t =$ time between the arrival of the shuttle on O location and the removal of the pallet by the conveyor technology, after the shuttle left it on the O location and departed.

The capacity of DHPWs to satisfy temporary fluctuations in demand is comparable to that of shuttle-based warehouses that can perform intermediate buffering on the base and is much higher than that of channel storages. However, the cost of Layout 1 is lower than that of shuttle-based system, because of the smaller size of the shuttle fleet, and only slightly higher than that of a channel storage, because of the only small shuttle fleet on the base level of Layout 1.

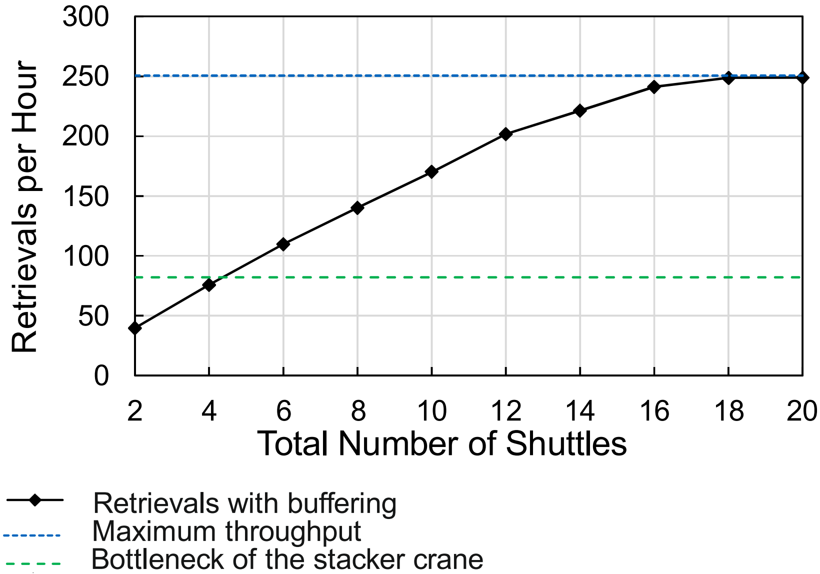



*Figure 7-3: Demonstration of capacity of DHPWs to satisfy high peaks in demand thank to the presence of a shuttle level on the base [Sic-2020]*

## 7.3 Scalability of Performance

The aim of this section is to demonstrate the high scalability of performance for DHPWs. Therefore, it is shown that the introduction of additional shuttles and stacker cranes in DHPWs causes a strong improvement of throughput.

In order to do so, the focus is on Layout 1. If it is demonstrated that Layout 1, despite having the connection between shuttles and stacker cranes only on the base, is easily scalable, it can be derived that also Layout 2 and 3, having flexible transfer buffers on all levels achieving the bottleneck of stacker cranes for an equal or higher number of shuttles on levels as Layout 1, provide a high scalability. The behaviour of the system is discussed just for double cycles as OOM. The reason is that if Layout 1 reaches a high scalability even for the case of double cycles, in which stacker cranes and shuttles must perform both retrievals in sequence and storages, it will also be very scalable when performing retrievals in sequence and storage as OOM.

In Figure 7-4 it can be observed that for one stacker crane in the aisle and two shuttles 20 double cycles can be performed per hour. If the number of shuttles is increased to three shuttles per zone, a total of eight shuttles in a module is reached and the throughput triples, becoming almost 60 double cycles per hour. This performance increase is remarkable, because it amounts to 10 further double cycles per hour for each further shuttle in the module. This is an indicator of a good scalability of the system's performance.

In this case, if the number of shuttles is further increased, no improvement of the throughput is possible because of the bottleneck of the stacker crane. Therefore, to further increase the performance it is necessary to add a second stacker crane in the aisle. This enables the system to elevate the throughput to more than 80 double cycles per hour if two additional shuttles are introduced per zone for a total of 12 shuttles in the module. In the case of two stacker cranes per aisle, each further shuttle in the module increases the throughput by about five double cycles per hour. If the performance of 20 double cycles per hour by one stacker crane and two shuttles per module is compared with the throughput of more than 80 double cycles per hour by two stacker cranes per aisle and 12 shuttles per module, it is deduced that the performance quadruplicated. This is a significant evidence of good scalability.

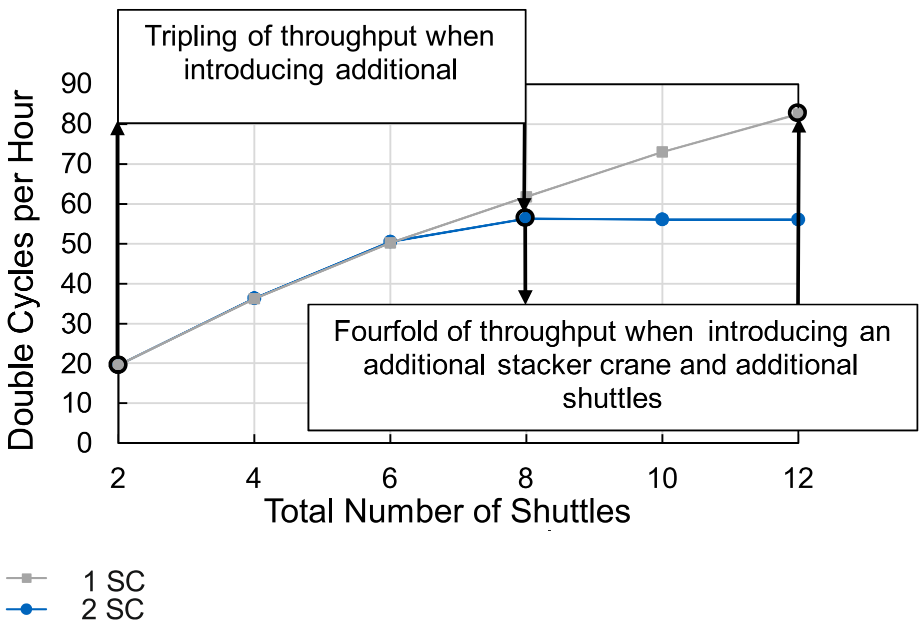



*Figure 7-4: Demonstration of high scalability of DHPWs thank to the synergies between shuttles and stacker cranes*

In case of storage or retrieval in sequence as OOM, the scalability is even higher. The throughput almost scales linearly if a further stacker crane is introduced in the aisle. This phenomenon is even more remarkable when the layout is short. A striking example is the layout with two sections i.e. 38 m long. With one stacker crane the plateau is reached with about 60 retrievals per hour, but as soon as a second stacker crane is introduced in the aisle it becomes 120 retrievals per hour. In conventional stacker-crane based systems, this notable performance increase would not be possible due to mutual obstruction of the stacker cranes. It can therefore be deducted that the design of the transfer buffer connection between shuttle base level and stacker cranes has a major role in contributing to a high scalability of the system.

All in all, DHPWs have a scalability that is higher than that of shuttle-based and stacker crane-based warehouses, because of the possibility not only to introduce further shuttles but also because of the presence of transfer buffer along the whole aisle. This enables any additional stacker crane to provide a contribution to the throughput that is higher than those provided by an additional stacker crane in the aisle of a conventional stacker crane-based warehouse or by an additional lift in the aisle of a shuttle-based warehouse. The reason is that the conventional stacker crane and the lift have a much smaller number of locations where to exchange pallets compared to the long transfer buffer of the stacker cranes of DHPWs.

## 7.4 Recommendations of Use

In the previous sections the potential in terms of performance of the synergies between shuttles and stacker cranes, which gives rise to DHPWs, has been demonstrated. In this section general recommendations of use for DHPWs are provided.

**Recommendation 1 – Field of Application**

*DHPWs can replace both stacker crane-based and shuttle-based warehouses to reach higher performance.*

Layout 1 can replace multiple-deep channel warehouses. The difference in cost between the two systems is given by the cost of rails for shuttles on the base and the cost of the shuttles themselves. In contrast to conventional multiple-deep channel warehouses, Layout 1 offers a high capacity to handle high peaks in demand, the possibility to sequence pallets on the shuttle base and a high scalability of performance.

Layout 3 can substitute shuttle-based systems. The differential costs are that of stacker cranes instead of lifts. Layout 2 can be used instead of Layout 3 if the higher throughput is required: in this case the number of shuttles required is very high, and Layout 3 would be limited because of the bottleneck of the stacker cranes.

**Recommendation 2 – Organization of Orders**

*Control algorithms of a DHPW are more complex than those of a conventional warehouse. The cornerstone is the precise creation of orders for shuttles and stacker cranes and the early reservation of locations of the transfer buffer by shuttles and stacker cranes.*

Most problems in the control system are caused when shuttles or stacker cranes reserve transfer buffer or storage locations on the levels too late or for too short time. Because there are so many components that need to be coordinated on such a large number of pallet exchange locations on the transfer buffer, even a short delay in reserving a location can cause deadlocks. Therefore, the sequence of actions within the component logic must be properly controlled. In order not to cause confusion and to guarantee traceability within the control system, it is advisable to keep the orders for the shuttles of each level in separate lists. Waiting orders for shuttles should also be in further separate lists. The complexity of the order management system is further increased for Layout 3, where further separate lists contain orders to move empty shuttles between the different levels.

**Recommendation 3 – Systematic Approach and Limit Situations**

*To build a control system for a DHPW it is strongly recommended to follow the approach shown in the diagram in* Figure 4-7*, because it supports a systematic development of strategies for the control system.*

Given the large number of components and pallet exchange areas in a DHPW, an orderly method of implementing the control system reduces implementation time and avoids errors and oversights. Particular attention should be paid to the operation of the algorithms when the edge cases of total occupation or total emptying of the transfer buffer of the base are reached. It is more likely that errors or oversights occur during the implementation of the algorithms for the control system that regulate edge cases.

## 7.5 Evaluation of the Approach for Answering the Research Questions

In this section the efficacy of the approach illustrated in this dissertation for answering to the research questions is evaluated. In the following the research questions are listed and their summary responses based on the results illustrated in the previous chapters.

- ***How to conceive the connection and coordination between shuttles and stacker cranes to exploit their synergies in the form of DHPWs?***
  The connection and coordination between shuttles and stacker cranes should be developed based on the study of layout optimization, of strategies for the control system and of performance analysis. As demonstrated through simulations in **Section 7.1**, the connection and coordination between shuttles and stacker cranes proposed in this dissertation enable DHPWs to reach higher throughputs than the conventional stacker crane-based and shuttle-based warehouses considered. Moreover, it ensures scalability of performance and capacity to satisfy high peaks in demand as shown in **Section 7.2** and **Section 7.3**.

  I. *Which **layouts** should be designed to investigate the connection between shuttles and stacker cranes? Which components should these layouts comprise?*
     The layouts to be investigated are Layout 1, obtained hybridizing a stacker crane-based warehouse with a shuttle base, Layout 2, obtained hybridizing a shuttle-based warehouse with stacker cranes in the main aisle, Layout 3, obtained considering Layout 2 and enabling the shuttles to be moved by the stacker cranes between levels. The components to be used in these layouts are either machines or layout components. Machines comprise bidirectional shuttles, stacker crane with satellites or stacker cranes with forks according to the type of layout. Layout components are transfer buffer locations, aisles to let the shuttles move, buffer locations on the base, storage locations on the levels, the main aisle where multiple stacker cranes are operating, I/O areas and I/O locations. **Section 4.1** provides an answer to this research sub-question.
  II. *How should the **material and information flow** be organized to guarantee a smooth coordination of shuttles and stacker cranes?*
     Separated flows should be considered for the shuttles on the base and the stacker cranes. The combination of the operating modes for shuttles and of those for stacker cranes enable to obtain different OOMs of the warehouse to perform single cycle retrieval in sequence, single cycle storage or double cycles. More details on the answer to this research sub-question are given in **Section 4.2**.

III. *Which* ***strategies for the control system*** *enable cooperation and coordination between shuttles and stacker cranes for each layout in the different operating processes?*
The strategies developed depend on the type of layout, on the OOM considered, on the component in focus and on whether the bottleneck in throughput is caused by shuttles or stacker cranes. The detailed explanation of the strategies for the control system is in **Section 4.3**.

IV. *Which* ***order assignment strategies*** *can be applied to the connection between shuttles and stacker cranes in the different operating processes to improve the throughput?*
Order assignment strategies to be applied depend on the OOM considered and are the combinations of policies for the operation having the most influence on throughput, whose interaction causes an improvement in throughput. The qualitative discussion of the specific order assignment strategies is in **Section 4.4**. The quantitative investigation shows that operations having the highest influence on throughput are those depending on the choice of shuttles or stacker cranes for a pallet or a location directly on the transfer buffer. A detailed discussion of operations based on simulation results is in **Section 6.4**.

V. *Which* ***optimization strategies*** *can be applied to improve the performance obtained with multiple stacker cranes in a single aisle?*
Depending on the different configurations of Layouts 1, 2 and 3, the main strategies to be applied to improve the throughput of the system are *One Direction*, *Double*, *Succession* and *Wait or Drive*. The logic followed by these strategies and the configurations of DHPWs enabling their use are qualitatively discussed in **Section 4.5**. The improvement provided by optimization strategies for the stacker cranes depend strongly on the configurations considered and the strategy applied. In most cases, the strategy *Succession* brings the highest improvement in throughput. Specifically, in the examples of Layouts 1 and 2 for two and one stacker crane respectively, in double cycles as OOM the throughput reached is almost as high as that provided by basic strategy when using an additional stacker crane. This corresponds to an improvement of about 39 % and 86 % respectively. A detailed discussion of the optimization strategies for the stacker cranes is in **Section 6.5.**

VI. *Which elements of* ***the macro- and the micro-layout*** *have a main influence on the performance of DHPWs?*
Depending on the type of layout and on the OOM, the design elements having the main influence on throughput are the number of sections and

levels of the warehouse, the allocation and configurations of I/O areas, the configuration of transfer buffer and the fleet dimension. A discussion of these elements based on quantitative simulation results is in **Section 6.2** and **Section 6.3**.

The main research questions and the research sub-questions were answered within this dissertation. Then, in **Sections 7.1, 7.2, 7.3**, the advantages of DHPWs in comparison to relevant conventional technologies have been demonstrated. Therefore, the research gap regarding strategies for the control system, design optimization and performance analysis for DHPWs is filled. Consequently, it can be concluded that the research method was effective. Reflecting on possible points of improvement, conducting a survey among logistics experts could have led to the identification of further possible elements acting as bottlenecks of throughput in DHPWs, which could have been mitigated by adapting design of and strategies for the control system.

# 8 Conclusion and Outlook

In the following the main results of this contribution are summarized. Afterwards possible future expansions of this work are discussed.

## 8.1 Conclusion

Dynamic Hybrid Pallet Warehouses are an innovative solution to exploit the synergies between shuttles and stacker cranes to reach even higher performance in automated pallet warehouses. They combine the advantages of conventional stacker crane-based and shuttle-based warehouses. There were no studies in the scientific literature on these innovative class of warehouses. Therefore, in this dissertation the research gap is filled regarding strategies for control system, design optimization and performance analysis of DHPWs.

First, three different layouts for DHPWs suitable for the fields of application of conventional warehouses were defined. Layout 1 is obtained by hybridizing a stacker crane based-warehouse using a shuttle level for the base. Layouts 2 and 3 result from the hybridization of a shuttle-based warehouse with stacker cranes instead of lifts. Unlike in Layout 2, in Layout 3 shuttles can be moved between levels. Layout 1 has the field of application of conventional stacker crane-based warehouses, while Layout 2 and 3 have that of conventional shuttle-based warehouses. Then, the material and information flow was defined in terms of shuttle operating mode, stacker crane operating modes and Overall Operating Mode (OOM) of the warehouse, such as sequenced retrieval, storage and double cycles, in order to be able to elaborate strategies for the control system. A systematic approach was crucial to develop and characterize these strategies. They were differentiated on the base of the layout of the DHPW considered, on the OOM, on the components considered and finally on whether shuttles or stacker cranes are the throughput bottleneck of the system. After the basic strategies for the control system were designed, order assignment strategies could be formulated for Layout 1 to obtain an improvement in throughput for the warehouse. Layout 2 and 3 have equivalent operations and order assignment strategies. To reach a further increase in throughput, configurations and coordination strategies for performance optimization of multiple stacker cranes in a single aisle were developed for Layouts 1, 2 and 3. To demonstrate the improvement provided by optimized order assignment strategies and coordination strategies, a simulation study was necessary due to the complexity of interactions among components of a DHPW. To perform this study, the

DHPWs were modelled in the discrete-event simulation environment Tecnomatix Plant Simulation, verified the model analytically and validated it against the real sub-systems. For the validation of the shuttle base of DHPWs an analytical method was developed to calculate test positions based on the distance travelled by a shuttle during an average cycle.

In the simulation study it was started by investigating design factors. Regarding the macro-layout, throughput increases when reducing the length of the aisle but not always when reducing the number of levels, depending on the DHPW considered and on whether shuttles or stacker cranes are the bottleneck. With respect to the micro-layout, the use of I/O areas on both sides, instead of only one, is critical when performing double cycles to reach a high throughput, especially for Layout 3. Moreover, the configuration of the I/O area can be the major limiting factor of the throughput of the warehouse when shuttles and stacker cranes operate according to performant strategies for the control system. Also, the configuration of the transfer buffers, i.e. the disposition of storage and retrieval locations along the aisle that can be served by both stacker cranes and shuttles, has a significant influence on throughput, specifically in case retrieval is performed in Layout 2 and the stacker cranes are the bottleneck of throughput. As further micro-layout element, the fleet dimension can be optimized for Layout 2 until a certain minimal number of shuttles on levels is reached, because only the shuttles on the base have a major influence on throughput.

For the order assignment strategies, the operations having the main influence on throughput were investigated quantitatively. From these operations the most promising combinations of order assignment strategies were derived. After further simulations, the combinations for storage, retrieval and double cycles providing circa 6 % increase in throughput, were identified on the example of Layout 1.

Moreover, the simulation study shows that a large improvement in throughput can be reached when applying optimization strategies for multiple stacker cranes in the aisle. To this point, the optimized coordination strategy *Succession,* applicable when the stacker crane has at least two pallet or shuttle positions, proves to be for all Layouts the one providing the highest throughputs. Specifically, in the case of double cycles, for Layouts 1 and 2 it reaches almost the same throughput as the basic strategy with an additional stacker crane when using respectively two or one stacker cranes. This is an increase in throughput of about 39 % for Layout 1 and 88 % for Layout 2.

After the simulation study the higher throughput achievable by Layout 1 when compared to single-, double- and nine-deep storage stacker cranes has been demonstrated in the form of a critical discussion. Then it has been shown that Layout 2 and 3 are able to reach higher throughputs compared to a shuttle-based warehouse having the same configuration of levels. Afterwards, the high scalability of performance and the high capacity to satisfy high peaks in demand bypassing the stacker cranes' bottleneck were demonstrated for DHPWs and recommendations of use were provided.

All in all, in light of the research results presented in this dissertation, DHPWs prove to have valuable characteristics that collocates them among the currently most advanced systems for handling pallets.

## 8.2 Outlook

For future research, given the complex interaction between shuttles and stacker cranes, it would be interesting to investigate the generation of optimized storage and retrieval strategies for the control system using artificial intelligence. The research project SeSoGEN at Chair of Materials Handling, Material Flow, Logistics at TUM, also coordinated by the author of this dissertation, has as objective the development of a self-learning warehouse management software to generate optimized storage strategies using neural networks. The neural network model based on reinforcement learning developed in the project SeSoGEN could be adapted, further developed and applied to DHPWs. To enable differentiating between pallets with different logistical requirements the models of DHPWs in the discrete-event simulation environment Tecnomatix Plant Simulation should be extended to include the representation of different categories of products. The neural network can then be connected to the simulation models and trained on them, optimizing the cycles time of shuttles, of the stacker cranes and the total time to store or retrieve a pallet. The aim would be to obtain strategies for the control system of stacker cranes and shuttles that, by reducing the size of the fleet of shuttles and the number of stacker cranes, enable to reach throughputs even higher than those reachable with the strategies proposed in this dissertation.

Another future field of investigation could be the generation of a framework to optimize the design features of DHPWs according to the specific application. This framework could require, as input, parameters such as the average throughput desired for retrieval and storage, the maximum peaks in demand to be expected, the storage capacity needed, the maximum affordable investment, the position of the interfaces between layout of the DHPW and other facilities such as the area to load and unload lorries. The framework would give then as output for example the macro-layout, micro-layout, the number of shuttles, the number of stacker cranes and the value of the average dynamic parameters that constitute the DHPW layout. This framework should realize different configurations of DHPWs as models of the simulation environment.

These configurations should represent many different combinations of the variables later calculated as output by the framework. Then the DHPWs should perform different overall operating modes while registering the variables that then will become the input parameter of the framework. Due to the complexity of the problem artificial intelligence could be applied. Specifically, neural networks could be trained on the simulation to learn the relationships between performance and design features. The same neural networks would then replicate these dependencies within the framework to generate the optimal layout given the input parameters. The use of neural networks could be extended to generate DHPWs having layouts different from Layouts 1, 2 and 3 and fulfilling further requirements.

Another interesting field of research could be the retrofit of conventional stacker crane-based and shuttle-based warehouses. It could be investigated with which components and according to which layout to integrate conventional warehouses already existing in plants in order to increase their throughput approaching that of DHPWs. This could be done for example for existing stacker crane-based warehouses by introducing shuttle levels above the frontal loop[13].

[13] The author is grateful to Dipl.-Wirtsch. -Ing. Jörg Eder of Gebhardt Fördertechnik GmbH for having the idea of introducing shuttle levels in the front of a conventional stacker crane-based warehouse in order to retrofit it to a DHPW.

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## Student works supervised by the author

The following student works were created as part of the research topic addressed by this dissertation. The preparation of the work was scientifically and content-wise instructed by the author[14].

| Reference | Title | Author | Type | Submission |
|---|---|---|---|---|
| | Entwicklung von Routingstrategien für fahrerlose Transportfahrzeuge in einem automatisierten Lagersystem | Xiaobing, Dai | Semester's Thesis | 2020/05 |
| | Development of Order Processing Sequence Strategies for Driverless Transport Vehicles in a Dynamic Storage System | Yu, Yue | Semester's Thesis | 2020/05 |
| | Modellierung von mehreren Regalbediengeräte in derselben Gasse mit festen Bereichsgrenzen in einem hoch dynamischen Paletten Lagersystem und Untersuchung deren Einfluss auf den Durchsatz des Gesamtsystems | Durek, Anna | Semester's Thesis | 2020/06 |
| | Analyse verschiedener Steuerungsstrategien zur Koordination von mehreren Regalbediengeräten in einer Gasse | Durek, Anna | Master's Thesis | 2021/03 |
| | Einfluss der Verfügbarkeit auf den Durchsatz in einem hoch-dynamischen hybriden Lagersystem | Hohenthal, Lelia Annmarie | Semester's Thesis | 2021/04 |

[14] Originaltext "Im Rahmen der durch diese Dissertation aufgegriffenen Forschungsthematik wurden nachfolgende Studienarbeiten erstellt. Die Anfertigung der Arbeiten wurde durch den Autor wissenschaftlich und inhaltlich angeleitet."

| | | | | |
|---|---|---|---|---|
| [fml-2021] | Optimisation of the performance of a highly-dynamic hybrid warehouse system | Yu, Yue | Master's Thesis | 2021/04 |
| | Investigation of the investment and operating costs of a compact automated storage system | Samanski, Patrik | Semester's Thesis | 2021/04 |
| | Entwicklung und Simulation von einem Retrofit Konzept für Regalbediengerät-basierte Lagersysteme zur Leistungsoptimierung | Huber, Martina | Semester's Thesis | 2021/09 |
| | Identification of the Parameters for Evaluation of a Warehouse System | Blanch Descarrega, Fatima | Master's Thesis | 2021/09 |
| | Einfluss verschiedener Designs auf die Leistung eines hybriden Lagersystems | Moro, Adrian Branko | Semester's Thesis | 2022/05 |
| | Studie über die Optimierung von dynamischen hybriden Paletten-Lagern | Moro, Adrian Branko | Master's Thesis | 2022/11 |

# List of Figures

## Main Part

**Appendix A**

**Appendix B**

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**Main Part**



**Appendix C**

# Appendix A Strategies for the Control System

In the following diagrams, given the higher complexity of the strategies for the control system of Layouts 2 and 3 compared to Layout 1, the connection points between components are indicated using small black blocks. In a black block, C$n$S represents the start of a connection, while C$n$E is the end of that same connection.

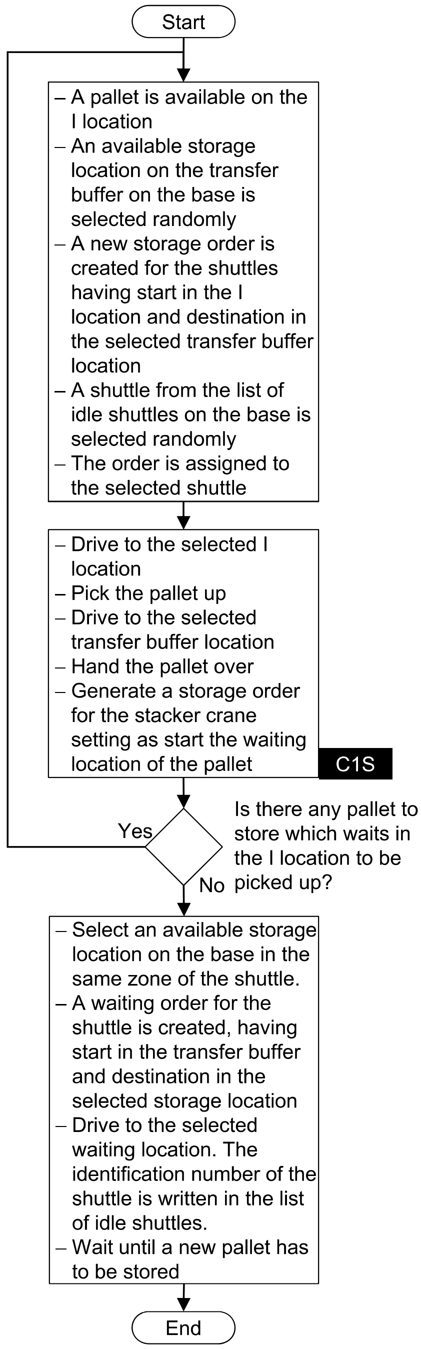


*Figure A-1: Control Logic – Layout 2, Storage, Shuttles on Base*

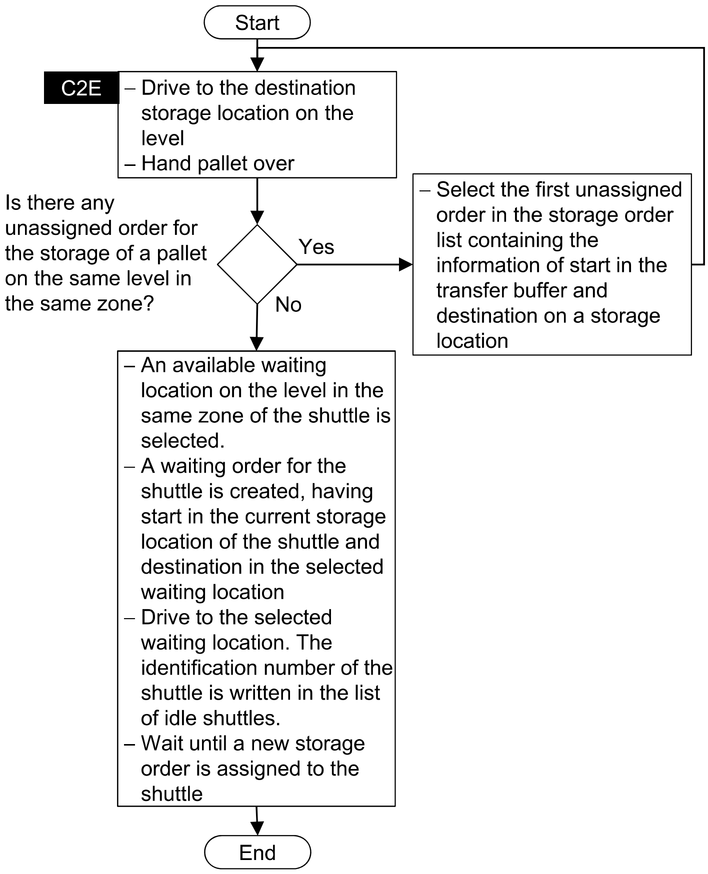


*Figure A-2: Control Logic – Layout 2, Storage, Shuttles on Levels*

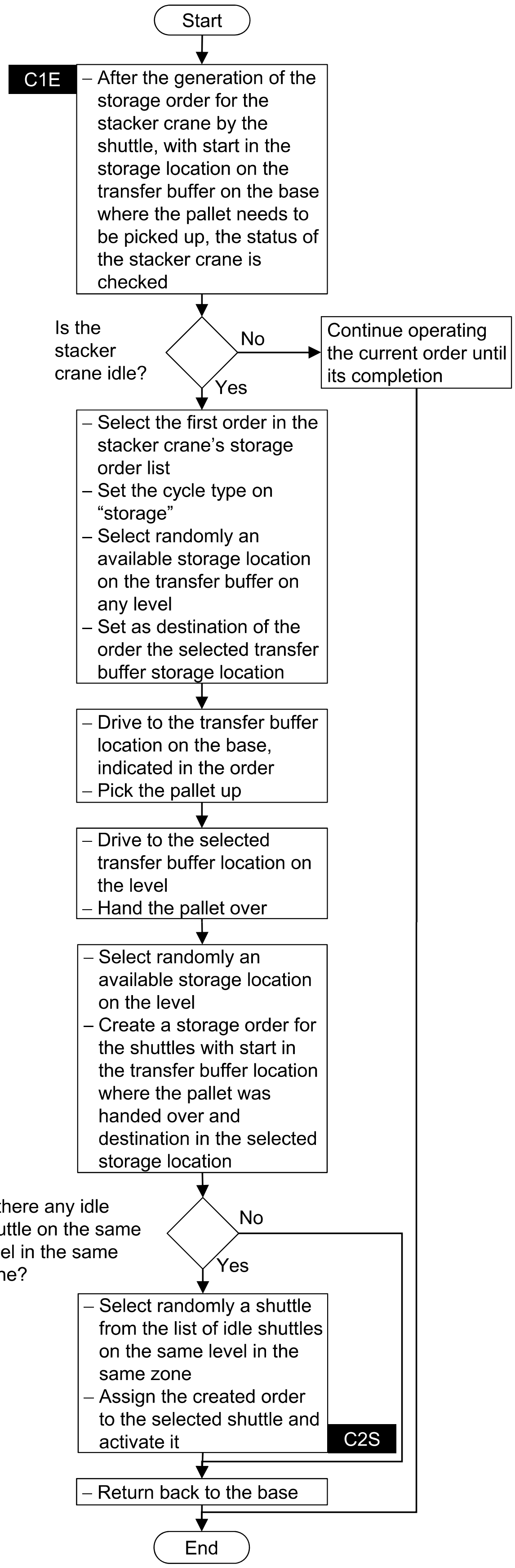


*Figure A-3: Control Logic – Layout 2, Storage, Stacker Crane*

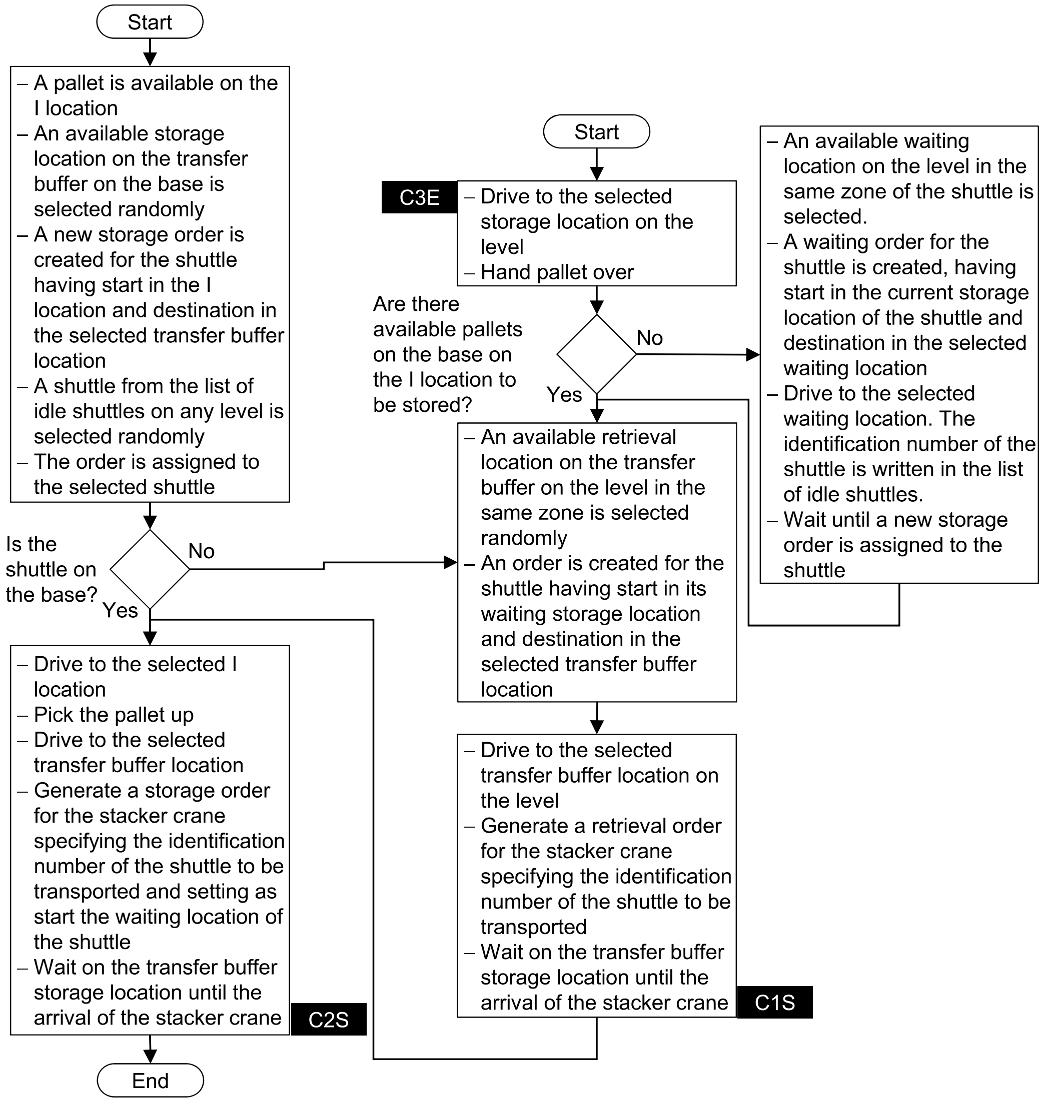


*Figure A-4:* *Control Logic – Layout 3, Storage, Shuttles on Base and Shuttles on Levels*

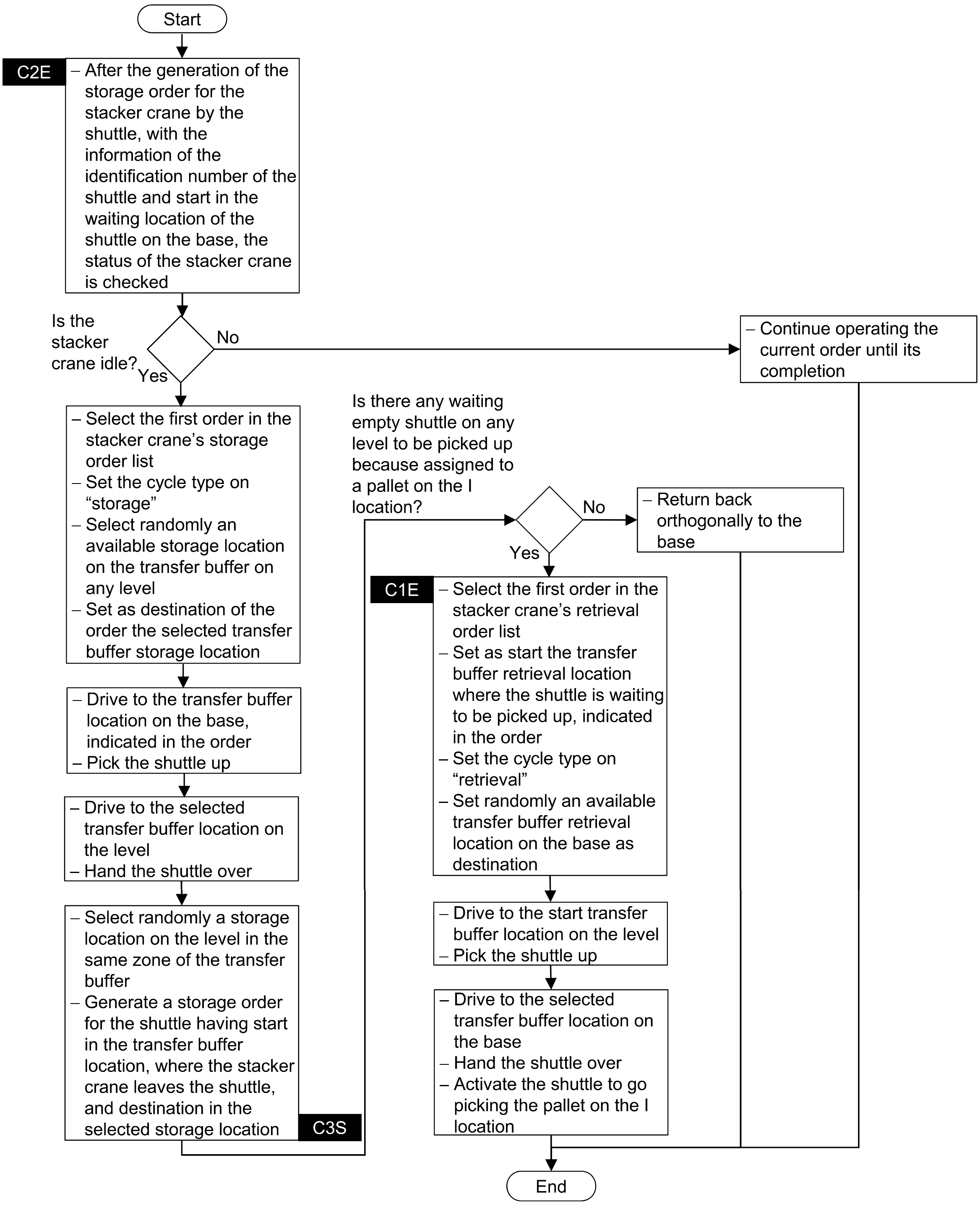


*Figure A-5: Control Logic – Layout 3, Storage, Stacker Crane*

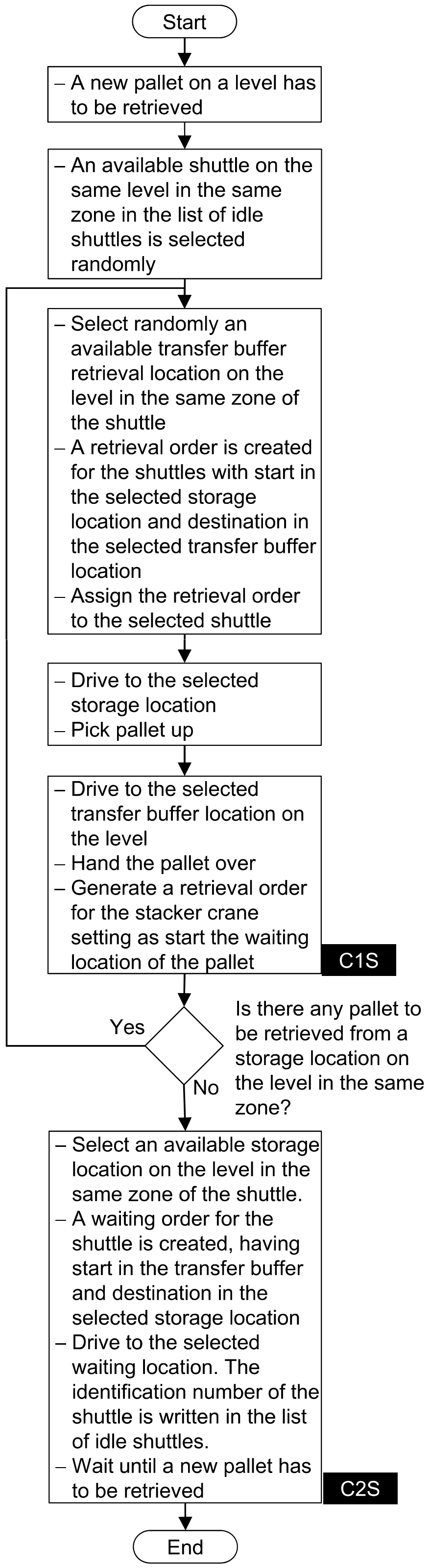


*Figure A-6: Control Logic – Layout 2, Retrieval, Shuttles on Base*

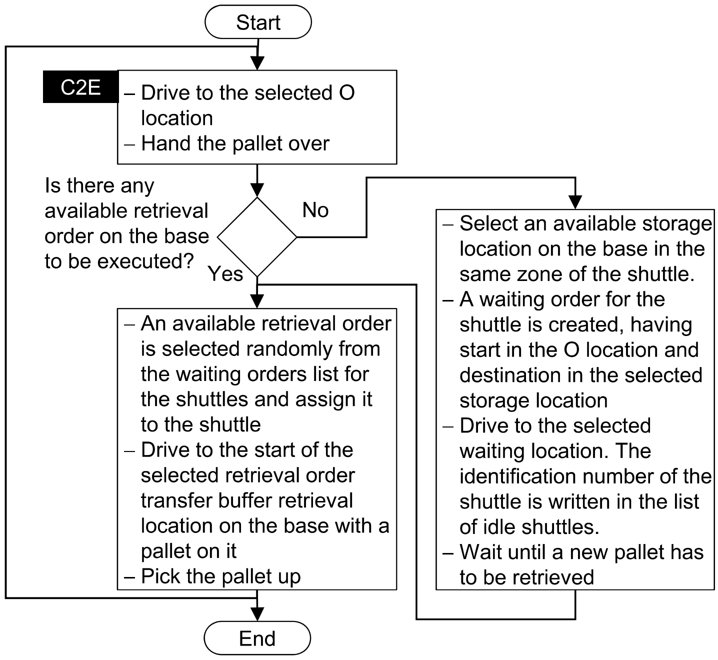


*Figure A-7: Control Logic – Layout 2, Retrieval, Shuttles on Levels*

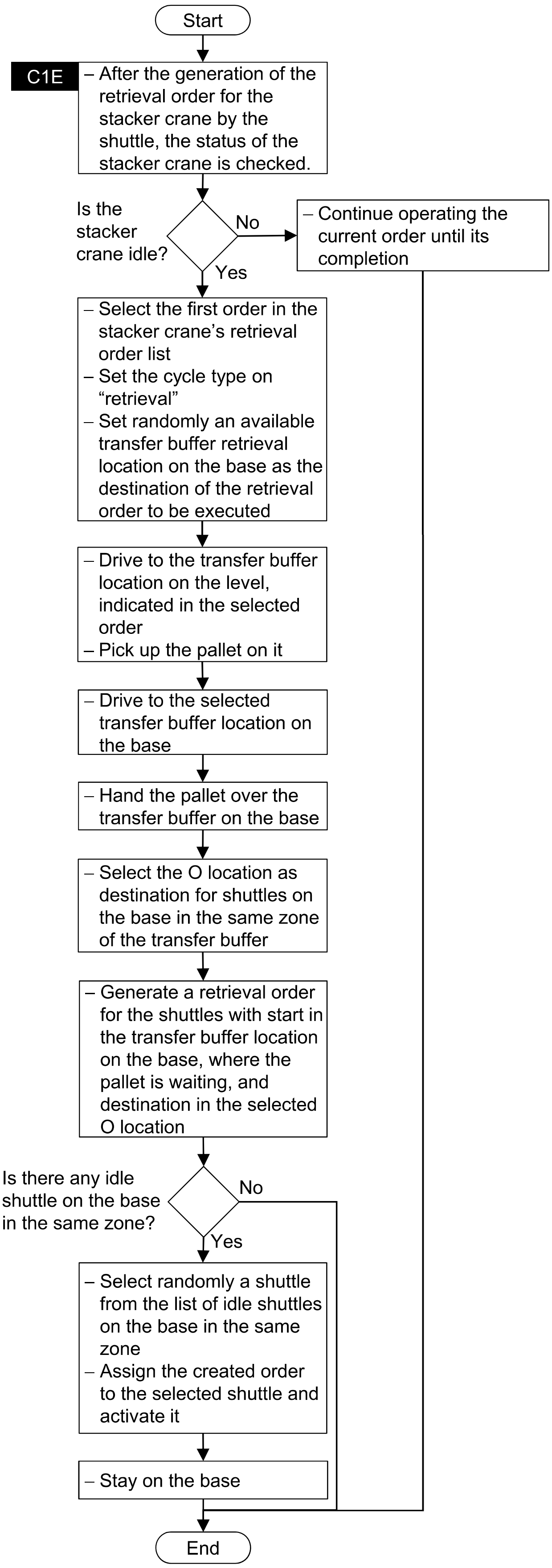


*Figure A-8: Control Logic – Layout 2, Retrieval, Stacker Crane*

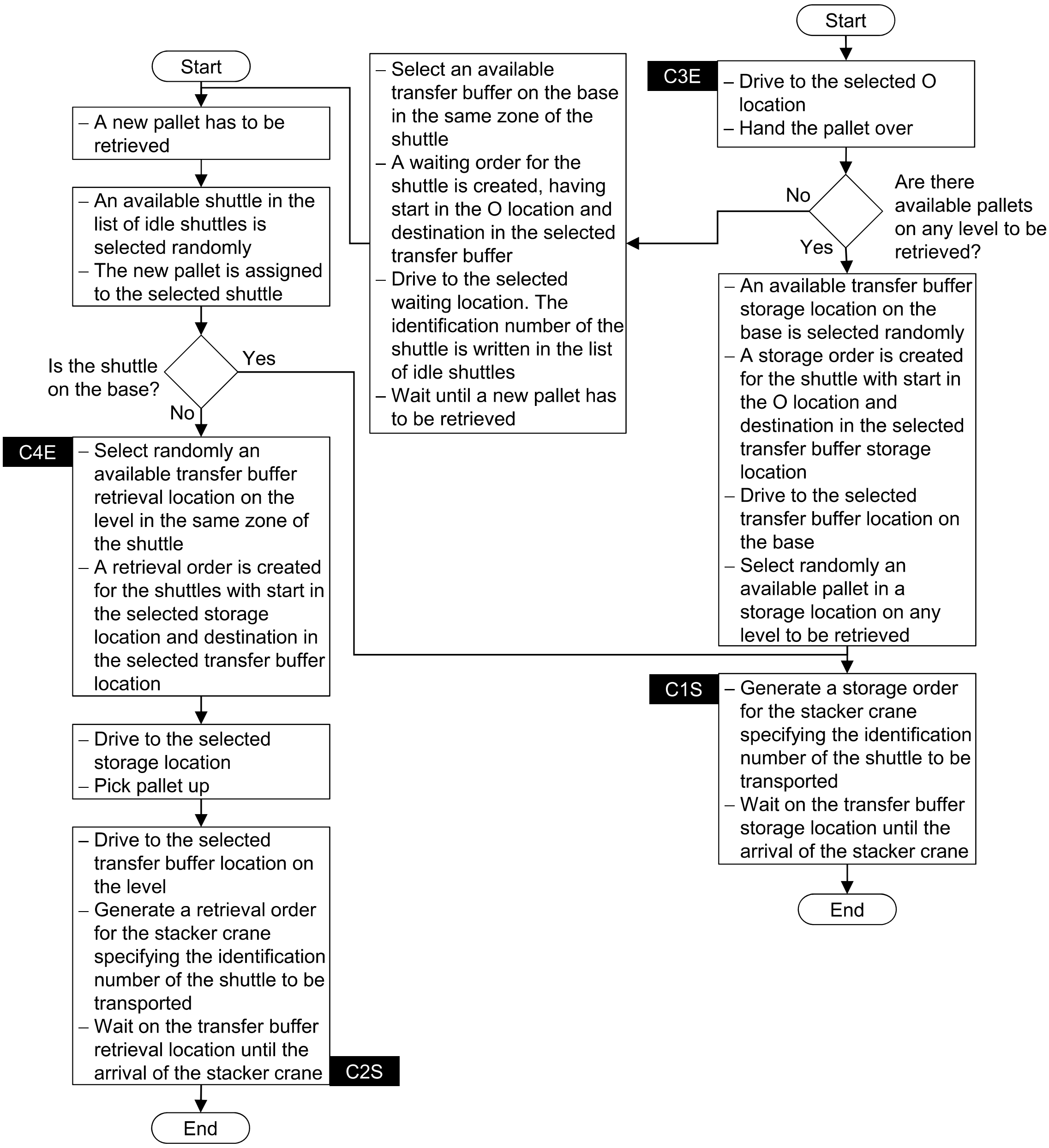


*Figure A-9: Control Logic – Layout 3, Retrieval, Shuttles on Base and Shuttles on Levels*

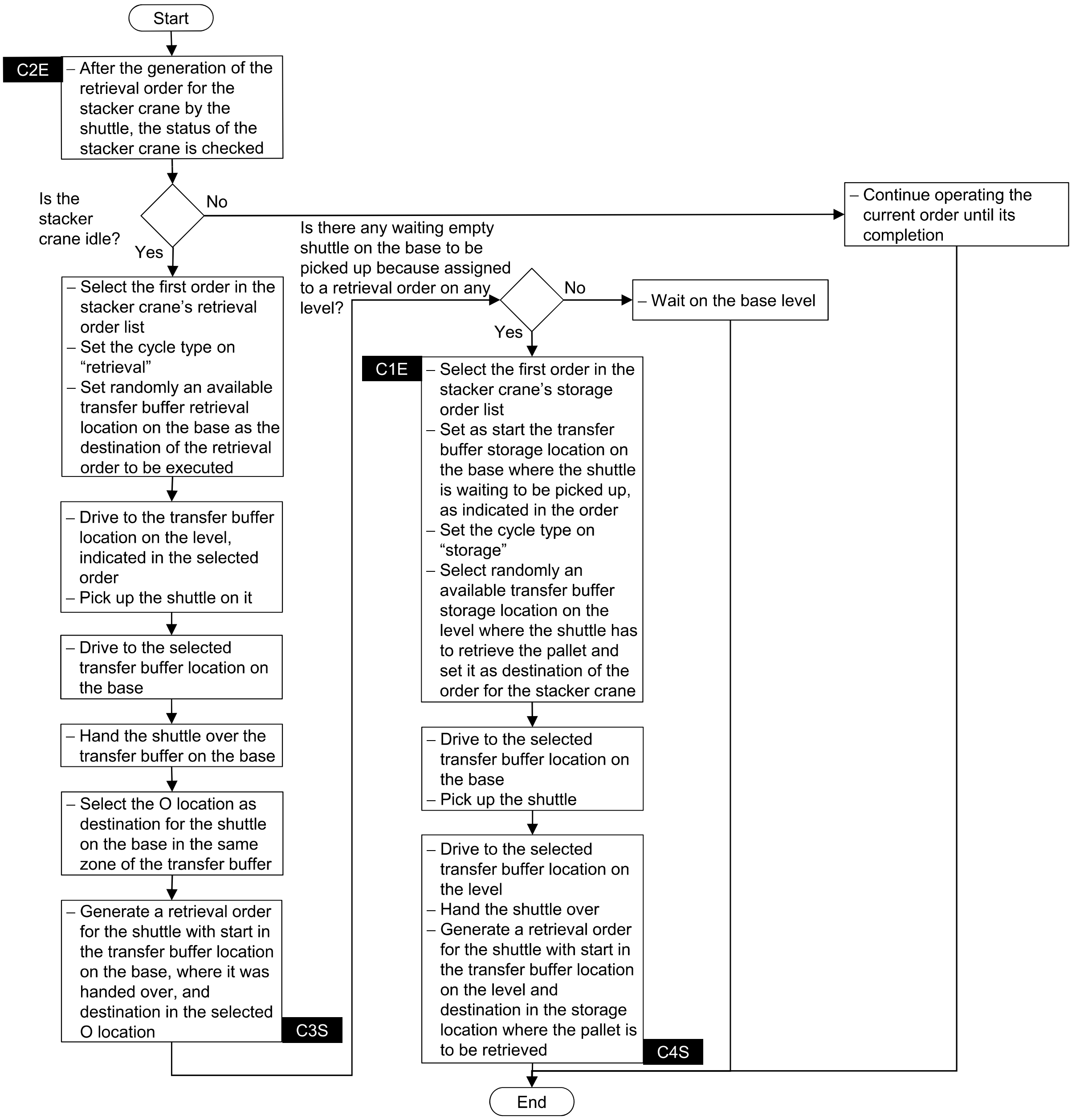


*Figure A-10: Control Logic – Layout 3, Retrieval, Stacker Crane*

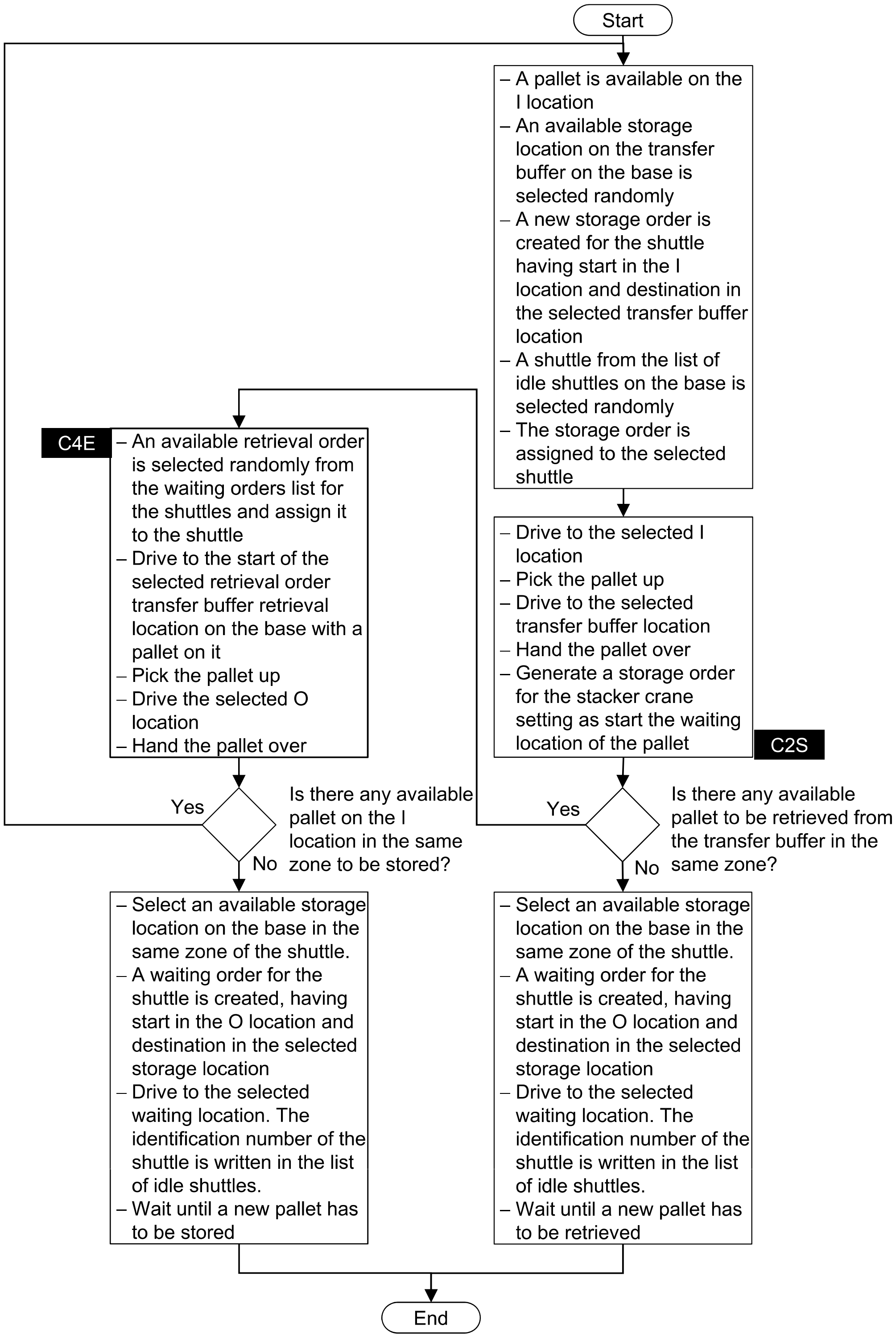


*Figure A-11:* *Control Logic – Layout 2, Double Cycles, Shuttles on Base [Sic-2022c]*

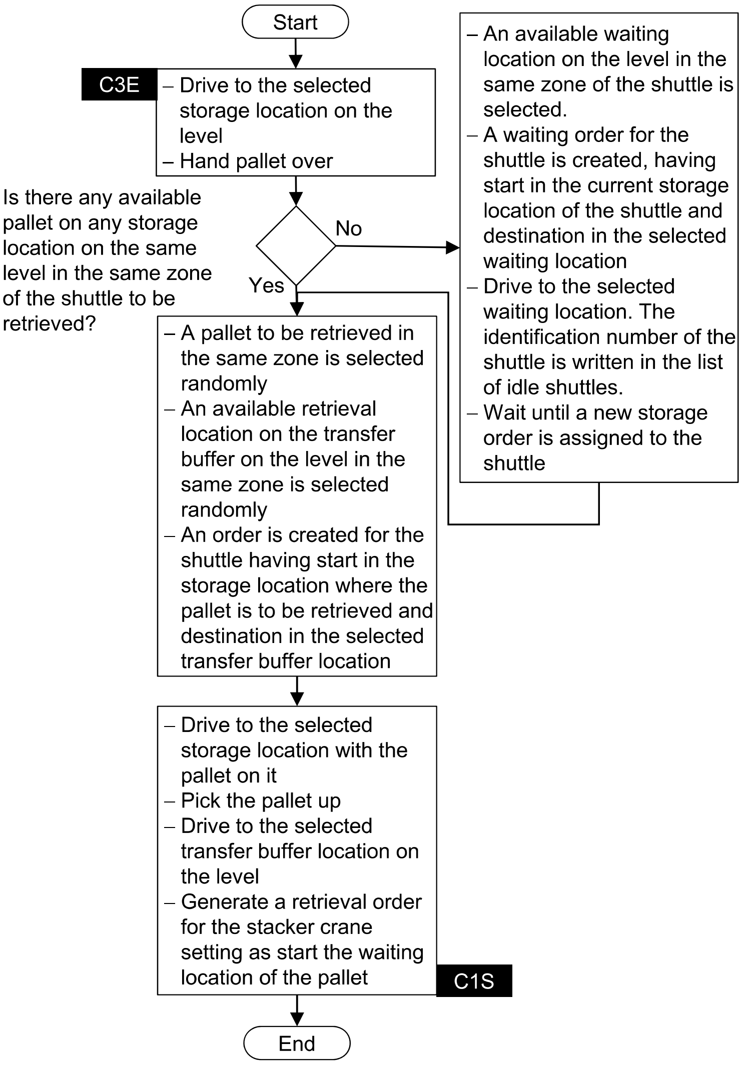


*Figure A-12: Control Logic – Layout 2, Double Cycles, Shuttles on Levels [Sic-2022c]*

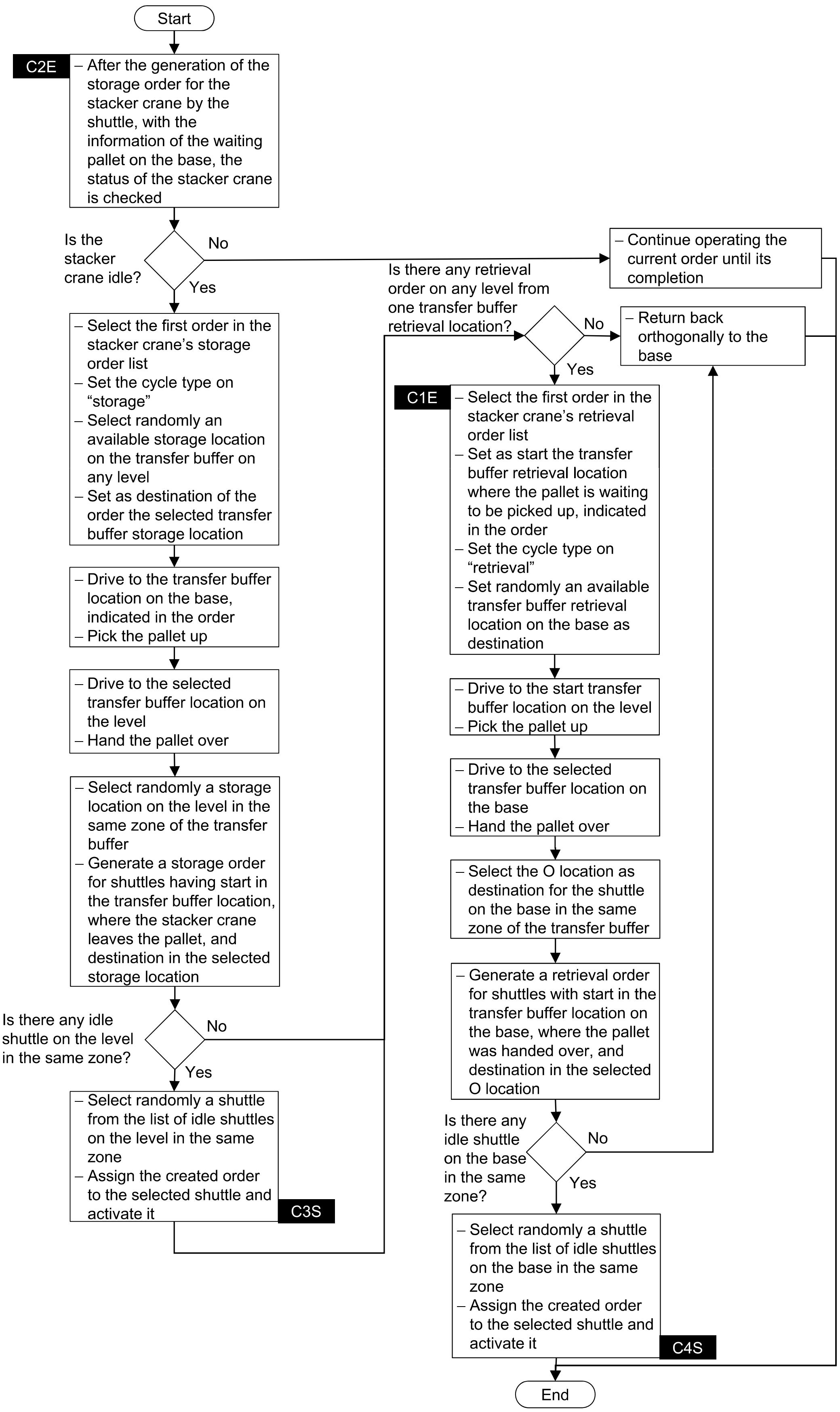


*Figure A-13: Control Logic – Layout 2, Double Cycles, Stacker Crane [Sic-2022c]*

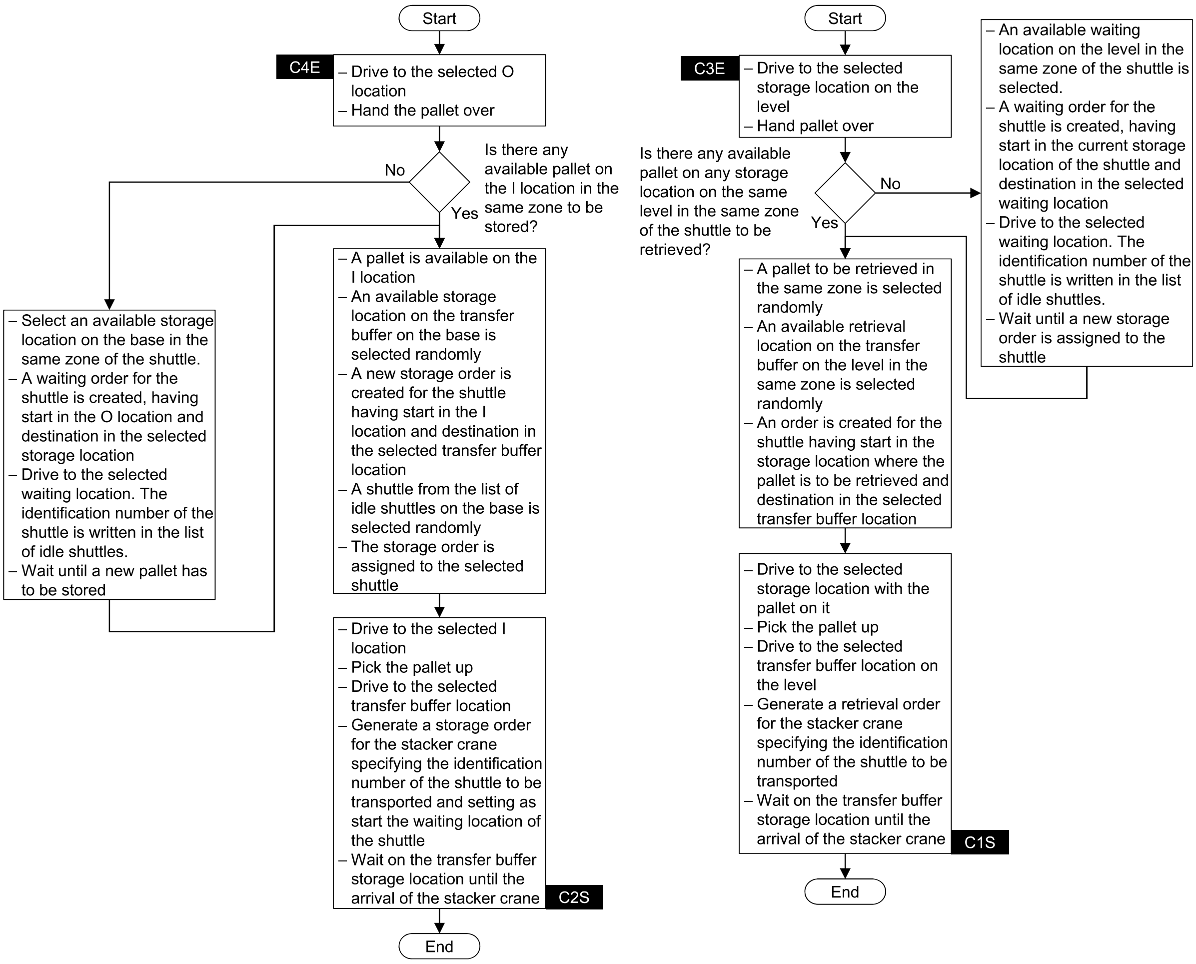


*Figure A-14: Control Logic – Layout 3, Double Cycles, Shuttles on Base and Shuttles on Levels [Sic-2022c]*

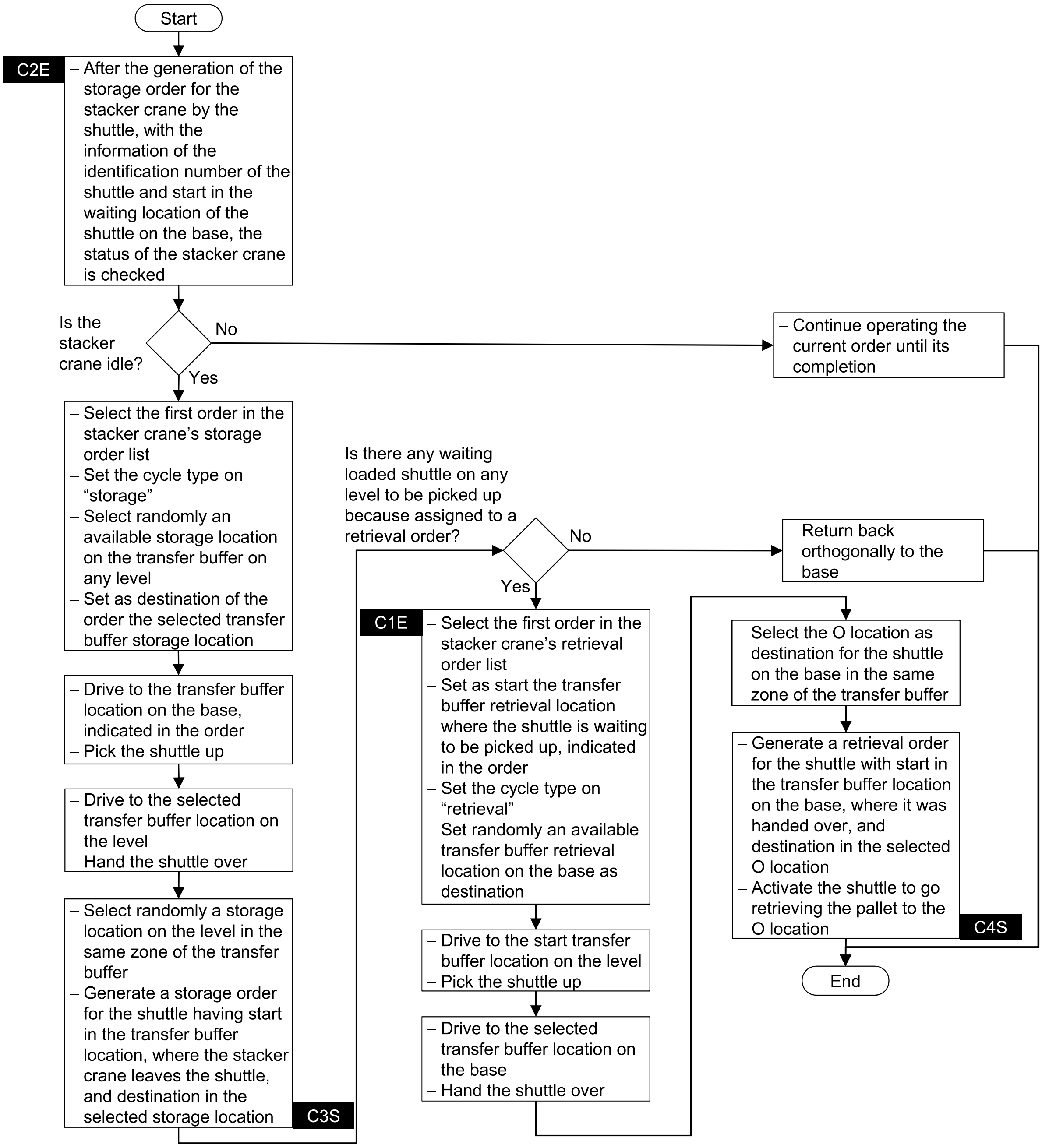


*Figure A-15: Control Logic – Layout 3, Double Cycles, Stacker Crane [Sic-2022c]*

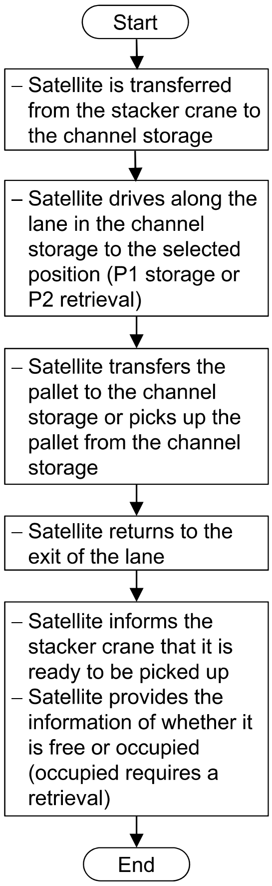


*Figure A-16: Control Logic – Layout 1, Satellite (in case multiple satellites are assigned to each stacker crane with a single satellite position) [Sic-2022a]*

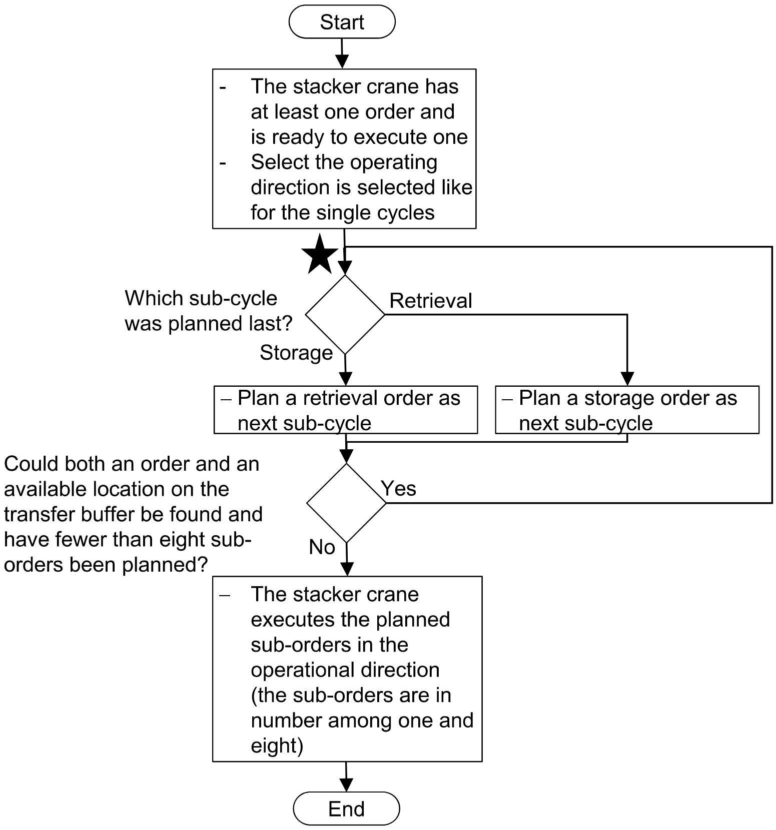


*Figure A-17: Optimization strategy One Direction – Layout 2, Double Cycles, Stacker crane*

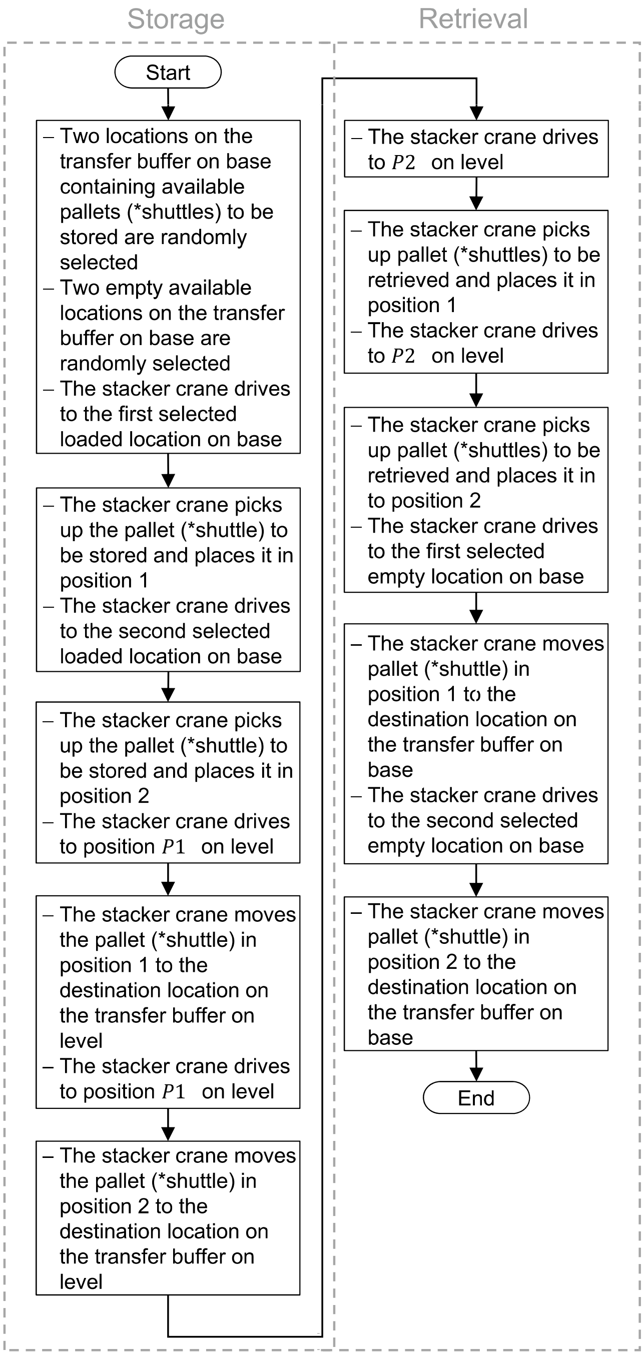


*Figure A-18: Optimization strategy Double – Layout 2, Double Cycles, Stacker crane*

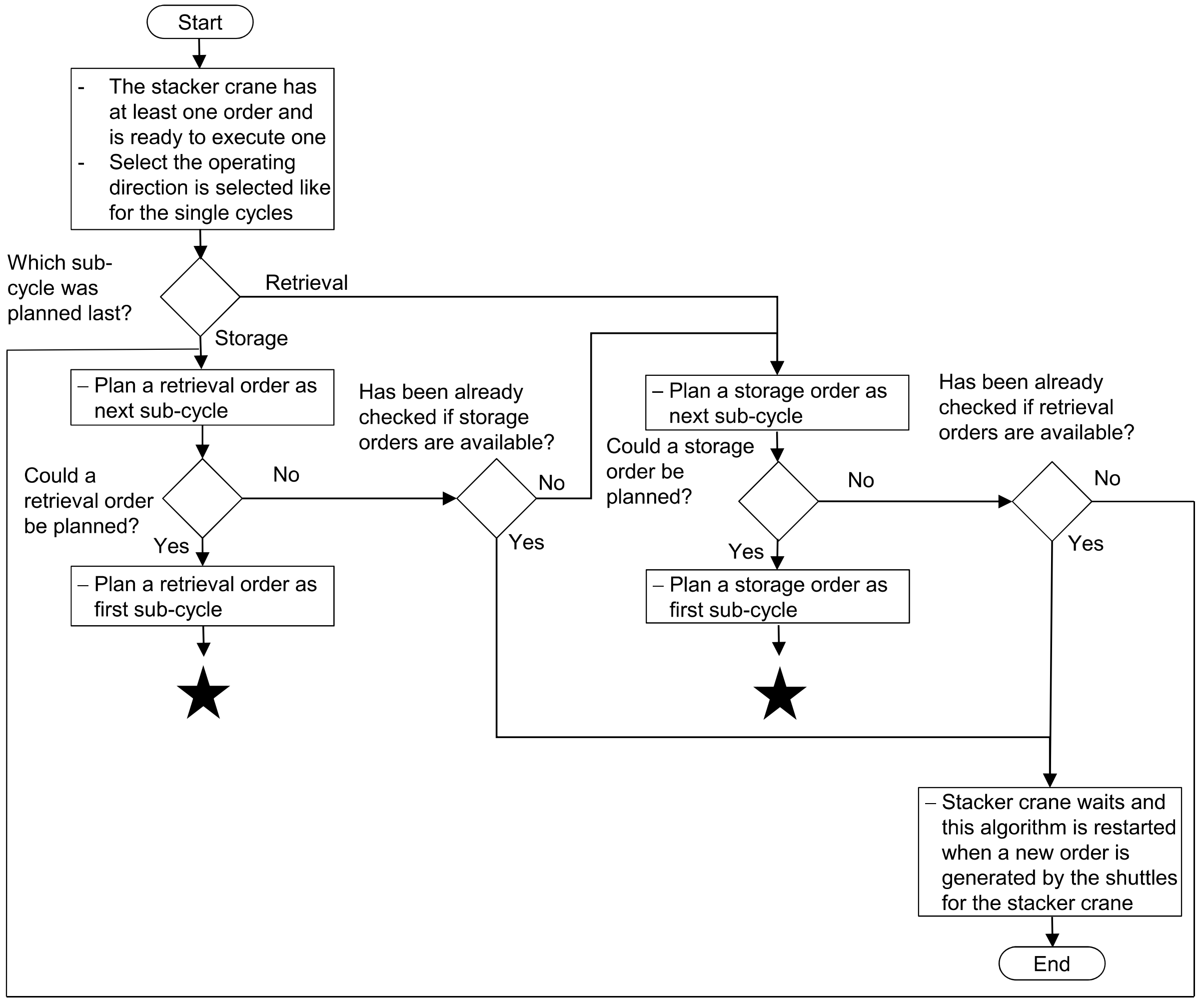


*Figure A-19: Optimization strategy Double – Layout 3, Double Cycles, Stacker crane*

# Appendix B Configuration of Transfer Buffer

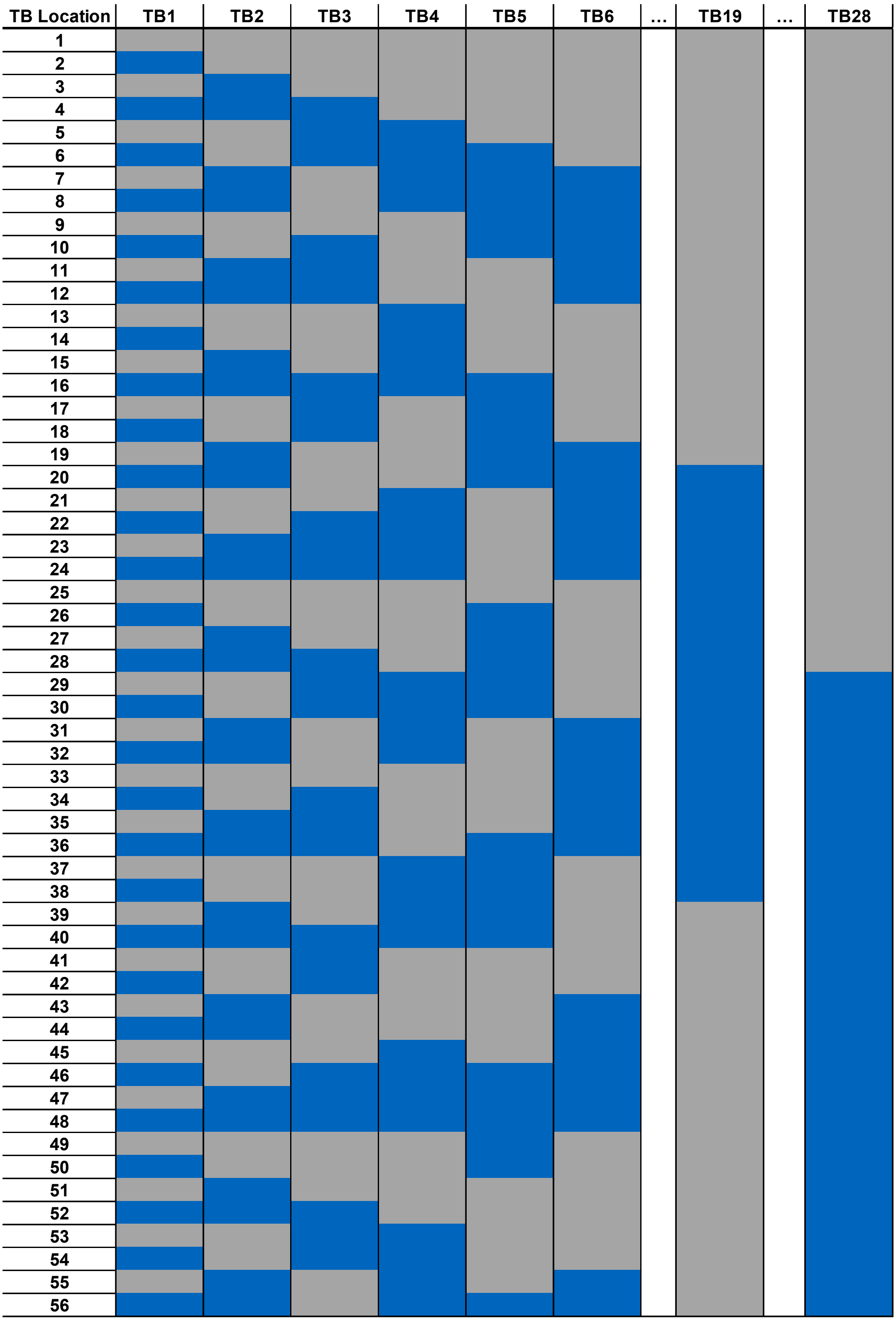


*Figure B-1:* *Investigated designs of transfer buffer for none or one stacker crane [Sic-2022c]. Blue blocks indicate RLTBs and grey blocks indicate SLTBs*

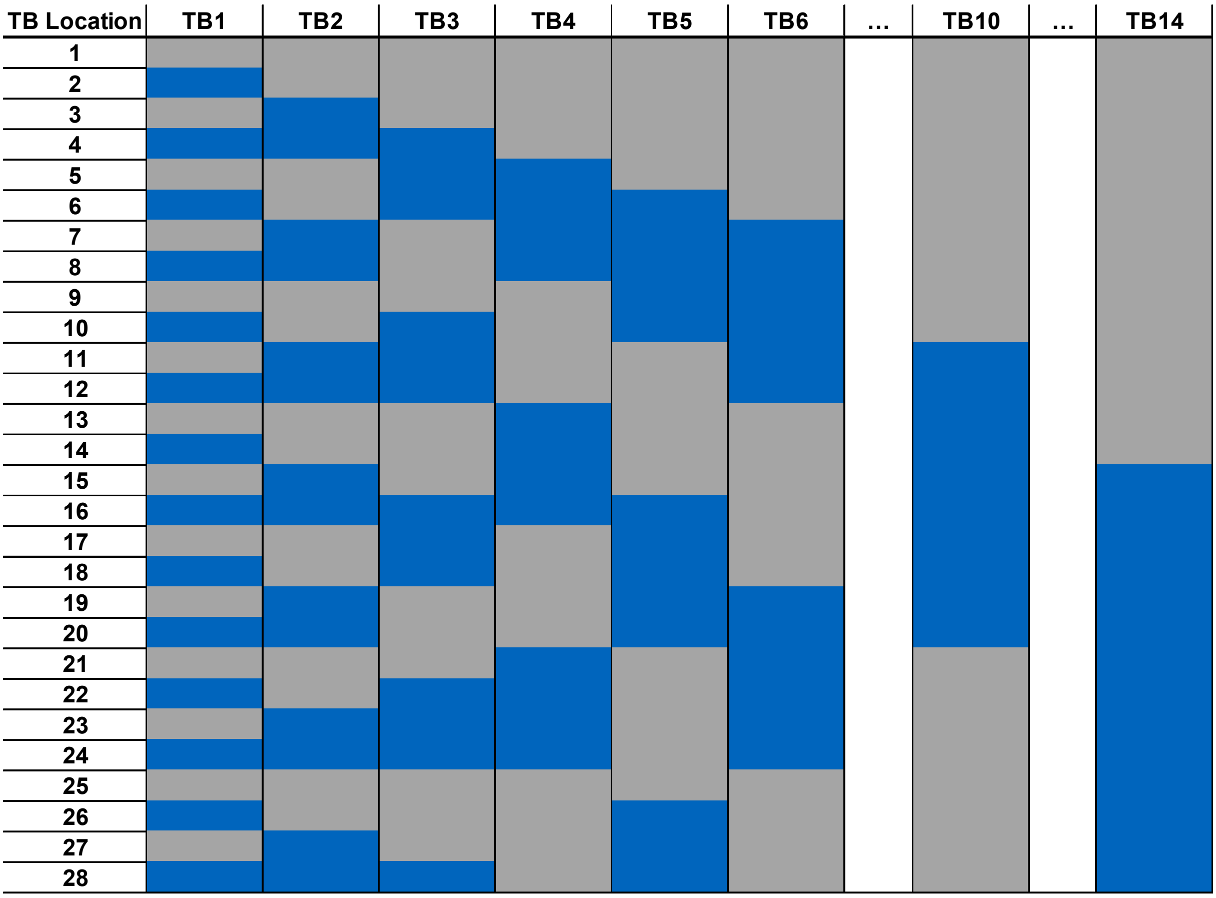


*Figure B-2:* *Investigated designs of transfer buffer for two stacker cranes [Sic-2022c]. Blue blocks indicate RLTBs and grey blocks indicate SLTBs*

# Appendix C Parameters

*Table C-1: Stacker crane parameters.*

| Parameters | Value |
| --- | --- |
| **Travel speed x** | $4.0\ m/s$ |
| **Travel acceleration x** | $1.0\ m/s^2$ |
| **Lifting speed y** | $1.5\ m/s$ |
| **Lifting acceleration y** | $1.0\ m/s^2$ |
| **Satellite speed z** | $1.2\ m/s$ |
| **Satellite acceleration loaded z** | $0.5\ m/s^2$ |
| **Satellite acceleration unloaded z** | $1.0\ m/s^2$ |
| **Time of pallet handover** | $1.0\ s$ |
| **Time of satellite handover** | $4.0\ s$ |
| **Time for positioning in channel** | $1.0\ s$ |
| **Time for positioning in front of channel** | $0.5\ s$ |