MASOUD MIRZAEI

Advanced Storage and Retrieval Policies in Automated Warehouses

ADVANCED STORAGE AND RETRIEVAL POLICIES IN AUTOMATED WAREHOUSES

Advanced Storage and Retrieval Policies in Automated Warehouses

Geavanceerde methoden voor in- en uitslag in automatische magazijnen

Thesis

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Masoud Mirzaei
Eindhoven, 2020

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Chapter 1

Introduction

Warehouses play a critical role in supply chains. They are responsible for storing products and distributing them to customers. The performance of a warehouse depends on the storage and retrieval systems and their control methods. With the advent of new automated and robotic technologies, new storage and retrieval methods have emerged, which can help the warehouse to become more efficient and responsive. This thesis aims to develop new storage and retrieval policies and methods that benefit from such automated technologies. Section 1.1 reviews important trends that influence warehouse operations. Section 1.2 discusses different choices in storage assignment. Section 1.3 explains different types of automated storage systems that are studied in this thesis. Section 1.4 gives an overview of research questions, corresponding methodologies and contribution of different chapters.

1.1. Current Trends in Warehousing

Over the last decades, market competition has put pressure on companies to reduce their customer order delivery time. In retail, single-day delivery has become a standard service. The so-called "Retail Apocalypse" in the U.S. (Washingtonpost.com, 2019) shows that customers are no longer satisfied with the limited assortment and services in brick-and-mortar stores and demand shifts to online shopping. In the Netherlands, 11% of the shops are closed since 2010 due to the shift towards online shopping (CBS, 2019). According to Brynjolfsson *et al.* (2011), the sales of retailers such as Amazon may no longer follow the Pareto principle, but rather exhibit a "long tail" curve. The long-tail theory, popularized by Anderson (2004, 2008), refers to the fact that customers demand a wider variety of products and tend to buy more niche products rather than the popular ones. Additionally, land shortage stimulates development of compact storage systems that increase space efficiency. However, this is often at the expense of lower throughput capacity.

These developments, on one hand, result in distribution centers that grow in size, which leads to long order picking travel times. On the other hand, however, they should offer short delivery times. Therefore, distribution centers require operations that allow reduced throughput times. Since the labor cost is increasing while the technology is becoming more affordable than before, using new technologies and robotics may be a viable option. According to Tompkins *et al.* (2010), more than 50% of the order picking time in manual warehouses is spent on traveling to the inventory locations and retrieving requested quantities. Developing advanced storage and retrieval policies can reduce order retrieval time. The next section gives an overview of storage assignment policies used in practice and studied in the literature.

1.2. Choices in Storage Assignment

Products can be assigned to storage locations in various ways. A storage assignment policy decides to which location a product should be assigned and in what quantity. It thereby determines the distance of a product to the order drop-off point and hence impacts picking time. Extensive literature has studied the role of storage assignment policies in warehouses. Here, we review policies commonly used in practice. In a random storage policy, products are stored randomly in available storage locations in the warehouse. For convenience, the closest available location may be used which results in random storage after a longer period of use (Malmborg, 1998). The random policy is easy to implement and is widely used in practice. It requires a smaller storage space compared to other policies because each storage location can be used by the inventory of any product (Malmborg, 1996). However, it does not result in a fast retrieval process since customer demand is not random and often follows a pattern. Many papers study the random assignment, and it is often used as a benchmark to other policies (see De Koster *et al.*, 2007; Roodbergen and Vis, 2009; Onal *et al.*, 2017).

Turnover-based policies rely on historical data of customer demand to identify frequently requested products. Products may be ranked based on several criteria such as units picked, lines picked, or the cube-per-order index (COI, see Heskett, 1963), which relates product turnover to the number of loads stored in the system.

The products are then assigned to a dedicated storage zone close to order delivery points, based on their rank. Products may be grouped first in storage zones, and then, stored randomly in storage locations within each storage zone. The turnover-based assignment using such zones is called a class-based policy (also known as ABC class-based storage, referring to classes A, B, and C, although more than three classes may be used). If the number of zones equals the number of products, the storage policy is called full turnover-based storage. The decision on the number of zones is a design choice for the warehouse. Yu *et al.* (2015) suggest that few zones, usually two or three, result in the minimum picking travel time. Compared to random assignment, turnover-based assignments result in shorter order picking retrieval time for popular products.

Another assignment choice is to disperse a product over the storage locations, i.e. splitting the inventory of a product and spreading it over the storage system. Specifically, when orders contain more than one product, a dispersed approach can help to find the requested products at closer proximity compared to when each product is assigned to only one location (Weidinger and Boysen, 2018). However, this may require a higher replenishment effort when a received product must be spread over multiple locations each time. Another dispersion approach is to replenish a product to only one location, but different from the current inventory locations. This approach results in less dispersion compared to the other dispersion method but requires less replenishment effort. The main difference between random and dispersed assignments is that the inventory of one product is assigned to the required number of storage locations in random storage while it can be assigned to any desired number of storage locations in dispersed storage. Literature studying the impact of dispersed assignment policies is not yet abundant.

Correlated assignment is yet another different storage policy. It uses the information of product correlations in historical customer demand data on the frequency of joint requests for products in multiple line orders. This relative historical frequency is called product correlation. A correlated storage policy assigns highly correlated products in close proximity in order to reduce the total retrieval time in order picking. The correlated assignment is relatively new in the literature and is also known as similarity-based assignment (Bindi *et al.*, 2009), cluster-based assignment (Jane and Laih, 2005) and affinity-based assignment (Li *et al.*, 2016).

Table 1 provides an overview of different storage assignment policies. The second column of the table shows the main decision factor for each policy. The third column shows some typical examples that study systems using such policies and their impact on retrieval time performance.

Table 1. Storage assignment policies.

Policy	**Decision Factor**	**Papers**
Random	Random	De Koster *et al.* (2008), Fukunari and Malmborg (2008)
Class-based	Product Turnover Frequency	Yu *et al.* (2015), Yu and de Koster (2009)
Dispersed	Random / Product Correlation	Weidinger and Boysen (2018), Onal *et al.*, (2017, 2018)
Correlated	Product Correlation	Garfinkel (2005), Chiang *et al.* (2011, 2014), Li *et al.* (2016)

1.3. Automated Storage Systems

Recently, new warehouse automation and robotic systems have been introduced to store and handle individual products and product loads. This thesis focuses on three types of automated systems, puzzle-based storage (PBS), automated storage and retrieval (AS/R), and autonomous robotic mobile fulfillment (RMF) systems.

A puzzle-based storage (PBS) system is a very compact storage system that stores loads on shuttles on the storage locations. Figure 1.1(a) shows a PBS system used in an automated parking garage where each car is stored on a mobile shuttle. The driver leaves the car at the entrance, and a shuttle will move the car inside the system and store it on an empty location. One or more lifts transport the cars in vertical direction, between the storage tiers. This type of system uses the available space very efficiently, as no transport aisles are needed for moving cars. It is used in areas where space is expensive, like city centers and airports. Figure 1.1(b) shows a mini-load AS/R system where loads are stored in bins which are stored in high-rise shelves. AS/R systems are compact systems where cranes can move within narrow aisles to access the bins at different levels and bring them to pick stations. At a pick station, the requested quantity of a product is picked, after which a crane returns the bin to a storage location. Figure 1.1(c) shows an RMF system where products are stored on multi-level pods. Available space on each pod is divided into compartments that allow storing multiple products on each pod. Autonomous robots pick up the entire pod from the storage area and move it to a pick station, where customer orders are picked. After picking, robots return the pod to the storage area. Robots can travel underneath the pods when empty. RMF systems save labor costs compared to manual order picking systems and are easy to expand by adding more pods and robots to increase the storage capacity and throughput capacity, respectively. They have been adopted by big players in ecommerce such as Amazon and Alibaba.

(a) (b) (c)

Figure 1.1. (a) An automated compact parking lot (source: Japan Parking System Manufacturers Association Incorporated, 2019) (b) a mini-load AS/R system (source: Ferretto Group, 2019) (c) Autonomous robots carrying storage pods (source: Reuters.com, 2019).

1.4. Research Questions and Outline of the Dissertation

Warehouses and distribution centers are increasingly adopting automated systems. Employing an efficient storage and retrieval policy is important to achieve short order throughput times and a high system throughput capacity. This thesis, therefore, focuses on developing advanced storage and retrieval policies that particularly support such automated systems. In the following sections, the outline of the dissertation, research questions and methodology of each chapter are discussed.

Chapter 2. Modeling Load Retrievals in Puzzle-based Storage Systems

Space is at a premium in many locations, such as densely populated areas. Compact storage systems are designed to achieve high space utilization. Puzzle-based storage (PBS) systems are very compact storage systems, without transport aisles. However, a major drawback of these systems is a long retrieval time due to lack of transportation space. Chapter 2 studies retrieval time models in PBS systems with maximum space utilization. The system consists of loads stored on shuttles that are placed right next to each other, i.e. no access aisles for a robot or picker are available. There is only one open location available in the system that allows the reshuffling of the storage locations. This configuration resembles the well-known 15-tile puzzle. Retrieval in such systems has been modeled for a single load by Gue and Kim (2007), but in this chapter, the problem of retrieving multiple loads is addressed. The following research question is answered.

What is the optimal retrieval method in PBS systems (i.e. minimizing the number of required moves) to retrieve multiple requested loads, using one open location?

A finite algorithm is developed for the optimal joint retrieval of two loads by joining them at an intermediary location first and moving them together afterward. Closed-form expressions are derived for joint retrieval of two adjacent loads (see Theorem 1). This chapter proves this is the optimal path. For the case of two requested loads, the position of the optimal intermediary locations is determined. For multiple loads, close-to-optimal joining locations are determined. Based on this, an efficient heuristic is developed for the retrieval of multiple loads simultaneously. The results show that large savings can be achieved using multiple-load retrievals compared to sequential single-load retrievals in these systems.

Chapter 3. The Impact of Integrated Cluster-based Storage Assignment in Automated Warehouses

Historical demand data can provide rich information on the customer demand profile. Various storage assignment policies, such as class-based and full turnover-based storage take advantage of historical order information. However, they mainly look at the turnover frequency of demand for a certain product and use it to identify popular products. Few studies look at the information on the correlation between products in customer demand. Correlated assignment models in the literature (such as those proposed by Garfinkel, 2005, Xiao and Zheng 2010, 2012 and Chiang *et al.*, 2014) mainly take a sequential approach to find the clusters of correlated products and then assign them to storage areas/zones. These methods are suboptimal, as they first maximize the correlation of products in the clusters and then assign the clusters to storage areas. Additionally, because clusters of products are assigned to storage zones or aisles, these models are only applicable to manual order picking where a picker runs a picking tour of several lines. In robotic warehouses, a robot (or shuttle) visits a storage location and picks up the entire storage pod/bin which carries some of the requested products. Here, grouping correlated products is beneficial only if products in a group are stored on the same storage pod, not in the same storage zone. This chapter answers the following research question.

How does integrated clustering and storage assignment of correlated products affect the order picking performance in automated warehouses?

An integer linear program is developed that models the optimal integrated clustering and storage assignment of the products to minimize the total retrieval time. The model is solved with a general optimization solver and tested for multiple levels of correlation, turnover frequency and order size. The performance of the model is evaluated for both mini-load AS/R and for RMF systems (see Section 1.3), where each cluster of products is assigned to a storage bin or storage pod consisting of multiple compartments sufficient to house the number of products in the cluster. A comparison of the proposed integrated model with the sequential correlated assignment and turnover-based assignment shows that integrated assignment can yield considerable benefits when the correlation of the products is high, and the product turnover frequency curve is not highly skewed.

Chapter 4. Correlated Dispersed Storage Assignment in Robotic Warehouses

This chapter builds on chapter 3, by not only looking at correlated storage assignment but also combining it with product dispersion. This combination of storage policies is applied to RMF systems (see Section 1.3). Chapter 4 investigates the effect of this combined policy on the expected retrieval time and compares it with random, class-based, correlated (but not dispersed), and dispersed (but not correlated) assignment policies. The following research questions are studied.

What is the effect of product dispersion and storage clustering on the expected order picking retrieval time in RMF systems? How do product correlation and product turnover frequency contribute to the performance of the policies?

First, a mixed-integer linear program is developed for optimal product to cluster and cluster to zone allocation to minimize the expected retrieval time to a closest pick station. Note that, if orders contain a large number of lines, downstream order consolidation may be needed before the order can be shipped. Such possible consolidation time is not included in the analysis. The retrieval time expressions are developed for different zone configurations and positions of pick stations. Solvers such as Gurobi 9.0 are able to solve small instances of the model. An efficient heuristic method is proposed to enable solving real size instances of the problem. Particularly, a thorough analysis of the impact of turnover frequency and correlation of the products on the performance of different storage policies is conducted using a dataset of the warehouse of a wholesaler in personal care products. The analytical results show that, for this warehouse, the correlated dispersed assignment leads to a significantly shorter expected retrieval time compared to the benchmarks. Furthermore, the correlation in customer demand plays a major role in the performance of the models while the turnover frequency showed a minor influence in the cases we tested.

Chapter 5. Summary and Conclusion

Chapter 5 gives an overview of the results of previous chapters. This summary highlights the contribution of this dissertation by revisiting the main research questions and findings. The limitations of the conducted research are also discussed. An outlook of further research on storage and retrieval policies applicable to automated warehouses is also presented.

Research Statement

All the chapters of this dissertation are written by the author. The author is responsible for the research questions, methodology and analytical results of each chapter. The models and results have been validated using simulation, benchmarks, and numerical analysis. The promoters had a great impact on the quality of the chapters by providing continuous critical feedback during my Ph.D. program. Feedbacks from the doctoral committee helped to improve the quality of the dissertation. Chapter 2 is published as Mirzaei *et al.* (2017) which benefitted from the constructive comments from reviewers. Chapter 3 is submitted to a journal for peer review and Chapter 4 will be submitted soon.

Chapter 2

Modeling Load Retrievals in Puzzle-based Storage Systems

2.1. Introduction

Warehouses are important nodes in the supply chain as they allow to match supply with customer demand and to achieve economies of scale in transport. Warehouses are labor-intensive and consume much space. Bartholdi and Hackman (2016) state that the fundamental idea of warehouse management lies in two resources: space and labor. While labor is usually available in urban areas, land is expensive. Space efficient storage systems offer a solution to this problem.

A conventional storage system consists of racks and aisles. Aisles are used for transporting goods to and from the storage racks. They take up space which could alternatively be used efficiently for storing loads. If space is not used efficiently, larger distances may have to be traveled to transport loads, requiring more resources. According to Tompkins et al. (1996), Roodbergen and De Koster (2001) and De Koster et al. (2007), non-value adding travel forms the majority of an order picker's time in such conventional storage systems. In the 60s, Automated Storage/ Retrieval (AS/R) systems were introduced. These systems can store a large number of unit loads on a limited footprint. These systems have received much attention from researchers focusing on, e.g., travel time models and system size optimization (see e.g. Bozer and White, 1984 and Lee, 1997). In order to use the space even more efficiently, very high density storage (or puzzle-based) systems were introduced by storing the loads multi-deep (De Koster et al., 2008).

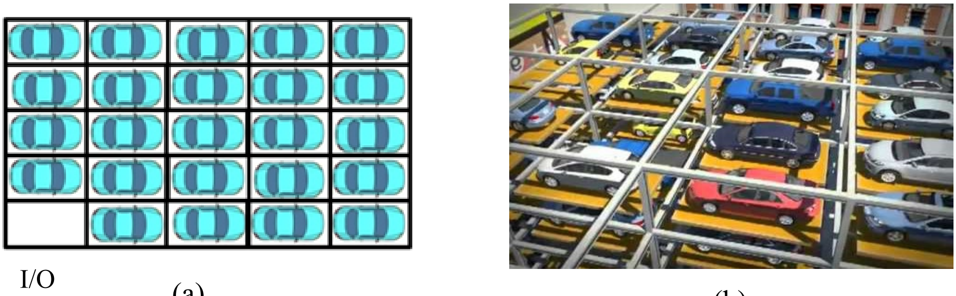
Recently, so called "puzzle-based" storage systems have been introduced. The term Puzzle-based Storage (PBS) system comes from Gue and Kim (2007). PBS systems are very compact storage systems which are fully automated. Unit-loads are stored dense, without even a single aisle, yet each unit load can be retrieved independently. Applications of PBS systems can be found in warehouses and distribution centers (DCs), automated car parking systems, and container terminals (Zaerpour, Yu and De Koster 2015).

2.1.1. Description of the PBS System

The main components of a PBS system are: (1) shuttles that can move in horizontal x- and y- directions, carrying the unit loads, (2) a depot (I/O point), (3) a lift for vertical transportation in case of a multilevel system, and (4) one or more empty locations which provide sufficient maneuvering space for shuttles to move. Such an open location is also called an "escort" because of its role of escorting the load to the destination. To bring a requested unit load to the I/O point, other shuttles have to move to first bring an escort next to the requested load. Then, the load is escorted to the I/O point by the escort.

A PBS system with one escort is comparable to the well-known 15-tile puzzle game. This game consists of 15 numbered tiles which are randomly distributed in a 4×4 square with one missing tile. The mission is to sort numbers by shuffling the tiles. In the same fashion, N^2-1 unit loads can be stored at each level in an $N \times N$ PBS system. This results in very high space usage efficiency.

Figure 1(a) shows the top view of a typical PBS system. Cars in the picture represent loads stored in the system and the white cell represents the escort. The escort is initially located at the lower left corner, next to the I/O point. Figure 1(b) shows a PBS car parking system. Each unit load (a car) is stored on its own shuttle which can move in both horizontal directions. When an order for retrieving a load is released, the escort moves towards the requested load. This means all shuttles on the path have to move in the opposite direction. Once the escort reaches a position next to the load (down or left), depending on the load's location, the shuttle which contains the load will move to the empty location. Then the escort will end up at the right or top of the requested load. It again needs to move to either down or left of the requested load to provide space for it to move. This repeats until the load arrives at the I/O point. In this way, any load can be accessed individually with no more than one empty space unit in the storage area. Although PBS systems are extremely space efficient solution, they are not fast. Therefore it is of the utmost importance to furnish this solution with faster methods. The multiple load retrieval method proposed in this chapter addresses this drawback and makes PBS systems more responsive.



(a) (b)

Figure 1. (a) A top view of a PBS, (b) A 3D view of a PBS car parking system (source Eweco, 2013).

2.1.2. Literature Review

Literature on unit-load compact storage systems is not abundant. In practice, most compact storage still have at least one aisle. A crane, or S/R machine, operates in the aisle and retrieves unit loads using a satellite connected to the crane. Sari et al. (2005) study a flow rack compact storage system where the pallets are stored and retrieved at different rack sides by two S/R machines responsible for storage and retrieval respectively. De Koster et al. (2008) and Yu and De Koster (2009, 2012) study a compact crane-based storage system with built-in multi-deep circular conveyors. The system is fully automated, and every pallet stored is accessible individually by rotating conveyors. Zaerpour et al. (2015) derive the optimal storage allocation for a crane-based compact storage system, operating in a cross-dock when all destinations of incoming loads are known.

Carousel systems constitute another category of compact automated storage and retrieval systems in which accessing an item requires moving other items. These systems consist of a number of linked drawers carrying small and medium-sized products that rotate in a closed loop. Litvak (2006) proposes optimal picking of large orders based on the shortest rotation time and she studies the number of items collected before a turn. Hwang et al. (1999) study standard and double carousel systems and analytically measure the effect of double shuttles on throughput.

Studies on PBS systems are new. Gue and Kim (2007) appear to be the first researchers to study PBS systems. They study a PBS system where unit loads are retrieved one by one using single or multiple empty locations. They compare storage density and retrieval time of puzzle-based systems with traditional low-density aisle-based warehouses. While traditional warehouses usually perform better than puzzle systems in terms of retrieval time, they have lower space efficiency. Kota, Taylor and Gue (2015) analytically derive the single-load retrieval time expression when multiple escorts are randomly placed within the system. They extend the expression to a system with two escorts and formulate an integer program for the general case with multiple escorts. Alfieri et al. (2012) propose heuristics for using a limited set of shared shuttles to transport unit loads in puzzle-based systems. They consider multiple I/O points, partition the storage area, and then assign shuttles to partitions based on expected workload. Shuttles move parallel where possible. Gue et al. (2013) propose a decentralized control for a deadlock-free puzzle system named GridStore. Loads arrive at one side of the system, can move individually within the system, and leave at the opposite side of the system. Each unit load communicates with neighboring locations to decide its route. Zaerpour, Yu and De Koster (2015) study the optimal configuration of a multi-level PBS system (they call them live-cube systems) by assuming sufficient empty locations exist at each level to create virtual aisles and multiple loads can move simultaneously. When a virtual aisle has been created, determining the retrieval time is similar to a traditional, aisle-based, warehouse. The minimum number of empty locations to create a virtual aisle at a given storage level equals the maximum of the rows and columns of the system. Yu et al. (2016) propose a method to find the optimal retrieval path for a requested load, with multiple open locations and with so-called block load movement. All these studies assume the loads all have the same size. Flake and Baum (2002) and Hearn and Demaine (2005) study the rush hour problem in a PBS car parking system, with the objective to store as many cars of different sizes in a compact storage.

While previous studies have focused on single load retrieval, in practice, information of multiple retrieval requests is usually available. Hence, multiple loads may be retrieved simultaneously, improving the performance of PBS systems significantly. In this chapter, we study multiple load retrieval in a PBS system. We answer questions like how and in which sequence loads should be retrieved in order to minimize total retrieval time. This question has not yet been addressed in literature. We develop an optimal method for this problem based on joint load retrieval. The results show that by using joint retrieval, the total retrieval time can be reduced significantly compared to individual retrieval. We first present a retrieval method for two loads that finds the minimum number of retrieval moves. Then, we extend this optimal method for jointly retrieving three loads and afterward, generalize it to retrieve multiple loads using approximate analysis. Table 1 summarizes the literature on PBS systems and highlights the contribution of this chapter. The second column shows whether an optimal solution is provided or a heuristic. Column three defines the number of open locations assumed in the system. Column four shows whether there is a single move at a time or multiple loads can move simultaneously. The last column defines the number of loads that the system can retrieve together.

Table 1. Comparing the papers on PBS systems.

Paper	**Optimal/ Heuristic**	**Number of escorts**	**Simultaneous load moves**	**Single / Multiple Load**
Gue and Kim (2007)	Optimal	One, many	No	Single
Kota et al. (2015)	Optimal & Heuristic	Many (randomly)	No	Single
Alfieri et al. (2012)	Heuristic	Many	Yes	Single
Zaerpour et al. (2015)	Heuristic	Many	Yes	Single
Gue et al. (2014)	Heuristic	Many	Yes	Single
Yu. et al. (2016)	Optimal	One, many	Yes	Single
This chapter	Optimal & Heuristic	One	No	Multiple

The remainder of the chapter is organized as follows. Section 2.2 describes an optimal retrieval method for two arbitrary loads in the system. Section 2.3 extends the dual-load retrieval method to three or more loads. Section 2.4 compares the results with single- load retrieval. In the last section, conclusions are drawn.

2.2. An optimal Dual-load Retrieval Method

In case two loads need retrieval, it is possible to reduce travel time, as compared with individual retrieval, by retrieving them jointly. We propose a dual-load retrieval method for this and demonstrate optimality by enumeration. Three methods are distinguished for retrieving two loads: (1) moving loads individually towards the I/O point using the algorithm of Gue and Kim (2007), (2) moving loads A and B by alternating between them, requiring the escort to move back and forth between the loads, and (3) bringing both loads to a given joint location and then moving them together. Obviously, the method (2) is not optimal, due to unnecessary extra moves of the escort traveling between the loads. We prove method (3) leads to an optimal solution, for a joint position where the loads are adjacent.

We make the following assumptions for the system:

(1) All loads are stored on shuttles, which can move in both horizontal directions. This assumption is valid for particular types of PBS systems.
(2) The storage system has *N* rows and *N* columns. This can be extended to non-square systems.
(3) The I/O point is located at the lower left corner.
(4) There is only one escort, which is initially located at position (1, 1), next to the I/O point. Usually, escort will be found here, after each retrieval.
(5) Only one load moves at a time, even when multiple loads need to move in the same direction.
(6) We distinguish only retrievals on a single storage level. For multiple levels, a lift fulfills the vertical transportations.

We first define several concepts to ease the exposition.

Definition 1 (Joining location for two loads in the PBS grid): A location where the two requested loads become adjacent for the first time in their retrieval path. The joining location is defined as the location of one of these two adjacent loads, namely the one which is the closest to the I/O point.

Definition 2 (Dual load move): Moving two loads consecutively on the same retrieval path with no other loads between them.

Definition 3 (Optimal joining location): A joining location for two loads, which leads to the minimum total number of retrieval moves.

Now we can formulate the following lemma.

Lemma 1: Dual-load retrieval from an optimal joining location, always performs better than or equal to two single-load retrievals, in terms of the total number of moves.

Proof: Setting the joining location at (1, 1), immediately transforms the dual-load retrieval problem into two single load retrievals. Indeed, a better joining location saves moves.

■

As Lemma 1 shows, retrieving two loads using an optimal joining location always results in a total number of moves less than or equal to the number of moves of two individual single load retrievals. Gue and Kim (2007) propose an optimal method for single load retrieval, where each load first moves by several so-called 3-moves, followed by so-called 5-moves when the load reaches the side of the system. In the 3-moves, the empty location moves from a location behind (above) the load one step down and one step left to reach a location below (in front of) the load. Now, it makes space available for the load. to approach the I/O point with one more step. It takes the empty location 4 moves to move around a load at the bottom or left side of the system.

Therefore, in the optimal dual-load retrieval method, the loads are first brought together at an optimal joining location, using optimal single load moves, and are then moved toward the I/O point jointly by optimal dual-load moves. Figure 2 gives a flow diagram of the dual-load retrieval method. This procedure can be explained in four steps. Algorithm 1 illustrates the steps in this method. Optimality of the joining location is ensured by enumerating all possibilities with a complexity of $O(N^2)$. Optimality of the adjacent location of the joining location, to which the second load will be brought, is ensured again by enumeration in step 2. Optimality of the single load moves is ensured by the method of Gue and Kim (2007). Moving the loads jointly in an optimal fashion in step 3 is explained in theorem 1. The two requested loads are (i_1, j_1) and (i_2, j_2). The load closest to the I/O point is labeled as the first load and the other load is labeled as the second load. In the case of equal distances, they can be labeled randomly.

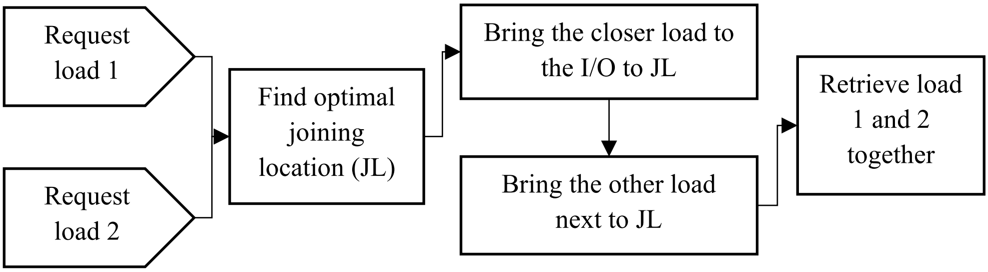


Figure 2. Flow diagram of dual-load retrieval.

Algorithm 1: Optimal dual-load retrieval method

```
Step 1
 for $i = 1: max\ \{i_1, i_2\}$
     for $j = 1: max\ \{j_1, j_2\}$
           let $(i,j)$ be the joining location.
           calculate the minimum number of moves, $M_1(i,j)$,
           needed to bring  the first load to $(i,j)$.
Step 2
           for $k = 1:4$
```

```
            calculate the minimum number of moves, $M_0(k)$,
            needed to bring the second load to one of the 4
            adjacent locations of $(i,j)$.
        end for
    pick the location $k := Argmin\{M_0(k)| k = 1,2,3,4\}$.
    $M_2(i,j) := M_0(k)$.
  Step 3
    calculate the minimum number of moves, $M_3(i,j)$, needed
    to bring the loads jointly to the I/O point.
    $M(i,j) := M_1(i,j) + M_2(i,j) + M_3(i,j)$.
    end for
end for
  Step 4
pick the solution with optimal joining location $(i,j)$
    which minimizes $M(i,j)$.
```

Algorithm 1 determines the optimum joining location, by enumerating all possible locations and comparing the results. In a system of size $N \times N$ there are N^2 possible joining locations. But, in practice, certain areas can be excluded from enumeration, depending on the position of the loads. We show in lemma 2 the number of locations that need to be enumerated is actually less than N^2. This accelerates the process of finding the joining location. Figure 4(a) shows two requested loads in the system. A joining location is marked by a 'plus' sign. The dashed lines show the boundary of locations to be enumerated.

Lemma 2: The Manhattan distance to the I/O point of an optimal joining location, is less than or equal to the Manhattan distance of the requested loads (i_1,j_1) and (i_2,j_2) to the I/O point.

Proof: a) Assume a location $L = (i_0, j_0)$ with a Manhattan distance larger than that of at least one of the loads, is nominated as the optimal joining location. See figure 3. This means $i_0 + j_0 > i_1 + j_1$ or $i_0 + j_0 > i_2 + j_2$. Without loss of generality, we assume $i_0 + j_0 > i_1 + j_1$ and $i_0 + j_0 < i_2 + j_2$. We show that joining location (i_1, j_1) outperforms L in the required number of moves to retrieve the loads. The number of moves to bring the two loads to L equals to the number of moves needed to bring the load (i_2, j_2) to L plus the number of moves to further move it next to (i_1, j_1). However, this, at most, equals to the minimum number of moves to bring (i_2, j_2) directly to (i_1, j_1). Furthermore, we know that, by definition, (i_1, j_1) is closer to the I/O point than L. Therefore, less joint moves is required from there to the I/O point. Thus, L cannot be located farther than any of the two loads.

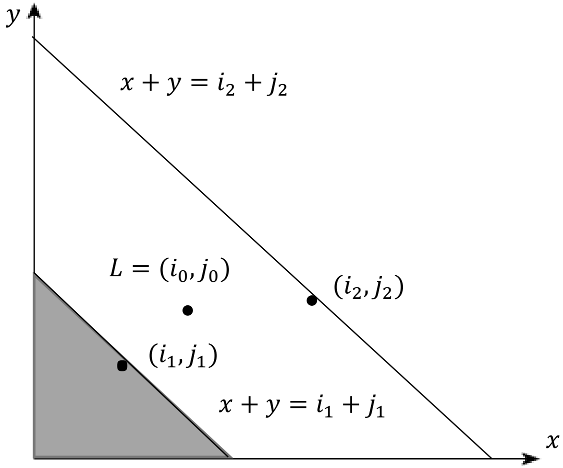


Figure 3. The search area for the optimal joining location.

■

In a number of situations, the joining location can be predefined, and no enumeration is needed. Table 2 provides a list of such conditions. In condition 1, when both requested loads are located at the left side of the system (i.e. i_1, i_2=1), the escort goes directly to the farther load and brings the closer load to $(1, j_1\text{-}1)$ on its path. This is the joining location for the loads. The same procedure can be applied for condition 2. In condition 3, where both loads are on the diagonal, again the optimal path for the escort is to directly go to the farther load and bring it next to the closer one. This involves moving the closer load to either (i_1, j_1-1) or (i_1-1, j_1). In the worst case scenario of condition 4, one load is located anywhere at the left side of the system and the other one is anywhere at the bottom side. Then the joining location is (1,1) which basically means two individual retrievals.

Table 2. Conditions that lead to a predefined optimal joining location.

Nr.	**Condition**	**Predefined optimal joining location**
1	i_1, i_2=1 and j_1<j_2	(1, j_1-1)
2	j_1, j_2=1 and i_1< i_2	(i_1-1,1)
3	i_1=j_1 and i_2=j_2	(i_1, j_1-1) and (i_1-1, j_1)
4	(1,j_1) and (i_2,1)	(1,1)

In the first step of algorithm 1, we need to know the number of steps to bring the first load to the joining location via the shortest path for each possible joining location. Figure 4(b) shows this transfer. This can be done by the single-load retrieval method of Gue and Kim (2007); the only difference is the I/O point as the destination has been replaced by the joining location.

The second step brings the second load next to the first one. It selects the best locations adjacent to the joining location such that the total number of moves is minimized. It is determined by enumeration and comparing the results for each adjacent location. Figure 4(c) shows how the second load joins the first one. The enumerated locations are marked by '×'. Note that bringing the second load to some of these adjacent locations might alter the location of the first load. In Figure 4(c) for example, moving the second load to the adjacent location on the left side of the first load, moves the first load one step down. We ignore this because such candidate joining locations lead to higher total retrieval moves (extra moves to make them adjacent again) and are not chosen as the optimal joining location. At the end of this phase, as shown in Figure 4(d), the loads are adjacent, in a horizontal position. However, depending on the position of the loads, vertical optimal joining configurations are possible.

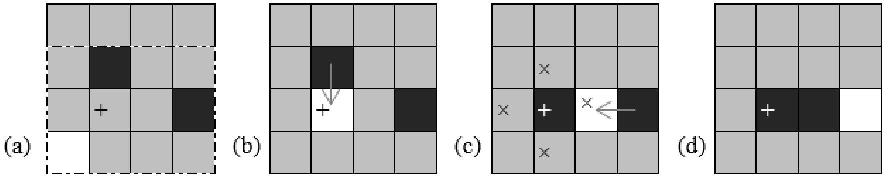


Figure 4. Joining procedure of two loads in dual-load retrieval: (a) joining location is selected, (b) first load moves there, (c) second load moves to its adjacent, (d) loads are ready to be retrieved together.

The third step calculates the number of moves needed to bring the loads jointly to the I/O point. In lemma 3 we prove the optimal way to move two adjacent loads is via so-called “dual-load” moves. Regardless of a horizontal or vertical position of the loads at the joining location, two types of dual-load moves are available: 5-moves and 7-moves. In the following, we explain them in detail. The smallest series of steps that is needed to perform a joint move is via 5-moves. As shown in Figure 4(a), the escort takes three steps to reach the proper position that makes space for the loads to move closer to the I/O point. Then it takes two more steps to move both loads ahead. A series of 5-moves are performed until no more move of this type is possible, i.e. the loads reach one side of the grid. After that, 7-moves are performed as shown in Figure 5(b). Here, the escort takes 5 steps to reach the proper position, and then two more steps are required to move the loads. This is repeated until the loads are retrieved. In the fourth step of the algorithm, the solution is picked with the total minimum number of moves.

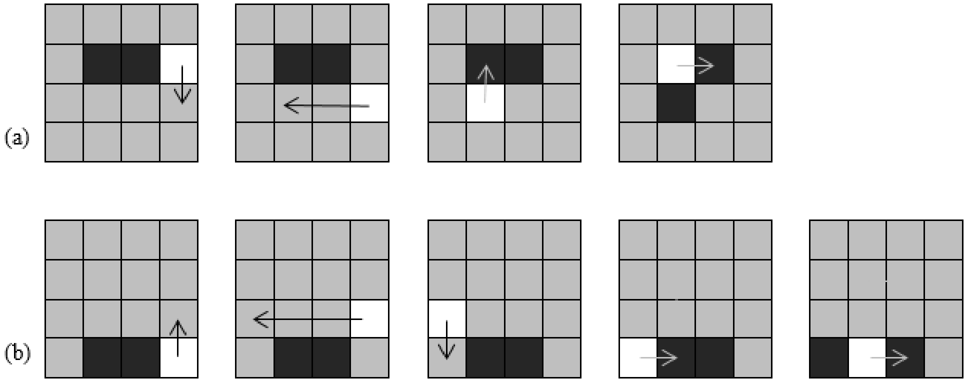


Figure 5. Demonstration of moves in dual-load retrieval: (a) 5-step, (b) 7-step.

Lemma 3: Moving two adjacent loads to the I/O point is optimal when there is no load between them during the retrieval steps.

Proof: We prove this lemma by contradiction. Suppose that one or more items are located between the two loads, we then show the number of steps can be reduced if there is no intermediary item. Assume there is one item between the loads, this means their rectilinear distance is two. As demonstrated in Figure 6(a), at least nine steps are required to move both loads one space unit. By simply eliminating the in-between item, as shown in Figure 6(b), the number of steps reduces to seven. This single item between loads results in two extra escort steps merely to bypass this item. The same argument holds for the case where the loads are vertically aligned. In a similar fashion, having *k* >1 items between the loads will result in 2*k* extra escort steps to reposition the loads one space unit. This means having no load between the loads leads to the minimum number of steps.

■

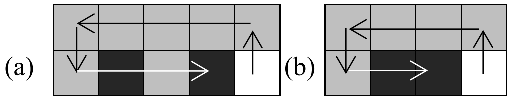


Figure 6. Moving loads with different amount of interspace: (a) one interspace, (b) no interspace.

Theorem 1 formulates the number of moves needed in an optimal method of retrieving two adjacent loads. Before that, we make the following observations.

Observation 1: In order to determine the number of steps required to retrieve loads from given positions, it is sufficient to track the number of moves made by the escort. This is because each load move corresponds to an escort move.

Observation 2: Due to symmetry of the system, the number of moves required to retrieve two load at locations (i, j) and (j, i) are equal.

Theorem 1: The minimum number of moves to retrieve two horizontally aligned adjacent loads in a puzzle system is:

$$\begin{array}{ll} 7i + 3j - 9 & i > j \\ 10i - 9 & j = i \\ 7j + 3i - 13 & i < j \end{array}$$

where (i, j) is the location of the load closer to the I/O point and the escort is behind them.

Proof: According to Lemma 3, two adjacent loads should travel by dual-load moves. In this strategy, we keep track of the route of the first load and the second load follows it. The first load can move either leftward or downward, using 5-moves and 7-moves. Figure 7 shows an example of a typical route in this approach. An observed property of the dual-load moves is that the route changes direction every time after two 5-moves. In the case of $j > i$ there are *i* pairs of 5-moves necessary for a total of $5(2i) = 10i$ moves, after which the position of the first load should be $(1, j - i - 2)$. Next, $j - i - 2$ 7-moves are required to retrieve the first load for $7(j - i - 2)$ moves. In the end, an additional one move is performed to retrieve the second load, thanks to extra empty space obtained by retrieving the first load. Therefore, in total $10i + 7(j - i - 2) + 1 = 7j + 3i - 13$ escort moves are necessary. In case *j*= *i*, and *i* is an odd number, the first load can reach the I/O point with i-1 pairs of 5-moves. An additional move is necessary to retrieve the second load for a total of $5 \times 2(i - 1) + 1 = 10i - 9$ moves. If *i* is an even number, 2i-3 5-moves is needed, and then an extra 7-move and an additional single move are needed to retrieve both loads. In total $5(2i - 3) + 7 + 3 = 10i - 9$ moves are needed which shows the results are the same for both even and odd i. the case for $j < i$ follows in a similar fashion.

■

As a corollary to this theorem, according to the symmetry property stated in Observation 2, the same approach can be used for the case of vertical alignment of the loads. The formulation is as follows:

$$\begin{array}{ll} 7j + 3i - 9 & j > i \\ 7i + 3j - 13 & j < i \\ 10i - 9 & j = i \end{array}$$

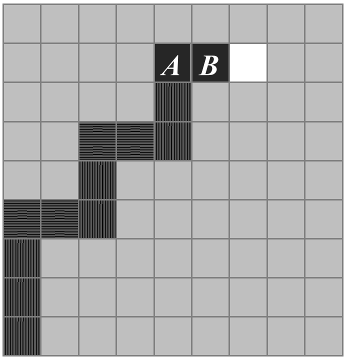


Figure 7. A typical dual retrieval route for two loads *A* and *B*.

In the dual-load retrieval method of algorithm 1, the optimal joining location is not unique. For instance, when the adjacent loads are located at the diagonal, two optimal joining locations exist: one space unit to the left and one space unit to the south.

Algorithm 1 helps to find the optimal solution. However, since the number of joining locations that are evaluated is $O(N^2)$, and the number of steps to jointly retrieve the loads is $O(N)$, the algorithm is $O(N^3)$, where *N* is the size of the system. Therefore, in addition to this optimal method, we propose a heuristic, that yields a near-optimal solution in a considerably shorter time. This heuristic can be easily adapted to retrieve more than 2 loads as will be explained in section 2.3. Algorithm 2 shows the steps required for two loads (i_1, j_1) and (i_2, j_2). The location of the load closest to the I/O point is denoted by (i_c, j_c) and the location of the farther load is denoted by (i_f, j_f). The subroutine introduced in this algorithm finds *J* and *L* as the joining location and the location of the adjacent load respectively, based on location of the loads as the input. For $(i,j) \neq (i_c, j_c)$, either $(i_f - i) = 0$ or $(j_f - j) = 0$.

Therefore, the formula in line 5 results in $(i+1,j)$ or $(i,j+1)$, if $i_f > i_c$ or $j_f > j_c$ respectively.

Algorithm 2: Heuristic method for two loads

```
1: let $(i,j) = (min\{i_1,i_2\}, min\{j_1,j_2\})$ be the joining location
2: Subroutine $JL\ (J, L, (i_1,j_1), (i_2,j_2))$
3:    if $(i,j) \neq (i_c,j_c)$ then
4:      $J := (i,j)$
5:      $L := (i + \frac{i_f - i}{(i_f - i)+(j_f - j)}, j + \frac{j_f - j}{(i_f - i)+(j_f - j)})$
6:      else $L := (i_c,j_c)$
7:      if $i > j$ then $J := (i-1,j)$
8:      else $J := (i,j-1)$
9:      end if
10:   end if
11: End subroutine JL
12: move the load located at $(i_c,j_c)$ to $J$
13: bring the other load to $L$
14: move the loads jointly to the I/O point
```

To compare the performance of the heuristic with the optimal method, numerical results for 20 random instances of dual-load requests are presented in Table 3. To generate random requests, for any given N, two unique locations with random coordinates $(i\ ,j)$ are picked. Then, the loads stored at these locations are retrieved using both optimal and heuristic methods to compare the results. This is repeated 20 times for each system size. The optimal and approximate number of moves for dual-load retrieval are presented in column Avg. Opt. and Avg. Aprx., for systems of different sizes, averaged over 20 instances. The average gap between the number of optimal and heuristic methods is presented in column Avg. Gap, together with the minimum and maximum gap. The last column shows the average computation time for the optimal method. The computation time for the heuristics is negligible. The heuristic method appears to perform near-optimal. In fact, it appears the heuristic performs optimally in more than half of the instances.

Table 3. Comparison between optimal dual-load retrieval and the heuristic method.

System Size (N)	Avrg. Opt.	Avrg. Aprx.	Avrg. Gap	Compt. time (s)
5	21.4	22.1	0.7, (0, 2)	0.18
7	38.0	38.4	0.4, (0, 2)	0.61
10	63.4	63.8	0.4, (0, 2)	1.64
20	133.8	135.9	2.1, (0, 10)	18.62
50	346.2	358.6	12.4, (0, 46)	273.10

2.3. Multiple Load Retrieval Method

In this section, we first consider retrieving three loads in the system and then generalize it to more than three loads. In the case of three requested loads, each load can be retrieved individually or together with one or two other loads. Lemma 4 proves that joining loads is required to obtain the minimum number of moves, similar to lemma 1.

Lemma 4: Retrieving three loads jointly from an optimal 3-load joining location, performs better or equal to retrieving one or all of them individually.

Proof: Setting the joining location at (1, 1), immediately transforms the joint retrieval of three loads into three single-load retrievals, or a single-load retrieval and a dual-load retrieval. A better choice of joining locations saves moves.

■

To join and retrieve three loads, different combinations and sequences for the loads A, B and C exist. For example (AB, ABC) means the loads A and B join first at an intermediate joining location, and then they join C at a final joining location. Similarly, the other alternatives are (AC, ACB) and (BC, BCA). These are the main alternatives for joining the loads, but there are other alternatives that are sub-cases of these main alternatives. For instance, individual retrievals is a case when the joining location is set at (1, 1), or joining all loads at one location is a case when the intermediate and the final joining locations are at the same point. Therefore, we only evaluate the three main combinations in Algorithm 3.

One way to obtain the optimal solution to the problem is enumerating all move sequences to all possible joining location. Therefore the number of moves would be $O(m!\,N^m)$where m is the number of loads to be retrieved. As this number grows very rapidly with m and N we propose a heuristic method for three loads or more. Suppose that the third load (i_3, j_3) is requested in addition to the other two loads. Algorithm 3 shows the steps required to retrieve them together. (i_a, j_a) and (i_b, j_b) are the locations of the first two loads in the combination k. (i_l, j_l) is the location of the last load in the combination k.

Algorithm 3: Heuristic method for three loads

```
let $(r,q) = (min\{i_1,i_2,i_3\}, min\{j_1,j_2,j_3\})$ be the joining location
for $k = 1{:}3$
    Subroutine $JL\,(J, L, (i_a, j_a), (i_b, j_b))$
    calculate the number of moves needed to bring the
    first two loads in the combination to $J$ and $L$ for $M_1(k)$
    moves.
    calculate the number of moves needed to bring these
    two loads jointly to the $(r,q)$ for $M_2(k)$.
    $L_2 := (r + \frac{i_l - r}{(i_l - r)+(j_l - q)}, j + \frac{j_l - q}{(i_l - r)+(j_l - q)})$.
    calculate the number of moves needed to bring the
    third load $(i_l, j_l)$, to $L_2$ for $M_3(k)$.
```

```
    $M(k) := M_1(k) + M_2(k) + M_3(k)$.
end for
pick the combination $k := Argmin\{M(k) | k = 1,2,3\}$.
move the loads jointly from $(r, q)$ to the I/O point.
```

In the heuristic method for three loads, usually, an intermediate joining location is established for combining two loads, in order to minimize the individual moves and maximize dual-load moves. Theorem 2 shows the number of moves required to retrieve the loads after they become adjacent. For more loads, the algorithm can be extended using the same approach.

Theorem 2: The minimum number of moves to retrieve three adjacent loads in a puzzle system is:

$$
\begin{array}{ll}
9i + 5j - 11 & i > j \\
14i - 13 & i = j, j = 3,6,9, \ldots \\
14i - 6 & i = j - 1, j \neq 4,7,10, \ldots \\
14i - 1 & i = j - 2, j = 4,7,10, \ldots \\
14i + 8 & i = j - 3, j = 4,7,10, \ldots \\
9j + 5i - 17 & \text{O.W.}
\end{array}
$$

where (i, j) is the location of the load closest to the I/O point and loads are horizontally aligned, having the escort behind them.

Proof: The proof is similar to theorem 1. Again, the moves of the first load are tracked, and the other two loads follow it. The only difference is that the loads move using 7-moves and 9-moves due to an extra load.

■

According to the symmetric property stated in Observation 2, the same approach applies to the case of the vertically aligned loads. The formulation is as follows:

$$\begin{array}{ll}
9j+5i-11 & j>i \\
14j-13 & j=i, i=3,6,9,\ldots \\
14j-6 & j=i-1, i\neq 4,7,10,\ldots \\
14j-1 & j=i-2, i=4,7,10,\ldots \\
14j+8 & j=i-3, i=4,7,10,\ldots \\
9i+5j-17 & \text{O.W.}
\end{array}$$

2.4. Numerical Results

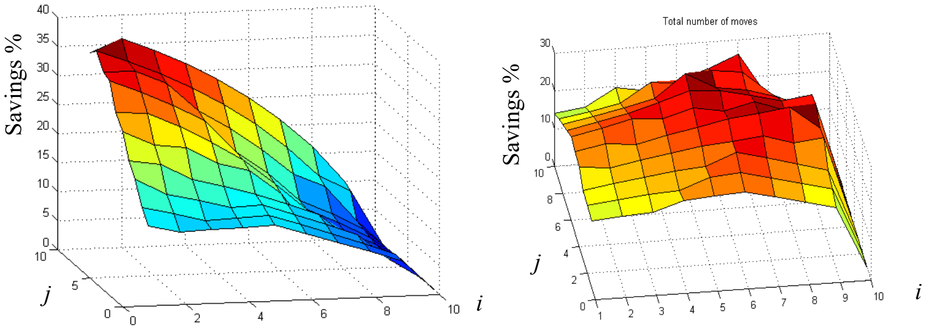
To evaluate the performance of the multiple load retrieval method presented in this chapter, we here compare the total number of moves required to retrieve the loads with single load retrieval method. All calculations are done in MATLAB.

For any given system size, two unique locations are randomly generated. These random locations represent requested loads. For the case of three-load retrieval, three unique locations are randomly generated. The numbers of steps required for retrieval of these loads by different methods are calculated. This is repeated for 100 instances.

Table 4 compares the dual-load retrieval method to individual retrieval and shows savings the dual-load retrieval method can obtain. AvgSL and AvgDL are the averages of the total number of moves in single-load and dual-load retrieval, respectively. The maximum savings are obtained when the loads are positioned at (1, *N*) and (1, *N*-1). The average saving is calculated as (AvgSL- AvgDL)/ AvgSL × 100%. According to Table 4, for large values of *N*, the maximum savings are about 33% and the average savings are about 17% of the number of moves needed for individual retrieval. Note that the savings for small systems are higher than for large systems. This is caused by the effect of the second empty spot that appears next to the I/O point, after the first load has been retrieved, and which makes the distance of the second load to the I/O point one unit shorter. This effect disappears for systems larger than 10.

Table 4. Savings for the optimal dual-load retrieval compared to individual retrieval.

N	AvgSL	AvgDL	Max savings (%)	Avrg. savings (%)
5	31.3	24.5	41	20
7	45.6	36.4	38	20
10	82.5	65.8	35	19
15	129.2	105.9	35	19
20	157.4	129.5	34	18
50	437.1	367.3	33	17
100	911.5	755.6	33	17



(a) (b)

Figure 8. Savings achieved for a given first load located at (a) (1,10), and (b) (5,5), and the second load is at (i, j).

Based on the experiment and Figure 8, we can make the following observation.

Observation 3: when one load is located at (1,*j*) for *j*=1..*N* and the other load at (*i*,1) for *i*=1..*N*, savings in dual-load retrieval are not significant (see Figure 8(a)). Apparently, too many single-load moves are required before the loads become adjacent. On the other hand, when the loads are located at (1,*j*) and (1,*j*-1) for *j*=1..*N* or (*i*,1) and (*i*-1,1) for *i*=1..*N*, savings are substantial. This is due to the fact that they are already adjacent, and they are located at the very end of the grid.

Table 5 shows the saving that can be obtained by the three-load retrieval method, as compared to individual retrieval. AvgTL is the averages of the total number of moves in three-load retrieval. The maximum saving is calculated when the loads are located at (1, *N*) and (1, *N*-1). The average savings are shown in the last column.

Table 5. Savings for three-load retrieval heuristics.

N	**AvgSL**	**AvgTL**	**Max savings (%)**	**Avrg. savings (%)**
5	41.6	29.1	59	30
7	75.3	54.2	52	28
10	113.4	83.5	49	26
15	179.5	134.6	47	25
20	254.8	193.9	46	24
50	886.9	682.3	45	23
100	1683.1	1296.4	45	23

Savings achieved by three-load retrieval shows significantly better performance than single-load. Based on the results, the performance is on average 6% higher than the dual-load retrieval. The values converge as the size of the system grows.

2.4.1. A Parking Lot Case Study

In the numerical study, we considered random load requests. However, in a real system, where a pool of retrieval requests is available, there is an opportunity to group the loads that are close together and gain higher savings. To demonstrate such benefits and to illustrate the effect of joint retrieval in practice, we apply the multiple load retrieval method to a medium-sized car parking system. We consider a 10×10 and a 20×20 single-tier puzzle-based car parking system (total capacity of 99 and 399 cars respectively), where the size of each shuttle is 2.5×4.8 m (see multi-story car parks, 2016). The shuttle speed is 52 m/min in *x*-direction and is 100 m/min in *y*-direction. Given these specifications of the system, each move in both directions takes 2.88 seconds. Therefore, although the system's shape is rectangular (25×48 m and 50×96 respectively), it is square in terms of travel time. The system follows the dual-load retrieval method when possible. We assume always 3 people are waiting to retrieve their car with a flexible first-come first-served policy, which means for every retrieval, we take the first car request and pair it with the closer one of the other two car requests. The parking lot operates 24/7 and we perform a Monte Carlo simulation for 1000 random car requests. Table 6 shows the time it takes to retrieve cars individually and in pairs. The total retrieval time for 1000 cars using the dual-load retrieval method is 23.59 hours for the 10×10 105.44 hours for the 20×20 case. On the other hand, the total retrieval time using the individual retrieval method is 30.80 and 132.78 hours respectively. Thus, we can obtain at least 20% improvement in total retrieval time using the dual load retrieval method. This basically means more than 7 hours less retrieval time on a daily basis. Note that these savings are even higher than the average saving for the random case in Table 4, as we first examine the location of the three retrieval request and then pair the closer cars.

Table 6. Savings for a real car parking system.

Number of Bays	Individual retrieval time (h)	Dual-load retrieval (h)	Average saving (%)
99	30.80	23.59	23
399	132.78	105.44	20

2.5. Conclusions

Puzzle-based storage systems are fully automated, unit-load, high-density storage systems that pair a small footprint with high efficiency in retrieval. In this chapter, we first proposed an optimal dual-load retrieval method that, compared to single-load retrieval, saves on average 17 % in retrieval time by bringing the loads first together to an optimal joining location. In addition, a heuristic method is proposed for retrieving loads in pairs that finds a near-optimum solution much faster. This heuristic is then extended to retrieve three and more loads. For three-load retrieval, the results show that on average a 23% saving can be achieved compared to single-load retrieval. Puzzle-based storage systems are still quite rare in practice. However, as the technology becomes less expensive, space becomes scarcer, and as we move into a 24/7 economy, these systems provide a great opportunity to provide high fulfillment performance. Our algorithms and insights can help to realize such high performance, by properly grouping requests and retrieving them jointly.

This chapter makes some assumptions which may be relaxed in future research. First, we study retrieval of loads on a single storage tier. In multi-tier systems, our results will apply per tier. Second, we assume a single escort. Extension of exact results to systems with multiple escorts is not straightforward, but heuristics results may be possible. Third, the proposed algorithms can be embedded in a simulator to obtain the cycle time savings of different system configurations. Last, we assume loads move only one step at a time, and only one load can move at a time. This assumption is valid, depending on the type of mechanical retrieval system, but it may be possible to extend results to systems with simultaneous load movements.

Chapter 5

Summary and Conclusion

5.1. Summary

Automated storage and retrieval systems are adopted by many companies to reduce the operational costs in warehouses and to rapidly fulfill customer demand. Automation technology also allows better space usage, e.g. by more narrow transport aisles. Compact automated storage systems do not need transport aisles and allow very high density storage. Deciding on storage and retrieval policies in such systems is an important choice as it affects product retrieval time performance. Chapter 2 discusses optimal and near-optimal retrieval methods in compact storage systems. Chapters 3 and 4 model correlated and dispersed storage and retrieval methods using information on the historical customer demand.

Chapter 2 studies efficient retrievals in puzzle-based storage (PBS) systems, a new type of compact storage system that operates without transport aisles. In these systems, loads are stored on shuttles. Retrieving loads resembles solving a 15-tile sliding puzzle. These systems bring extreme space usage efficiency but can result in long storage and retrieval times. Previous research studies optimal retrieval methods for single loads in which only one load is retrieved at a time. In practice, often, multiple loads are requested together. This chapter proposes a multiple-load retrieval method that minimizes the total retrieval time. The main research question is "*What is the optimal retrieval method in PBS systems (i.e. minimizing the number of required moves) to retrieve multiple requested loads, using one open location?*" This question is answered by first modeling simultaneous retrieval of two requested loads. The optimal retrieval paths for two loads, which go through an intermediary joining location, are obtained. Based on this model, an efficient heuristic is developed that obtains near-optimal retrieval paths for multiple requested loads. Numerical analysis shows that up to 23% savings in total retrieval time can be achieved compared to sequential optimal single-load retrievals.

Chapter 3 studies a correlated storage policy, which assigns product pairs that are ordered frequently together to the same storage bin to save retrieval time. This assignment policy considers information on both turnover frequency of products and correlation between them. In the literature, models use a sequential approach that first cluster correlated products, and then assigns the clusters to storage zones. These models are suboptimal because the objectives of the decomposed problems are to maximize the total product correlation in clusters and then minimize the order picking time. On the other hand, in an integrated approach, the objective is to minimize the order picking time by simultaneously considering product turnover and correlation. Furthermore, current models are developed for manual order picking and are not directly applicable to automated storage and retrieval systems, where each cluster is assigned to a storage pod that is retrieved automatically. The main research question in this chapter is "*How does integrated clustering and storage assignment of correlated products affect the order picking performance in automated warehouses?*" To answer this question, an integrated mathematical model is developed that clusters the products and assigns the cluster to storage locations in order to minimize the total order picking retrieval time. The model is tested for two types of automated systems: crane-based automated storage and retrieval (AS/R) systems and robotic mobile fulfillment (RMF) systems. The performance of the integrated model is evaluated by comparing it to product turnover-based assignment and sequential correlated assignment. The model is solved using Gurobi 7.5. The numerical analysis shows that applying the integrated model, saves up to 40% and 26%, respectively, on retrieval time compared to the benchmark policies.

Chapter 4 studies a dispersed correlated storage policy, which clusters correlated products and, in addition, allows the inventory of each product to be broken up and spread over the forward storage area. Several papers have studied the benefits of random dispersion (Onal *et al.*, 2017, 2018) and evenly spreading (Weidinger and Boysen, 2018) product inventory, but not dispersion considering historical order information. RMF systems, that use robots to move storage pods, are good candidates for implementing such policies for the reason that each pod has several compartments, each providing space for part of product inventory. RMF systems, additionally, are good candidates for the correlated assignment because each storage pod can carry multiple correlated products, which can be retrieved to pick order lines requesting those products. The main research questions in this chapter are "*What is the effect of product dispersion and storage clustering on the expected order picking retrieval time in RMF systems? How do product correlation and product turnover frequency contribute to the performance of the policies?*" to answer this, we develop travel time expressions for different warehouse layouts in robotic mobile fulfillment systems. A mixed-integer program is presented to disperse the inventory, cluster correlated products on pods, and assign the inventory to customer orders. The objective function of the model minimizes the total expected retrieval time of picking all orders. The performance of the dispersed correlated assignment (CDA) policy is compared with random, class-based, correlated and dispersed assignments using a real warehouse dataset. The results show significant benefits of using the CDA policy. Further numerical analysis reveals that a more skewed product correlation (Pareto curve) results in higher performance of the CDA model.

5.2. Outlook

Developments in automation and robotic technology are moving fast. This suggests an increasing need for advanced storage and retrieval policies to control such systems. This section gives an overview of research directions on storage assignment and retrieval methods in compact storage robotized systems.

Puzzle-based storage systems are very compact with a long throughput time. To reduce the throughput time, in addition to optimal two-load retrieval, chapter 2 studies near-optimal multiple-load retrieval in presence of one open location. Future research should study the retrieval methods of such systems when multiple open locations are available. High space utilization may result in reduced system performance due to sub-optimal storage assignment and additional internal relocation which, in general, elongates the storage and retrieval time. Since the number of open locations has a strong effect on the performance of the system, presence of more open locations may speed up the operations. Future research should particularly consider multiple load retrievals in systems with multiple open locations. Also, note that different variants of these systems exist, e.g., a system that allows 'block' movements, that is all loads is a row or column can move simultaneously. We assume the loads move sequentially. Numerical analysis and simulation models can be used to evaluate the performance of such systems.

Chapter 3 highlights the benefits of using correlated storage assignment in AS/R and RMF systems that can facilitate simultaneous picking of multiple lines of an order from the same retrieved storage unit. In the model presented, products are stored using dedicated storage. A dedicated storage policy requires a system with higher storage capacity and longer replenishment time compared to systems using shared storage allocations such as a class-based storage policy. In addition, this model only considers the assignment problem and does not consider the replenishment. Future research should investigate a 'dynamic' correlated storage assignment that takes into account the changing assortment and is flexible in inventory allocation. Faster and more robust solution approaches are needed to handle real size problems.

Chapter 4 introduces the correlated dispersed assignment (CDA) policy that allows inventory to be spread over multiple locations. Numerical analysis on one case, with a large number of lines in each order, shows considerable benefits of such a policy. Further numerical analysis is needed to support the applicability of

CDA to more general cases, especially where orders have smaller sizes, or the order profile has a different turnover and correlation pattern. Furthermore, this chapter does not consider the extra replenishment effort required due to inventory dispersion which may be addressed in further research. Another research direction is to evaluate and optimize the sequencing and assignment of orders to pick stations so that pick requests at each station include correlated products, which are already assigned to the same storage pod, in order to minimize the retrieval times.

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Masoud Mirzaei was born on 20 March 1985 in Arak, Iran. He received his BSc and MSc degrees in Industrial Engineering from Iran University of Science and Technology (2007) and Shahed University (2010), respectively, in Tehran, Iran. For two years, he worked as operations and data analyst in industry, before becoming a PhD candidate at Rotterdam School of Management, Erasmus University Rotterdam in February 2013. In 2013, he was a visiting scholar at the Department of Information Management and Decision Science, University of Science and Technology of China, Hefei, China. His research interests include supply chain management, design and analysis of warehouses and fulfillment centers, logistics and material handling, operations research. His research findings has been presented in many international conferences including INFORMS Annual Meeting (2015), POMS (2012) and European Conference on Operational Research (2018, 2019). He is involved in coordinating and teaching several courses, and supervising students at master and bachelor levels. Masoud is currently a Postdoctoral fellow at Department of Industrial Engineering & Innovation Sciences, Eindhoven University of Technology.

Portfolio

Publications

JOURNAL PUBLICATIONS

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PhD Courses

Facility Logistics Management
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Teaching

COORDINATOR AND/OR LECURER
Quantitative Methods and Techniques: Mathematics, BAP053 (2018 – 2019)
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Research Training and Bachelor Thesis, BAD10 and BKBBTH (2016 – 2019)

TUTURIAL LECURER
Global Supply Chain Management, BM-IM03CC (2013 – 2018)
Operations Management (2014 – 2016)
Facility Logistics Management, BM04SCM (2015 – 2016)

Conferences Attended

European Conference on Operational Research, Valencia (2018) and Dublin (2019).
International Conference on Logistics and Maritime Systems, Rotterdam (2014) and Singapore (2019).
Odysseus, Cagliari, Italy (2018).
INFORMS Annual Meeting, Nashville, TN, USA (2016).
POMS Annual Conference 2016, Orlando, FL, USA (2016).
CEMS Research Seminar on supply chain management, Riezlern, Austria (2015,18, 19).
European Logistics Association Doctorate Workshop, Wroclaw, Poland (2017).
TRAIL PhD congress, Utrecht, Netherlands (2016).
International Conference on Operations Research, Rotterdam, the Netherlands (2013).

Summary

Warehouses are key components in supply chain. They facilitate the product flow from production to distribution. The performance of supply chains relies on the performance of warehouses and distribution centers. Being able to realize short order delivery lead times, in retail and ecommerce particularly, is important for warehouses. Efficient and responsive storage and retrieval operations can help in realizing a short order delivery lead time. Additionally, space scarcity has brought some companies to use high-density storage systems that increase space usage in the warehouse. In such storage systems, most of the available space is used for storing products, as little space is needed for transporting loads. However, the throughput capacity of high-density storage systems is typically low. New robotic and automated technologies help warehouses to increase their throughput and responsiveness. Warehouses adapting such technologies require customized storage and retrieval policies fit for automated operations. This thesis studies storage and retrieval policies in warehouses using several common and emerging automated technologies.

Chapter 2 studies puzzle-based storage systems, in which loads are stored on transport shuttles, which carry the unit loads autonomously in a high-density storage

system. Loads are stored next to each other. The system does not have transport aisles. Only few open locations are available for the shuttles to move. The system shuffles loads consecutively to make space available to retrieve a requested load. As such, it resembles the traditional 15-tile sliding puzzle. The system has been studied in literature, in particular how to retrieve one load at a time. This chapter proposes a multiple-load retrieval method that brings two or more requested loads together to an optimal joining location, and then retrieves them simultaneously. Closed form expressions are derived for the number of moves required to retrieve multiple loads. A fast heuristic is developed to find near-optimal joining locations for the loads. Numerical analysis shows that multiple-load retrieval results in a shorter retrieval time than optimal sequential single-load retrieval.

Chapter 3 studies the impact of correlated storage assignment on order retrieval time in automated storage and retrieval (AS/R) systems. In an AS/R system, automated cranes move within narrow aisles and transport storage bins between storage shelves and pick stations. The assignment of products to storage bins impacts the order retrieval time, especially multiple line orders. A correlated storage policy groups product that appear jointly in customer orders frequently in product clusters. These clusters are then assigned to storage bins. Each bin has multiple compartments that can house the products of a cluster. This correlated policy can reduce the number of bin retrievals required to pick all the lines of an order. In this chapter, an integrated linear program is formulated that clusters the correlated products and assigns the clusters to storage bins to minimize the total retrieval time. The numerical analysis shows that it performs better than sequentially clustering products and assigning clusters to storage bins. Additionally, it outperforms the turnover frequency-based assignment when the skewness of the Pareto curve of the turnover frequency of the products in the assortment is low to moderate, for even low correlation between products.

Chapter 4 extends the correlated storage policy of the previous chapter by including dispersion of product inventory. In such a case, the inventory of each product is split and dispersed over multiple storage locations. Dispersion makes each product more accessible from different pick stations. A product can now also be stored in multiple product clusters, depending on its correlation with other products. This can reduce the order picking retrieval time, especially for robotic mobile fulfilment systems where autonomous robots move the storage pods carrying inventory of multiple products to a pick station and return it after the customer order has been picked. This chapter formulates a integer linear program for correlated dispersed storage in which products are assigned to storage pods, storage pods are assigned to storage locations and the inventory is assigned to customer orders to minimize the total retrieval time. Retrieval time expressions are developed for different layouts of the warehouse. Since the model is NP-hard, a simple and efficient heuristic is developed that is capable to solve real size problems. To evaluate the performance of the model, we apply it to a dataset consisting of three-month order history of a warehouse in personal care products. The outcome is compared with that of random, class-based, correlated but not dispersed, and dispersed but not correlated storage policies. The results show that the correlated dispersed storage outperforms the other policies for the instances tested. We use regression models to predict the performance of the policies based on correlation and turnover frequency Pareto curves. The results show significant association between the total retrieval time and the skewness of the correlation Pareto curve in the correlated dispersed policy for the case tested.

Samenvatting (Summary in Dutch)

Magazijnen zijn een belangrijk onderdeel van de supply chain. Ze ondersteunen de productstroom van productie naar distributie. De prestatie van een supply chain hangt af van de prestaties van magazijnen en distributiecentra. Het realiseren van korte levertijden is belangrijk voor magazijnen, met name in de detailhandel en e-commerce. Efficiënte en responsieve opslag- en orderverzamelprocessen kunnen helpen bij het realiseren van een korte levertijd van bestellingen. Gebrek aan beschikbare ruimte heeft sommige bedrijven ertoe gebracht zeer compacte opslagsystemen te gebruiken die de ruimte in het magazijn maximaal benutten. In dergelijke opslagsystemen wordt het grootste deel van de beschikbare ruimte gebruikt voor het opslaan van producten, aangezien er weinig ruimte nodig is voor het transport van ladingen. De doorzet van compacte opslagsystemen is echter laag. Nieuwe robot- en geautomatiseerde technologieën helpen magazijnen hun doorzet en responsiviteit te vergroten. Dergelijke magazijnen vereisen bedrijfsspecifieke in- en uitslagstrategieën die geschikt zijn voor geautomatiseerde processen. Dit proefschrift bestudeert in- en uitslagstrategieën in magazijnen voor verschillende veelgebruikte en nieuwe geautomatiseerde technologieën.

Hoofdstuk 2 bestudeert ‘puzzelgebaseerde’ compacte opslagsystemen, waarin ladingen worden opgeslagen op shuttles, die zich autonoom kunnen verplaatsen in een compact opslagsysteem. Ladingen worden dicht naast elkaar opgeslagen. Het systeem heeft geen transportgangen. Om de shuttles zichzelf te laten verplaatsen is een beperkt aantal open locaties beschikbaar. Het systeem verplaatst achtereenvolgende ladingen zodat er ruimte ontstaat om een gevraagde lading op te halen. Dit systeem heeft wat weg van de bekende schuifpuzzel met 15 tegels. Een dergelijk systeem is al eerder onderzocht in de literatuur, met name hoe één lading tegelijk kan worden opgehaald. In dit hoofdstuk wordt een ophaalmethode voorgesteld voor meerdere ladingen, waarbij twee of meer gevraagde ladingen telkens naar een optimale verbindingslocatie worden gebracht en vandaar gezamenlijk worden opgehaald. Analytische uitdrukkingen worden afgeleid voor het aantal bewegingen dat nodig is om meerdere ladingen op te halen en een snelle heuristiek wordt ontwikkeld om een nagenoeg optimale verbindingslocaties voor de ladingen te vinden. Numerieke analyse toont aan dat het gecombineerd ophalen van meerdere ladingen resulteert in een kortere ophaaltijd dan het optimale sequentiële ophaalplan met één lading per keer.

In Hoofdstuk 3 bestudeert de impact van gecorreleerde opslagtoewijzing op de benodigde uitslagrijtijd voor het ophalen van ladingen in geautomatiseerde opslagsystemen (zogeheten automated storage and retrieval, AS/R, systemen). In een AS/R-systeem verplaatsen geautomatiseerde kranen zich in smalle gangpaden en transporteren ze opslagladingen (bakken of pallets) tussen opslaglocaties en pickstations. De toewijzing van producten aan opslagbakken en opslagbakken aan locaties heeft invloed op de benodigde tijd voor het ophalen van orders, met name orders bestaande uit meerdere regels. Een (vraag)gecorreleerde opslagstrategie groepeert producten die vaak gezamenlijk voorkomen in klantorders, in productclusters. Deze clusters worden vervolgens toegewezen aan opslagbakken. Elke bak heeft meerdere compartimenten waarin de verschillende producten van een cluster kunnen worden ondergebracht. Deze gecorreleerde opslagstrategie kan het aantal ophaalopdrachten verminderen dat nodig is om alle regels van een bestelling te verzamelen. In dit hoofdstuk wordt een geïntegreerd lineair programma geformuleerd dat de gecorreleerde producten clustert en de clusters toewijst aan opslagbakken om de totale ophaaltijd te minimaliseren. Uit de numerieke analyse blijkt dat deze methode beter presteert dan sequentiële clustering van producten en het vervolgens toewijzen van clusters aan opslagbakken. Bovendien overtreft het de op omloopsnelheid gebaseerde toewijzing wanneer de scheefheid (skewness) van de Pareto-curve van de omzetfrequentie van de producten in het assortiment laag tot matig is, zelfs als de vraagcorrelatie tussen producten laag is.

Hoofdstuk 4 breidt het gecorreleerde opslagbeleid van het vorige hoofdstuk uit met de verspreiding van productvoorraad. In een dergelijk geval wordt de voorraad van elk product opgesplitst en verspreid over meerdere opslaglocaties. Dispersie maakt een product sneller toegankelijk vanaf verschillende startposities. Een product kan nu ook worden opgeslagen in meerdere productclusters, afhankelijk van de correlatie met andere producten. Dit kan de ophaaltijd voor het orderverzamelen verminderen, vooral voor mobiele fulfilment-systemen waarbij autonome robots de opslagrekken met inventaris van meerdere producten naar een pickstation verplaatsen en retourneren nadat de klantbestelling is verzameld. Dit hoofdstuk formuleert een lineair geheeltallig programma voor gecorreleerde verspreide opslag waarin producten worden toegewezen aan opslagrekken,

opslagrekken worden toegewezen aan opslaglocaties en de productvoorraad wordt toegewezen aan klantorders om de totale ophaaltijd te minimaliseren. Voor verschillende indelingen van het magazijn worden uitdrukkingen ontwikkeld voor de uitslagtijd. Aangezien het model NP-hard is, wordt een eenvoudige en efficiënte heuristiek ontwikkeld die in staat is om problemen van praktische grootte op te lossen. Om de prestaties van het model te evalueren, wordt het toegepast op een dataset bestaande uit een bestelgeschiedenis van drie maanden van een magazijn met producten voor persoonlijke verzorging. Het resultaat wordt vergeleken met een random opslagstrategie, een strategie gebaseerd op opslagklassen, een gecorreleerde, maar niet verspreide strategie, en een verspreide, maar niet gecorreleerd opslagstrategie. De resultaten laten zien dat voor de geteste instanties de gecorreleerde en verspreide opslag beter presteert dan de andere strategieën. We gebruiken regressiemodellen om de prestaties van het beleid te voorspellen op basis van correlatie- en omzetfrequentie Pareto-curven. De resultaten tonen voor de geteste casus een significant verband aan tussen de totale uitslagtijd en de scheefheid van de correlatie Pareto-curve in de gecorreleerde verspreide strategie.

چکیده (Summary in Farsi)

انبارها از بخش‌های کلیدی در زنجیره تامین محسوب می‌شوند. آنها جریان کالا از تولید تا توزیع را تسهیل می‌کنند. عملکرد زنجیره تامین وابسته به عملکرد انبارها و مراکز توزیع است. کوتاه کردن زمان تحویل سفارش، به‌ویژه در خرده‌فروشی و فروش اینترنتی، برای انبارها حائز اهمیت است. عملیات انبارش و بازیابی کارامد و پاسخگو، مسیر دستیابی به زمان کوتاه تحویل سفارش مشتری را هموار می‌کند. افزون بر این، کمبود فضا برخی از شرکت‌ها را به استفاده از سامانه‌های انبارش متراکم سوق داده است تا از فضای موجود استفاده‌ی بهتری نمایند. در این نوع از سامانه‌های انبارش، بخش عمده‌ی فضای موجود برای انبارش کالا استفاده می‌گردد، زیرا به فضای اندکی برای جابجایی کالا نیاز است. با این وجود، بهره‌وری سامانه‌های انبارش متراکم پایین است. فن‌آوری‌های نوین خودکار و رباتیک به انبارها کمک می‌کنند تا بهره‌وری و سطح پاسخ‌گویی خود را افزایش دهند. انبارهایی که از این‌گونه فناوری‌ها استفاده می‌کنند نیازمند راهبردهای انبارش و بازیابی جدیدی هستند. این پایان‌نامه به مطالعه راهبردهای انبارش و بازیابی در انبارهایی که از فن‌آوری‌های خودکار نوظهور یا رایج بهره می‌برند می‌پردازد.

فصل ۲ به بررسی سامانه‌های «انبارش متراکم مبتنی بر پازل» می‌پردازد که در آن‌ها کالا بر روی شاتل‌های نقلیه قرارداده شده که قابلیت جابجایی خودکار کالاها در سامانه انبارش متراکم را دارند. این سامانه فاقد راهروهای جابجایی کالا است. تنها تعداد محدودی فضای خالی برای جابجایی شاتل‌ها در دسترس می‌باشد. سامانه با حرکت دادن مداوم کالاها به اطراف فضای مورد نیاز برای بازیابی کالای درخواستی را فراهم می‌کند. این کارکرد، مشابه بازی قدیمی پازل ۱۵تایی است که در آن با جابجایی کاشی‌های متحرک شامل اعداد یک تا پانزده، ترتیب صعودی از اعداد ایجاد می‌گردد. پژوهش‌های پیشین به مطالعه این سامانه به ویژه روش‌های بازیابی انفرادی کالا پرداخته‌اند. این فصل یک روش برای بازیابی دو یا تعداد بیشتری کالا به صورت همزمان ارائه می‌دهد. در این روش ابتدا کالاهای درخواستی جابجا می‌شوند تا در یک «مکان همگرایی بهینه» کنار یکدیگر قرار بگیرند، سپس همزمان به محل نهایی استخراج کالا انتقال داده می‌شوند. معادلات ریاضی فرم بسته برای محاسبه تعداد حرکت‌های مورد نیاز برای بازیابی چند کالا ارائه شده است. یک روش ابداعی سریع برای یافتن مکان همگرایی نزدیک به بهینه نیز توسعه داده شده است. تحلیل‌های عددی نشان می‌دهند بازیابی چند کالا منجر به زمان بازیابی کوتاه‌تری در مقایسه با بازیابی انفرادی می‌گردد.

فصل ۳ به بررسی تاثیر «تخصیص موجودی همبسته» بر بازیابی سفارش در سامانه‌های خودکار انبارش و بازیابی می‌پردازد. در این سامانه‌ها، جرثقیل‌های خودکار در میان راهروهای باریک حرکت کرده و قفسه‌های انبارش را مابین قفسه‌ها و ایستگاه آماده‌سازی سفارش جابجا می کنند. نحوه تخصیص کالاها به قفسه‌های انبارش تاثیر بسزایی روی زمان بازیابی سفارش دارد، به ویژه در سفارش‌های مشتمل بر چند کالا. تخصیص موجودی همبسته، کالاهایی را که مکررا در سفارش‌های مشتری با هم دیده می‌شوند، در گروه‌های مجزا دسته‌بندی می‌کند. سپس، این دسته‌های کالا به قفسه‌های انبارش تخصیص داده می‌شوند. هر قفسه متشکل از چندین محفظه بوده که می‌تواند کالاهای یک دسته را در خود جای دهد. این تخصیص همبسته می‌تواند تعداد دفعات بازیابی که برای آماده‌سازی اقلام موجود در سفارش مشتری مورد نیاز است را کاهش دهد. در این فصل

چکیده

یک برنامه‌ریزی خطی یکپارچه برای دسته‌بندی کالاهای همبسته و تخصیص دسته‌ها به جعبه‌های انبارش ارائه شده که کل زمان بازیابی را کمینه می‌کند. تحلیل‌های عددی نشان می‌دهد مدل یکپارچه عملکردی بهتری از دسته‌بندی کالا و تخصیص دسته‌ها به جعبه‌های انبارش به صورت متوالی دارد. به علاوه، در مواردی که چولگی منحنی پارتو فراوانی سفارش کم تا میانه باشد، این مدل عملکرد بهتری نسبت به تخصیص مبتنی بر فراوانی سفارش کالا دارد، حتی در شرایط همبستگی پایین بین کالاها.

فصل ۴ راهبرد تخصیص همبسته در فصل گذشته را توسعه داده تا پراکندگی موجودی کالا را نیز در نظر بگیرد. در این حالت، موجودی هر کالا تقسیم شده و در چندین مکان انبارش می‌شود. پراکندگی، دستیابی به کالاها را برای ایستگاه‌های مختلف آماده‌سازی سفارش مشتری آسان‌تر می‌کند. همچنین یک کالا با توجه به همبستگی آن با دیگر کالاها می‌تواند در چندین گروه کالایی دسته‌بندی شود. این روش می‌تواند زمان بازیابی سفارش مشتری را کاهش دهد، به ویژه در سامانه‌ی «رباتیک سیار تکمیل سفارش» که در آن ربات‌های خودکار قفسه‌های انبارش را جابجا می‌کنند که حاوی موجودی چندین کالا می‌باشد. ربات‌ها قفسه‌ها را به ایستگاه آماده‌سازی سفارش مشتری برده و پس از بازیابی اقلام مورد نیاز به فضای انبار بازمی‌گردانند. این فصل یک برنامه‌ریزی خطی عدد صحیح برای تخصیص همبسته پراکنده ارایه می‌دهد که کالاها را به قفسه‌های انبارش، قفسه‌های انبارش را به مکان‌های انبارش و موجودی را به سفارش مشتری تخصیص می‌دهد تا کل زمان بازیابی کالا کمینه گردد. معادلات زمان بازیابی کالا برای جانمایی‌های مختلف انبار توسعه داده شده است. به دلیل پیچیده (NP-hard) بودن مساله، یک روش ابداعی ساده و کارامد توسعه داده شده که قادر به حل مساله در ابعاد واقعی می‌باشد. ما این روش را بر روی داده‌های سه‌ماهه انباری از کالاهای بهداشت شخصی اجرا کردیم تا کارایی آن را ارزیابی کنیم. نتایج حاصله با راهبردهای تخصیص تصادفی، مبتنی بر دسته‌بندی، همبسته بدون پراکندگی و پراکنده بدون همبستگی مقایسه شده است. یافته‌ها حاکی از عملکرد بهتر راهبرد تخصیص همبسته پراکنده برای داده‌های موجود است. ما از مدل‌های رگرسیون برای پیش‌بینی عملکرد راهبردهای

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Warehouses are key components in supply chain. They facilitate the product flow from production to distribution. Automation technology and robotics help warehouses to be efficient and responsive. Storage and retrieval policies determine the performance of a warehouse. Conventional storage and retrieval policies are not applicable to automated storage and retrieval system due to operational and technological disparities. This thesis studies several new storage and retrieval polices in automated warehouses. Puzzle-based storage systems are high-density storage systems that store loads on autonomous shuttles. Such systems have low throughput capacity due to lack of transport aisles. Chapter 2 studies an efficient multiple-load retrieval method that brings the loads together at an optimal joining location and then retrieves them simultaneously. This leads to shorter retrieval time compared to sequential sing-load retrievals. In another group of compact storage and retrieval systems, automated cranes transport storage bins using narrow aisles. The assignment of products to the bins and bins to the shelves are important choices that affect system's performance. Chapter 3 proposes a correlated assignment that groups products, that are frequently order together in historical customer demand, to the same product cluster. Each cluster is then assigned to a storage bin. The correlated assignment reduces the total retrieval time compared to turnover frequency-based assignment. Chapter 4 further investigates the impact of splitting the inventory of a product and dispersing it over multiple storage pod. Each pod is transported using autonomous robots and carries several dozens of correlated products.

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