IMPACT OF INTEGRATING ZONE BYPASS CONVEYOR ON THE PERFORMANCE OF A PICK-TO-LIGHT ORDER PICKING SYSTEM

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Xia Xu

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SUPERVISORY COMMITTEE:

Reza A. Maleki
Chair

Donald A. Andersen

Kambiz Farahmand

Jun Zhang

Approved:

March 6, 2012
Date

John Cook
Department Chair

ABSTRACT

This thesis investigates the impact of integrating Zone Bypass (ZBP) conveyor to a Pick-To-Light (PTL) order picking system. This integration results in a new system (PTL+Z), which could be helpful to achieve higher levels of productivity in warehousing operations.

Two options have been proposed to improve the current PTL system productivity. One is to adapt the ZBP conveyor, which will help each order to bypass unnecessary zones with nothing to pick. Another one is to better plan stock keeping units (SKU) assignment by applying level loading assignment.

Mathematical models are developed to evaluate system throughput of PTL system with random assignment (PTL/R), PTL system with level loading assignment (PTL/L), PTL+Z system with random assignment (PTL+Z/R), and PTL+Z system with level loading assignment (PTL+Z/L). Simulation models are validated to test the reliability of mathematical models. Also, economic analysis is developed in term of payback period for decision purpose.

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CHAPTER 1. INTRODUCTION

1.1. Background

Warehouse is a place for receiving incoming goods, processing and shipping fulfilled orders. Heragu *et al*. (2004) state that a warehouse is usually divided into three functional areas; they are reserve storage area, forward area and cross-docking area. A reserve storage area is also known as the bulk storage area, which is a unique area for storing most of the Stock Keeping Units (SKU) in a warehouse. It is considered as the most economic way for storing. A forward area is the most important area for storing the most popular SKUs in a warehouse to offer conveniently picking.

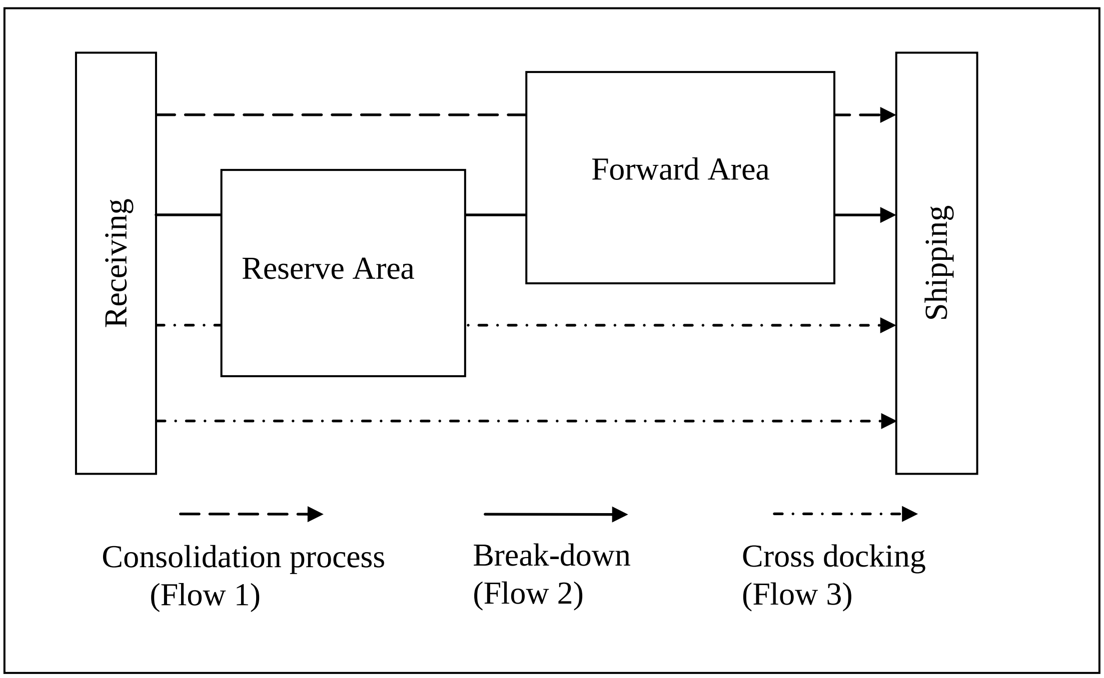

Figure 1.1. Relations between Forward Area and Reserve Area

A summary of product flows in a typical warehouse can be seen in Figure 1.1. Flow 1 indicates the consolidation operation that products already in required pack size are put into forward area for necessary consolidation before shipping. Flow 2 is a typical warehouse operation indicates the break-down process that the pallet loads of bulk package products are received in this area first, and then the products are waiting to be consolidated in the forward area before shipping. Flow 3 indicates the cross-docking operation. There are two situations that might be happening in this process. First, the receiving products might be storing in reserve area for some time before they get shipped out. Second, the products might be transferring to shipping area without any storage process. Normally, the reserve storage is aiming at achieving the high space utilization, which compares to a relatively smaller forward area for performing fast-moving goods picking process. A better organized warehouse can achieve higher productivity by shortening the traveling time and order processing time within the warehousing activities.

Warehousing is a series of activities happening in a warehouse. It consists of several activities such as receiving, prepackaging, put-away, storage, order picking, packaging, sortation, packing and shipping, cross-docking and replenishment (Tomkins *et al.* 1996). For the first three steps, the incoming goods that are in full package will be broken down based on their properties. Then, the broken-down items will be placed in a carton, a tote or an alternative container into a specific storage area before picking. Warehousing should be continuously improved, like rearranging the warehouse plan to make total travel time comparatively shorter and applying technologies to increase total productivity. Studies in how to balance the needs of current warehouse situation and budget are highly desired. This thesis is only focused on the activities in the forward area, and to be more specific on the order picking system (OPS).

Order picking can be referred as a process that with the correct quantity of the correct SKUs at the correct time are retrieved for the storage location in a warehouse specified on a picking list in order to fulfill customers' needs (Pan and Wu, 2009). One or more pickers will be responsible for finishing picking an order according to different picking policies (Rouwenhorst *et al*. 1999), which is considered as the most labor-intensive activity.

In particular, an OPS is the unique area for assigning pickers and arranging the racks for SKUs in order to meet the demand within the constraints of labor and facilities. The entire OPS shares the strategic goal as improving the throughput and the utilization of each workstation. At the meantime, the OPSs are trying to minimize the average processing time. Tompkins *et al.* (1996) and Yu and De Koster (2007) indicate that order picking occupies about 55% of operating cost and takes about 50% of total order picking time in travel time. Coyle *et al.* (1996) conclude that up to 65% of the operating costs of warehouses would be consumed in the OPSs. Therefore, the criteria of choosing right OPSs and the design of OPSs are becoming critical (Gillespie, 2009, Dallari *et al.* 2006, and Dallari *et al.* 2009).

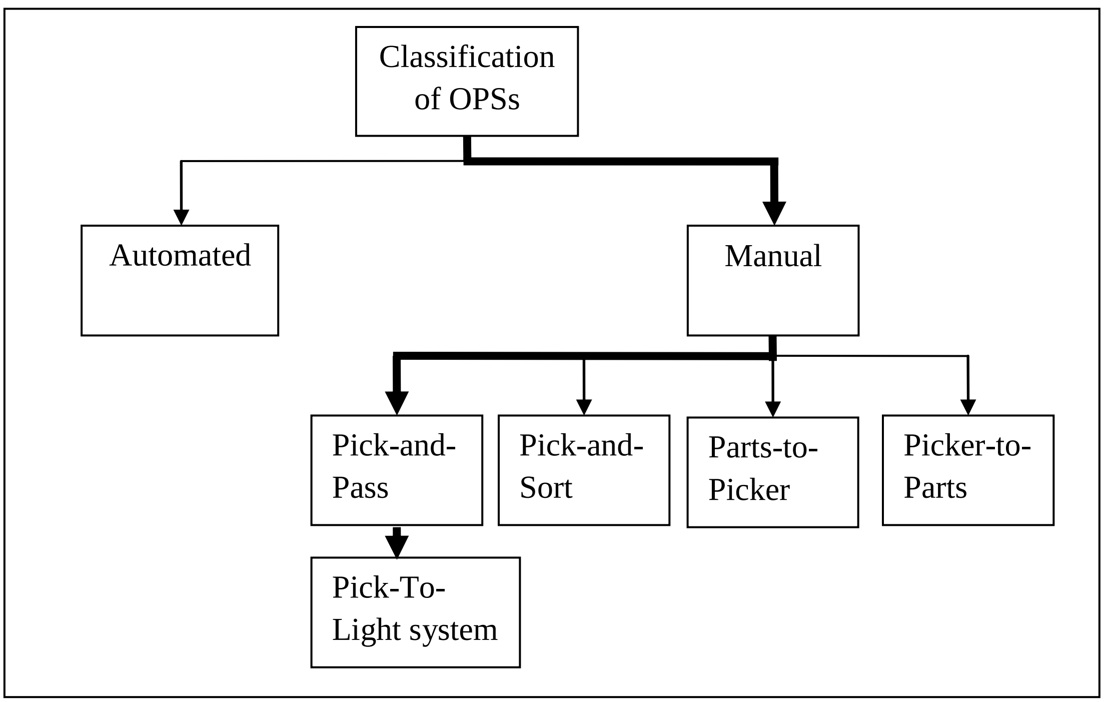

Figure 1.2. Classifications of OPSs

Figure 1.2 illustrates the detail of the classifications of order picking process with highlighted arrows showing the approach of this thesis topic. By taking the final picking process into consideration, the OPS can be divided into two major parts as automated picking and manually picking. For automated picking, there will be no labor attached to the whole process, machines and robot will finish all the orders. By taking the travel direction between pickers and SKUs into consideration, the manual picking process can be divided more specifically into “Picker-to-Parts”, “Parts-to-Picker”, “Pick-and-Sort”, and “Pick-and-Pass”.

“Picker-to-Parts” system can be considered as the basic picking activity. Picker will travel along the aisles to retrieve items from racks for each order. “Parts-to-Picker” system will be using technologies, like carousal systems and retrieval systems (AS/RS) to bring the SKUs to the picking station and the picker will select the required items to finish picking. “Pick-and-Sort” system is dealing with wave picking, which means that picker will only pick one item at one time and all the orders only can start next picking by completing the current picking.

Furthermore, a new branch of manual picking as “Pick-and-Pass” (PAP) system is proposed in De Koster *et al.* (2007) to better define OPS. This system is dealing with zone picking that each order will travel along the zones and the picker will be responsible for picking the required items in each zone.

Several researches have been done in the area of Forward Reserve Problem (FRP), whose topics are including the picking routines, storage polices, and the influence of applying the updated technologies. One common system that implements both PAP and FRP system in practice is a Pick-To-Light (PTL) system (Pan and Wu, 2009). In the growing number of warehouses, PTL systems are commonly used because of their efficient and accurate methods that deal with sorting, picking and assembling. In the PTL system, lights will inform pickers where the SKUs are and how many SKUs should be picked for this specific order. However, PTL systems are usually dealing with small-sized and human-friendly handling SKUs with a large volume of demand.

In an effort to further improve system's productivity, some operations integrate conveyors to speed up. By considering various automated conveyor systems can move boxes more time-effectively and minimize the chance for manual operations and total picking time, a Zone Bypass (ZBP) conveyor is proposed in English *et al.* (2007). Therefore, PTL system with ZBP conveyor (PTL+Z) system is proposed based on integrating a ZBP conveyor to the current PTL system.

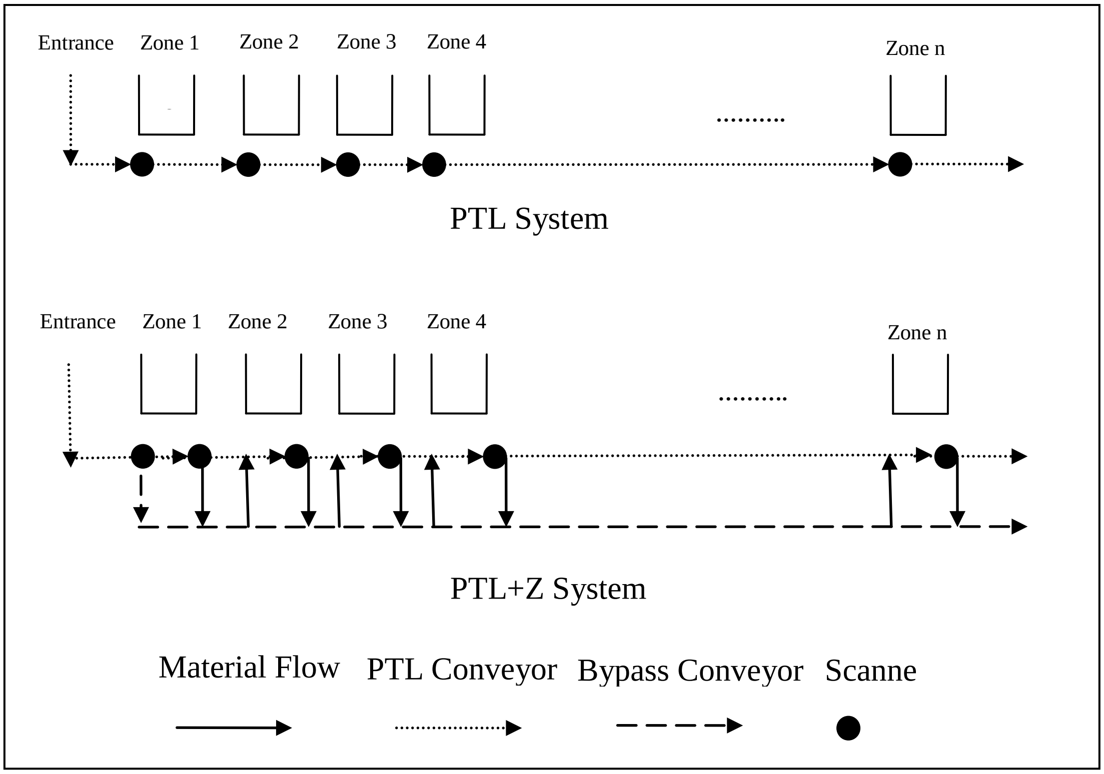

Figure 1.3. Workflows of Systems

A comparison is shown in Figure 1.3 to present the workflows in PTL and PTL+Z systems. First, in the PTL system, an order travels on the conveyor to be scanned at the beginning of each zone. Then, the lights in each zone will help the picker with the locations and quantities of SKUs after scanning the barcode on each box. After finishing picking SKUs in a zone, the picker will manually push the order to the next zone to continue picking.

The difference in the PTL+Z system are the extra ZBP conveyor and one more scanner, an order will wait to be scanned at the first scanner before entering the system. The scanner will decide where to push this order, either the bypass conveyor or the PTL conveyor. Then, the procedures for picking are exactly the same as PTL system. However, after done with picking in one zone, the conveyor will automatically push the order to either the next zone through PTL conveyor or the following zones through bypass conveyor. In PTL+Z system, each order will only need to enter the zones, where SKUs need to be picked.

In addition, the proper placement of SKUs has a significant impact to the performance of system. Generally, random assignment can be referred as allocating SKUs randomly in the storage area without considering the priorities of SKUs. In the beginning, random assignment was applying to the picking system, but with the development of warehouse management, new principles of balancing the workload of the picking are established in order to reduce the travel time and increase the picking efficiency.

Gray *et al.* (1992) hold the goal as by balancing the total picks in zones to minimize picking time associated with labor cost. The conclusion can be drawn as by assigning SKUs based on their demand priorities requires less time for picking than by using different storage type in each zone. Kong (2007) and Kong and Masel (2008) present a heuristics method for storage assignment, whose objective is to evenly balance the expected picks among picking zones based on the demand of SKUs, which can be divided into several levels as expected. This goal is complied with the lean principles to eliminate any idle time in the process.

Also, English *et al*. (2007) propose a storage policy as level loading, which can be considered as one of the optimum assignments for PTL system. In this method, the product demand is leveled through each zone and placed accordingly to the ease of access for the pickers.

For instance, the highly demanded SKUs will be allocated in the most optimum locations for the pickers to reach. Two principles will be used to define level loading assignment. The first one is ABC analysis, which is a method to organize inventory to divide them into A, B, and C level. A level item takes a large proportion of overall value but only a small percentage of total items. The second one is called Pareto Principle, which is also known as 80-20 rule; it states that roughly 80% of the effects come from 20% of the causes. This principle can be applied to the warehouse environment that 80% of the order can be fulfilled by 20% of all the available SKUs, which can be considered as the most popular SKUs. However, in the modern warehouse, most of the facilities discover that their orders exceed the 80-20 rule percentage, which is to say that almost 90% of the orders can be fulfilled by 10% of the SKUs (Specter, 2010). By applying a more advanced picking strategy in the forward area, where the most popular SKUs can be stored, the strategy can help increasing the order handling speed and reducing the overall pickers' travel time.

1.2. Motivation

The major issue for further improving the PTL system performance is how to benefit from different combinations of applying technologies and new SKU storage policy. On one hand, the advantages for adapting PTL system has already been proved by increasing the efficiency to about 50% and 99% of accuracy (Lin, 2010). On the other hand, Roodbergen and Vis (2006) state that namely routing, batching, and storage assignment will impact the order picking efficiency. In this thesis research, two advantages can be drawn from using PTL+Z system and level loading assignment. First, the advantage of adapting a ZBP conveyor system is to help orders to bypass the unnecessary zones, where no SKUs need to be picked. By delivering orders directly to the must-pick zones to finish picking will improve the system throughput significantly. Second, the advantage of adapting level loading assignment is especially by balancing the demand of SKUs in each zone in order to avoid any imbalance between busy zones and idle zones.

1.3. Research Objective and Methodology

The objective of this thesis research is to compare the system throughput in PTL and PTL+Z systems with two different assignments, random assignment and level loading assignment. The purpose of the comparison is to test which combination of system and storage policy will have a better performance and which investment option will have a shorter simply payback period as PTL system to PTL+Z system and random assignment to level loading assignment. The idea for a 2 by 2 comparison design is given in Table 1.1 in order to measure the four system throughputs.

Table 1.1. Measurements for Different Combinations of Assignments and Systems

	Systems	
	PTL	PTL+Z
Random Assignment	System Throughput	
Level Loading Assignment		

In order to model the system throughput, the average system throughput needs to be addressed first. However, some of the time related factors, including setup time, total picking time and travel time will be affected by the associated storage policy, more detailed study will be further discussed in Chapter 3.

This thesis research will be contributing to both academic research and industry application. The mathematical models in Chapter 3 are aimed at studying the proposed system and also provide future potentials to be expanded for future work by relaxing more assumptions and constant variables like setup time and number of SKUs in each order. In addition, knowledge that has been obtained from this study can be applied to practical use to help decision makers to further optimize current system within budget.

1.4. Thesis Outline

This thesis is organized as follows. Chapter 1 presents the background of this research and motivations to conduct this thesis. Chapter 2 reflects the literature review and other related work done by the previous research. Moreover, the significance of this thesis research will be explained in this chapter. Chapter 3 introduces the situation for the environment setting, and the mathematical models are presented. In chapter 4, numerical studies and validated simulation models are presented to prove the reliability of the mathematical models. Economic analysis is followed to show the simple payback period of all the available conversions. Also, sensitive analysis is carried out to study the relation between gross profit per order and payback period. The final chapter, chapter 5 is the conclusions derived from the study. In addition, future research about the potential area has been enhanced in this chapter.

CHAPTER 2. LITERATURE REVIEW

In this chapter, previous studies on the warehouse operation, OPSs, storage policies and modern technologies will be concluded. These topics will be discussed in length as following, from the generally idea of warehouse management, classifications of OPSs, storage policies, and advanced technologies. Finally, a discussion will be stated for the unique idea of this thesis research based on the known area.

2.1. Warehouse Management

Nowadays, companies are trying to reduce the total inventory level to shorten product life cycles, which creates more research opportunities in the warehouse environment. Warehouse management is dealing with material handling activities, like receiving, picking and shipping. Warehouse management system is a part of applications of supply chain management principles to fulfill the requirement of each warehouse to satisfy customers within the acceptable shortest response time (Van den Berg, 1999 and Gu *et al.* 2007). Three types of warehouses can be divided into distribution warehouses, production warehouses, and contract warehouse.

In the literature, the emphasis of warehouse management can be tracked down with multiple variables, which should be considered and defined coherently. Rouwenhorst *et al.* (2000) classify the warehouse design decision making into strategic level, tactical level, and operational level. At strategic level, the forward and reserve areas are planned for long term impact. At operational level, most of the decisions are regarding to batching and storage policies. Since there are so many criteria that should be met from different perspectives, it is hard to carry out a warehouse layout.

Therefore, based on the principle of warehouse design, several studies address on the design models of warehouse aiming at different goals. Roodbergen and Vis (2006) present a model for warehouse layout design to minimize the average travel distance for the pickers. Hwang and Cho (2006) develop a mathematical model to minimize the operating cost by minimizing the number of pickers. Furthermore, Hsieh and Tsai (2006) invent an analytical method to find the optimum combination for the warehouse design by considering the cross aisle quantity, storage level, and order picking policies together.

In addition, the storage area is usually divided into two area as reserve area and forward area (Kong, 2007 and Van den Berg and Zijm, 1999), which has already been briefly introduced in Chapter 1. In the forward area is used for storing a limited amount of fast-moving SKUs, which won't occupy too much space for a long time and for performing value added services or order collation (Heragu *et al.* 2004). Research in this forward area can be called as a forward reserved problem (FRP).

FRP is a non-trivial problem for assigning a SKU to the forward area, which will reduce the labor cost and address relevant replenishment issues (Van den Berg *et al.* 1998 and Gu, 2005). FRP is a typical tactical level problem based on the principles that describe in Rouwenhorst (2000). The studies in the FRP are mainly focused on what type of SKUs can be classified as the high priority items, and how many of them should be placed in the forward area. Hackman *et al.* (1990) propose a heuristic method aiming at minimizing the total cost for picking and replenishing by considering both assignment and location in the forward area. The result proves that the cost for picking and replenishing in the forward area depends on the size of the forward area. Also, the authors present an analytical method for deciding the quantities and proving it is useful to rank the priority of the SKUs. Van den Berg *et al.* (1998) develop a minimum linear programming function in order to minimize the cost of picking and replenishing to find the most optimal solution for the storage allocation in the forward area. Heragu *et al.*

(2004) carry out a model to minimize the total cost of material handling by assigning SKUs to their respective area. Frazelle *et al.* (1994) use the heuristic method to design a framework of making decision of the size of forward area and also the allocation of SKUs. In addition, Kong and Dasel (2008) propose a heuristic method for SKUs assignment, which is using the average number of picks per zone and space assignment. Martinez (2008) presents an assignment model for the fast picking area in the warehouse as well.

Frazelle (2002) summarizes several references on measuring warehouse performance. The measurements can be divided into financial performance, productivity performance, quality performance and cycle time performance. Especially in the order picking system, the key performance indicators are the picking cost per order line, order lines picked per man-hour, percentage utilization of picking labor and equipment, percentage of perfect picking lines, and order picking cycle time (per order). Also, Frazelle discovers a way to combine these indicators into a single performance indicator.

After the layout and function designs of a warehouse, researches are going into more detailed classification. Van den Berg and Zijm (1999) divide the warehouse into three categories as manual warehousing, automated warehousing and automatic warehousing. In the warehousing activities, order picking is a process that withdraws items in the warehouse to fulfill customers' needs. It can be considered as the most important part and the most cost-consuming labor intensive activity in the warehouse operations.

2.1.1. Order picking system classification

As the order picking is indentified as the most labor intensive and costly activity, review the available studies for the OPSs available in the past, Yoon and Sharp (1996) introduce the complexity of OPSs and list eight major departments for a OPS, which are receiving area, pallet reserve area, case pick area, item pick area, sorting area, utilizing area, shipping area and auxiliary areas. A structured procedure for the OPSs' system analysis and design is presented by considering relations between the different functional departments.

Dallari *et al.* (2009) lead the approach to divide a fairly new OPS classification based on the previous research of Yoon and Sharp (1996), Dallari *et al.* (2006) and De Koster *et al.* (2006), this classification includes five categories, which are "Picker-to-Parts" system, "Parts-to-Picker" system, "Pick-and-Sort" system, "Pick-to-Box" system, and automated picking through the case studies of several actual warehouses on the order volume, number of order lines, and the number of items. Figure 2.1 illustrates the proposed classifications of OPSs.

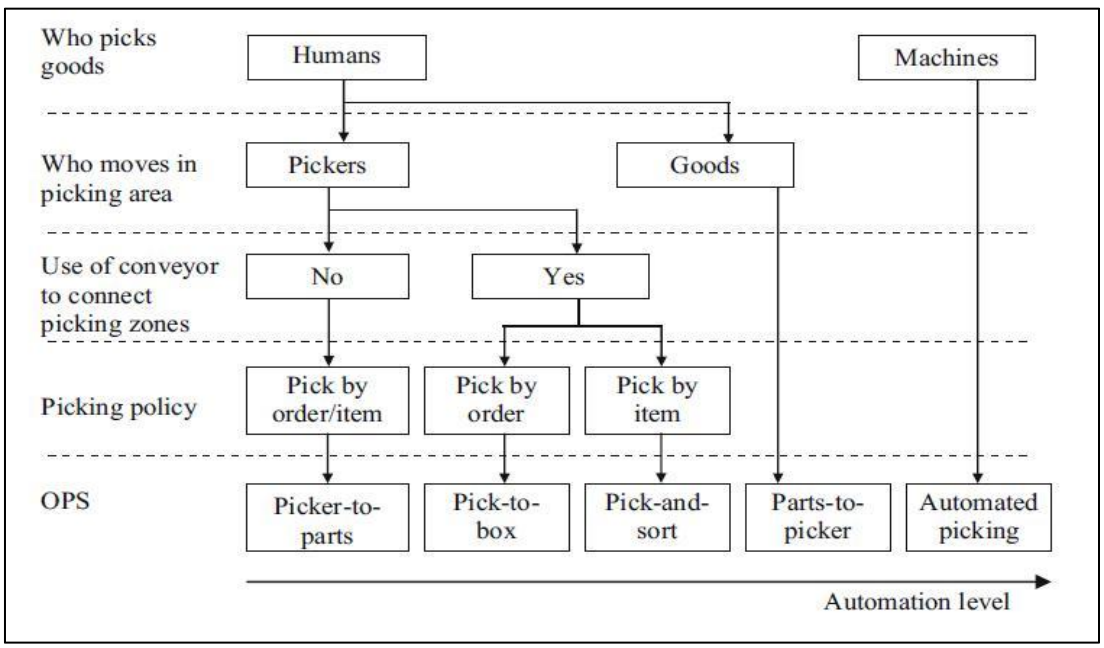

Figure 2.1. Classification of OPSs, adapted from Dallari *et al.* (2009)

2.1.2. Order picking system selections and design

Since a significant number of design and cost parameters should be considered to design the most proper OPS, Dallari *et al.* (2006) and Dallari *et al.* (2009) develop a way to help decision makers for choosing the most suitable OPS by carrying out the in-depth survey of distribution centers in Italy. The results show that the number of order lines picked per day, the number of items and the average order size, are the key parameters in the OPS selection.

In addition, Gillespie (2010) summarizes the critical factors for companies to operate a warehouse or a distribution center, which can be listed as followed.

1). Minimize picker travel time and distances

2). Minimize product touches

3). Use of "golden zoning" principles

4). Incorporate dynamic work zones or flexible picking zones

5). Utilize slotting principles and techniques

6). Use of task interleaving

7). Use of picking technology aids

In addition, by taking the demand levels, labor rates, order sizes, and other related factors into consideration, Russell and Meller (2003) develop a descriptive model to help the decision makers to decide whether choosing automated OPSs or remaining manual picking to minimize the total cost and to meet the demand constraints. Also, an analytical model is developed in order to determine the optimal batching level for manual system in a set of constraints in picking and packing.

In the study of OPSs' design, Brynzer and Johansson (1995) propose the factors that influence the OPSs' design. They are location of the OPS, batching policy, and zone picking. The conclusion can be drawn that the picking efficiency and accuracy can be further improved by improving SKUs' priorities and storage policies. Furthermore, Brynzer and Johansson (1996) present a description of restructuring components and information for pickers, which leads to a more efficient material handling process.

Peterson (2002) studies that the capacity of picking area, the storage allocation policies, and the order sizes have essential effects on the performance with in the picking area. Hsieh and Tsai (2006) summarize the factors that could impact the performance of order picking system, which include the order batching, picking strategy, storage allocation, and picking area zoning.

By setting the minimum cost as the goal, which is constrained by the throughput and storage space, Hwang and Cho (2006) present a mathematical model to measure the system's performance. The picker's total time can be calculated, which includes traveling, picking and pausing time in front of each picking zone. The conclusion can be also drawn as the number of aisles can be optimized in an aisle picking area.

2.1.3. Pick-and-Pass OPS

In the determination of picking strategy, previous researches are mainly focused on discrete picking, batch picking and zone picking. Discrete picking can be referred as single order picking, which indicates that each picker is responsible for only one order upon a time. Then, batch picking indicates that each picker is responsible for one SKU in a batch. Batching is a popular strategy for reducing the mean travel time per order, which is often used in conjunction with zone picking and automated material handling equipment. However, orders must be accumulated in the system until there are enough similar picks to create the batches. Le-Duc and De Koster (2007) evaluate the travel time assumption in a 2-block warehouse setting and also the order batching effects.

Zone picking indicates that each picker will be assigned to zones to fulfill all the orders. It is to remove items form zone to zone and push the order bin to the next zone when the previous zone is done. The picking strategy is verified as the most effective in large operations with high total numbers of SKUS, high total number of orders, and low to moderate picks per order. The labor assignment in each zone is accommodated enough for the picks (Piasecki, 2003). Le-Duc and De Koster (2005a) present a method to determine the proper number of zones in the zoning system in order to minimize the total order processing time.

In the study of mail order companies, Petersen (2000) evaluates the different picking policies of strict order, batch picking, sequential zone, batch zone, and wave picking in the labor requirements, processing time, and customer service. The conclusion shows that wave picking and batch picking won't be influenced by the daily order demand. However, the zone picking, batch and sequential will be affected by the increasing order sizes significantly. For sequential zones, the zone imbalances and order sequencing will cause the delay of picking. Workload-imbalance is more prominent when the order sizes increase.

Parikh and Meller (2008) present a mathematical model for choosing from batch picking and zone picking in the OPS. Several parameters are considered, such as the effects of pick-rate, blocking problem, workload balance problem, and the sorting system requirement. The conclusion is that zone picking requires pickers only pick those SKUs within their assigned picking zone. A reduction of travel time will lead to a will lead to the order throughput time and warehousing costs as well. The size of the picking zones depends on the total number of SKUs in the warehouse, the amount of time available for order processing, and the number of pickers available to process the order.

The Pick-and-Pass system (PAP) can be referred as an application of zone picking. In this system, conveyor systems are used to move orders from zone to zone, and it is very important to balance the number of picks from zone to zone to maintain a consistent flow. According to the principle of zoning, two approaches of zoning have been discussed (De Koster *et al.* 2006). The first approach is about the order's progressive assembly, where the PAP divides the picking area into zones with one or more pickers assigned to each picking zone. In particular, the picking zone can be divided into equal size and unequal sizes. Petersen (2002) draws the conclusion that with the equal sized picking area, larger picking zones will reduce picking productivity and increase the travel time correspondingly. Otherwise, small picking zones will increase the picking productivity and the setup time for each particular zone, but decrease the intensive of labor at the same time.

There are only limited references focused on the PAP problem. An approximation method based on G/G/m queuing method to evaluate the performance of PAP system has been presented by Yu and De Koster (2008). The effects of storage policies, station sizes with numbers of pickers, batching orders and slitting orders to the system performance are tested. Furthermore, Yu and De Koster (2009) propose an approximation model based on queuing network to identify the impact of order batching and picking area zoning in a PAP order picking system. By taking more different parameters into consideration, such as the setup time per zone and order arrival rate, the results show that the mean order throughput time is quite robust for a varying number of zones around the optimum number of zones. In addition, the arrival rate only has slight impact on the mean order throughput time. Yu and De Koster (2009) confirm the relations between the number of zones and optimization. With the increasing order size, the operational cost will reduce, whereas the average throughput time intends to grow, which indicates that PAP system might be suitable for the order size increasing and will be more advantage to have more picking zones.

By taking the SKUs' priorities into consideration, Melacini *et al.* (2010) use two levels of SKUs and whose demands are evenly distributed over the products, also the authors propose a frame work for PAP order picking system aiming at minimizing the whole picking cost with the considerations of the required service level. Pan and Wu (2009) develop an analytical model to describe the operation as a Markov Chain for the estimation of the expected travel distance of the picker in a picking line and three different ways are considered as single picker, multiple pickers with equal size zones and with unequal size zones. In addition, they propose three algorithms for optimally allocating item to storages for the cases of a single picking zone, a picking line with unequal-sized zones, and a picking line with equal-sized zones in a PAP system to show that both equal size zones and unequal sized might have the shorter travel time than the model that has been presented in Jewkes *et al.* (2004), where the storage location in a rectangular or linear storage racks are considered. The algorithms have been presented to minimize the order finishing cycle time and to decide the optimal product allocation and server location.

2.2. Storage Policy

De Koster *et al.* (2006) discuss five frequently used storage assignment, which are random assignment, closest open location assignment, dedicated storage, full turnover storage, and class-based storage. There are three common storage location assignments as dedicated storage, randomized storage and class-based storage. In the randomized storage, SKUs are assigned to all eligible empty locations with equal probability (Petersen, 1997).

The closest open location assignment is referring as the SKUs will be assigned to the first storage location that the picker firstly encountered. However, Hausman *et al.* (1976) state that this assignment performance is similar to the random assignment if only full pallets moving considered. The dedicated storage is referring as the SKUs are having the fixed location to be stored. However, this assignment is usually applied to small-sized area. The full turnover storage is referring as the storage allocation is based on the SKUs’ turnover rate. For instance, the higher rate of turnover, the easier assessable location the SKUs will be assigned to. The early application of this method was Cube-per-Order (COI) rule that has been proposed in Heskett (1963, 1964). It is referred to the ratios of the SKU's total required space to the number of picks per unit time.

Le-Duc and De Koster (2005b) are focused on the class-based storage assignment in inventory control management. Pareto's method is generally used to level the SKUs into classes based on the priorities of fulfilling orders. The classifications of SKUs are often broken down into maximum three levels. A level can be referred as the fastest moving SKUs, which take the first place of priorities, and followed as B and C level. In addition, by taking the return routing into consideration, Le-Duc and De Koster (2005c) demonstrate that the across-aisle storage method is better optimized than the class-based storage assignment. Petersen *et al.* (2005) introduce the new storage assignment policy that is involved with the golden zone, which slot high demand SKUs at the height between the pickers' waist and shoulders. The result shows the saves of order finishing time.

Roodbergen and Vis (2006) discuss that in order to improve the efficiency of warehouse operations, three groups of policies have the potentials to improve, namely routing, batching, and storage policy. A not well-optimized storage policy might results in having lower the picking speed and longer the travel distance, which will cause more congestion during picking process. Bartholdi and Eisenstein (1996) discuss about the importance to balance the workload in the picking system.

In order to evaluate the performance of how the storage assignment is going to influence the OPSs, diversity of models have been studied in this area. Maleki (2009) discusses the ways to improve order picking throughput by integrating the "level loading" method for optimizing inventory position by using popularity ranking matched up with the location ranking, which is listed in the order of accessibility and proximity to the stating location (English *et al.* 2007, Barrett *et al.* 2007, and Rooks *et al.* 2005).

In the further study of work balance in the picking system, Jane (2000) proposes several heuristic methods in order to balance the workloads among the order picker and to adjust the zone size in order to achieve a better system performance. Based on the lean principles of avoiding idle time, Kong (2007) proposes a method of designing a lean OPS and further economic analysis is provided in Lin (2010). In addition, Jane and Laih (2005) provide a heuristic algorithm to balance the workload among all pickers in order to improve the utilization of OPSs and to reduce the time consuming. Overall, the storage allocation is one of the crucial parameters that should be paid more attention to.

2.3. Modern Picking Technology

In a traditional warehouse using the paper-based system to follow an order, locating the items will increase the traveling time and labor cost. Also, there are some follow-up steps need to be done after the final picking of each order. In these steps, there might be possibilities for errors, which will result in investing more in the quality control system. Nam *et al.* (2004) study how to reduce the error rate in OPSs. Therefore, if a new technology can be brought in to reduce the error chances, the whole system efficiency can be increased significantly.

In order to improve the picking efficiency and accuracy, there are several automation technologies that can be used in material handling, however, three of them are highly occupied, which are Automated Storage and Retrieval System (AS/RS), Carousel system and PTL system.

2.3.1. Automated storage and retrieval system (AS/RS)

AS/RS is a storing technology for the fast moving items. Most of the studies are focused on the storage policies. This advanced storing system can provide close depot, retrieve and lower storage space requirements of random storage policy in the warehouse (Van den Berg and Gademann, 2000). Available studies on the class-based storage policy (Hausman *et al.* 1976, Yang, 1988, Rosenblatt and Eynan, 1989, Goetschalckx *et al.* 1990, Eynan and Rosenblatt, 1994, Kouvelis and Papanicolaou, 1994, and Malmborg, 1996). In addition, Ashayeri *et al.* (1996) study the maximum capacity of system throughout of AS/RS system under different storage policies. Simulation is also used to test the impact of storage policies (Guenov and Raeside, 1992, Lee, 1992, and Muralidharan *et al.* 1995).

2.3.2. Carousel system

Nowadays, carousel systems are one of the popular order picking systems because of the easier access, minimal picker required and increased throughput capabilities. Carousel systems allow pickers to remain in one location while product to be picked travels around a track. Throughput is increased by minimizing pickers' travel distance compared to traditional warehouse.

Carousel systems are available in a wide variety of heights, widths and depths, one example can be seen in Figure 2.2. It allows for simultaneous picking by one picker on multiple carousels. Carousels utilize similar PTL technology to automate their process and further reduce picking time. When the orders are scanned into the system, the carousel automatically begins rotating to bring the SKU to the picker. A vertical light bar tells the picker the SKUs' location and quantity to be picked. When the picker completes the pick, they push the complete button and the carousel automatically begins to move the next product to be picked forward. As one item is being picked from carousel A for example, another carousel, carousel B, is bringing the next SKU to be picked next. The picker will then pick from carousel B while carousel A is bringing the next SKU to be picked next. Following that pick, the picker will move back to carousel A. This process is repeated until all items have been picked.

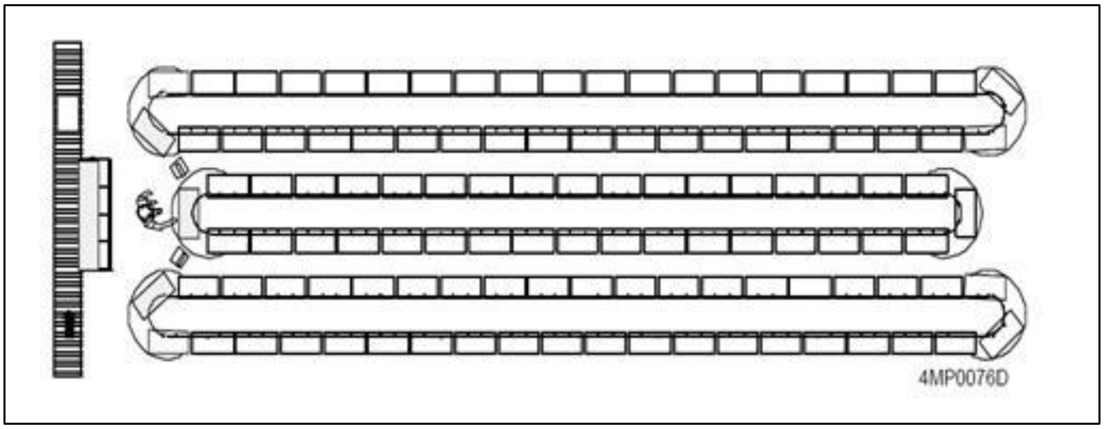

Figure 2.2. Top View of Horizontal Carousel System, adapted from English *et al.* (2007)

Carousels provide an alternative by bringing the items to the pickers instead of the pickers going to the items. When two or three carousels are operated by one picker, each carousel may be driven independently to position containers so that each picker will never wait for an item. The density of storage can be greatly improved because the carousel units can be placed closer together eliminating the wide aisles typically needed for forklifts or carts. Using carousels, picker can pick at a rate of 150-600 picks per hour. Picker efficiency and accuracy can be assured through the use of light bars to indicate the appropriate container.

In addition, carousel system is commonly used with other picking technologies, such as PTL system and A-frame, which can maximize each system's advantages.

2.3.3. Pick-To-Light system

Technically, the PTL system can be considered as a real practice for a PAP system and using the zone picking theory. The basic idea of PTL system is to use lights to indicate the location of the needed items. After scanning the barcode associated to an order, the lights that in charge of each SKU will be illuminated. When the picker collects the required amount of items, the lights will be flashed to notice the picker to confirm finish picking. By using this light-directed picking method, the pickers won't travel around to find the items and no need to read the paper list, which dramatically increases the picking effort. Specter (2010) draws the conclusion that the PTL system is best for fast-moving goods, and split case items.

Nowadays, the trend of small sized order is increasing, which calls for the most desired picking method for fast-moving items. Trunk (2002) explains the increasing usage of PTL system than any other picking technologies. By using PTL system, it will cut about half the time to finish the orders. Meanwhile, it could also reduce errors by 70 to 90 percentages comparing to the paper-based picking lists. Sharp *et al.* (1996) develop a method for choosing the order picking equipments. A comparison between PTL system and other system is carried out in both quantitative and qualitative in some case studies.

2.4. Conveyor System

Conveyor systems are used to route totes from one picking location to the next instead of routing totes to all the pick area (Levans, 2009). Conveyor systems are the essential parts in transporting and connecting between each picking zone in the PTL system. Nowadays, the speed of conveyor can go up to 700 feet per minute in high throughput facilities. Also, the conveyors system can be adjusted base on the identical requirements for ergonomic loading or picking. It is important to have a well-designed conveyor system, which has an operational life expectancy for 15 to 20 years in average. Also, it has lots of options to get modernized and extended system's life. Several advanced improvement of conveyors have been studied in (Trebilcock, 2010).

However, there are only a few literatures about the conveyor systems. The Bypass conveyor is first brought up by Soemon Takakuwa. Takakuwa (1990) provides a performance evaluation of conveyor systems in various picking conditions. It uses the chance-constrained goal programming to make the multiple objective decisions about the optimal job-assignment and different conveyor systems. Four particular types of conveyor systems are presented as single container/continuous system, multiple containers/continuous system, single container/discontinuous conveyor system and bypassed conveyor system.

The major idea for ZBP conveyor is to assign several pickers to the equal-numbered successive sections respectively and the picker should walk within these areas to accomplish their responsibilities. The logic feature behind ZBP conveyor is to control the accumulation and the movement from zone to zone and to allow units to bypass certain work areas if no picking is required. The proposal enhances the flexibility at the same time increases the productivity. In addition, ZBP conveyor has the capabilities to be incorporated into systems that contain other automated processes such as carousel and A-Frame systems (English *et al.* 2007).

The summary of the literature review can be shown in Table 2.1.

Table 2.1. Summary of Literature Review

Topics	Literature
Warehouse management	Van den Berg, 1999 Gu *et al.* 2007
Warehouse layout design	Roodbergen and Vis, 2006 Hwang and Cho, 2006 Hsieh and Tsai, 2006
Warehouse decision	Rouwenhorst *et al.* 2000
Forward reserved problem(FRP)	Hackman *et al.* 1990 Frazelle *et al.* 1994 Van den Berg *et al.* 1998 Van den Berg *et al.* 1998 Gu, 2005 Kong and Dasel, 2008 Martinez, 2008
Order picking system(OPS)	De Koster *et al.* 2006
Pick-and-Pass system(PAP)	Yu and De Koster, 2008 Pan and Wu, 2009 Melacini *et al.* 2010
Storage policy	Van den Berg and Zijm, 1999 Kong, 2007

2.5. Discussion

Upon the literature review of important relevance associated with warehouse management, order picking systems (OPSs) studies, and the advanced technologies that are available nowadays, storage policies certainly obtain a significant position to influence the system performance in the OPSs. By updating the equipments to the more advanced ones will provide a better system performance as well.

The unique points of this thesis research are listed below. First, among the classification of OPSs, few literatures are addressing on the Pick-and-Pass (PAP) system, where the pick-To-light (PTL) system is an application. No models have been found in analyzing the system performance in PTL system. Even though the ZBP conveyor has been proposed before in the literature, no detail quantitative studies were carried out to evaluate the system throughput for the PTL with the bypass conveyor (PTL+Z) system. Furthermore, no benchmarks have been done in the PTL and PTL+Z systems. Then, since the storage polices are playing an important role in the system performance, however, no studies have been done in the storage policies as well as comparing the correlated influence in both PTL and PTL+Z systems. At last, this thesis research doesn't only evaluate the system throughput in the proposed systems, but also further economic and sensitivity analysis are studied to test the trend of simple payback period and the relations between certain parameters and the system throughput.

CHAPTER 3. METHODOLOGY

In this chapter, the details of the proposed order picking systems in the forward area will be presented. The assumptions and explanations according to the proposals will be described. The mathematical models for system throughput, which can be defined as the quantities of order that can be processed within specific time will be carried out in four systems, as PTL/R, PTL/L, PTL+Z/R, and PTL+Z/L respectively.

3.1. Systems Description

The environment setting of this thesis is for a mail-order and internet marketing distributor, such as vitamins and books, which are majorly focused on the small sized fast-moving SKUs. The PTL system is applied to help pickers to work more efficiently and accurately. In the following section, PTL and PTL+Z systems will be introduced separately as well as two storage policies, random assignment and level loading assignment.

3.1.1. PTL system vs. PTL+Z system

Since a brief introduction of PTL and PTL+Z systems has been mentioned in Chapter 1, more detailed information will be discussed later. In PTL and PTL+Z systems, the order picking process is initiated by the customer orders entered into a computer system to get filtered. Typically, the order sizes drive the sequence of the orders onto the order picking assembly line since batching the orders by box size reduces the set-up times on the box erector. The order picking process begins at the box erector. Boxes are erected onto the rolling conveyor by the box erector and sent to the purchase order inserter. The purchase order is inserted into the bottom of the box and then travels to the barcode labeler. The barcode is printed on a sticker and placed onto the outside of the box automatically by the labeler. This barcode is for internal use as it contains the order information and is separated from the shipping label.

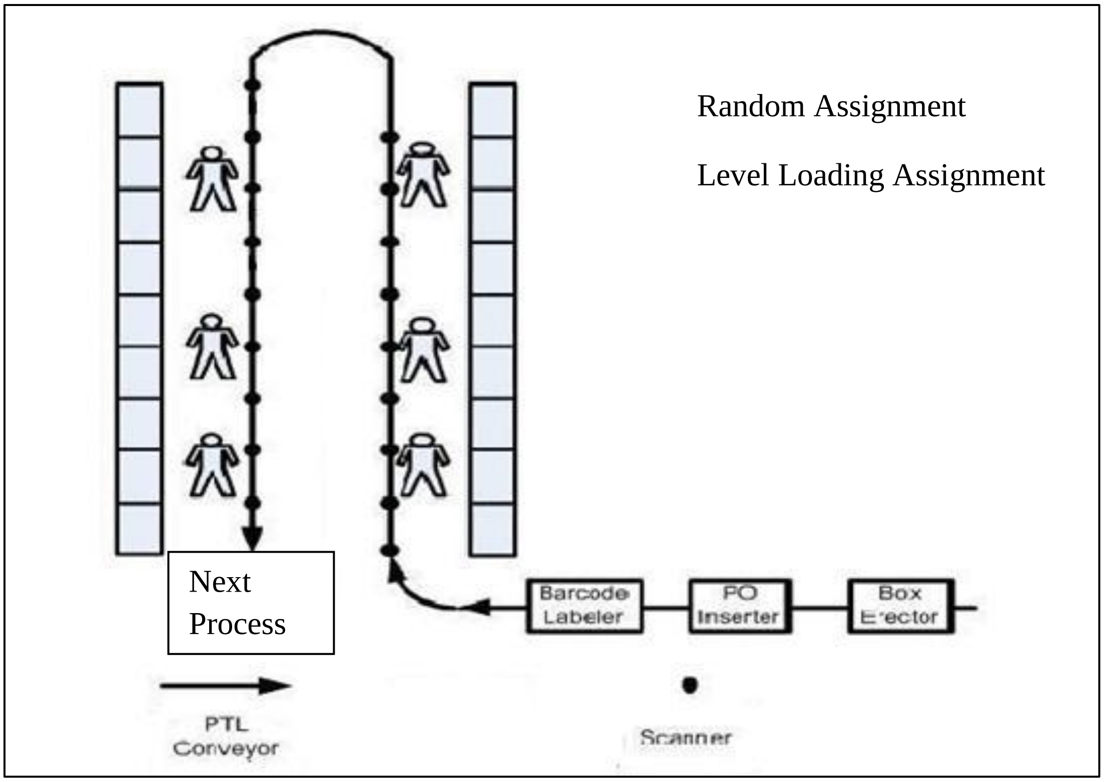

Figure 3.1. Layout of the PTL System

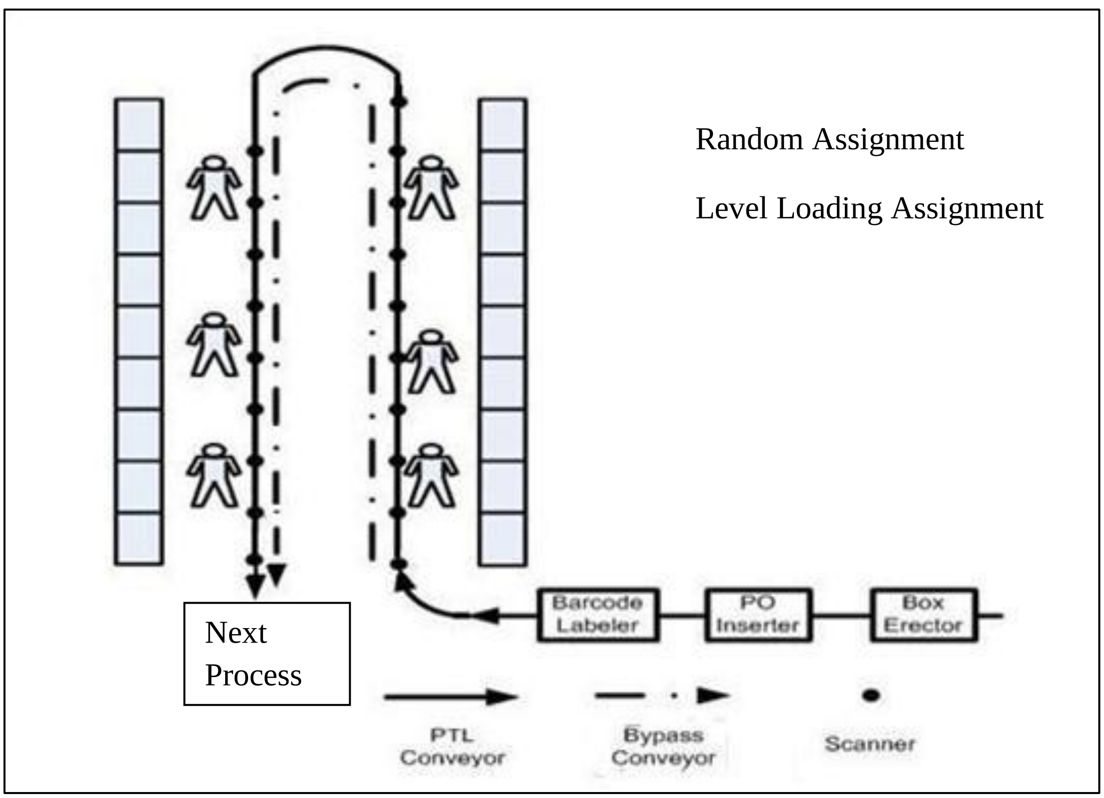

Figure 3.2. Layout of the Proposed PTL+Z System

Figure 3.1 and Figure 3.2 present the basic idea of PTL and PTL+Z systems respectively, where the differences can be easily indentified. Figure 3.1 shows the layout of a standard PTL system, which includes several major components as the box erector, PO inserter, barcode labeler, scanner, rack shelves, and PTL rolling conveyor. As long as the box being transferring onto the conveyor from the box erector, a copy of purchase order will be put into the box automatically. After each order being labeled, the order will be scanned by the first scanner in zone 1 to start picking. After finishing picking in a zone, the order will be pushed manually to the next zone to be continually fulfilled. The order will travel along the conveyor in this system to retrieve the required SKUs.

Figure 3.2 shows the layout of the proposed PTL+Z system, which has an extra automatic bypass conveyor and scanner. After each order being labeled, the order will be scanned at the very first scanner. This scanner will instruct the conveyor where to transport this order, either onto the PTL conveyor to start picking in the first zone or onto the bypass conveyor to travel to other zones directly. When the picking completed in the zone, the conveyor will automatically decide where to push the order to continue picking.

In the picking process of each zone, the system will indicate the pick and quantity in that zone by turning on the corresponding light on the rack. Once the picker picks the SKU, the picker hits the red button and continues this process to other SKUSs until the picks are completed in this zone. After all of the picks are completed in the zone for this order, the picker hits the green button, push this order to next zone and will scan a new box.

3.1.2. Random assignment vs. level loading assignment

Random assignment is applied as every SKU in the system that is sharing the same probability of allocating into each picking zone. No priorities will be taking into consideration.

Level loading is applied as balancing the workload among the picking zones. In this method, the product demand is leveled through each zone and placed accordingly to the ease of access for the pickers. The ABC analysis will be applied for leveling the fast-moving SKU, three levels of fast-moving SKUs will be decomposed. By assigning different frequencies to all the levels and different number of SKUs in each zone, the probability of a SKU stored in zone j can be expressed. The frequencies of each level in an order will be considered as well. In addition, the allocation of SKUs to different shelves within a zone is considered to impact the pickup time. For instance, if the SKUs are at the optimal height for the picker, it takes less time for picking.

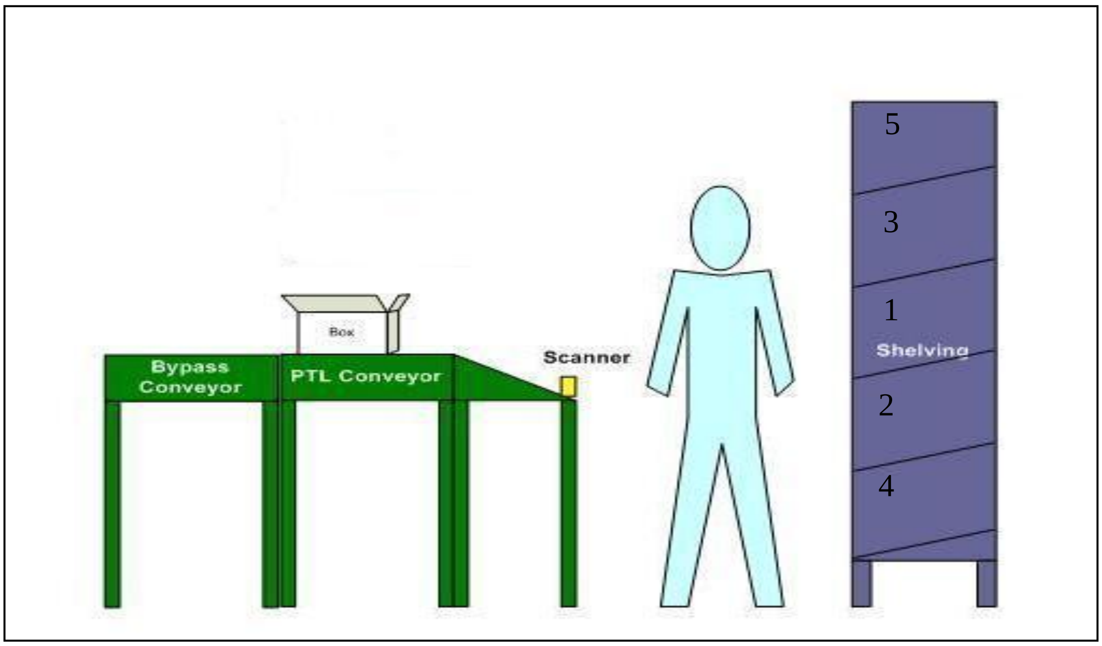

Figure 3.3. Side View of a Zone in the PTL System

As shown in Figure 3.3, the side view of a zone in the PTL system, five levels have been divided in a shelf; shelf 1 is the most optimal location for picking, which will take the shortest time per one SKU picking. For shelf 2 and 3 will be allocated the second highly-demand SKUs to have a longer time to retrieve a SKU. As for shelf 4 and 5 will be assigned to the least highly-demand SKUs, which generates the longest time among the pickings.

3.2. Assumptions

Before developing these models, several assumptions should be made in order to better model the systems:

1) Setup (waiting and scanning) and picking time inside zones are constant in PTL and PTL+Z systems. However, PTL+Z system has a shorter waiting time.

2) The orders' next position can be notified after scanning.

3) Every zone will be reloaded when the inventory level reaches certain standard so that no replenishment will be considered in this thesis.

4) The identical box size is sufficiently large enough to handle all required SKUs in one order.

5) The time for traveling between PTL conveyor and bypass conveyor is negligible.

6) The order will travel along the whole system to continue picking, the total travel distance for both systems will be $j \times l$.

7) Each zone has the same length l , and the same number of SKUs S. In addition, every bin holds one SKU respectively.

8) The average speed on PTL conveyor in PTL system will be slower than the PTL conveyor in PTL+Z system.

9) Each zone is assigned one picker with identical picking and traveling speed.

3.3. System Throughput Model

The system throughput models have been characterized in figure 3.1 and 3.2, in order to present the measurement of a system, the average throughput time per order needs to be addressed first. According to Melacini *et al.* (2010), the definition of average throughput time will have three components as the average processing time, travel time, and the total setup time per order. Then, based on the average processing time per zone, the system throughput can be carried out correspondingly. Table 3.1 summarizes all of the parameters that will be used in the models later.

Table 3.1. Summary of Model Parameters

	Parameters	Description
Basic Inputs	f_l	Order frequencies of lth level of fast-moving SKUs
	j	Total number of zones
	L	Length of a zone
	n	Number of SKUs per order
	P_l	Probability of lth level of fast-moving SKUs in level loading per order, $l = 1,2,3$ *Note: the number l stands for level A, B, and C respectively*
	S	Total number of SKUs per zone
	S_{il}	Number of SKUs in lth level of fast-moving SKUs in zone i
	T_f	Travel time from box erector to the first scanner *(constant)*
	$T_p(T_p{}', T_p{}'')$	Picking time per SKU (random, level loading)
	T_{pl}	Picking time per lth level in level loading
	$T_s(T_s{}', T_s{}'')$	Setup (waiting and scanning) time per order (PTL, PTL+Z)
	T_{shift}	Working hour per day
	$V_{PTL}\ (V_{PTL}{}', V_{PTL}{}'')$	Average travel speed on the PTL conveyor (PTL, PTL+Z)
	V_{ZBP}	ZBP conveyor speed, $V_{PTL}{}' < V_{PTL}{}'' < V_{ZBP}$
Basic Formulas	$PS_i\ (PS_i{}', PS_i{}'')$	Probability of a SKU in zone i (random, level loading), $i = 1,2, \dots j$
	$PO_i\ (PO_i{}', PO_i{}'')$	Probability of an order entering zone i per order (random, level loading), $i = 1,2, \dots j$
	PS_{il}	Probability of a SKU belongs to lth level of fast-moving SKUs in zone i
	$ENZ_i\ (ENZ_i{}', ENZ_i{}'')$	Expected number of zones will be visited per order (random, level loading)
	Tj_{sc}	Total setup time per order, $c = 1,2,3,4$ *Note: the number c stands for PTL/R, PTL/L, PTL+Z/R, and PTL+Z/L respectively*
	$T_{PTL}\ (T_{PTL}{}', T_{PTLR}{}'')$	Average travel time on the PTL conveyor (PTL, PTL+Z)
	T_{ZBP}	Average travel time on the bypass conveyor per order
	$TP(TP', TP'')$	Total expected picking time per order, (random, level loading)
Main outputs	AST_c	Average system throughput time per order, $c = 1,2,3,4$
	APT_c	Average processing time per zone, $c = 1,2,3,4$
	ST_c	System throughput per day, $c = 1,2,3,4$

3.3.1. PTL system with random assignment

In the PTL system, all the orders will travel along the PTL conveyor without skipping zones, it will be unnecessary to have the expected number of visiting zones. Besides, with random assignment attached, no SKU allocations will be considered either. As a result, the average system throughput time can be carried out directly based on the model parameters.

In calculating the average system throughput time in the PTL system, four different task times, including average time from box erector to the first scanner (T_f), average travel time along the PTL conveyor (T_{PTL}), total average setup time before picking (Tj_s), and total expected picking time through the system (TP). As a result, average system throughput time can be expressed as:

$$AST_1 = T_f + T_{PTL}' + Tj_{s1} + TP' \quad (3.3\text{-}1.1)$$

Where,

$$T_f = Constant\ Value \quad (3.3\text{-}1.2)$$

$$T_{PTL}' = \frac{j \times L}{V_{PTL}'} \quad (3.3\text{-}1.3)$$

$$Tj_{s1} = T_s' \times j \quad (3.3\text{-}1.4)$$

$$TP' = T_p' \times n \quad (3.3\text{-}1.5)$$

Therefore, equation 3.3-1.1 can be rewritten as:

$$AST_1 = T_f + \frac{j \times L}{V_{PTL}'} + T_s' \times j + T_p' \times n \quad (3.3\text{-}1.6)$$

Average system throughput time can be explained as the cycle time for processing one order. However, in order to have a clear idea of deciding which system has the best performance; the cycle time needs to be converted into system throughput in an hourly standard. Since the system is processing orders simultaneously, the average processing time per zone (APT) should be addressed to approach system throughput, which can be expressed as:

$$APT_1 = \frac{AST_1}{j} \tag{3.3-1.7}$$

Therefore, the system throughput for PTL with random assignment can be expressed as:

$$ST_1 = \frac{T_{shift}}{APT_1} \tag{3.3-1.8}$$

3.3.2. PTL system with level loading assignment

In the PTL system with level loading assignment, the equations for the average system throughput time, average processing time per zone and system throughput are similar as 3.3-1.1, 3.3-1.7 and 3.3-1.8. The only difference comparing to PTL system with random assignment is the total picking time, which is expected to be much shorter. Since the percentage of each level in one order has been taking into consideration for level loading assignment, the SKUs allocation is optimized in order to save processing time and labor cost, the allocation structure can be seen in Figure 3.3. Three levels of SKUs as level A, B, and C for each order are considered for different frequencies, the total picking time for PTL system with level loading assignment can be expressed as:

$$TP'' = \sum_{l=1}^{3} T_{pl} \times n \times P_l \tag{3.3-2.1}$$

Therefore, equation 3.3-1.1 for average system throughput time, 3.3-1.7 for average processing time per zone, and 3.3-1.8 for system throughput can be rewritten as:

$$AST_2 = T_f + \frac{j \times L}{V_{PTL}{}'} + T_s{}' \times j + \sum_{l=1}^{3} T_{pl} \times n \times P_l \tag{3.3-2.2}$$

$$APT_2 = \frac{AST_2}{j} \tag{3.3-2.3}$$

$$ST_2 = \frac{T_{shift}}{APT_2} \tag{3.3-2.4}$$

3.3.3. PTL+Z system with random assignment

In PTL+Z system, orders can bypass idle zones that have no SKUs need to be picked. When PTL+Z system is adapting random assignment as storage policy, the major difference to the PTL system with random assignment can be identified as the shorter travel time by skipping zones. So in PTL+Z system, it is necessary to calculate how many zones the order needs to enter.

According to Yu and De Koster (2009), the idea for random assignment for every order line can be applied for SKUs. In the setting of random assignment of SKUs, SKUs are sharing equal probability to be allocated. Since the PTL+Z system has been divided into j equal zones for storing SKUs without repetitive, the probability of a SKU being allocated in zone i in the random assignment can be expressed as:

$$PS_i{}' = \frac{1}{j} \tag{3.3-3.1}$$

The probability that an order will enter zone i can be expressed as:

$$PO_i{}' = 1 - (1 - PS_i{}')^n \tag{3.3-3.2}$$

Accordingly, the expected number of zones for an order to visit can be expressed as:

$$ENZ_i{}' = PO_i{}' \times j = \frac{PO_i{}'}{PS_i{}'} \tag{3.3-3.3}$$

Since the PTL+Z system has an extra ZBP conveyor, the travel time on this bypass conveyor (T_{ZBP}) should be added to equation 3.3-1.1, which can be expressed as:

$$AST_3 = T_f + T_{PTL}{}'' + T_{ZBP} + Tj_{s3} + TP' \tag{3.3-3.4}$$

The task time can be expressed respectively as:

$$T_{PTL}{}'' = \frac{ENZ_i{}' \times L}{V_{PTL}{}''} \tag{3.3-3.5}$$

$$T_{ZBP} = \frac{(j - ENZ_i{}') \times L}{V_{ZBP}} \tag{3.3-3.6}$$

$$Tj_{s3} = T_s'' \times ENZ_i' \quad (3.3\text{-}3.7)$$

Therefore, equation 3.3-3.4 and 3.3-1.7, 3.3-1.8 in PTL+Z system with random assignment can be rewritten as:

$$AST_3 = T_f + \frac{ENZ_i' \times L}{V_{PTL}''} + \frac{(j - ENZ_i') \times L}{V_{ZBP}} + (T_s'' \times ENZ_i') + T_p' \times n \quad (3.3\text{-}3.8)$$

$$APT_3 = \frac{AST_3}{j} \quad (3.3\text{-}3.9)$$

$$ST_3 = \frac{T_{shift}}{APT_3} \quad (3.3\text{-}3.10)$$

3.3.4. PTL+Z system with level loading assignment

When the level loading assignment applies to a PTL+Z system, the major difference comparing to random assignment is the order frequency of each level that has been taking into consideration, the expected visiting zone numbers will be becoming a key factor to model instead of traveling along all the conveyors. Yu and De Koster (2006) bring up the idea for basing on the order frequency of the ith class items, which is also mentioned in Melacini *et al.* (2010). The idea of class-based storage policy will be applied for fast-moving SKUs in the forward area, three levels will be considered as level A is for the most demanding item in this thesis study. The probability that a SKU that belongs to the lth level of fast-moving SKUs is assigned to zone j can be expressed as:

$$PS_{il} = f_l \times \frac{S_{il}}{S} \quad (3.3\text{-}4.1)$$

The probability of a SKU being allocated in zone i in the level loading assignment considering three levels (A, B, C) can be expressed as:

$$PS_i'' = \sum_{l=1}^{3} PS_{il} \quad (3.3\text{-}4.2)$$

Accordingly, the probability that an order will enter zone i for one order in PTL system with level loading assignment can be expressed as:

$$PO_i'' = 1 - (1 - PS_i'')^n \quad (3.3\text{-}4.3)$$

Similar to PTL+Z system with random assignment, the expected number of zones should be calculated first in order to calculate the total picking time and travel time. However, due to the different SKU assignment, the expected number of zones that will be visited for an order can be rewritten as:

$$ENZ_i'' = \frac{PO_i''}{PS_i''} \quad (3.3\text{-}4.4)$$

Since the average system throughput time in PTL+Z system with level loading shares the same task times as equation 3.3-3.4, which can be rewritten as:

$$AST_4 \ = T_f + \frac{ENZ_i'' \times L}{V_{PTL}''} + \frac{(j - ENZ_i'') \times L}{V_{ZBP}} + (T_s'' \times ENZ_i'') + \ \sum_{l=1}^{3} T_{pl} \times n \ \times P_l \quad (3.3\text{-}4.5)$$

In addition, this system has the same expression for average processing time per zone and system throughput as 3.3-1.7 and 3.3-1.8, which can be also rewritten as:

$$APT_4 = \frac{AST_4}{j} \quad (3.3\text{-}4.6)$$

$$ST_4 = \frac{T_{shift}}{APT_4} \quad (3.3\text{-}4.7)$$

3.3.5. Summary

Because of the different characters of different systems and storage policies, the models are carried out based on one system at a time. The major difference appears especially when it comes to the frequencies of SKUs and expected number zones that one order needs to travel into. In order to provide a clear view of all the equations and inputs in four different systems, Table 3.2 summarizes all the outputs and required inputs for the models that were developed before. The first three rows are showing the final results of the model, which is aimed at calculating the system throughput (ST). The remaining rows show the basic model inputs and formulas that are required in the calculation.

Table 3.2. Summary of Output/Input Parameters

	Parameters	Systems Assignments			
		PTL		PTL+Z	
		Random	Level loading	Random	Level loading
Main Outputs	AST	$T_f + T_{PTL} + Tj_s + TP$		$T_f + T_{PTL} + T_{ZBP} + Tj_s + TP$	
	APT	$\frac{AST}{j}$			
	ST	$\frac{T_{shift}}{APT}$			
Basic Input and Formulas	T_f	$Constant\ Value$			
	T_{PTL}	$\frac{j \times L}{V_{PTL}{}'}$		$\frac{ENZ_i \times L}{V_{PTL}{}''}$	
	Tj_s	$T_s{}' \times j$	$T_s{}' \times j$	$T_s{}'' \times ENZ_i$	$T_s{}'' \times ENZ_i$
	T_{ZBP}	N/A		$\frac{(j - ENZ_i) \times L}{V_{ZBP}}$	
	TP	$T_p{}' \times n$		$\sum_{l=1}^{3} T_{pl} \times n \times P_l$	
	ENZ_i	$\frac{PO_i}{PS_i}$			
	PO_i	$1 - (1 - PS_i)^n$			
	PS_i	$\frac{1}{j}$	$\sum_{l=1}^{3} f_l \times \frac{S_{il}}{S}$	$\frac{1}{j}$	$\sum_{l=1}^{3} f_l \times \frac{S_{il}}{S}$

CHAPTER 4. ANALYSIS AND RESULTS

This chapter includes three sections. First, a numerical study is presented by the Excel program to evaluate the mathematical models of the four systems. It is expected that the PTL+Z system with level loading assignment will have the best system performance in terms of system throughput. Then, validated simulation models are used to test the reliability of the mathematical model. At last, an economic analysis is presented to evaluate the cost effective and the sensitivity analysis is conducted to test the relation between the gross profit per order and payback period.

4.1. Scenario Description

To better describe the scenario, Figure 4.1 shows the flows in both systems. In the PTL system, at the beginning of each zone, the scanner decides if there is any SKUs need to be picked in that zone. If yes, the picking process will be followed. If no, the order will continuously travel to next zones. After finishing picking in one zone, the final zone 23 will be examined. If it is the zone 23, the order will be completed at this point. Otherwise, the order will have to travel to the next zone for continuous picking. The differences between PTL and PTL+Z systems could be seen as: 1) an extra scanner is installed in front of the whole picking sections in order to identify whether the first picking zone is zone 1. If yes, the order will travel to the PTL conveyor directly to start picking. Otherwise, ZBP conveyor will be used before the order entering the zones traveling to PTL conveyor before scanning. 2) After checking if the zone is the final zone, the scanner will notify the next location for picking if it is the next zone or several zones after. It follows the loop of checking whether to push onto PTL conveyor or ZBP conveyor. The major difference of the scanner position is, in PTL system, the scanners are located at the beginning of each zone, in PTL+Z system, the scanners are by the end of each zone, which increase the usage of each conveyor sections. Also, the extra scanner in this system is at the same position of the first scanner in PTL system.

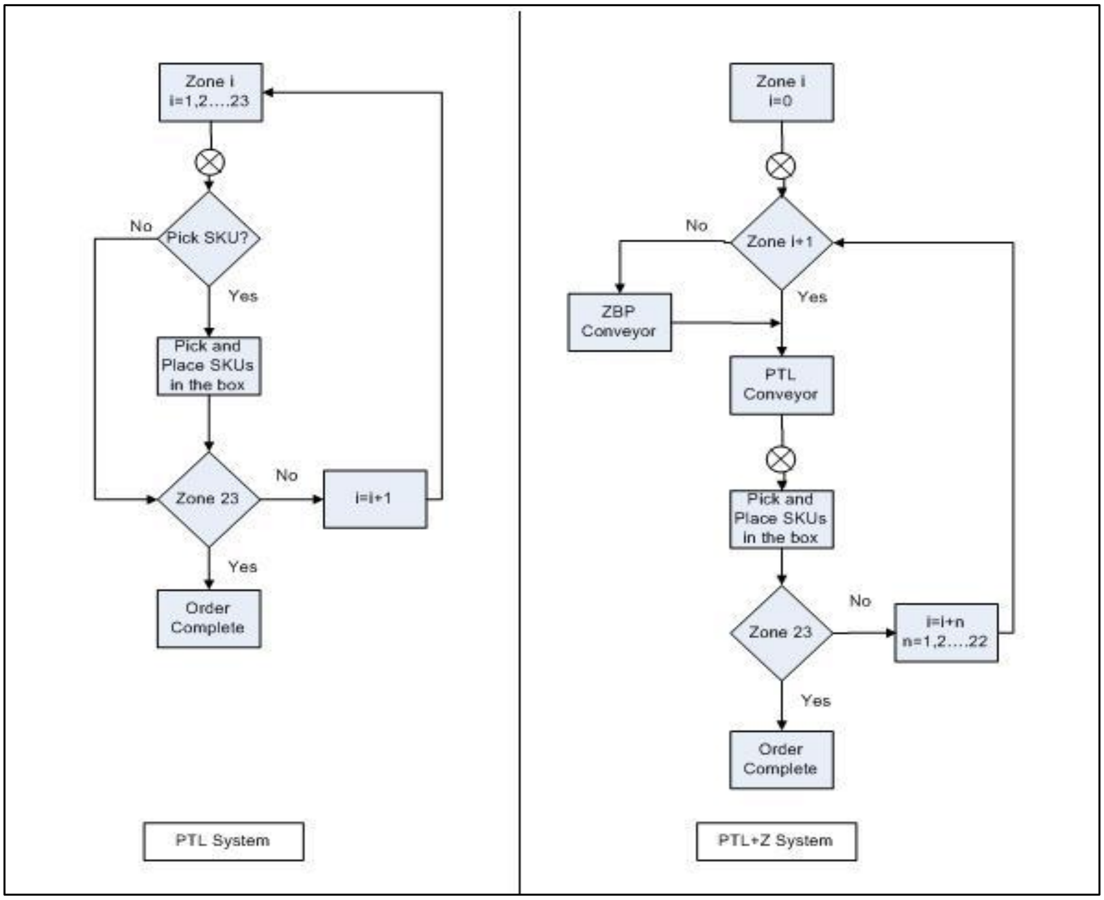

Figure 4.1. Flow Chart in PTL and PTL+Z Systems

4.2. Numerical Study

Based on the models that have been presented in Chapter 3, Table 4.1 provides a summary of the input parameters that will be used in this numerical study. All the values are based on practical principle, which can be made references from English *et al.* (2007) and Melacini *et al.* (2010).

The sequence of calculation will be followed as the expected number of SKUs needs to be picked in one zone and the expected number of zones that each order needs to enter. Also, the average system throughput time includes travel time on the PTL conveyor or ZBP conveyor, total setup time, and total picking time. In order to dealing with the simultaneously order picking completion, average processing time per zone can be used to represent the final processing time when the order will be done. As a result, the system throughout can be calculated accordingly.

Table 4.1. Input Parameters and Value Used in the Numerical Study

Basic Inputs	Description	Value
f_l	Order frequency per level	f_1=0.8 f_2=0.15 f_3=0.05 [2]
j	Number of zones	23
L	Length per zone	8.5 [1] [ft]
n	Number of SKUs per order	10
P_l	Probability of lth level of fast-moving SKUs in level loading per order	P_1=0.8 P_2=0.15 P_3=0.05 [2]
S	Total number of SKUs per zone	40 [1]
$\frac{S_{il}}{S_i}$	Percentage of lth level of fast-moving SKUs in zone i	P_1=0.2 P_2=0.3 P_3=0.5 [2]
T_f	Average travel time from box erector to first scanner	10 [1] [sec]
$T_p{}'$	Picking time per SKU in random assignment	2.3 [sec]
T_{pl}	Picking time per SKU in level loading per level	T_{p1}=1 T_{p2}=2.5 T_{p3}=3 [sec]
$T_s{}'$	Setup time per order in PTL system	14 [sec]
$T_s{}''$	Setup time per order in PTL+Z system	10 [sec]
T_{shift}	Work hour per day	8 [1] [hr]
$V_{PTL}{}'$	Average travel speed on the PTL conveyor in PTL system	1.5 [ft/sec]
$V_{PTL}{}''$	Average travel speed on the PTL conveyor in PTL+Z system	2 [ft/sec]
V_{ZBP}	Bypass conveyor speed	2.5 [ft/sec]

[1], data is adapted from English *et al.* (2007)
[2], data is adapted from Melacini *et al.* (2010)

Table 4.2 shows a detailed sample calculation in this numerical study for task times in seconds that are based on the values provided in Table 4.1 for four different systems with different storage policies. Furthermore, the main outputs of the systems can be seen in Table 4.3. All the calculations are contributing to the final system throughput.

Table 4.2. Calculated Inputs

Calculated Inputs	Systems Assignments			
	PTL		PTL+Z	
	Random	Level loading	Random	Level loading
T_{PTL}	130.33	130.33	35.08	17.12
Tj_s	322.00	322.00	82.54	40.29
T_{ZBP}	N/A	N/A	50.14	64.50
TP	23.00	13.25	23.00	13.25

Table 4.3. Main Outputs in the Four Systems

Main Outputs	Systems Assignments			
	PTL		PTL+Z	
	Random	Level loading	Random	Level loading
AST (second)	485.33	475.58	200.76	145.17
APT (second)	21.10	20.68	8.73	6.31
ST in hour	170.60	174.10	412.44	570.38

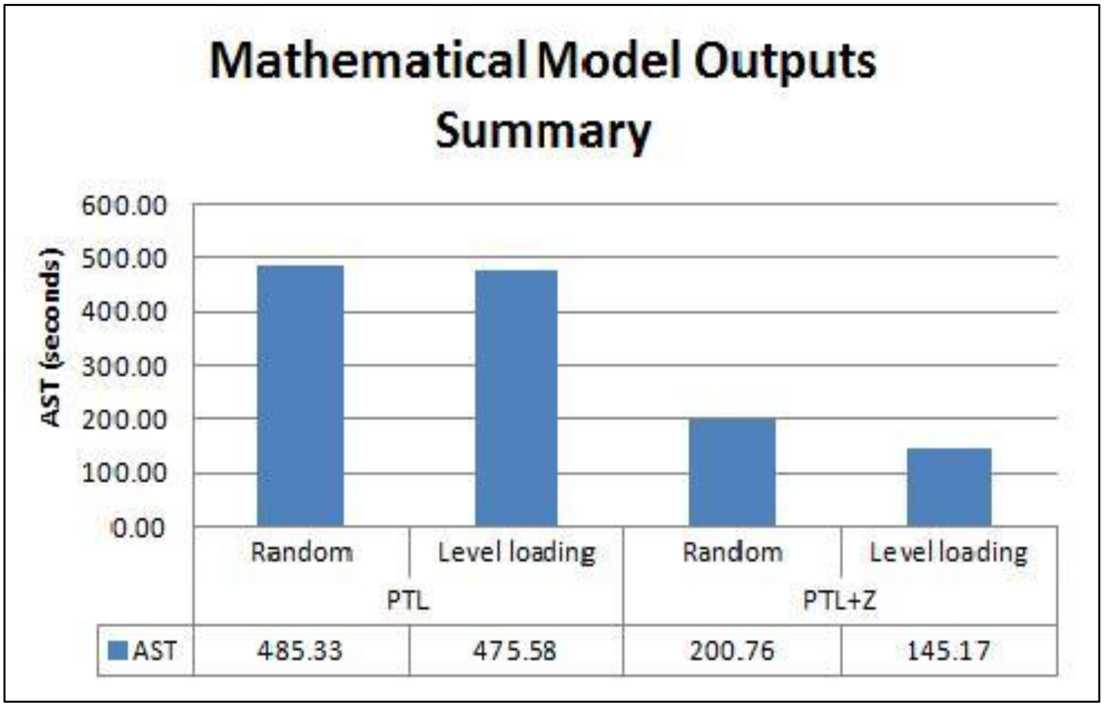

Figure 4.2. Average System Throughput (AST) Time Output Summary

In order to have better view of the results, Figure 4.2 presents the comparison the average system throughput time per order in all the systems. It can be seen that PTL+Z system with the level loading assignment method has the shortest processing time per each order for about 145.17 seconds, followed with PTL+Z with random assignment, PTL with level loading assignment, and PTL with random assignment. According to the results, in random assignment by choosing PTL+Z system, the AST will be improved by approximately 40%, and in level loading assignment, the AST will be improved by 60%. The reason for the significant improvement can be explained by the extra bypass conveyor to bypass several unnecessary zones in order to speed up in the picking operation.

In the PTL system, the difference between random assignment and level loading is only about 10 second in this numerical study. But, when the system converts into PTL+Z system, the processing time no matter in what storage policies will have a remarkable reduce.

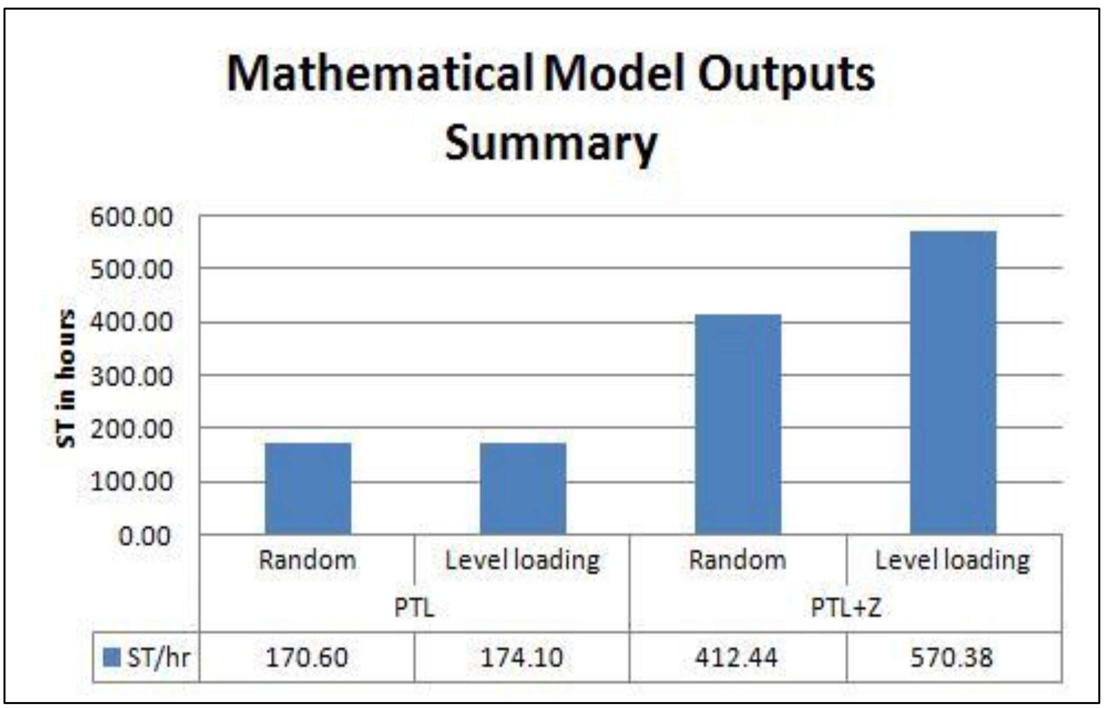

Figure 4.3. System Throughput (ST) Output Summary

Meanwhile, Figure 4.3 shows the results of system throughput in all four systems, which can be seen that PLT+Z with level loading assignment has the best system performance as the system can process up to 571 orders in an hour. The output demonstrates that the storage policy plays an important role in increasing the system throughput. The level loading is more optimized than random assignment by considering the ergonomic issues during picking by differentiating the locations in the shelves based on the SKUs' priorities, for instance, the most desired SKUs will be placed at the most optimum location with the least retrieving time. As a result, by adapting this level loading method, the total picking time in level loading assignment is shown to be comparatively less than the same order components in random assignment.

However, more cost will be applied for adapting this advanced assignment. SKUs will be required to relocate based on the demand trend, which will lead to a shut down cost that the system won't be able to perform in two days, and the rearrangement occurs once every quarter. Also, the computer program will need the filtering process in order to match the rearranged SKU locations. All the details will be discussed later in this chapter.

4.3. Simulation Model

In order to verify the feasibility of the mathematical model, simulation models are built by Automod Simulation Software exactly according to the environment settings of the mathematical model. All the operating parameters shared the same value with the numerical study, which has been listed in Table 4.1. In addition, Figure 4.4 shows the layout of the picking system only with PTL conveyor. Figure 4.5 shows the layout of the PTL+Z system, which has one extra scanner and ZBP conveyor. Since there was travel happening between PTL and ZBP conveyor, the connections between the two were bi-direction.

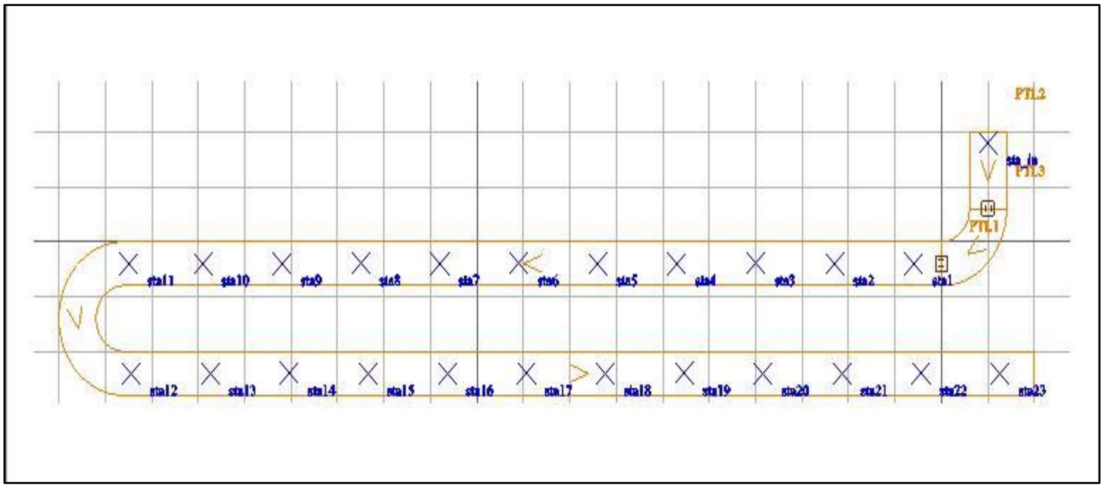

Figure 4.4. PTL System in Simulation

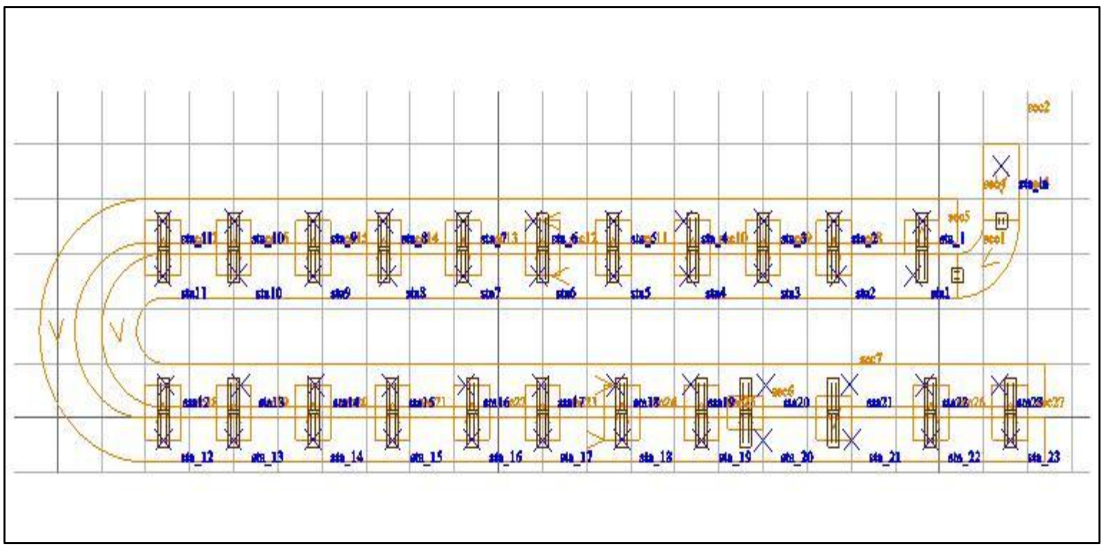

Figure 4.5. PTL+Z System in Simulation

4.3.1. Simulation results and comparison

The simulation model was aimed at verifying the mathematical models. Two processes were divided in order to accumulate the total processing time. The first one was the get-on process that the order got processed right before the picking process through box erector. The second one was the picking process that the order traveled along the system to get fulfilled. Two groups of tests have been done in running the simulation models. One was with the average SKUs number within one order as 10 for all four systems. The detailed results are shown in

Appendix A, Table A.1- A.4. The second group is set the number of SKUs in an order to follow the Normal Distribution, whose mean is 10 and with standard deviation is 2. In this situation, with 95% confidence level is considered, the range of the SKUs' number will be varied from 6 to 14. The detailed simulation results can be seen in Appendix A, Table A.5-A.8. Table 4.4 presents the simulation test result of average time system throughput time, where PTL+Z system with level loading assignment has the shortest processing time among other systems. Also, the result of the average system throughput time from numerical study is longer than that in the simulation tests for the first three systems.

Table 4.4. Average System Throughput (AST) Time Results and Comparison

		AST (Average System Throughput Time per Order)			
		PTL		PTL+Z	
	Order Size	Random	Level Loading	Random	Level Loading
Mathematical Model	10	485.33	475.58	200.76	145.17
Simulation Model	10	468.10	458.35	167.35	157.60
	Normal Distribution $\mu = 10\ \sigma = 2$	434.06	425.05	154.55	145.95

Table 4.5. System Throughput (ST) Results and Comparison

		ST (Number of orders can be processed within specific time)			
		PTL		PTL+Z	
	Order Size	Random	Level Loading	Random	Level Loading
Mathematical Model	10	170.60	174.10	412.44	570.38
Simulation Model	10	176.89	180.65	494.77	525.38
	Normal Distribution $\mu = 10\ \sigma = 2$	190.76	194.80	535.75	567.32

Accordingly, Table 4.5 presents the system throughput for the four systems in numerical and simulation tests respectively.

4.3.2. Simulation model verification and validation

In order to determine if the simulation model is correctly representing the conceptual model, there are several ways to verify and validate a simulation model, such as find the practical results for the model or calculating the extreme examples manually to test the simulation model (Song, 2010).

For the purpose of verifying the simulation model, manual calculation was done using sample data which represent extreme situation. The data includes 10 SKUs, which will be traveling to the first 10 zones for picking. Table 4.6 shows the results of the manual calculation. The table also shows the corresponding simulation result, with the same set of data used for manual calculation.

Table 4.6. Simulation Model Validation Summary

ST / Systems	Extreme example results	Simulation results
PTL/R	177.27	176.89
PTL/L	181.77	180.65
PTL+Z/R	496.25	494.77
PTL+Z/L	528.76	525.38

According to Table 4.6, the result of manual calculations and simulation model is very close. The minor differences are due to the different traveling time through the corner either by the PTL conveyor or the ZBP conveyor. Based on the verification and validation, the conclusion can be drawn as the simulation model is providing the reasonable test for the systems.

In addition, according to the literatures that have both mathematical and simulation tested (Kong, 2007, Pan and Wu, 2009 and Melacini *et al.* 2010), it is acceptable to have a slightly different result among these three tests, since the difference can be explained as in calculating the travel time on the conveyors other than setting up the travel speed in the simulation tests. The estimation of travel time around the corner of conveyor will also cause the time difference in the accumulation of average system throughput time. In addition, the travel time between PTL and ZBP conveyor is negligible in the mathematical model, but it has been accumulated in the simulation test. Therefore, based on the uncontrollable difference in between the two tests, the output of mathematical and simulation models measuring system performance are reasonably consistent and the mathematical model could be practically used.

4.4. Economic Analysis

In the actual application of a warehouse, cost is one of the most important issues to consider besides the system throughput performance, which will influence the management decisions. In the following economic analysis, discussion is mainly focused on the shortest payback period.

The annual gross profit can be expressed as:

Annual Gross profit = Number of orders processed/year × Gross profit/order

The investment cost from PTL to PTL+Z system can be expressed as:

Investment cost to PTL+Z system = ZBP conveyor cost + Scanner cost

However, due to different storage policies, more operation cost will be occurred when the system is going to use level loading assignment comparing with random assignment. The investment cost from random assignment to level loading assignment can be expressed as:

Investment cost to level loading = SKU reallocation + Shut down cost + Filtering system

The investment estimation break down is presented in Table 4.7 based on the local vitamin company and the past literatures in the practical warehouse. According to English *et al.*

(2007) and Vold *et al.* (2010), The ZBP conveyor is measuring in feet along the original PTL conveyor, except they share the same amount of conveyors before one order actually goes into the picking session. One more scanner is required in PTL+Z system before zone 1. However, the system maintenance cost and labor cost are excluded in this thesis research.

Table 4.7. Investment Summary [1]

Investment	Item	Qty	Unit Cost	Total Cost
System Conversion	ZBP Conveyor	205.5 [ft]	$275	$56,512.50
	Scanner	1	$300	$300
	Estimated Installation			$50,000
			Total Investment	$106,812.50
SKU Leveling	SKU Reallocation	32 [hr]	$15	$480
	Shut Down Cost	64 [hr]	$687.50	$44,000
	Filtering System	32 [hr]	$90	$2,880
			Total Investment	$47,360

[1], excluding maintenance cost

4.4.1. Economic analysis—without external constraint

Assuming that there is no external constraint being considered, each of systems will perform the maximum system throughput capacity within specific time. First, Table 4.8 presents the annual gross profit for the four situations of system respectively by operating 255 days, 8 hours per day and 65 dollars average profit per order to calculate the annual gross profit among the systems.

Table 4.8. Annual Gross Profit Comparison (Without External Constraint) [1]

	PTL		PTL+Z	
Output	Random	Level loading	Random	Level loading
ST in hour [2]	170.60	174.10	412.44	570.38
Gross Profit in year	22,622,142.86	23,085,922.55	54,689,906.47	75,631,736.30

[1], based on 65 dollars gross profit per order (English *et al*. (2007))
[2], from Table 4.3

Simple payback period means the time for recovering the investment to evaluate the decisions is introduced to make it easier for managers to make decisions. The payback period can be expressed as:

$$Simple\ Payback\ Period = \frac{Investment}{Annual\ Cash\ Inflows} \tag{4.4-1}$$

Table 4.9. Decision Matrix of Payback Period (Without External Constraint)

New / Current	Payback Periods hours(days)		
	PTL Level loading	PTL+Z Random	PTL+Z Level loading
PTL Random	298.16(37.27)	9.76(1.22)	8.48(1.06)
PTL Level loading			**5.92(0.74)**
PTL+Z Random			6.64(0.83)

The simple payback period for each kind of investment can be seen in Table 4.9, which provides a decision matrix for comparison based on hourly (daily) standard in order to provide a better idea of making decisions. However, in this thesis research, the assumptions is made that the implementations cannot go backward, which means that the system cannot be turned back to a PTL system if it is already a PTL+Z system, as well as the current level loading cannot be reset to random assignment. As a result, the following matrix only shows the five available conversions between systems and storage policies.

Generally speaking, the PTL systems are having a comparatively shorter payback period than any other automated picking systems. Even though no exact time study has been done in calculating the payback period, Teres (2006) English *et al.* (2007), and Ant Technologies (2011) all mentioned that it would return fast for the investment. The results can be seen in Table 4.9, changing from random assignment to level loading in PTL system takes the longest payback period because of the highly associated service cost for SKU rearrangement, but comparatively small increase in total gross profit. In addition, conversions from PTL/R to PTL+Z/R, PTL/R to PTL+Z/L, and PTL+Z/R to PTL+Z/L share the similar payback period around 6 hours or more due to the compatible ratio of investment and total gross profit difference.

The shortest payback period belongs to the conversion from PTL system to PTL+Z system with level loading, which can be drew the conclusion that level loading is more advanced than random assignment in processing the order. According to the huge improvement in total annual gross profit by only introducing one minor extra bypass conveyor, which helps shorten the payback period about 3 hours comparing with the others excluding conversion from PTL with random assignment to PTL with level loading. The best investment plan can be drawn as upgrading the system first, and then the storage policy, which have a shorter payback period than upgrading both system and storage policy at the same time.

4.4.2. Economic analysis—with external constraint

However, in the actual applications, it is expected to see some possible external constraints to limit the system's maximum throughput in each process. In this thesis research, two constraints can be considered as the box erector efficiency and next process efficiency. The box erector efficiency could limit the maximum number of incoming orders per hour. Based on the information from a local vitamin company, the rate is around 700 boxes per hour without any downtime considered. However, the rate can be varied upon different capabilities of box erectors. In order to obtain a more realistic result in calculating the simple payback period, 20 percent of the downtime is assigned to this box erector, which leads to a final rate as about 560 boxes per hour. Also, the capacity of the next process could also be an external constraint, which will slow down the output rate.

Table 4.10 shows the actual system throughput by taking the external constraint into consideration. It will only influence the result of PTL+Z system with level loading assignment for about 11 orders less per hour.

Table 4.10. Main Outputs in the Four Systems

Main Outputs	Systems Assignments			
	PTL		PTL+Z	
	Random	Level loading	Random	Level loading
AST (second)	485.33	475.58	200.76	145.17
APT (second)	21.10	20.68	8.73	6.31
ST in hour	170.60	174.10	412.44	570.38
Actual ST in hour	170.60	174.10	412.44	**560.65**

Accordingly, Table 4.11 shows the comparison of the annual gross profit by having the external constraint that all the systems are the same with the situation without external constraint except PTL+Z system with level loading assignment, which is saying that the box erector cannot meet the maximum requirement of this system.

Table 4.11. Annual Gross Profit Comparison (With External Constraint)

	Profit			
	PTL		PTL+Z	
	Random	Level loading	Random	Level loading
Without Constraint	22,622,142.86	23,085,922.55	54,689,906.47	75,631,736.30
With Constraint	22,622,142.86	23,085,922.55	54,689,906.47	**74,342,190.00**

As a result, the actual throughput and new annual gross profit will influence the payback period results in the hourly (daily) standard to all the five available conversions, which can be seen in Table 4.12. By introducing the external constraint, it results in increasing the payback period from every kind of systems to PTL+Z/L for few hours.

Table 4.12. Decision Matrix of Payback Period (With External Constraint)

New / Current	Payback Periods hours(days)		
	PTL Level loading	PTL+Z Random	PTL+Z Level loading
PTL Random	298.16(37.27)	9.76(1.22)	8.72(1.09)
PTL Level loading			**6.08(0.76)**
PTL+Z Random			7.04(0.88)

In addition, the longest payback period is the conversion from random assignment to level loading in PTL system, which has incompatible investment and profit improvement. The shortest payback period stays in the same conversion, which is from PTL/L to PTL+Z/L according the huge improvement in total annual gross profit by only introducing one extra ZBP conveyor. The best investment plan will still be upgrading system to PTL+Z first and then to level loading assignment.

4.5. Sensitivity Analysis

In this section, the sensitivity analysis will be presented to study the relation between gross profit per order and simple payback period. Two situations will be considered as with or without external constraint. Since the time scale for conversion from PTL/R to PTL/L is too long to be clearly shown in a smaller scale, in order to better present the variations along with the changes of gross profit per order, two Figures are adapted respectively.

Figure 4.6 shows the sensitivity analysis of payback period that by only introducing level loading in PTL system will take the longest payback period due to the large investment and comparatively fewer profit increase. As the gross profit per order reaches 25 dollars, the payback period will have a significantly drop, then it will go down smoothly with the increasing of gross profit.

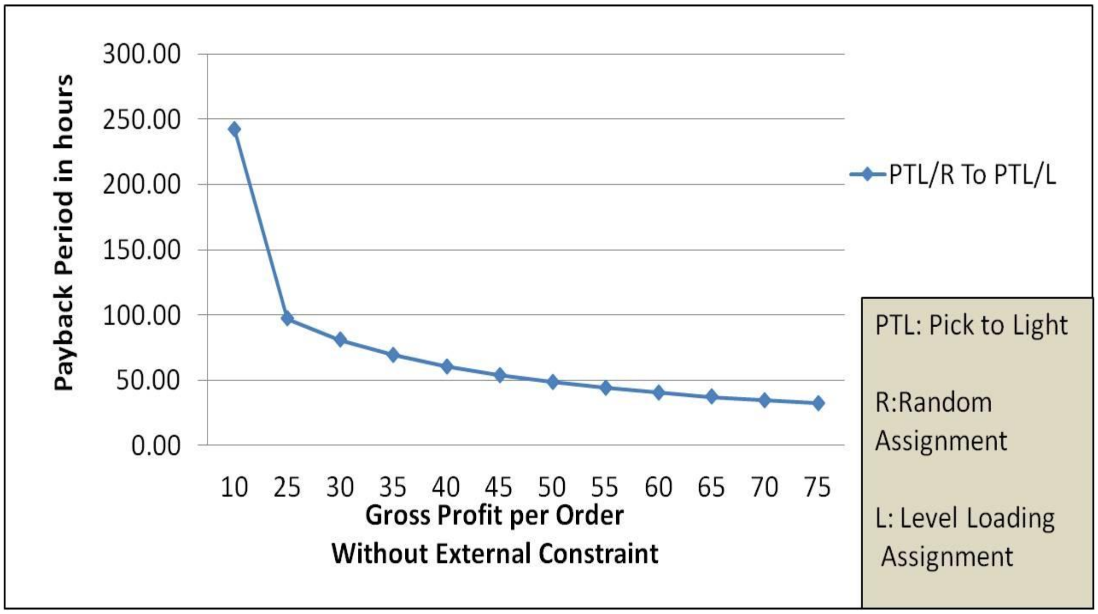

Figure 4.6. Sensitivity Analysis of of PTL/R to PTL/L (Without External Constraint)

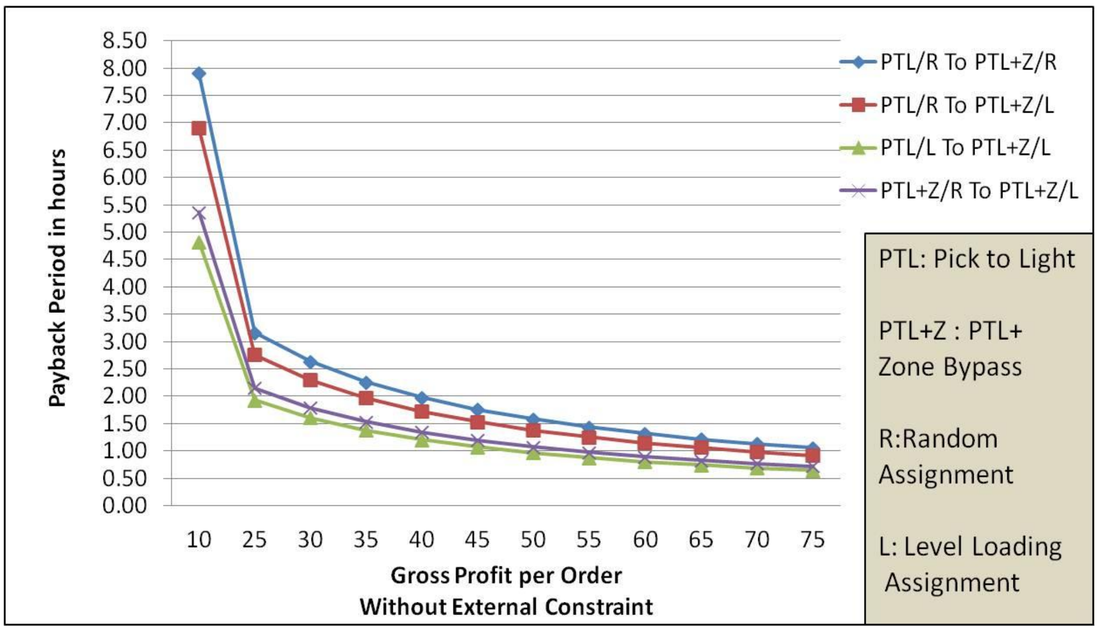

Figure 4.7. Sensitivity Analysis of Other Available Conversions (Without External Constraint)

Figure 4.7 shows the other available conversions under the same circumstances, which including conversions from PTL/R to PTL+Z/R, PTL/R to PTL+Z/L, and PTL+Z/R to PTL+Z/L. All the conversions take almost the same time to earn the money back along with the changes in gross profit per order. For example, at the same gross profit of 10 dollars per box, the conversion to PTL/L will require more than 97% of the time to get the investment back. Furthermore, the change from PTL/L to PTL+Z/L has the shortest payback period, which indicates the storage policy implementation has better system performance than the system implementation. Also, all the conversions are having a significant drop after the gross profit increasing to 25 dollars per box. The decrease in payback period shows exponential behavior, the more profit earned per order, the less payback period will cost.

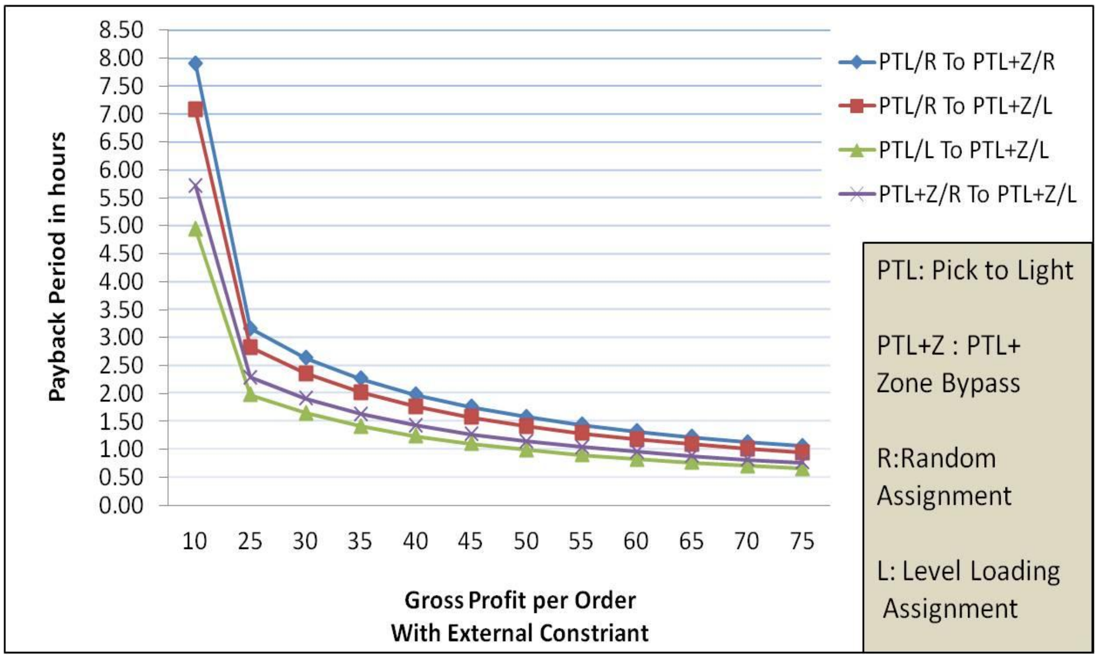

Figure 4.8. Sensitivity Analysis of Other Available Conversions (With External Constraint)

By taking the external constraint into consideration, Figure 4.8 shows the sensitivity analysis of four conversions. The trend of decreasing in simple payback period remains the same as no external constraint considered, which is shown in Figure 4.6. In addition, since only the PTL+Z system with level loading has been influenced by the external constraint, the conversions to PTL+Z/L will be affected. The conclusion can be drawn as all the conversions have a significant drop after the gross profit increasing to 25 dollars per box. However, the external constraint doesn’t bring a significant influence to the payback period.

CHAPTER 5. CONCLUSIONS AND FUTURE RESEARCH

In this conclusion chapter, the key results of this thesis research will be represented. The structure of this chapter is followed by a section illustrating the major contributions of this thesis research to academic warehouse management research. Also, during the progress of obtaining the results, several opportunities for future research will be presented in the last section.

5.1. Major Results of the Thesis Research

This thesis research examines the most profitable system among these four different systems, which are PTL system with random assignment, PTL system with level loading, PTL+Z system with random assignment, and PTL+Z system with level loading. Four groups of mathematical models are developed to compare the system throughput. Subsequently, expected number of zones that each order will visit is calculated based on the proposed SKU assignment as level loading assignment.

Overall, according to the analyses, the PTL+Z system with level loading achieves the most system performance profit, whether the system has the external constraint or not. As expected, the ZBP conveyors reduce dramatic amount of time in traveling along the system to get to next picking section because of the faster speed of belt conveyor and avoidance of unnecessary zones. The level loading assignment of SKUs provides a comparatively more optimal storage policy than random assignment. By rearranging the SKUs, each order will reduce the visiting number of zones to finish picking, which leads to less setup time and faster travel speed. In addition, the sequence of system performance can be followed as: *PTL+Z/L > PTL+Z/R > PTL/L > PTL/R.*

By conducting economic analysis for the numerical study, the payback period is presented to make the comparison between the four systems. Based on the assumption that implementations cannot be cancelled, only five possible conversions can be done by finally updating to PTL+Z system with level loading assignment. Comparing the effect of adding ZBP conveyor or optimizing SKU assignment in PTL system, the results show that by adding the extra ZBP conveyor will have a significant reduction in payback period other than implementing to level loading assignment. However, seen in the results, conversion from PTL to PTL+Z system with level loading requires the least time to make the profit again. In addition, sensitivity analysis of gross profit per order is also presented to show that the influence indicates a major drop in payback period when the profit is 25 dollars, and follows a major exponential behavior associated with the increase of gross profit.

5.2. Contributions of the Thesis Research

This thesis research evaluates the system performance of two systems, PTL and PTL+Z systems with two different SKU assignments, random assignment and level loading assignment. From the perspective of both academia and practice, this thesis study makes the following contributions.

First, this thesis research empirically documents from the general idea of warehouse management, order picking system to the seldom addressed issue of Pick-and-Pass order picking system. However, this thesis adapts the PAP system as the environment setting for the existing local company to analyze the system performance based on two different storage assignments. Also, a new PTL+Z system is studied for optimal improvement. The unique research design allows a better understanding of the PTL system and the influence of storage policy that will bring to the PTL and PTL+Z systems on the system performance.

Second, by comparing the system throughput of these four systems, PTL+Z system is the most profitable system based on the same environment setting.

Finally, unlike those previous studies on the warehouse, this thesis presents the economic analysis, which helps the decision maker to see clearly about the payback period based on their own situation. In addition, the sensitivity analysis is also presented to study the relation between gross profit per order and payback period.

5.3. Limitations and Future Research

Future researches can be explored by relaxing current assumptions. First, in this research, all the orders are assigned as 10 SKUs and the time settings are constant. Future work should be focusing on replacing current constant values with certain distribution patterns. For instance, the SKUs per order can follow a binominal distribution, as well as traveling time and setup time. The setup time could be modeled by the queuing theory as M/M/c or G/G/m, which has been discussed in Melacini *et al*. (2010), and Yu and De Koster (2007). This should be able to provide a more realistic result.

Second, all the zones in the current system are equally divided and one picker is assigned to each zone. However, in the practical situation, according to the foot print and limitations of each facility, zones can be unequally divided upon request and the picker assignment could be rearranged as well.

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APPENDIX A. THE SIMULATION RESULTS

Table A.1. Simulation Result for PTL System with Random Assignment (Average SKUs' Number n = 10)

n = 10	PTL/R
AST $[sec]$	468.10

Table A.2. Simulation Result for PTL System with Level Loading (Average SKUs' Number n = 10)

n = 10	PTL/L
AST $[sec]$	458.35

Table A.3. Simulation Result for PTL+Z System with Random Assignment (Average SKUs' Number n = 10)

PTL+Z/R n = 10				
ENZ	AST			
	First	Last	Middle	Ave
1	131.57	129.52	126.32	129.14
2	140.57	131.92	125.92	132.80
3	149.02	150.42	135.92	145.12
4	160.07	162.37	135.92	152.79
5	170.72	173.02	149.77	164.50
6	181.77	183.67	151.57	172.34
7	192.42	194.72	155.77	180.97
8	203.47	205.37	158.97	189.27
9	214.12	216.02	167.42	199.19
10	225.17	226.67	170.22	207.35
			AST	167.35

Table A.4. Simulation Result for PTL+Z System with Level Loading (Average SKUs' Number n = 10)

PTL+Z/L n = 10				
ENZ	AST			
	First	Last	Middle	Ave
1	121.82	119.77	116.57	119.39
2	130.82	122.17	116.17	123.05
3	139.27	140.67	126.17	135.37
4	150.32	152.62	126.17	143.04
5	160.97	163.27	140.02	154.75
6	172.02	173.92	141.82	162.59
7	182.67	184.97	146.02	171.22
8	193.72	195.62	149.22	179.52
9	204.37	206.27	157.67	189.44
10	215.42	216.92	160.47	197.60
			AST	157.60

Table A.5. Simulation Result for PTL System with Random Assignment ($\mu = 10, \sigma = 2$)

PTL/R			
n	Weight	*AST*	AVE
6	0.02	458.90	10.33
7	0.05	461.20	20.75
8	0.07	463.50	31.29
9	0.09	465.80	41.92
10	0.50	468.10	234.05
11	0.09	470.40	42.34
12	0.05	472.70	21.27
13	0.05	475.00	21.38
14	0.02	477.30	10.74
		AST	434.06

Table A.6. Simulation Result for PTL System with Level Loading ($\mu = 10, \sigma = 2$)

PTL/L			
n	Weight	*AST*	AVE
6	0.02	453.05	10.19
7	0.05	454.38	20.45
8	0.07	455.7	30.76
9	0.09	457.03	41.13
10	0.50	458.35	229.18
11	0.09	459.68	41.37
12	0.05	460.75	20.73
13	0.05	462.33	20.80
14	0.02	463.65	10.43
		AST	425.05

Table A.7. Simulation Result for PTL+Z System with Random Assignment ($\mu = 10, \sigma = 2$)

PTL+Z/R			
n	Weight	*AST*	AVE
6	0.02	140.25	3.16
7	0.05	147.05	6.62
8	0.07	153.77	10.38
9	0.09	160.60	14.45
10	0.50	167.35	83.67
11	0.09	174.18	15.68
12	0.05	171.95	7.74
13	0.05	188.01	8.46
14	0.02	195.36	4.40
		AST	154.55

Table A.8. Simulation Result for PTL+Z System with Level Loading ($\mu = 10, \sigma = 2$)

PTL+Z/L			
n	Weight	*AST*	AVE
6	0.02	134.40	3.02
7	0.05	140.23	6.31
8	0.07	145.97	9.85
9	0.09	151.83	13.66
10	0.50	157.60	78.80
11	0.09	163.46	14.71
12	0.05	169.16	7.61
13	0.05	175.34	7.89
14	0.02	181.71	4.09
		AST	145.95