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**DESIGN AND ANALYSIS OF ORDER ACCUMULATION AND
SORTATION SYSTEMS (OASS)**

by

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APPROVAL PAGE

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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ABSTRACT

In Supply Chain, the warehouses are located between supplier, manufacturer and end user. Some of the essential functions of the warehouses are order picking, packaging and shipping to the customers. While the orders are picked by workers, the most preferred method is zone picking procedure. The pickers who are responsible for one region prepare the packages, in order to send them according to the customers' needs. Thus, we encounter mixed accumulated packages which are waiting for shipping. Those should be sorted before sending to customer by putting together same items in one order together. This process called Order Sortation process affects performance directly like the other processes in warehouse. In this thesis, Order sortation strategies are examined in detail and related parameters are introduced. Length and speed of the conveyor, wave algorithm, size of the wave, number of the sortation lanes, and sortation strategies are the main parameters. Different types of sortation strategies and different types of conveyor configurations are analyzed. In available researches, all analytical models assume the same order size. This assumption will be relaxed and sortation strategies will be assessed using simulation tool by taking into account different size of order.

Keywords: Sortation Strategies, Inventory Management, Simulation

SİPARİŞ TOPLAMA VE SIRALAMA SİSTEMLERİNİN TASARIMI VE ANALİZİ

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ÖZ

Tedarik zinciri yönetiminde, tedarikçi, üretici ve müşteri arasında depo vardır. Depoların işlevleri arasında sipariş toplama ve hazırlayıp müşteriye gönderme vardır. Depoda siparişler toplanırken sıkça tercih edilen yöntemlerden bir tanesi, bölge atama (zone picking) yöntemidir. Siparişleri toplayan işçiler kendilerine atanan bölgelerden müşterilere gönderilmek üzere paketleri hazırlarlar. Bu yöntemle toplanan paketler sevkiyat alanına diğer siparişlere ait paketlerle karışmış olarak gelirler. Siparişlerin müşteriye teslim edilmeden önce ayrıştırılması (sorting) yani aynı siparişe ait paketlerin bir araya getirilmesi gerekir. Sipariş toplama gibi sipariş ayrıştırma süresi de sistemin performansını direk etkileyen depo içi faaliyetlerdendir. Bu tezde sipariş ayrıştırma sistemi detaylı olarak incelenmiş ve ayrıştırma süresini etkileyen parametreler ortaya konulmuştur. Konveyörlerin uzunlukları, hızları, paketlerin dalga halinde gönderilmesi, dalga büyüklüğü, ayrıştırma şeritlerinin sayısı ve ayrıştırma stratejisi başlıca parametlerdir. Bu çalışmada farklı ayrıştırma stratejileri ve farklı konveyör modelleri analiz edilmiştir. Mevcut analitik modeller bütün siparişlerin aynı büyüklükte olduğunu kabul eder. Bu varsayım esnetilerek, farklı büyüklükteki siparişlerin durumları dikkate alınmış ve simülasyon yöntemi ile ayrıştırma stratejileri çeşitli tasarımlar üzerinde değerlendirilmiştir.

Anahtar kelimler: Ayrıştırma stratejileri, Depo yönetimi, Simülasyon

To my parents

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TABLE OF CONTENTS

ABSTRACT.....	iv
ÖZ.....	v
ACKNOWLEDGEMENT.....	vii
LIST OF TABLES	x
LIST OF FIGURES.....	xii
ABBREVIATIONS	xiv
CHAPTER 1 INTRODUCTION	1
CHAPTER 2 LITERATURE REVIEW	4
2.1 OVERVIEW OF SORTATION OPERATIONS	4
2.2 CONVEYOR SYSTEM.....	6
CHAPTER 3 DESIGN PARAMETERS OF OASS.....	7
3.1 SORTATION PROBLEM	7
3.2 ORDER SELECTION PROCESS.....	8
3.2.1 Order Picking Subsystem.....	9
3.2.2 Order Accumulation Subsystem.....	9
3.2.3 Sorting Subsystem	11
3.3 SORTATION SYSTEM DESIGN	12
3.3.1 One-One Model	13
3.3.2 One-Many Model.....	14
3.3.3 Many- One Model.....	15
3.3.4 Many- Many Model	16
CHAPTER 4 OPERATIONAL PARAMETERS AND MODELS	17
4.1 ITEM COLLECTION METHODS	17
4.2 SORTATION STRATEGIES	18
4.2.1 Fixed Priority Rule (FPR)	19

4.2.2 Next Available Rule (NAR)	21
4.2.3 Earliest Completion Rule (ECR)	22
4.2.4 Examples about Sortation Strategies	23
CHAPTER 5 EXPERIMENTATION.....	26
5.1 ONE-ONE MODEL	26
5.1.1 Analytical Model	26
5.1.2 Simulation Model	33
5.1.3 Simulation Model versus Analytic Model	34
5.2 ONE-MANY MODEL.....	37
5.2.1 Simulation Model	37
5.3 MANY-ONE MODEL.....	38
5.3.1 Simulation Model	38
5.4 MANY-MANY MODEL.....	39
5.4.1 Simulation Model	39
5.5 SCENARIOS.....	41
5.5.1. Number of Orders versus Number of Items	41
5.5.2. Random and Equal Number of Items in the Order	44
5.5.3. Various Number of Sortation Lane	46
5.5.4. Effect of the Distance between Sortation Lanes	48
5.5.5. One –One Model versus One-Many Model	52
CHAPTER 6 CONCLUSION AND FURTHER RESEARCH.....	54
REFERENCES.....	57
APPENDIX.....	60

LIST OF TABLES

Table 2.1 Literature Review about Sortation strategies	5
Table 2.2 Literature Review about Conveyor Design	6
Table 4.1 Parameters	19
Table 4.2 Fixed Priority Rule Small Example in {4; 3} Design.....	24
Table 4.3 Next Available Rule Small Example in {4; 3} Design.....	24
Table 4.4 Earliest Completion Rule Small Example in {4; 3} Design	25
Table 5.1 Sorting Times for Numerical Examples in {10; 5} Design	27
Table 5.2 Sorting Times for Numerical Examples in {12; 6} Design	28
Table 5.3 Sorting Times for Numerical Examples in {48; 1} Design	29
Table 5.4 Sorting Time Comparison by Using Analytical Model {60; 1}.....	30
Table 5.5 Sorting Time Comparison by Using Analytical Model {10; 10}.....	31
Table 5.6 Sorting Time Comparison by Using Analytical Model {20; 5}.....	32
Table 5.7 Sorting Time Comparison for [1/1/10/5] Using Simulation Model	34
Table 5.8 Sorting Time Comparison in Analytical Model {24; 1}.....	34
Table 5.9 Sorting Time Comparison in Simulation Model {24; 1}	34
Table 5.10 Time Differences between Simulation and Analytical Model {24; 1}	36
Table 5.11 Sort of Spending Time for Simulation {24; 1}	37
Table 5.12 Sorting Time Comparison by Using Simulation Model [1/8/10/5]	38
Table 5.13 Sorting Time Comparison by Using Simulation Model [8/1/10/5]	38
Table 5.14 Sorting Time Comparison by Using Simulation Model [8/8/10/5]	40
Table 5.15 Total Sorting Time for {24; 1} order Configuration in (1/1) Model.....	41
Table 5.16 Total Sorting Time for {48; 1} order Configuration in (1/M) Model	42
Table 5.17 Total Sorting Time for {24; 1} order Configuration in (M/M) Model.....	43
Table 5.18 Sorting Time Comparison of Sorting Strategies According to O-OM.....	45
Table 5.19 Sorting Time Comparison of Sorting Strategies According to O-MM.....	45
Table 5.20 Sorting Time Comparison of Sorting Strategies According to M-MM.....	45
Table 5.21 Total Sortation Time for Different Sortation Lane in (1/M) Model.....	46
Table 5.22 Total Sortation Time for Different Sortation Lane in (M/M) Model.....	47

Table 5.23 Different Distances between Sortation Lanes [1/1/10/5]	49
Table 5.24 Different Distances between Sortation Lanes [1/2/10/5]	51
Table 5.25 One –One Model versus One-Many Model	53
Table 6.1 Overall outputs for all Sorting Strategies and all designs	54
Table 6.2 Overall Result	55
Table A.1 Data Set	60

LIST OF FIGURES

Figure 1.1 Main Functions of a Distribution Center	1
Figure 3.1 One- One Model Conveyor Design.....	14
Figure 3.2 One- Many Model Conveyor Design	15
Figure 3.3 Many- One Model Conveyor Design	15
Figure 3.4 Many- Many Model Conveyor Design.....	16
Figure 5.1 MAPPLE Software screenshot.....	26
Figure 5.2 Sorting Times for Numerical Examples {10; 5}	27
Figure 5.3 Sorting Times for Numerical Examples {12; 6}	28
Figure 5.4 Sorting Time Comparison by Using Analytical Model {48; 1}	29
Figure 5.5 Sorting Time Comparison by Using Analytical Model {60; 1}	30
Figure 5.6 Sorting Time Comparison by Using Analytical Model {10; 10}	31
Figure 5.7 Sorting Time Comparison by Using Analytical Model {20; 5}	32
Figure 5.8 One-One Design Model Simulation Screenshot	33
Figure 5.9 Analytical Model Result {24; 1}	35
Figure 5.10 Simulation Model Result {24; 1}	35
Figure 5.11 Extra Times Spending for Simulation	36
Figure 5.12 One-Many Design Model Simulation Screenshot.....	37
Figure 5.13 Many-One Design Model Simulation Screenshot.....	38
Figure 5.14 Many-Many Design Model Simulation Screenshot (Before)	39
Figure 5.15 Many-Many Design Model Simulation Screenshot (After).....	40
Figure 5.16 Total Sorting Time for {24; 1} order Configuration in (1/1) Model.....	41
Figure 5.17 Total Sorting Time for {48; 1} order Configuration in (1/M) Model	42
Figure 5.18 Total Sorting Time for {24; 1} order Configuration in (M/M) Model.....	43
Figure 5.19 Histogram of Random Items	44
Figure 5.20 Histogram of Equal Items	44
Figure 5.21 Total Sortation Time for different Sortation Lane in (1/M) Model	46
Figure 5.22 Total Sortation Time for Different Sortation Lane in (M/M) Model	47

Figure 5.23 Close Sortation Lane for O-OM.....	48
Figure 5.24 Remote Sortation Lane for O-OM.....	48
Figure 5.25 Effect of the Distance between Sortation Lanes [1/1/10/5]	49
Figure 5.26 Close Sortation Lane for (1/M) Model	50
Figure 5.27 Remote Sortation Lane for (1/M) Model	50
Figure 5.28 Effect of the Distance between Sortation Lanes [1/2/10/5]	51
Figure 5.29 One –One Model versus One-Many Model.....	52
Figure 5.30 Effect of the Distance between Sortation Lanes	53
Figure 6.1 Effect of the Distance between Sortation Lanes	55

ABBREVIATIONS

DC	Distribution Center
ECR	Earliest Completion Rule
FCFS	First Come First Serve
FPR	First Priority Rule
MHS	Material Handling System
NAR	Next Available Rule
OASS	Order Automated Sortation System
S/PS-1	Sort/ Post Sort 1
S/PS-2	Sort/ Post Sort 2
(1/1)	One – One Model
(1/M)	One –Many Model
(M/M)	Many – Many Model

CHAPTER 1

INTRODUCTION

An Order Accumulation and Sortation System (OASS) is a crucial part of any automated distribution center, Material Handling System (MHS). Reduced operating costs, better place utilization, faster order fulfillment, cut down on product damage and low maintenance and higher customer satisfaction can all be achieved by more efficient distribution centers. Effective management of distribution operation is also critical for successful Supply Chain. In every Supply Chain warehousing activities between supplier, manufacturer and customer have significant place in order to obtain maximum profit. Figure 1.1 represents the position of warehouse for a distributor. And five main activities within a warehouse are receiving, storage, picking, sortation and shipping.

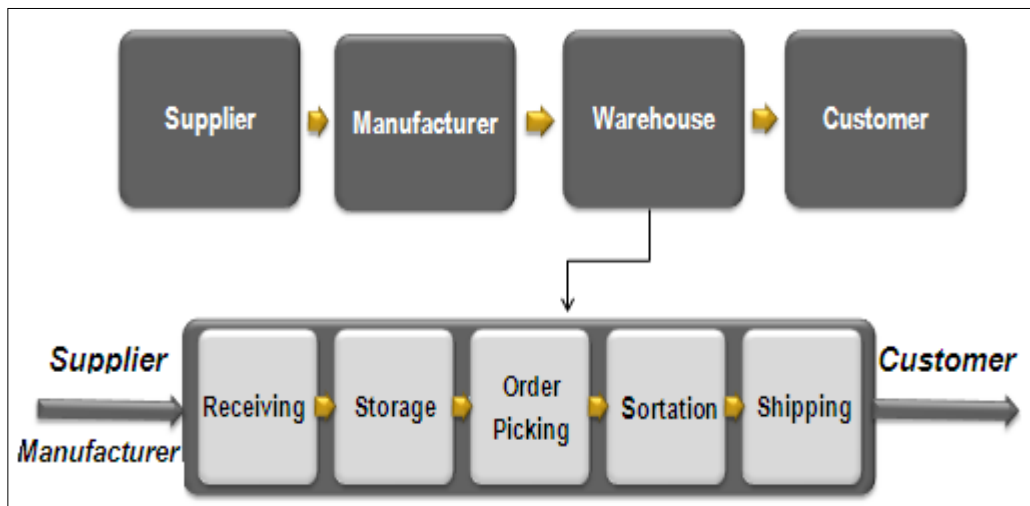


Figure 1.1 Main Functions of a Distribution Center

In today's competitive world, it is desirable that a distribution center runs at its optimal settings to gain a competitive advantage. Efficient distribution centers are needed to respond to the increasing competition and to an increased emphasis placed on time-based service.

While the orders are accumulated in a warehouse, one of the methods which are preferred frequently is zone picking procedure. Pickers prepare the packages in order to send them to the customers. With this procedure, the accumulated packages arrive to the shipment area in a mixed way with the packages of other orders. Before delivering to the customers, the orders have to be sorted; in other words, the packages that belong to the same order have to be put together. Like the order accumulation, the order sorting time is another warehouse function which directly affects the system performance.

The optimal condition for a system studied would be the one in which the rate of sortation (i.e., throughput rate) is maximized. So the wave sortation time without increasing the capital and operating costs is minimized. There is a trade-off between the rate and cost. Using more resources, such as labor and machines may increase the rate of sortation; however, the cost of sortation thus increases. This research focuses on maximizing the throughput rate of a given system and assumes that the other variables, such as cost and operating design parameters, are held within satisfactory limits.

In this thesis, the order sorting system is examined in detail and the parameters that affect the sorting time are determined. Major parameters are the length and speed of conveyors, sending the packages within a wave, the wave size, number of the sorting lanes and the sorting strategy. Different sorting strategies and different conveyor models are analyzed in this thesis. Available analytical models accept that all orders are the same size. By relaxing this assumption, which means that the situations of different size orders are taken into consideration, simulation method with sorting strategies is evaluated on different designs.

There have been some researches done to examine (OASS) systems. The literature review chapter gives a detailed review of the previous work. After studying existing (OASS) systems in some industries and with reference to previous research, a simulation model of an (OASS) was built depicting a real world situation. In the system

studied, groups of orders are delivered to a closed-loop conveyor where they are sorted into shipping lanes, packed and loaded onto waiting trucks. Simulation is used to determine the sortation time, which is the performance measure of the system (response variable).

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW OF SORTATION OPERATIONS

Accumulation and Sortation Order System (OASS) related publications are very few. Bozer and Sharp (1985) proposed loop conveyor sorting system to prevent lane blocking. However, in that study, sortation lanes are equal to number of orders whereas, multiple orders should be assigned to one sortation lane. Later (Bozer et al., 1988) developed the first sortation strategy, Fixed Priority Rule (FPR) for lane assignment by simulating different wave of orders. Sonderman (1982) develop an algorithm for the analysis of recirculation conveyors traffic behavior.

Johnson and Longren (1994) decomposed and designed accumulation and sortation system which is used Hewlett-Packard. Meller (1997) developed an algorithm and for this algorithm he has proved the increase in throughput rate. Based on incoming order items in other words wave algorithm, Meller offered the optimum assignment.

Johnson (1998) developed a dynamic sortation strategy which is called Next Available Rule (NAR) and compared it with an older method of "FPR" and evaluated total sortation time. Johnson suggested that assigning order when it is located on the conveyor is better than any fixed rule.

Schmidt and Jackman (2000) presented an analytical model can be extended to large conveying system for blocking and recirculation of load. Johnson (2002) developed split-case sorting system. If the same product will be sent to many customers, the model finds the sorting capacity of different systems.

Johnson and Meller (2002) proposed an analytical performance model which can be applied Split-Case sortation system includes stochastic operational condition. Le-Duc and De Koster (2005) determine optimal number of zones in order to minimize the overall time. Eldemir (2006) developed an alternative sortation strategy called Earliest Completion Rule (ECR) by using order statistics. A brief summary of important studies is given on Table 2.1.

Table 2.1 Literature Review about Sortation strategies

<i>Article</i>	<i>Method</i>	<i>Study</i>
Bozer and Sharp (1985)	Simulation	An empirical evaluation of general purpose automated order accumulation and sortation system used in batch picking
Bozer et al (1988)	Simulation	An evaluation of alternative control strategies and design issues for automated order accumulation and sortation systems.
Johnson and Lofgren(1994)	Simulation	Model decomposition speeds distribution center design
Johnson (1998)	Analytical	The impact of sorting strategies on automated sortation system performance
Meller (1997)	Analytical	Optimal order-to-lane assignments in an order accumulation/sortation system
Wang (1997)	Heuristic	An integrated construction/simulated annealing approach for designing sortation conveyor system in automated distribution center
Schmidt and Jackman(2000)	Analytical	Modeling recirculating conveyors with blocking
Johnson and Meller (2002)	Analytical	Performance analysis of split-case sorting systems
Russell and Meller (2003)	Descriptive Model	Cost and throughput modeling of manual and automated order fulfillment systems
Bozer (2004)	Analytical	Expected waiting times at loading stations in discrete-space closed-loop conveyors
Eldemir(2006)	Analytical	Earliest Completion Rule: An alternative order Sortation Strategy

2.2 CONVEYOR SYSTEM

Conveyor research is categorized into design and analysis of simple versus complex conveyor systems. A simple conveyor system is composed of the configuration of a line or closed-loop or is composed of just either accumulating or non-accumulating segment. On the other hand, complex conveyor system is composed of both accumulating and non-accumulating segments with different branches intersection points.

Closed-loop simple conveyor design researches contain different number of induction lane and number of sortation lanes. Especially the first studies are related to one induction and one sortation lane. However later on, depending on the many order and more product variability, the conveyor design converts into many induction and sortation lanes. Table 2.2 summarizes the literature on closed-loop conveyor system analysis according to number of its induction and sortation lane.

Table 2.2 Literature Review about Conveyor Design

<i>Sortation Literature Summary</i>					
Article	Method	Problem Setting			
		One Induction L	Many Induction L	One Sortation L	Many Sortation L
Bozer and Sharp (1985)	Simulation	√		√	
Bozer et al (1988)	Simulation	√			√
Johnson and Lofgren(1994)	Simulation	√			√
Johnson (1998)	Analytical	√			√
Meller (1997)	Analytical	√			√
Schmidt and Jackman(2000)	Analytical	√		√	
Johnson and Meller(2002)	Analytical		√		√
Russell and Meller(2003)	Descriptive Model		√		√
Bozer (2004)	Analytical		√		√
Eldemir (2006)	Analytical	√		√	

CHAPTER 3

DESIGN PARAMETERS OF OASS

3.1 SORTATION PROBLEM

In distribution centers, long list of orders are put together in an intensive way. Each customer order can involve different items and various numbers of items. In basic order picking procedure which is used when the coming orders are accumulated, each picker is assigned to only one order list and it is known that the products in this list are stored in different locations of the warehouse. Therefore, picker will look up every part of the warehouse in order to complete the list and will scan whether the items in the list exist or not. In this procedure, there are unnecessary transportation costs and utilization of ineffective workers. In another procedure, Zone picking method, the lists from different orders are arranged again (batch orders) and the same product types are determined because the products are stored in specific locations according to their types. With this method, order pickers are assigned to a specific zone. In this way, unproductive travel time will disappear. However, although this situation saves time and speed, these accumulated orders that come in different time from different pickers and with different line are collected in accumulation place in a completely mixed way. There is no doubt that these products have to be sorted according to the product type and amount which customer wants before sending them to the customer. At this point, sortation systems are used. Sortation strategies definitely affect sortation time. Furthermore, with both analytical and simulation methods, it will be checked whether the effects of these sortation strategies on different conveyor models are the same or not.

3.2 ORDER SELECTION PROCESS

Conveyor Sortation system's main functions are transportation, accumulation, identification, induction and separation of products. Besides, from literature point of view conveyor sortation systems divided by three essential subsystems: Order picking, Order accumulation and Sorting subsystem. Figure 3.1 represents the major functions in a warehouse.

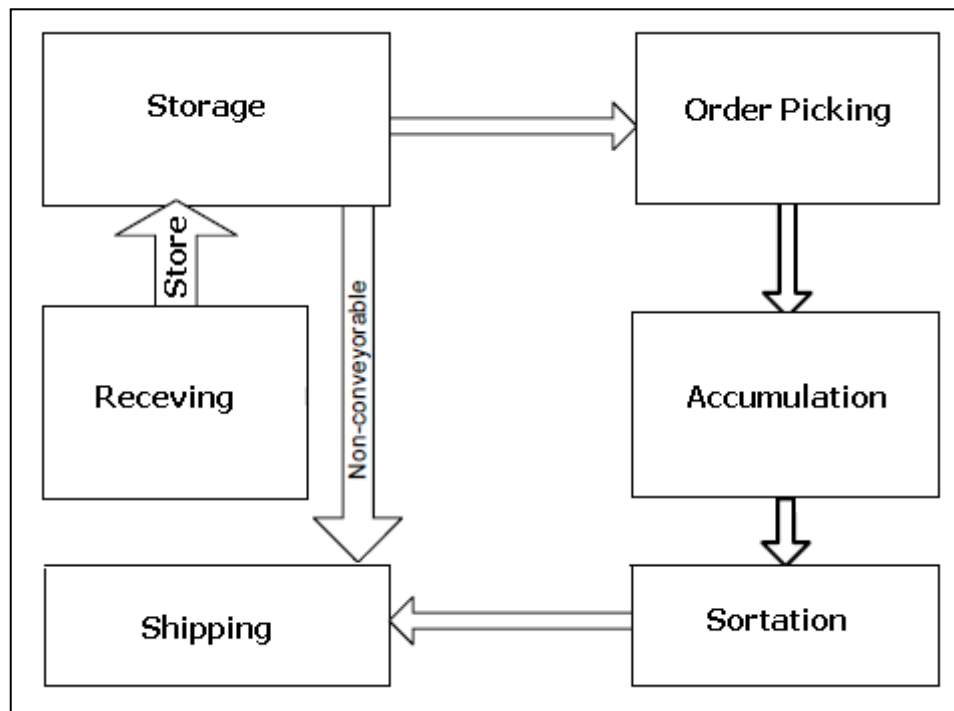


Figure 3.1 Warehouse's Functions

3.2.1 Order Picking Subsystem

3.2.1.1 Batch Picking:

In batch picking, a picker is responsible for many orders which are categorized according to a subset (zone) of SKUs. The batches from zones are combined then sorted to orders, destinations or specific carriers. Batch picking method is decided to use for order accumulation

3.2.1.2 Wave Picking:

A large-scale variation of batch picking is wave picking. Wave picking makes reference to the operation that the demands from large number of orders (50-100) are brought together and picked and carried to the conveyor as a batch. Wave picking is frequently useful in high volume distribution system where there are too many orders in progress. Additionally, wave picking is used when a set of orders which will be loaded to trucks that occupy all shipping doors. Wave picking moderates high picks per order. Due to different travel distances, different pick rates and the imbalance in the number of cases for a batch from each zone, some zones will finish early and others will finish late. In other words, lower utilization of the sorter towards the end of a wave and some pickers' inefficiency due to the idle time waiting for next wave to begin occur.

Synchronization issue should be taken into consideration in wave algorithm design. A wave algorithm determines how many orders to transmit in a wave. On the other hand, good Accumulation and Sortation system design and control can also improve the unbalanced situation.

3.2.2 Order Accumulation Subsystem

Accumulation subsystem is the conveyor system which gathers items and retrieves, accumulates, and prepares them before sortation. Its aim is to provide a constant wave of items to the conveyor system. Accumulation is used before sortation to arrange the peaks and valleys of the instantaneous input rates from different induction lanes.

These picked items are then combined with a line and sent out to the recirculation conveyor. Accumulation system is responsible for blending the incoming traffic from different sources into a main stream and handles the rate changes of the incoming traffic to succeed high sorter utilization.

Order Accumulation subsystem has high impact on the overall performance of the conveyor sortation system. First, accumulation system is responsible for the difficult task to achieve the uniform and high speed flow of items in the right sequence before sort. Secondly, Accumulation has large footprint. The waiting time on this subsystem explains large proportion of total cycle time. Thus, improving Accumulation subsystem efficiency has great potential in improving the order response time. Third, the motion and control of high speed flow are the most desired in technical terms. The construction and operating cost is very high in order to gain sophisticated accumulating and merging devices.

Design parameters of Accumulation system involve:

- Conveyor design
- Rate determination (Wave Algorithm)
- Accumulation design
- Material selection

Several considerations need to be taken into consideration in conveyor design such as one induction lane, many induction lanes and one sortation lane versus many sortation lanes.

Accumulation design needs to determine where to locate accumulation and how much the accumulation would be sufficient. Better accumulation design can provide balancing of peaks and valleys in the instantaneous loading rates on the conveyor so that high sorter utilization is achieved. Accumulation conveyor is much more expensive than traditional manual conveyor, so keep in the accumulation structure as low is desired, provided that it satisfies the operation requirements.

In Accumulation subsystem, there is a diversity of equipment offered to achieve the specific functionality. For example, one can prefer from wheel accumulation and live roller accumulation for accumulation and one can prefer from live roller merge, herringbone merge or sliding-shoe merge for merge. Usually, there is a maximum limit for each equipment group. Cost effective equipment should be chosen based on the item profile and rate requirements.

3.2.3 Sorting Subsystem

Sortation system sorts mixed orders or batches to appropriate shipment destinations. The sorting process involves identifying the item, tracking the item along its conveyor path destination and then physically transmitting the carton or packages to the appropriate destination. The function of the takeaway conveyor is to accept product diverted from the sorter conveyor so the sorter is not blocked.

Sortation systems were classified by (Bozer, 1988) for analysis aim into two types: S/PS-1 and S/PS-2 based on the relation between number of sortation lanes and number of orders.

In S/PS-1, the number of lanes is less than the number of orders. Direct customer order fulfillment systems, such as apparel industry, pharmacy industry, cargo industry, fall into this category. The items without lane assignment are re-circulated on the closed-loop conveyor. The major bottleneck of the S/PS-1 process is normally the recirculation loop.

In S/PS-2, the number of lanes is equal or more than the number of orders. Lanes are provided so that every incoming item will be assigned to a particular lane. Most retailer distribution centers serving stores within a certain region are inclined to this type of system. Recirculation occurs only when the corresponding lane is not empty or identification fails.

Several companies use both system types in their distribution facilities at the same time. Type 1 is used to sort the items into orders, while type 2 is used to sort the orders into shipments depending on the type of shipment required (UPS, FedEx, etc).

Design parameters of Sortation system involve:

- Number of sortation lanes
- The length of the sortation lane
- The length of the recirculation conveyor

Conveyor sortation system design should be taken into consideration in the overall warehouse design procedure because of its interrelationship with system requirement, warehouse layout, storage assignment and general flow template. Usually, several design iterations take place between sortation system design and a previous or subsequent step before the design gets finalized. In this research, the decisions made at conveyor sortation system design are concentrated.

3.3 SORTATION SYSTEM DESIGN

The sortation system is the core of the distribution operation. It has two main functions: the first one is to transmit the materials from the warehouse to the place where orders are prepared for shipment and loaded onto trucks, and the second one is sorting the boxes and sending them to the correct shipping lane. The sorting function is necessary since the picking function uses a wave approach. Using this wave approach, the pickers pick a group of orders simultaneously, instead of picking a single order at a time. If it is designed in a proper way, this approach saves much of the picker unproductive travel time. Each picker retrieves multiple orders per wave, so the challenge is to get the boxes in the right order in the shipping lane. The orders are sorted using a high-speed re-circulating conveyor (often referred to as a dog-track or closed-loop conveyor), and bar codes on the boxes that indicate their membership in a specific order of the wave and control system. As the boxes enter the re-circulating conveyor, a high-speed bar code scanner reads the label, passing the information on to the control system. The control system decides whether to divert the box into the proper shipping lane based on the order type and the congestion in the shipping lane. If the shipping lane is full or the box is for the wrong order, then, it is sent on a round trip of the re-

circulating conveyor, where the cycle is reinitiated. In designing the system, many different options to analyze, involving both physical changes and various control schemes are available. Physical considerations included the number of shipping lanes and number of the induction lanes, the length between two sortation lanes, the length of the re-circulating conveyor and the shipping lanes, and the speed of the re-circulating conveyor.

This study especially focuses on the various numbers of induction lanes (input lanes) and the sortation lanes (output lanes). Four different design models are constructed which are:

- One- One Model (one input versus one output)
- One-Many Model (one input versus many outputs)
- Many-One Model (many inputs versus one output)
- Many-Many Model (many inputs versus many outputs)

3.3.1 One-One Model

In this design model, one induction lane and one sortation lane is available. When the literature is evaluated thoroughly, it is observed that this model is the first applied model to the re-circulating conveyor. For instance, Bozer and Sharp (1985) have carried out this model in order to develop sortation strategies.

Mixed boxes picked from different pickers are loaded from one induction lane. While those are passing through in front of the scanner, labels which have the information about related customer are read. By the way, the sortation strategies, which will be applied, are defined before boxes are loaded. In this design, these boxes are sorted and sent to one sortation lane. Figure 3.2 demonstrates the model in a basic way.

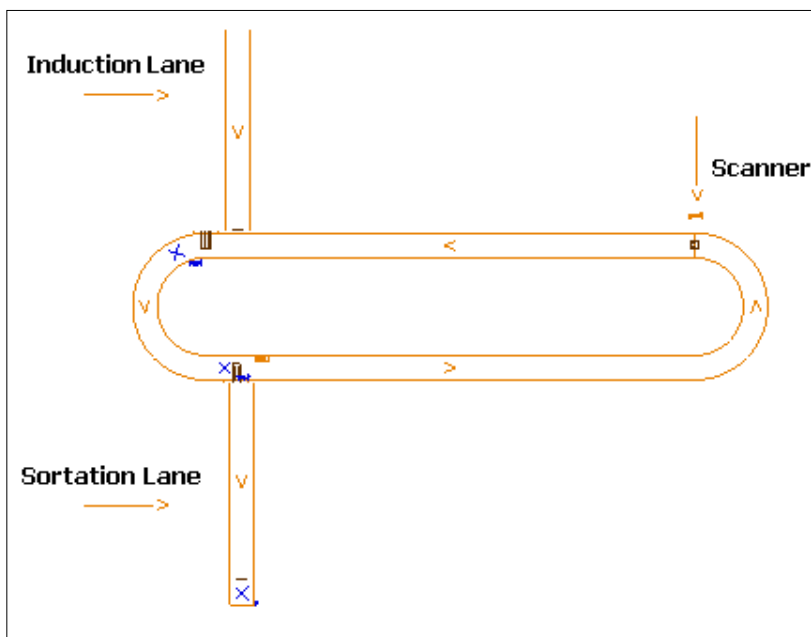


Figure 3.1 One- One Model Conveyor Design

3.3.2 One-Many Model

One –Many Model differs from previous model since it has more than one sortation lanes. When it is compared with others, this model is the most applied one. For instance, Johnson and Lofgren (1994), Johnson (1998), Meller (1997) have used this model in their studies.

If the company has a variety of product type, One-Many Model is more useful design to be applied. Namely, the wave size determines how many boxes are available on the re-circulating conveyor to be separated to the shipping lanes. However, if the re-circulating conveyor becomes too full, a grid-lock can occur. At the same time, boxes may take too many trips around the re-circulating conveyor (termed lapping) before being separated. These trips are called as lapping. In order to decrease lapping, the number of sortation lanes can be increased. It is the reason why this design is developed. Figure 3.3 demonstrates the model in a basic way:

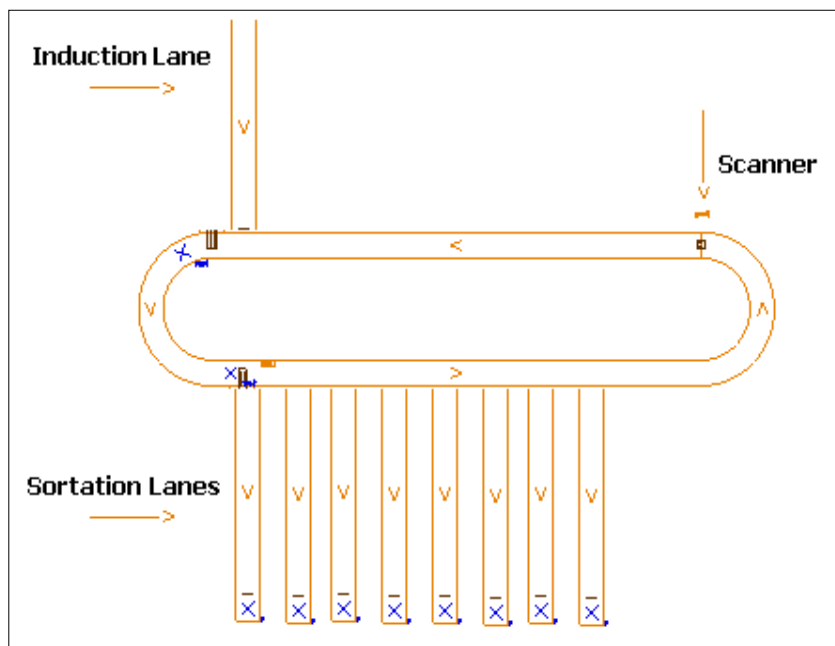


Figure 3.2 One- Many Model Conveyor Design

3.3.3 Many- One Model

In this model, there are more than one induction lanes whereas there is only one sortation lane. Until now, this model has not been observed in the previous studies. It is predicted that this model is not so different from One- One Model in total sorting time. The big difference from One-One Model might be that the package stream is more intensive. Figure 3.33.4 demonstrates the model in a basic way:

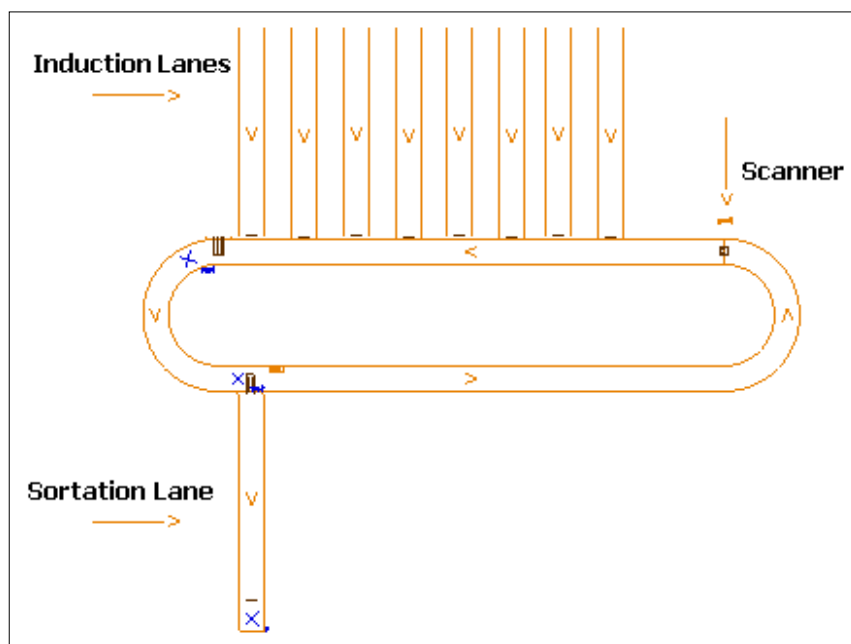


Figure 3.3 Many- One Model Conveyor Design

3.3.4 Many- Many Model

In this model, there are more than one sortation and induction lanes. Conveyor is designed with multiple sortation and multiple induction lanes in this design. Product range and customer range leads to waste of time both in loading of packages on the conveyor and in sortation. Accordingly, when product range and shipment range increases, this model might be applicable. Although adding one sortation lane can shorten the sortation time, it increases both construction cost and floor space cost. There is no doubt that it is a trade off. In their articles, Johnson and Meller (2002), Russell and Meller (2003) and Bozer (2004) carry out their analyses by using this model.

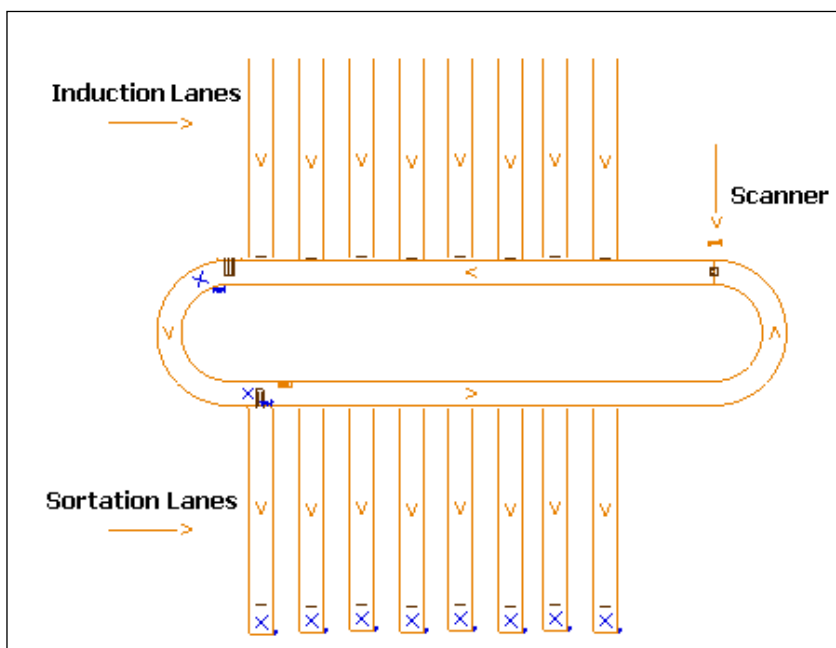


Figure 3.4 Many- Many Model Conveyor Design

CHAPTER 4

OPERATIONAL PARAMETERS AND MODELS

Design parameters, such as number of sortation lanes, conveyor type or length of the conveyor should be decided before the construction since a change in these parameters requires much more financial, labor resource and time. On the other hand, operational parameters are modified easily if it is compared with design parameters. Sortation strategies and item collection methods are the examples of operational parameters which are examined in detail.

4.1 ITEM COLLECTION METHODS

It is necessary that every product should be moved physically from one location to another, such as from manufacturers to end users or from supplier to production side within a logistics chain. During this process, they may be buffered or stored at specific places (warehouses) for a specific period of time. Many activities are executed in a warehouse. Among them, order-picking, which is the process of retrieving products from storage area (or buffer area) in response to a specific customer request or a batch order, is the most crucial activity. For a long time, it has been classified as a very labor rich operation in manual systems and a very capital rich operation in automated systems. It may consume a large part of all labor activities in the warehouse, and for a typical warehouse, the cost of order-picking is estimated to be as much as almost half of the total warehouse operating expense. For these reasons, warehousing professionals consider order-picking as the highest-priority activity for productivity improvements.

Batched orders are picked in a simultaneous way from different zones in the picking area by a group of pickers. After an order picker has completed a pick tour and all items of an order have been picked, the picked items are inducted on a conveyor and transported to the proper sortation lane and they are sorted and shipped.

In batch generation, orders -the requests from customers consisting of one or several items- arriving within a predetermined interval are arranged together in one batch for order pickers. Within a batch, orders are spread over the zones based on the storage locations or SKU. They are merged later at the accumulation area.

In picking operation, all batched items from the same zone are gathered by one order picker or a group of order picker. Each order picker is only responsible for at most one zone (zone picking) since each order picker can only pick a limited number of items in one pick route. The order picker starts a batch by obtaining a picking cart or pick lists (each is a list of items to be picked in one pick route) from a central location. After picking all required items, the order pickers convey them on the transportation conveyor, and go back to start a new batch. The transportation conveyor runs continuously to sort and move all picked items to the shipping lane.

4.2 SORTATION STRATEGIES

Sortation strategies can be classified into two families, fixed priority rules (FPR) and dynamic assignment rules. In fixed priority rules, the orders are prioritized before sortation based on a certain rule. Dynamic assignment rules are assignment strategies that consider the item locations on the conveyor. The most common examples of this family are the next available rule (NAR) and the earliest completion rule (ECR). Same assumptions are made to standardize the simulation analysis. Design models are based on the following assumptions:

- All packages are located onto conveyor before sorting
- The length of the sortation lane is long enough to hinder blocking
- The length of the induction lane is long enough to hinder blocking
- Conveyor speed is constant

- No overlapping of items
- Conveyor length is constant
- Number of items within a wave is the same.
- All sortation lanes are used in (1/M) and (M/M) Model

For this study, following notations are determined in order to make easy to understand design structure:

[a /s / m /y]: a induction lanes, s sortation lanes, m orders and y items

{ m; y } : m orders and y items

{ m; \bar{y} } : m orders and average of y items

All parameters are determined below:

Table 4.1 Parameters

y	<i>number of items within an order</i>
m	<i>number of orders within a wave</i>
L	<i>Length of the closed-loop conveyor</i>
v	<i>Speed of the conveyors</i>
T	<i>The time for an item to circulate around the main sortation line</i>
n	<i>Number of accumulation lanes</i>
i	<i>item index within an order</i>
j	<i>order index within a wave</i>
q	<i>the number of orders sorted thus far</i>

4.2.1 Fixed Priority Rule (FPR)

Sortation time evaluation by using Fixed Priority Rule is given follows. The number of accumulation lane is accepted as one and the number of items within the order is constant. The length of the track (closed-loop conveyor) is:

$$T = \frac{L}{v} \quad (1)$$

Supposed that the location of item i in the order j is uniformly distributed onto the conveyor Items will keep their positions on the conveyor throughout the sorting

process because closed-loop conveyors speed is constant. Thus sorting time is found from subtraction of the last item from the first item

The probability distribution function for the uniform distribution will be:

$$f_{l_{[j][1]}}(l) = \left(\frac{y}{T}\right) \left(1 - \frac{l}{T}\right)^{y-1} \quad 0 \leq l \leq T \quad (2)$$

The expected time for the first item to arrive sortation lane will be:

$$E(l_{[j][1]}) = \frac{T}{y+1} \quad (3)$$

In the same way, the probability distribution function of the last order statistic will be:

$$f_{l_{[j][y]}}(l) = \left(\frac{y}{T}\right) \left(\frac{l}{T}\right)^{y-1} \quad 0 \leq l \leq T \quad (4)$$

The expected location of the last item will be:

$$E(l_{[j][y]}) = \left(\frac{yT}{y+1}\right) \quad (5)$$

Thus, the expected time difference between the last item and first item will be:

$$E_{TS} = \frac{T(y-1)}{y+1} \quad (6)$$

Under FPR, the orders are ranked at the beginning of the sortation process. Two fixed priority rules which are commonly used in industry are smallest order first and largest order first. The expected disperse is the same for all orders since the location of the items in each order is independent from the other items of the other orders. Because of this reason, the index of $[j]$ is eliminated from the expression (5). The expected gap between order $[j-1]$ and following order $[j]$ is the expected difference between the position of the first box in order $[j]$ and the last box in previous order $[j-1]$.

$$E_{TG} = E(l_{[j][1]} - l_{[j-1][y]}) = \left(\frac{T}{y+1}\right) \quad (7)$$

Under FPR, The sorting time for all orders within the specific wave will be the summation of all the gaps and spreads as follows:

$$T_{FPR} = \frac{m.T.y}{y+1} \quad (8)$$

4.2.2 Next Available Rule (NAR)

In this Next Available Rule, the expected sorting time for each order is dependent of the number of orders which stays behind to be sorted. If it is supposed that the location of the items (l) in the remaining orders is independent and uniformly distributed, and q is the number of orders sorted thus further, then the following formulation shows the probability distribution function of the first box:

$$f_{l_{[q]}}(l) = \left(\frac{y(m-q)}{T} \right) \left(1 - \frac{l}{T} \right)^{y(m-q)-1} \quad 0 \leq l \leq T \quad (9)$$

The expected value of the gap between the last item of order $[q]$ and the next order which is given below:

$$E_{TG}(q) = \frac{T}{y(m-q)+1} \quad (10)$$

The expected location of the last item of the order $[q+1]$ is derived like that:

$$E(l_{[q+1][y]}) = T \left(1 - \frac{m-q}{y(m-q)+1} \right) \quad (11)$$

Additionally, the expected time difference between the last item and first item will be:

$$E_{TS} = T \left(1 - \frac{m-q+1}{y(m-q)+1} \right) \quad (12)$$

Under NAR, the sorting time for all orders within the specific wave will be as follows:

$$T_{NAR} = T \cdot \sum_{q=0}^{m-1} \left(1 - \frac{m-q}{y(m-q)+1} \right) \quad (13)$$

4.2.3 Earliest Completion Rule (ECR)

In dynamic assignment category, another sortation strategy model is Earliest Completion Rule (ECR). When sortation of an order is finished, the next order is determined based on the location of the last items. The order with the last item being closest to the accumulation lane is selected as next order to be sorted. Like NAR, the sortation time will be dependent on the number of orders which are going around on the main sortation lane. Assuming that all the items are randomly and uniformly distributed on the closed-loop conveyor and the item locations are independent of each other, from order statistics, the probability density function of the last item of an order (f_{l_y}) will be as following:

$$f_{l_y}(l) = \left(\frac{y}{T} \right) \left(\frac{l}{T} \right)^{y-1} \quad 0 \leq l \leq T \quad (14)$$

The cumulative distribution of l_y will be:

$$F_{l_y}(l) = \left(\frac{l}{T} \right)^y \quad 0 \leq l \leq T \quad (15)$$

The time of decision times comes for the next order; there are $m-q$ orders which are waiting to be sorted. Therefore, there will be $m-q$ last cartons which are distributed on the closed-loop conveyor with probability density function given by (14). Among these last cartons, the one with lowest l value which has the closest distance to accumulation lane will be selected. The probability density function of this smallest l value can be attained by using the first order statistics.

$$f_{l_y}^{m_q}(l) = (m-q) \cdot [1 - F_{l_y}]^{m-q-1} \cdot f_{l_y}$$

$$= (m-q) \cdot \frac{y}{T^y} \left[1 - \left(\frac{l}{T} \right)^y \right]^{m-q-1} l^{(y-1)} \quad 0 \leq l \leq T \quad (16)$$

The expected order sorting time $[q+1]$ can be found from the following statement:

$$E(l_{[q+1][y]}) = \frac{y(m-q)}{T^{y(m-q)}} \cdot \int_{l=0}^T [l^y \cdot (T^y - l^y)^{m-q-1}] dl \quad (17)$$

Therefore, in Earliest Completion Rule, the total wave sortation time is given:

$$T_{ECR} = \sum_{q=0}^{m-1} \left(\frac{y(m-q)}{T^{y(m-q)}} \cdot \int_{l=0}^T [l^y \cdot (T^y - l^y)^{m-q-1}] dl \right) \quad (18)$$

4.2.4 Examples about Sortation Strategies

A small example is given below to make sortation strategies easy to understand.

Suppose that the item arrival sequence at the induction point is

3 → 4 → 3 → 3 → 4 → 1 → 2 → 4 → 2 → 1 → 2 → 1

12 packages belong to 4 different orders and there is one unit time between them. Each number corresponds to a package showing the order that belongs to first package from order 1, then from order 2, then from order 1 again, etc.

For this small example;

Wave : 3 → 4 → 3 → 3 → 4 → 1 → 2 → 4 → 2 → 1 → 2 → 1

y: number of items within an order = 3

m: number of orders within a wave = 4 so the order configuration is {4; 3}.

4.2.4.1 Fixed Priority Rule Small Example (The oldest method)

Order	Sortation Time
1	7
2	11
3	6
4	12
Total	36

Table 4.2 Fixed Priority Rule Small Example in {4; 3} Design

3 → 4 → 3 → 3 → 4 → 1 → 2 → 4 → 2 → 1 → 2 → 1	(0. Step)
3 → 4 → 3 → 3 → 4 → 1 → 2 → 4 → 2 → 1 → 2 → 1	(1. Step)
3 → 4 → 3 → 3 → 4 → 2 → 4 → 2 → 2	(2. Step)
3 → 4 → 3 → 3 → 4 → 4	(3. Step)
4 → 4 → 4	(4. Step)

4.2.4.1 Next Available Rule Small Example

Order	Sortation Time
1	7
4	10
2	11
3	8
Total	36

Table 4.3 Next Available Rule Small Example in {4; 3} Design

3 → 4 → 3 → 3 → 4 → 1 → 2 → 4 → 2 → 1 → 2 → 1	(0. Step)
3 → 4 → 3 → 3 → 4 → 1 → 2 → 4 → 2 → 1 → 2 → 1	(1. Step)
3 → 4 → 3 → 3 → 4 → 2 → 4 → 2 → 2	(2. Step)
3 → 3 → 3 → 2 → 2 → 2	(3. Step)
3 → 3 → 3	(4. Step)

4.2.4.1 Earliest Completion Rule Small Example

Order	Sortation Time
2	6
3	6
1	7
4	10
Total	29

Table 4.4 Earliest Completion Rule Small Example in {4; 3} Design

3 → 4 → 3 → 3 → 4 → 1 → 2 → 4 → 2 → 1 → 2 → 1	(0. Step)
3 → 4 → 3 → 3 → 4 → 1 → 2 → 4 → 2 → 1 → 2 → 1	(1. Step)
3 → 4 → 3 → 3 → 4 → 1 → 4 → 1 → 1	(2. Step)
4 → 1 → 4 → 1 → 1	(3. Step)
4 → 4 → 4	(4. Step)

Sortation strategies and item collection methods are investigated in depth above. However, operational parameters do not only include them. Other operational parameters are as following;

- Number of Orders within a wave
- Conveyor Speed
- Order assignment specific lane before sorting
- Wave Algorithm

CHAPTER 5

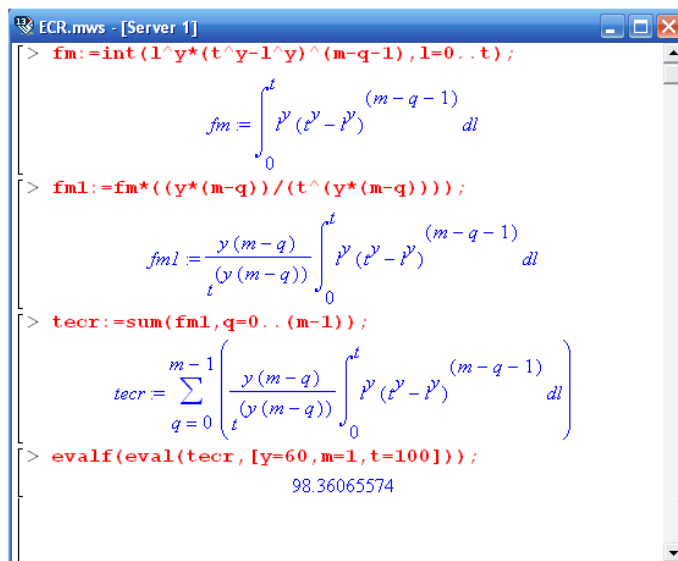
EXPERIMENTATION

In chapter 4, the models of sortation strategies are worked through deeply. However, effect of strategies for different situation and comparison of strategies were not discussed in previous chapter. On the other hand, in this chapter, by taking various design structures and order configurations, analytical and simulation analysis will be done.

5.1 ONE-ONE MODEL

5.1.1 Analytical Model

To compare ECR, FPR and NAR, an empirical method is used. In developing the analytical models, several assumptions are made to facilitate the analysis. To illustrate the expressions for the three sorting strategies, the time to traverse the re-circulating conveyor is $T = 100$ seconds. For analytical model experimentations MAPPLE software is used.



```
ECR.mws - [Server 1]
> fm:=int(1^y*(t^y-1^y)^(m-q-1),l=0..t);

$$f_m = \int_0^t \lambda^y (t^y - \lambda^y)^{(m-q-1)} dl$$

> fm1:=fm*((y*(m-q))/(t*(y*(m-q))));

$$f_{m1} = \frac{y(m-q)}{t(y(m-q))} \int_0^t \lambda^y (t^y - \lambda^y)^{(m-q-1)} dl$$

> tecr:=sum(fm1,q=0..(m-1));

$$tecr = \sum_{q=0}^{m-1} \left( \frac{y(m-q)}{t(y(m-q))} \int_0^t \lambda^y (t^y - \lambda^y)^{(m-q-1)} dl \right)$$

> evalf(eval(tecr,[y=60,m=1,t=100]));
98.36065574
```

Figure 5.1 MAPPLE Software screenshot

Table 5.1 shows the sorting time for each order and the overall wave sorting time. The order sorting times are listed according to the sequence in which the orders were sorted.

Table 5.1 Sorting Times for Numerical Examples in {10; 5} Design

Sorting Sequence (Order number)	Order Sorting time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
1	83.33	80.39	57.26	1.67	1.61	1.15
2	83.33	80.43	58.4	1.67	1.61	1.17
3	83.33	80.49	59.7	1.67	1.61	1.19
4	83.33	80.56	61.19	1.67	1.61	1.22
5	83.33	80.65	62.94	1.67	1.61	1.26
6	83.33	80.77	65.04	1.67	1.62	1.30
7	83.33	80.95	67.64	1.67	1.62	1.35
8	83.33	81.25	71.02	1.67	1.63	1.42
9	83.33	81.82	75.76	1.67	1.64	1.52
10	83.33	83.33	83.33	1.67	1.67	1.67
Total	833.3	810.64	662.29	16.67	16.21	13.25

In this example, single accumulation lane configuration is used. The results of this set of experiments can be examined clearly in Figure 5.22. Surely, great savings can be achieved in total sortation time by using ECR. Especially, for the first three orders, ECR provides a great savings.

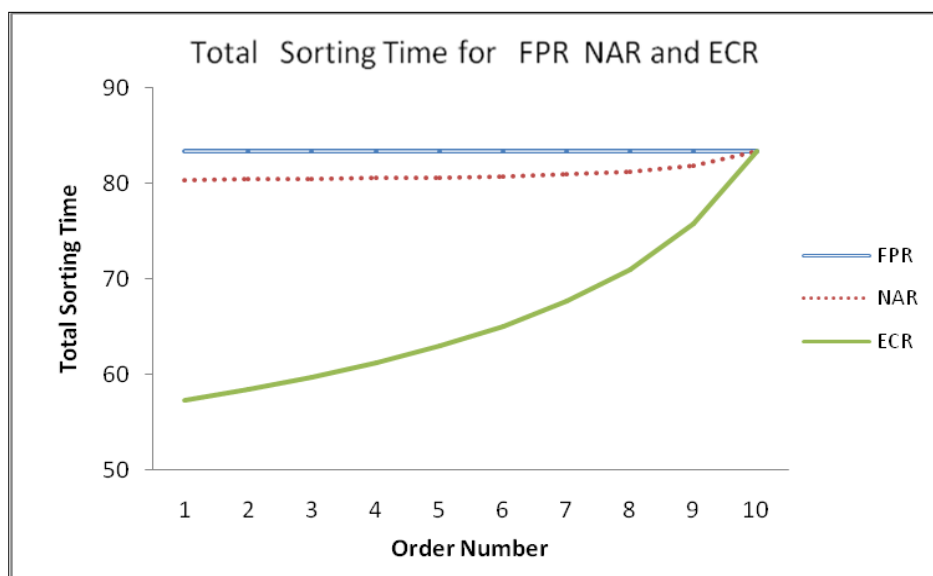
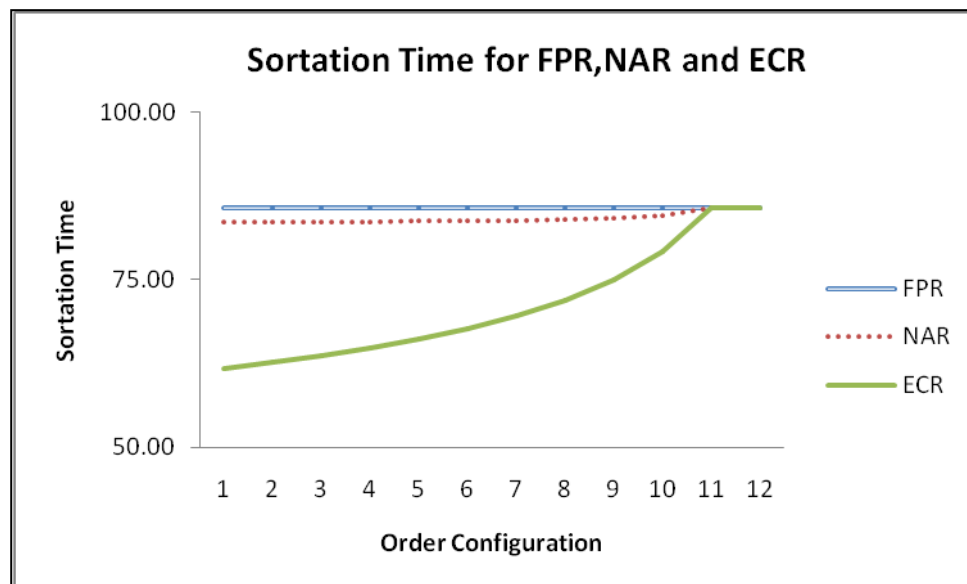


Figure 5.2 Sorting Times for Numerical Examples {10; 5}

Table 5.2 Sorting Times for Numerical Examples in {12; 6} Design

Sorting Sequence (Order number)	Order Sorting time (seconds)			Time Per Package (second)		
	FPR	NAR	ECR	FPR	NAR	ECR
1	85.71	83.58	61.67	1.19	1.16	0.86
2	85.71	83.61	62.61	1.19	1.16	0.87
3	85.71	83.64	63.65	1.19	1.16	0.88
4	85.71	83.67	64.83	1.19	1.16	0.90
5	85.71	83.72	66.18	1.19	1.16	0.92
6	85.71	83.78	67.76	1.19	1.16	0.94
7	85.71	83.87	69.64	1.19	1.16	0.97
8	85.71	84.00	71.96	1.19	1.17	1.00
9	85.71	84.21	74.96	1.19	1.17	1.04
10	85.71	84.62	79.12	1.19	1.18	1.10
11	85.71	85.71	85.71	1.19	1.19	1.19
12	85.71	85.71	85.71	1.19	1.19	1.19
Total	1028.57	1010.13	853.79	14.29	14.03	11.86

Same experimentation is repeated by using 12 orders with 6 items. Similarly, ECR provides much more time saving than other strategies.

**Figure 5.3** Sorting Times for Numerical Examples {12; 6}

Besides, different numbers of items and orders combinations are designed in order to comprehend the sortation strategies behavior for various situations. Table 5.3 presents the results of strategies.

Table 5.3 Sorting Times for Numerical Examples in {48; 1} Design

Orders / Wave	Items / Orders	Wave Sorting Time (seconds)			Time Per Package (seconds)		
		FPR	NAR	ECR	FPR	NAR	ECR
48	1	2400	347.7	347.7	50.00	7.24	7.24
24	2	1600	1279.6	690.7	33.33	26.66	14.39
16	3	1200	1099.5	741.4	25.00	22.91	15.45
12	4	960	917.3	700.1	20.00	19.11	14.59
8	6	685.7	673.6	580.2	14.29	14.03	12.09
6	8	533.3	528.6	481.2	11.11	11.01	10.03
4	12	369.2	368	351.6	7.69	7.67	7.33
3	16	282.4	281.9	274.8	5.88	5.87	5.73
2	24	192	191.9	190	4.00	4.00	3.96
1	48	98	98	98	2.04	2.04	2.04

In Figure 5.4, ECR's total sorting time is the least one in every case. At the same time, when the range of order increases, sortation times become closer to each other.



Figure 5.4 Sorting Time Comparison by Using Analytical Model {48; 1}

Furthermore, 12 combinations are laid out for {60; 1} order configuration. Table 5.4 presents the results of strategies:

Table 5.4 Sorting Time Comparison by Using Analytical Model {60; 1}

Orders / Wave	Items / Orders	Wave Sorting Time (seconds)			Time Per Package (seconds)		
		FPR	NAR	ECR	FPR	NAR	ECR
60	1	3000	369.9	369.6	50.00	6.17	6.16
30	2	2000	1584.9	790.8	33.33	26.42	13.18
20	3	1500	1368.5	875	25.00	22.81	14.58
15	4	1200	1143.7	839.2	20.00	19.06	13.99
12	5	1000	971.3	773.8	16.67	16.19	12.90
10	6	857.1	840.8	706.4	14.29	14.01	11.77
6	10	543.5	542.3	502	9.06	9.04	8.37
5	12	461.5	459.8	434.7	7.69	7.66	7.25
4	15	375	374.2	360.5	6.25	6.24	6.01
3	20	285.7	285.4	279.5	4.76	4.76	4.66
2	30	193.5	193.5	192	3.23	3.23	3.20
1	60	98.4	98.4	98.4	1.64	1.64	1.64

In this experiment, the same outcomes are emerged as well. ECR strategy is the best one in the whole situation. The results of different scenarios according to three sortation strategies are presented in Figure 5.5.

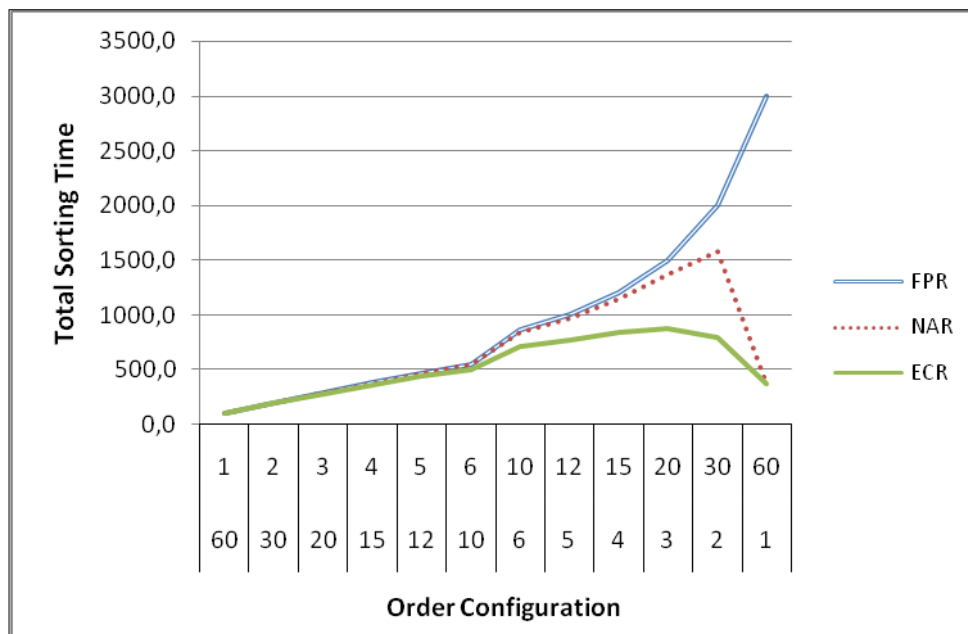


Figure 5.5 Sorting Time Comparison by Using Analytical Model {60; 1}

Table 5.5 Sorting Time Comparison by Using Analytical Model {10; 10}

Orders/ Wave	Items / Orders	Wave Sorting Time (seconds)			Time Per Package (seconds)		
		FPR	NAR	ECR	FPR	NAR	ECR
1	10	90.91	90.91	90.91	9.09	9.09	9.09
2	10	181.82	181.39	177.49	9.09	9.07	8.87
3	10	272.73	271.71	261.28	9.09	9.06	8.71
4	10	363.64	361.95	343.02	9.09	9.05	8.58
5	10	454.55	452.15	423.16	9.09	9.04	8.46
6	10	545.45	542.31	501.99	9.09	9.04	8.37
7	10	636.36	632.45	579.70	9.09	9.04	8.28
8	10	727.27	722.58	656.46	9.09	9.03	8.21
9	10	818.18	812.69	732.38	9.09	9.03	8.14
10	10	909.09	902.78	807.54	9.09	9.03	8.08

In this example, item size is fixed while order size is increasing step by step to understand the behavior of strategies. ECR is the best strategies for all case.

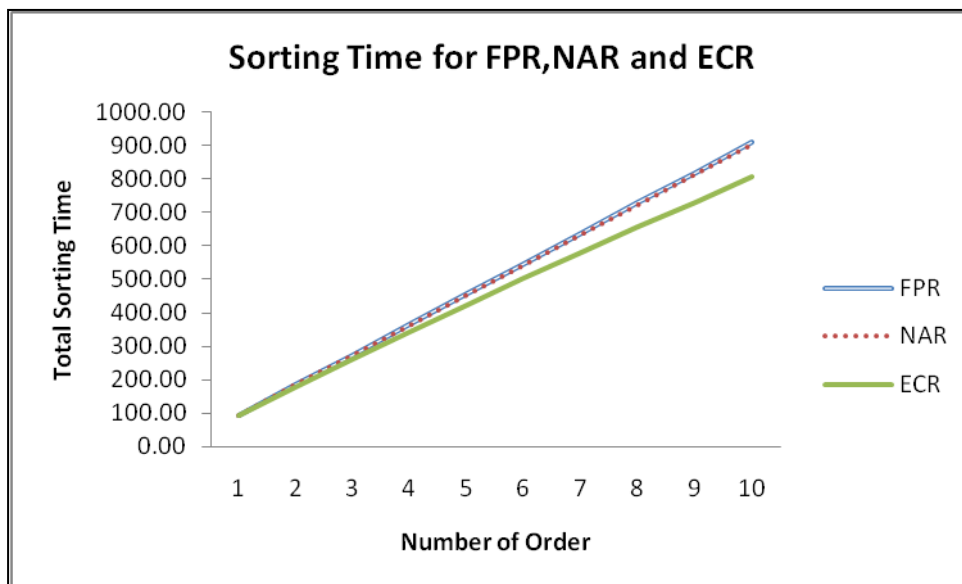
**Figure 5.6** Sorting Time Comparison by Using Analytical Model {10; 10}

Table 5.6 Sorting Time Comparison by Using Analytical Model {20; 5}

Orders/ Wave	Items / Orders	Wave Sorting Time (seconds)			Time Per Package (seconds)		
		FPR	NAR	ECR	FPR	NAR	ECR
1	5	83.33	83.33	83.33	16.67	16.67	8.33
2	5	166.66	165.15	159.09	16.67	16.52	15.91
3	5	249.99	246.40	230.11	16.67	16.43	15.34
4	5	333.32	327.35	297.75	16.67	16.37	14.89
5	5	416.65	408.12	362.79	16.67	16.32	14.51
6	5	499.98	488.77	425.73	16.67	16.29	14.19
7	5	583.31	569.32	486.93	16.67	16.27	13.91
8	5	666.64	649.81	546.63	16.67	16.25	13.67
9	5	749.97	730.25	605.03	16.67	16.23	13.45
10	5	833.30	810.64	662.29	16.67	16.21	13.25
11	5	916.63	891.00	718.52	16.67	16.20	13.06
12	5	999.96	971.32	773.83	16.67	16.19	12.90
13	5	1083.29	1051.63	828.31	16.67	16.18	12.74
14	5	1166.62	1131.91	882.02	16.67	16.17	12.60
15	5	1249.95	1212.17	935.02	16.67	16.16	12.47
16	5	1333.28	1292.42	987.36	16.67	16.16	12.34
17	5	1416.61	1372.65	1039.10	16.67	16.15	12.22
18	5	1499.94	1452.87	1090.27	16.67	16.14	12.11
19	5	1583.27	1533.08	1140.91	16.67	16.14	12.01
20	5	1666.60	1613.28	1191.04	16.67	16.13	11.91

Previous experimentation is done again with 5 items. ECR is the best strategy for the whole case. At the same time, the difference between strategies is increasing when order size increases.

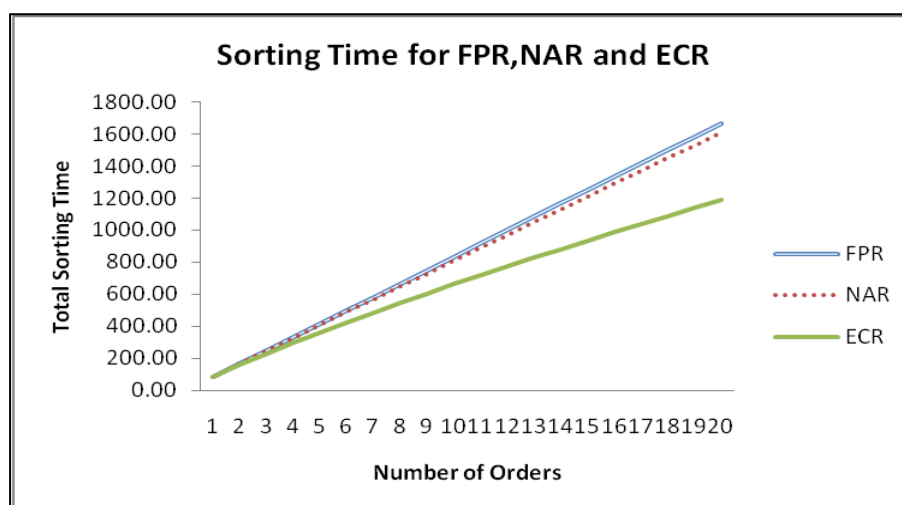
**Figure 5.7** Sorting Time Comparison by Using Analytical Model {20; 5}

Table 5.7 Sorting Time Comparison for [1/1/10/5] Using Simulation Model

Model	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
One-One Model	2248.78	2179.25	1841.70	44.98	43.59	36.83

5.1.3 Simulation Model versus Analytic Model

Simulation model and Analytical model outputs, according to different scenarios are illustrated in Table 5.8.

Table 5.8 Sorting Time Comparison in Analytical Model {24; 1}

Orders/ Wave	Items/ Orders	Wave Sorting Time (seconds)			Time Per Package (seconds)		
		<i>Analytical Model</i>			<i>Analytical Model</i>		
		FPR	NAR	ECR	FPR	NAR	ECR
24	1	2676	214	214	111.50	8.92	8.92
12	2	1784	1478	992	74.33	61.58	41.33
8	3	1338	1246	974	55.75	51.92	40.58
6	4	1070	1033	878	44.58	43.04	36.58
4	6	765	754	695	31.88	31.42	28.96
3	8	595	591	563	24.79	24.63	23.46
2	12	412	411	403	17.17	17.13	16.79
1	24	214	214	214	8.92	8.92	8.92

Table 5.9 Sorting Time Comparison in Simulation Model {24; 1}

Orders/ Wave	Items/ Orders	Wave Sorting Time (seconds)			Time Per Package (seconds)		
		<i>Simulation Model</i>			<i>Simulation Model</i>		
		FPR	NAR	ECR	FPR	NAR	ECR
24	1	2915	442	442	121.46	18.42	18.42
12	2	2033	1724	1484	84.71	71.83	61.83
8	3	1574	1507	1268	65.58	62.79	52.83
6	4	1298	1279	1120	54.08	53.29	46.67
4	6	1003	991	920	41.79	41.29	38.33
3	8	823	829	792	34.29	34.54	33.00
2	12	640	643	634	26.67	26.79	26.42
1	24	442	442	442	18.42	18.42	18.42

The following two figures, Figure 5.9 and Figure 5.10 display analytical and simulation model outputs. Both figures are similar and ECR model distinctly has the smallest total sortation time so it is the best one.

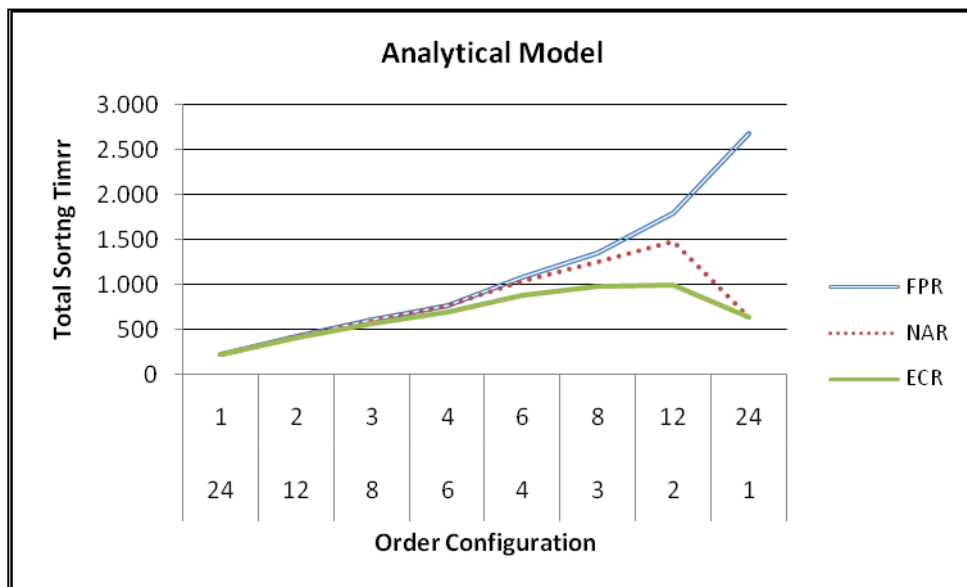


Figure 5.9 Analytical Model Result {24; 1}

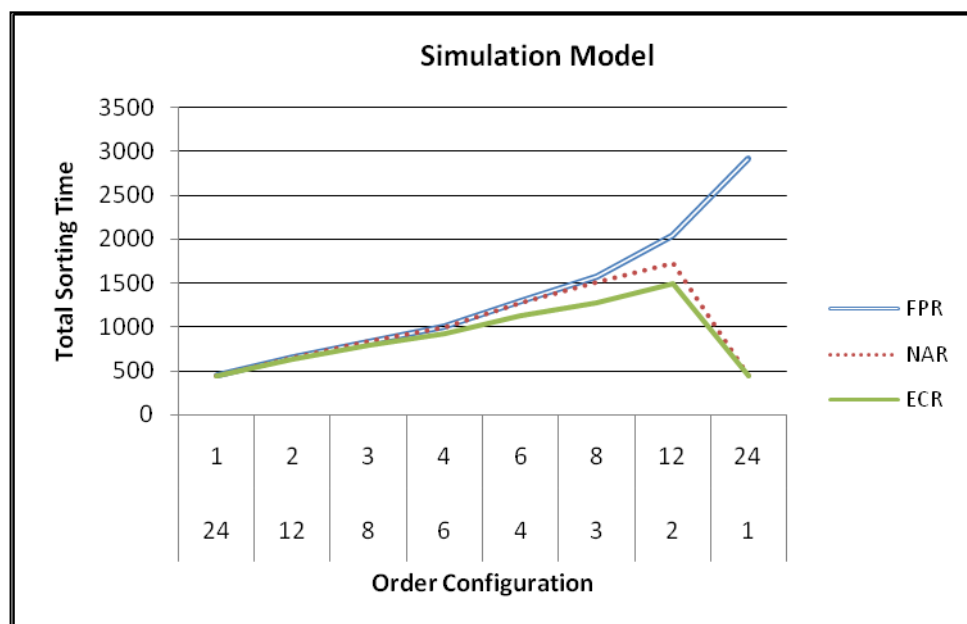


Figure 5.10 Simulation Model Result {24; 1}

It can be realized above Table 5.9 that the results of Simulation Model are greater than Analytical Model in every case. The reason of this is that in simulation model, there are some additional times spent. The following shape points out spending time locations on the simulation system.

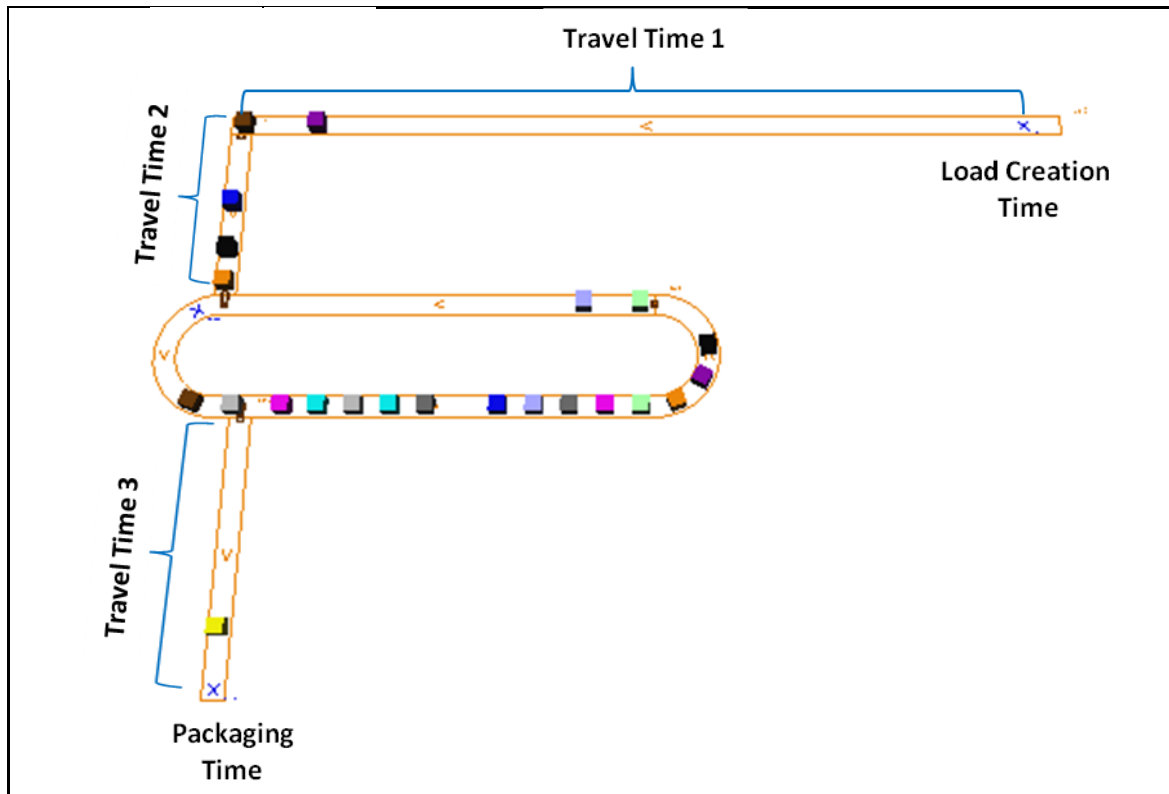


Figure 5.11 Extra Times Spending for Simulation

In Table 5.10, there are averages of extra time for each spending point which are shown in preceding shape. Besides, if subtraction is taken from simulation model to analytical model, the average difference is approximately 248 seconds. Also, summation of the extra spending time is 238.86 seconds. Thus, it can be said that these two numbers are too close to each other.

Table 5.10 Time Differences between Simulation and Analytical Model {24; 1}

Orders/ Wave	Items/ Orders	Wave Sorting Time (seconds) <i>Simulation Model</i>			Wave Sorting Time (seconds) <i>Analytical Model</i>			Difference Time (seconds)		
		FPR	NAR	ECR	FPR	NAR	ECR	FPR	NAR	ECR
24	1	2915	442	442	2676	214	214	239	228	228
12	2	2033	1724	1484	1784	1478	992	249	246	492
8	3	1574	1507	1268	1338	1246	974	236	261	294
6	4	1298	1279	1120	1070	1033	878	228	246	242
4	6	1003	991	920	765	754	695	238	237	225
3	8	823	829	792	595	591	563	228	238	229
2	12	640	643	634	412	411	403	228	232	231
1	24	442	442	442	214	214	214	228	228	228
Average of Difference								234	239	271

Table 5.11 Sort of Spending Time for Simulation {24; 1}

Spending Time	Duration
Travel Time 1	49.5
Travel Time 2	29.76
Travel Time 3	35.2
Load Creation time	69.7
Packaging Time	50.7
Transfer Time	4.0
Total Time	238.86

5.2 ONE-MANY MODEL

5.2.1 Simulation Model

To compare ECR, FPR and NAR considering One-Many Model, a simulation method is used as well. Same assumptions are made to facilitate the simulation analysis like One-One Model. For instance, the time to traverse the re-circulating conveyor is $T = 222, 8$ seconds. One induction lane is available whereas eight sortation lanes are constructed. A hundred snaps are repeated as well for this design. Figure 5.12 is the screenshot of the Automod software for One-Many Design Model.

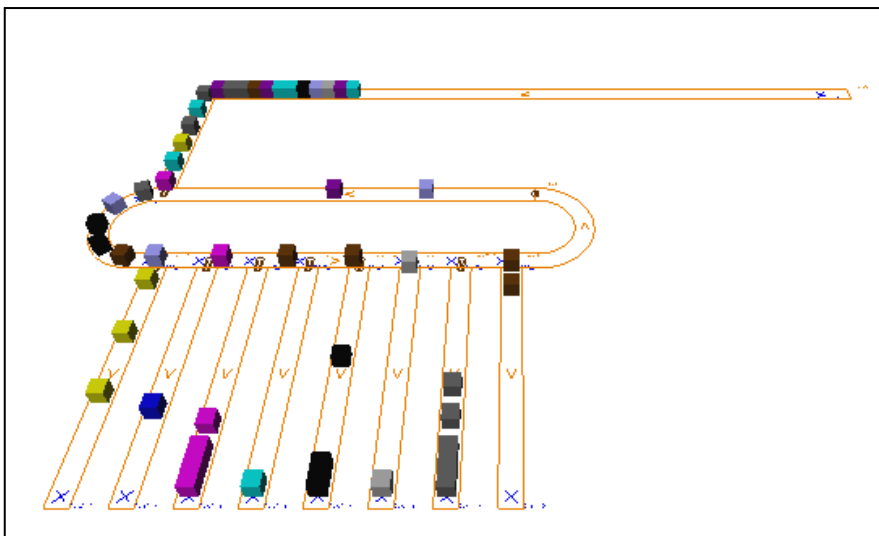
**Figure 5.12** One-Many Design Model Simulation Screenshot

Table 5.12 presents the total sorting time according to sortation strategies when considering the One-Many Model. As it can be seen clearly, the best one is ECR model as One-Many Model since the lowest value which emphasizes the average of the total sorting time is for ECR model.

Table 5.12 Sorting Time Comparison by Using Simulation Model [1/8/10/5]

Model	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
One-Many Model	690.61	678.72	651.21	13.81	13.57	13.02

5.3 MANY-ONE MODEL

5.3.1 Simulation Model

This model does not differ from One- One Model in total sorting time. The big difference from One-One Model is that the package stream is more intensive. In other words, if the speed of the wave is increased, an intensive situation is faced with.

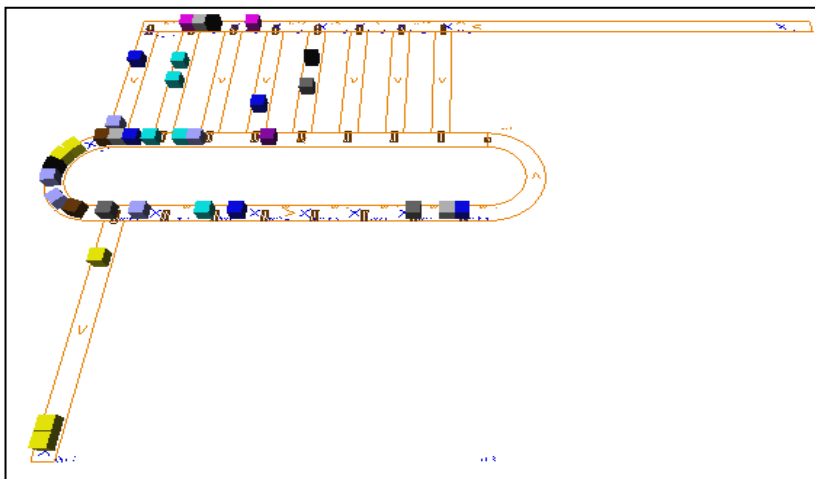


Figure 5.13 Many-One Design Model Simulation Screenshot

Table 5.13 Sorting Time Comparison by Using Simulation Model [8/1/10/5]

Model	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
Many-One Model	2,017.72	2,045.25	2,096.48	40.35	40.91	41.93
One-One Model	2,248.78	2,179.25	1,841.70	44.98	43.59	36.83

Table 5.13 demonstrates the total sorting time according to sortation strategies when considering the Many-One Model. As it can be seen clearly, the best one is FPR. Also, the values of both models are similar to each other.

5.4 MANY-MANY MODEL

To compare ECR, FPR and NAR considering Many-Many Model, a simulation method is used as well. Same assumptions are made to facilitate the simulation analysis like other both design. For instance, the time to traverse the re-circulating conveyor is $T = 222, 8$ seconds. Eight induction lane and sortation lane are designed. A hundred snaps are repeated as well for this design. Figure 5.14 is the screenshot of the Automod software for Many-Many Design Model.

5.4.1 Simulation Model

For Many-Many Model, firstly, following structure in Figure 5.20 was considered. Although eight induction lanes are located as it can be seen, the outcomes of the simulation model are completely the same with One-Many Model since all packages are coming from just one canal. Then, these packages are divided into distinct induction lanes randomly. Thus, according to arrival time of packages even if they come from different induction lanes, they are located onto conveyor at the same order.

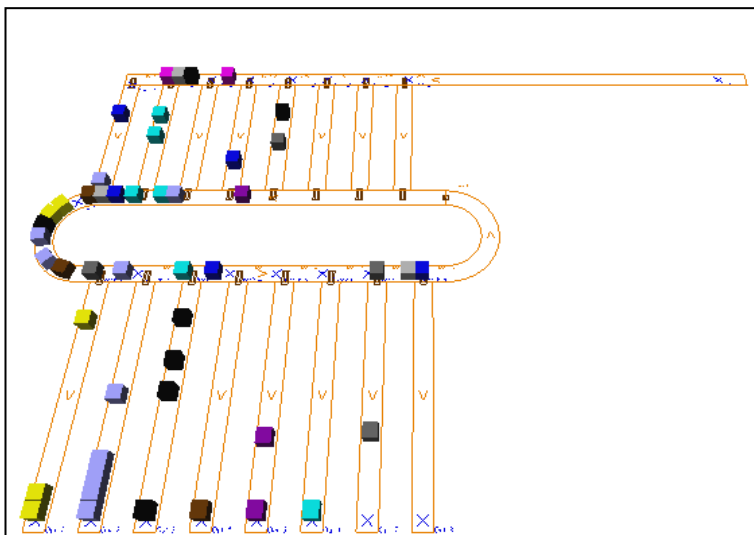


Figure 5.14 Many-Many Design Model Simulation Screenshot (Before)

Therefore, a new structure is designed which is that eight induction lanes are separated from each other and it is demonstrated below in Figure 5.15.

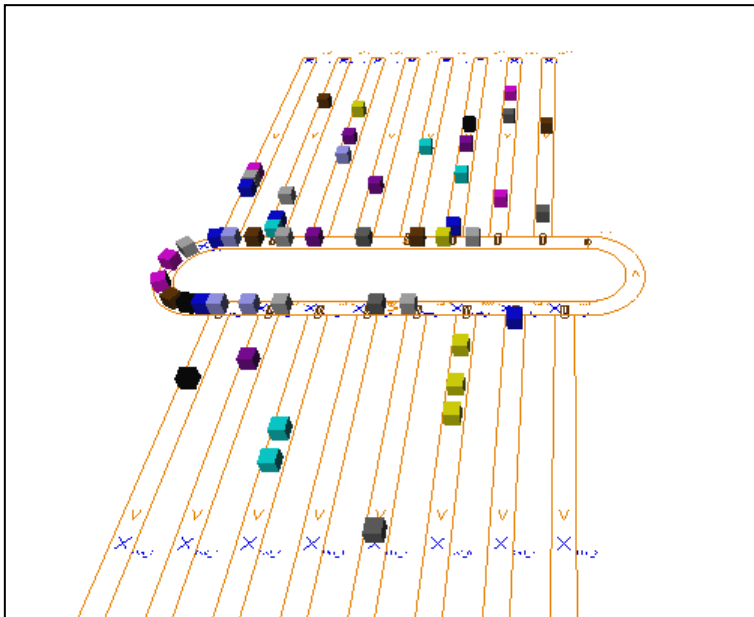


Figure 5.15 Many-Many Design Model Simulation Screenshot (After)

Table 5.14 presents the total sorting time according to sortation strategies when considering the Many-Many Model. As it can be seen clearly, the best one is FPR model. Since, the lowest value which emphasizes the average of the total sorting time is belongs to FPR strategy unlike other two strategies. Even though total sorting times for all sortation strategies have close to each other. The cause of this situation is that determination rules before sort provides timesaving.

Table 5.14 Sorting Time Comparison by Using Simulation Model [8/8/10/5]

Model	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
Many-Many Model	538.77	550.58	564.08	10.78	11.01	11.28

5.5 SCENARIOS

In this part, four models with various numbers of orders and items within a wave, size of items in an order, number of sortation lanes, distance between sortation lanes and so forth are simulated.

5.5.1. Number of Orders versus Number of Items

Various experiments for different numbers of items and order combinations are rerun. The results of this set of experiments are listed in Table 5.15.

Table 5.15 Total Sorting Time for {24; 1} order Configuration in (1/1) Model

Orders/ Wave	Items/ Orders	Wave Sorting Time (seconds)			Time Per Package (seconds)		
		FPR	NAR	ECR	FPR	NAR	ECR
24	1	2915.41	441.80	441.80	121.48	18.41	18.41
12	2	2032.74	1723.56	1484.25	84.70	71.82	61.84
8	3	1574.19	1506.52	1268.18	65.59	62.77	52.84
6	4	1297.91	1279.31	1119.80	54.08	53.30	46.66
4	6	1003.05	990.58	919.74	41.79	41.27	38.32
3	8	822.74	828.92	792.45	34.28	34.54	33.02
2	12	639.51	642.73	634.12	26.65	26.78	26.42
1	24	441.80	441.80	441.80	18.41	18.41	18.41

As can be seen in Figure 5.16, great savings can be accomplished in total sortation time for every experiment by using ECR.

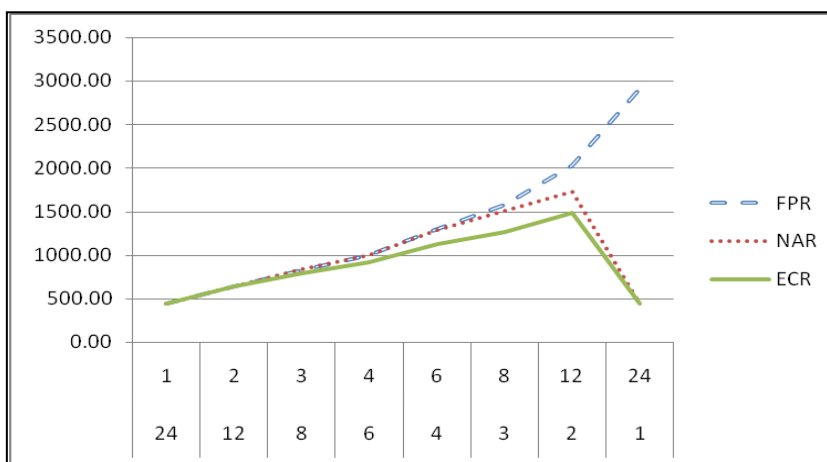


Figure 5.16 Total Sorting Time for {24; 1} order Configuration in (1/1) Model

Table 5.16 Total Sorting Time for {48; 1} order Configuration in (1/M) Model

Orders/ Wave	Items/ Orders	Wave Sorting Time (seconds)			Time Per Package (seconds)		
		FPR	NAR	ECR	FPR	NAR	ECR
12	4	714.03	694	675	14.88	14.46	14.06
16	3	769	787	704	16.02	16.40	14.67
24	2	874	857	749	18.21	17.85	15.60
48	1	1091	536	536	22.73	11.17	11.17

As can be seen in Figure 5.17, great savings can be accomplished in total sortation time for every experiment by using ECR.

**Figure 5.17** Total Sorting Time for {48; 1} order Configuration in (1/M) Model

Table 5.17 Total Sorting Time for {24; 1} order Configuration in (M/M) Model

Orders/ Wave	Items/ Orders	Wave Sorting Time (seconds)			Time Per Package (seconds)		
		FPR	NAR	ECR	FPR	NAR	ECR
24	1	607.07	473.86	377.85	25.29	19.74	15.74
12	2	545.85	470	396.23	22.74	19.58	16.51
8	3	484.63	450	384.24	20.19	18.75	16.01
6	4	397.1	404.54	383.46	16.55	16.86	15.98
4	6	397.06	395.07	380.11	16.54	16.46	15.84

As it can be seen in Figure 5.18, great savings can be accomplished in total sortation time for every experiment by using ECR.

**Figure 5.18** Total Sorting Time for {24; 1} order Configuration in (M/M) Model

5.5.2. Random and Equal Number of Items in the Order

Previous studies assumed that number of item in an order are same. For Example, In Johnson (1998)'s article an assumed item number is $y=5$ for every case. In practice, it is known that it does not possible all the time. Item number might vary from one order to another order. The following two MINITAB software outputs are showed below and random item size, which is more realistic, fits normal distribution rather than equal item size.

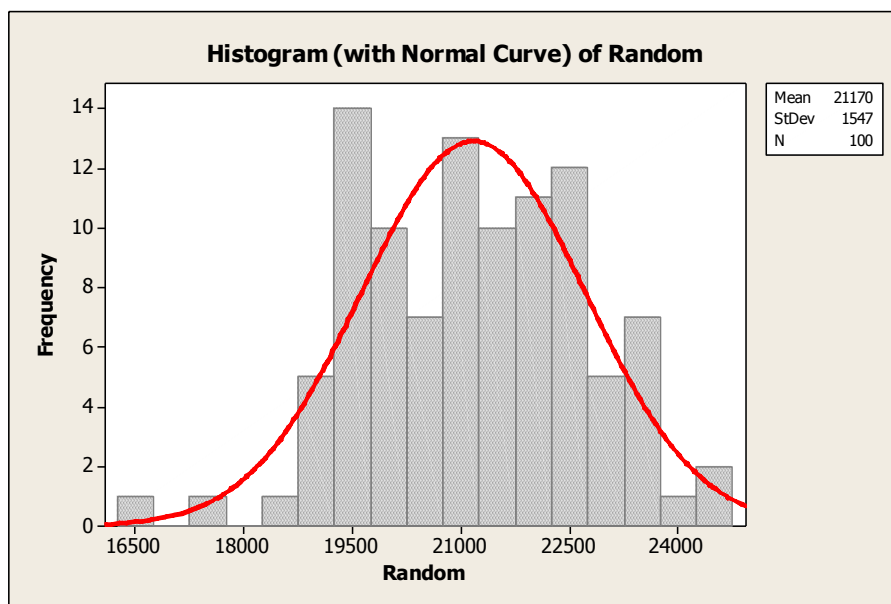


Figure 5.19 Histogram of Random Items

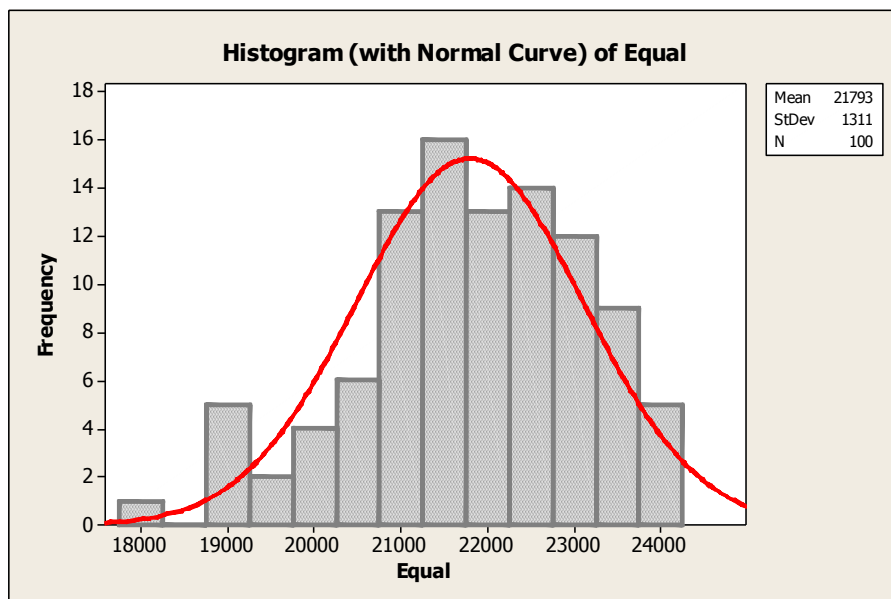


Figure 5.20 Histogram of Equal Items

In order to examine the effect of random or equal item size for each model type based on sortation strategies, simulation model is rerun for 18 times. The results of this set of experiments are listed in Table 5.18, Table 5.19 and Table 5.20.

Table 5.18 Sorting Time Comparison of Sorting Strategies According to O-OM

Number of Item	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
Random	2142.65	2116.97	1818.30	42.85	42.34	36.37
Equal	2248.78	2179.25	1841.70	44.98	43.59	36.83

Table 5.19 Sorting Time Comparison of Sorting Strategies According to O-MM

Number of Item	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
Random	668.95	650.04	636.46	13.38	13.00	12.73
Equal	690.61	678.72	651.21	13.81	13.57	13.02

Table 5.20 Sorting Time Comparison of Sorting Strategies According to M-MM

Number of Item	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
Random	518.60	523.18	602.91	10.37	10.46	12.06
Equal	538.77	550.58	564.08	10.78	11.01	11.28

In Tables 5.18, 5-19 and 5-20, random item size provides more time saving than equal item size and additionally, it does not reflect reality. Consequently, it can be assumed that each order has equal items while making design. In this way, that design would be made according to the worst scenario.

5.5.3. Various Number of Sortation Lane

In One- Many Model and Many-Many Model, eight sortation lanes are taken for the whole analysis. No doubt that the number of sortation lanes affects the total sortation time. Therefore, in order to measure the effects of sortation lane, a total of 24 different experimentations are examined. The results of this set of experiments are listed in Table 5.21.

Table 5.21 Total Sortation Time for Different Sortation Lane in (1/M) Model

# of Sortation Lane	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
1	2142.65	2116.97	1998.68	42.85	42.34	39.97
2	1320.20	1502.12	1177.70	26.40	30.04	23.55
3	1016.33	1140.44	924.51	20.33	22.81	18.49
4	886.47	973.34	812.44	17.73	19.47	16.25
5	790.03	830.23	743.49	15.80	16.60	14.87
6	752.38	765.19	714.73	15.05	15.30	14.29
7	714.12	690.09	675.36	14.28	13.80	13.51
8	668.95	650.04	636.47	13.38	13.00	12.73

As it can be seen in Figure 5.21, for any number of sortation lanes, ECR has the smallest value. Besides, even though increasing sortation lane always decreases total sorting time, after specific point, increasing sortation lanes does not significantly contribute to the effects.

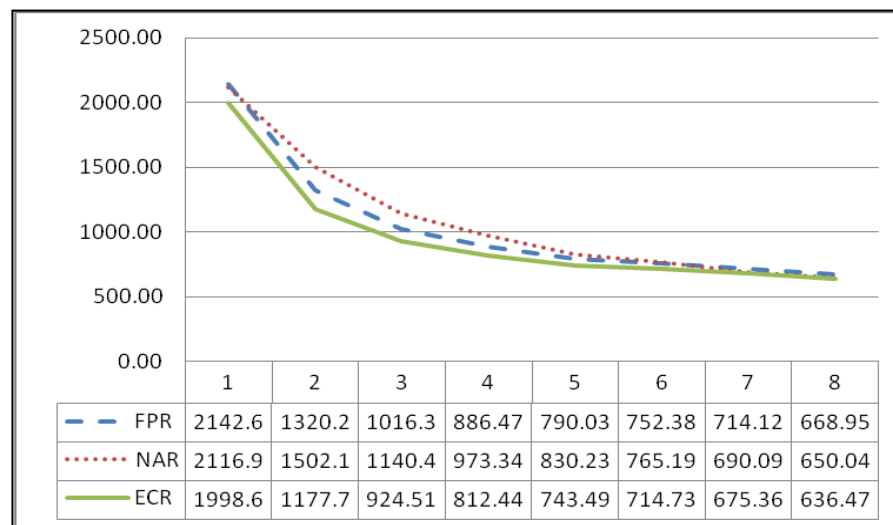
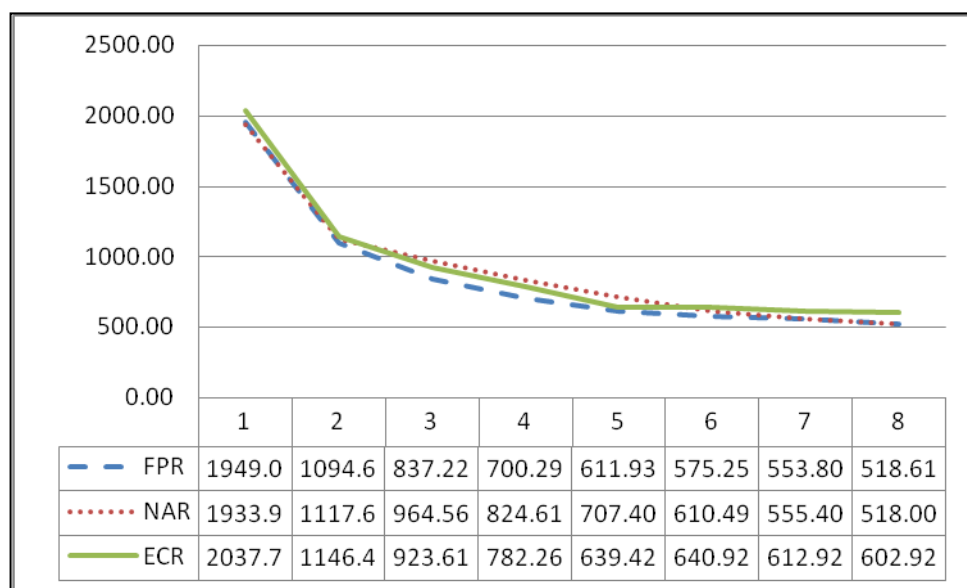


Figure 5.21 Total Sortation Time for different Sortation Lane in (1/M) Model

Table 5.22 Total Sortation Time for Different Sortation Lane in (M/M) Model

# of Sortation Lane	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
1	1949.00	1933.94	2037.77	38.98	38.68	40.76
2	1094.64	1117.67	1146.44	21.89	22.35	22.93
3	837.22	964.56	923.61	16.74	19.29	18.47
4	700.29	824.61	782.26	14.01	16.49	15.65
5	611.93	707.40	639.42	12.24	14.15	12.79
6	575.25	610.49	640.92	11.51	12.21	12.82
7	553.80	555.40	612.92	11.08	11.11	12.26
8	518.61	518.00	602.92	10.37	10.36	12.06

In Many-Many Model, same results are obtained. However, the best strategy is FPR instead of ECR. Although, when sortation lane is equal to 1 and 8, the results of NAR is smaller than FPR, it can be said that from general point of view, FPR is the best strategy among them.

**Figure 5.22** Total Sortation Time for Different Sortation Lane in (M/M) Model

5.5.4. Effect of the Distance between Sortation Lanes

In this section, it will be discussed that the significance of distance between sortation lanes are whether sufficient or not. In order to understand the effect, different model configurations are redesigned. Following two shapes are about One-One Model. In the first design, sortation lane is located close to induction lane to avoid waste of time to reach sortation lane. In the second one, sortation lane is placed at the furthest point from induction lane.

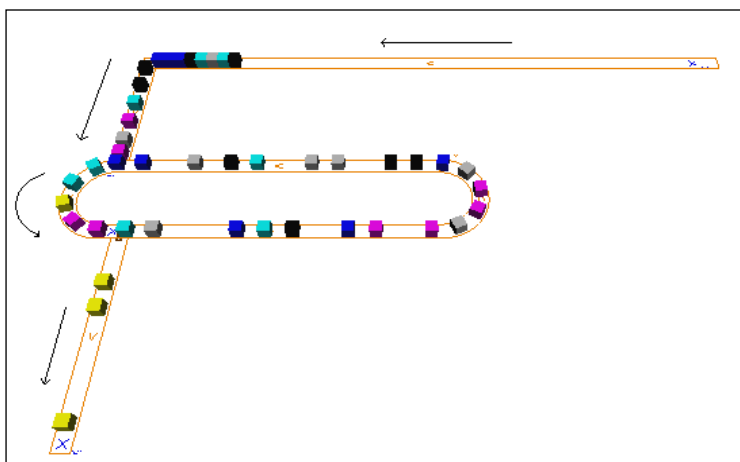


Figure 5.23 Close Sortation Lane for O-OM

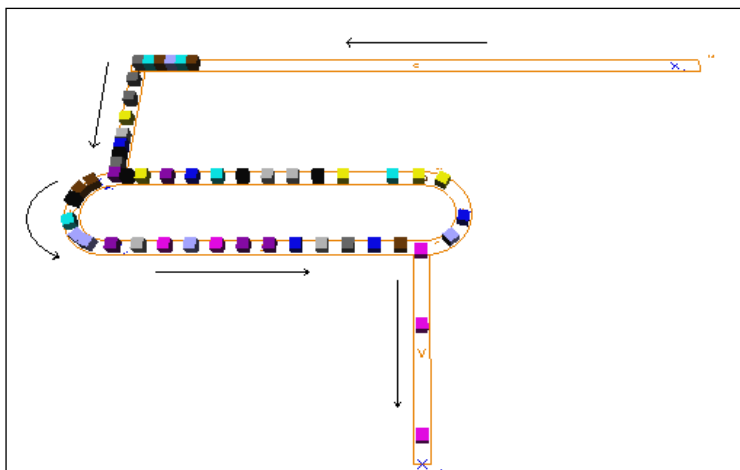


Figure 5.24 Remote Sortation Lane for O-OM

By sending same number of order and item, two designs are compared. Results are shown in Table 5.23.

Table 5.23 Different Distances between Sortation Lanes [1/1/10/5]

Position of Sortation Lane	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
Close	2248.78	2179.26	1841.71	44.98	43.59	36.83
Remote	2248.03	2179.14	1841.61	44.96	43.58	36.83

As it can be understood from both Table 5.23 and Figure 5.24, there is no significant difference in total sortation time between “Close” and “Remote” design. Thus, the effect of the distance between sortation lanes in One-One Model is negligible.

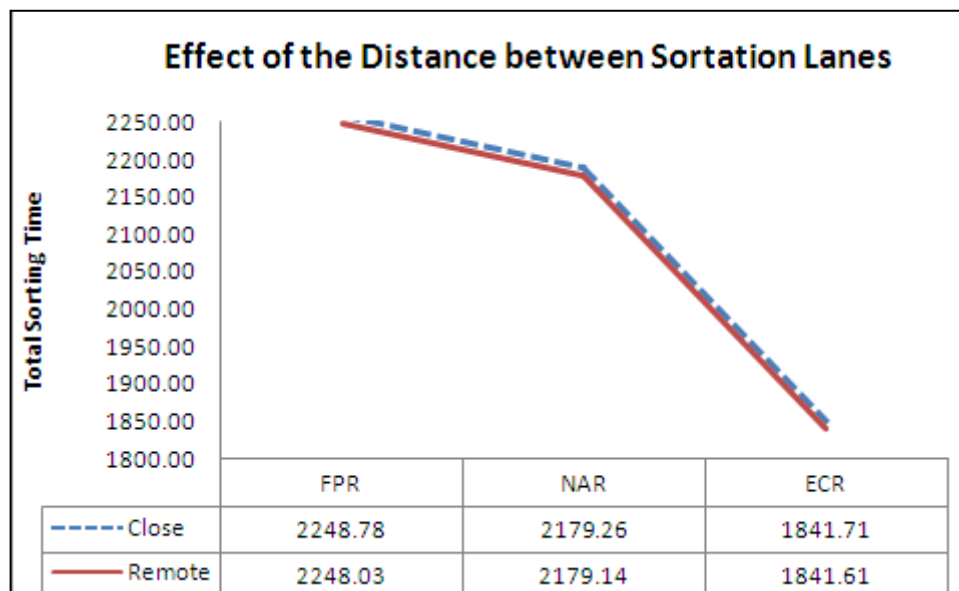


Figure 5.25 Effect of the Distance between Sortation Lanes [1/1/10/5]

Sending same number of order and item, two designs are compared. Results are shown in Table 5.24.

Table 5.24 Different Distances between Sortation Lanes [1/2/10/5]

Position of Sortation Lane	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
Close	1320.20	1502.12	1177.70	26.40	30.04	23.55
Remote	1375.42	1553.47	1261.14	27.51	31.07	25.22

As it can be seen in Figure 5.28 close sortation lane gives best results. In fact, the difference between two designs is not too much but it is not assumed that it is totally insignificant.

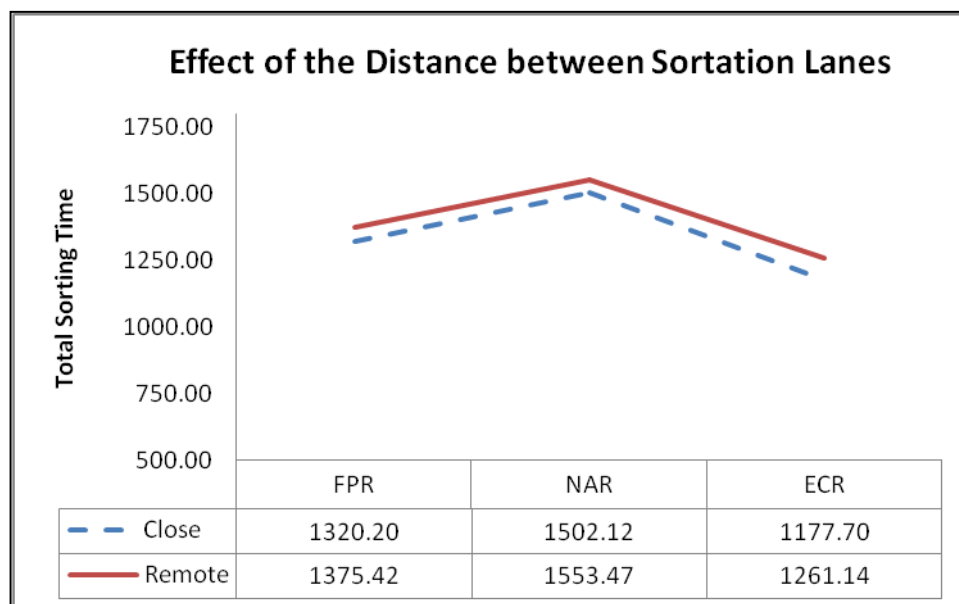


Figure 5.28 Effect of the Distance between Sortation Lanes [1/2/10/5]

5.5.5. One –One Model versus One-Many Model

In the under mentioned situations, 5 orders having just 5 items are sent to One-One Model, while doubled orders in other words 10 orders having 5 items are sent to One-Many Model which has two sortation lanes. Before sortation, the expectation was that both outputs would be close to each other since the second one seems that it has double performance if it is compared to the first one. That's why; it is thought that twice as much order can be sorted at the same time.

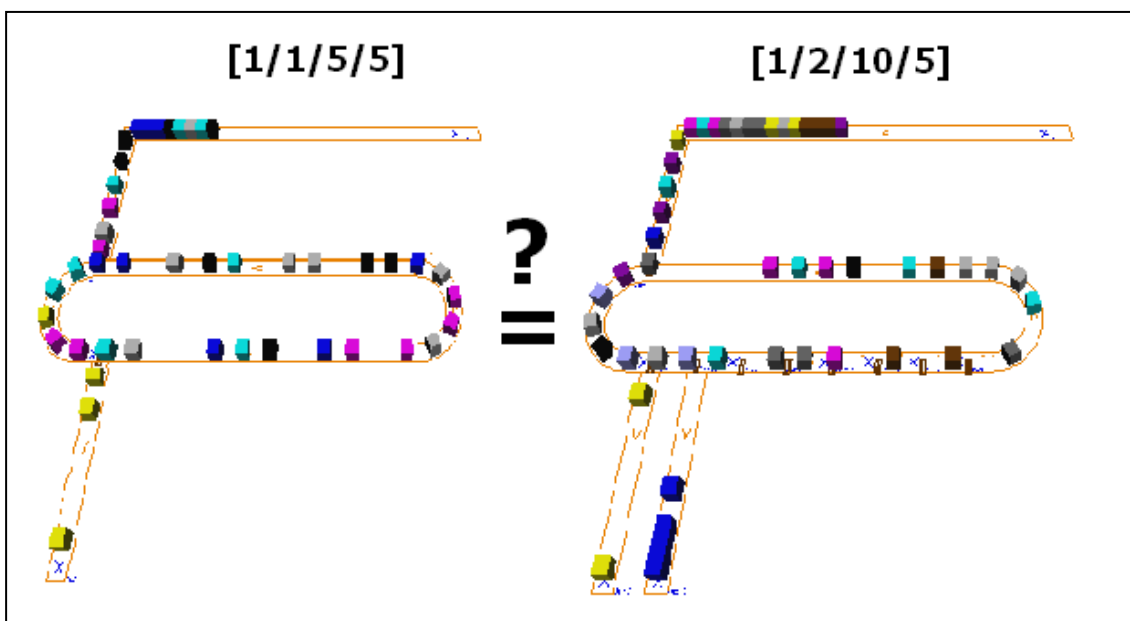


Figure 5.29 One –One Model versus One-Many Model

In this experimentation, number of orders $m= 10$ and number of items $y=5$ are taken firstly. Then, number of orders is reduced by half. The results of this set of experiments are listed in Table 5.25.

Table 5.25 One –One Model versus One-Many Model

Model	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
[1/1/5/5]	1174.40	1147.94	1036.34	23.49	22.96	20.73
[1/2/10/5]	1320.20	1502.12	1177.70	26.40	30.04	23.55

Distinctively, One-One Model for all strategies has smaller sortation time than One-Many Model. Thus, increasing order size as twice takes much more time even if one sortation lane is added.

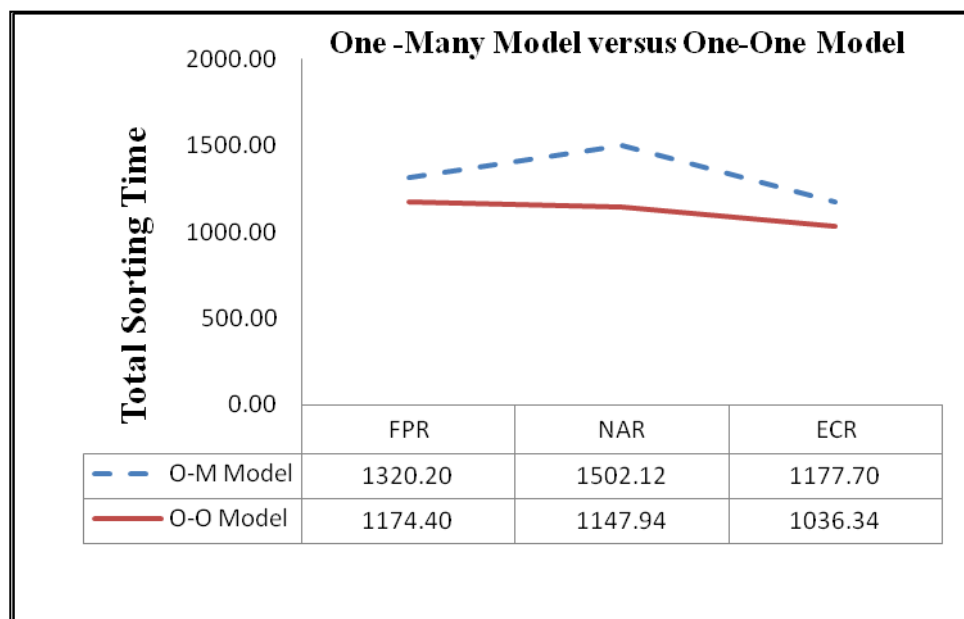


Figure 5.30 Effect of the Distance between Sortation Lanes

CHAPTER 6

CONCLUSION AND FURTHER RESEARCH

In this thesis, available sortation strategies are compared and a set of modeling approach in simulation and in analytical is developed for the design and analysis of conveyor sortation system. Consequently, the following contributions are made:

- Different design configurations such as, {48; 1} and {60; 1} are examined and the results are found. Thus, the behavior of sortation strategies according to different scenarios can be contemplated.
- Simulation models are developed for all the designs. Therefore, the results of simulation models are compared with analytical models. By this way, the validation of simulation is provided.
- Based on simulation models; FPR, NAR and ECR strategies are compared. Overall outputs are represented as follows in Table 6.1.

Table 6.1 Overall outputs for all Sorting Strategies and all designs

Model	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
(1/1) Model	2248.78	2179.26	1841.71	44.98	43.59	36.83
(1/M) Model	690.62	678.73	651.21	13.81	13.57	13.02
(M/M) Model	538.78	550.59	564.09	10.78	11.01	11.28

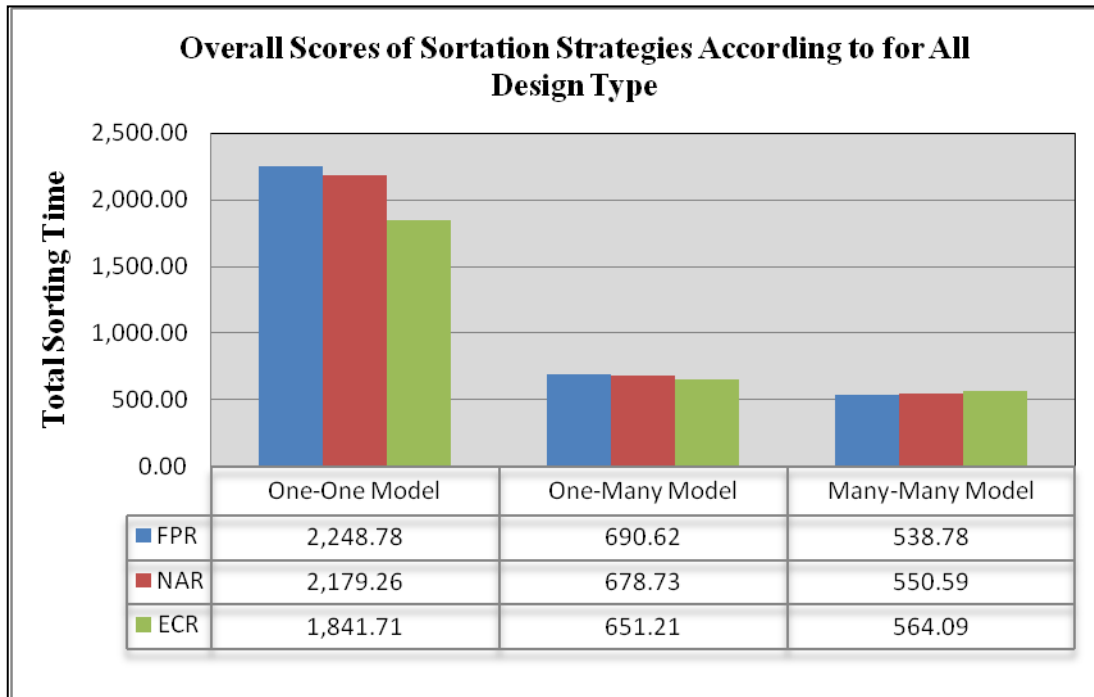


Figure 6.1 Effect of the Distance between Sortation Lanes

Table 6.2 Overall Result

Model	Wave Sorting Time (seconds)			Time Per Package (seconds)		
	FPR	NAR	ECR	FPR	NAR	ECR
[1/1/10/5]	2248.78	2179.25	1841.70	44.98	43.59	36.83
[1/1/10/5-]	2142.65	2116.97	1818.30	42.85	42.34	36.37
[1/1/5/5]	1174.40	1147.94	1036.34	46.98	45.92	41.45
[1/2/10/5]	1320.20	1502.12	1177.70	26.40	30.04	23.55
[1/2/10/5]	1375.42	1553.47	1261.14	27.51	31.07	25.22
[1/8/10/5]	690.61	678.72	651.21	13.81	13.57	13.02
[1/8/10/5-]	668.95	650.04	636.46	13.38	13.00	12.73
[8/1/10/5]	2017.72	2045.25	2096.48	40.35	40.91	41.93
[8/8/10/5]	538.77	550.58	564.08	10.78	11.01	11.28
[8/8/10/5-]	518.60	523.18	602.91	10.37	10.46	12.06
[8/8/32/4]	1956.42	1992.25	2122.13	15.28	15.56	16.58

- Different configurations are simulated by varying design and operational parameters. For instance, despite of the literature, random item size in an order supports better results. Besides, it is more appropriate for a real case.
- Although it is known that adding sortation lane reduces total sorting time, after 5 lanes, the effects start to decrease. In other words, there is no linear relationship between sortation lane and sorting time.
- The impact of distance between sortation lanes is examined by designing model configurations. For One-One Model, there is no significant effect whereas in One-Many Model, the effects of distance cannot be ignored.
- Design parameters and operational parameters are compared. In this study, adding extra sortation lane is insufficient to sort twice number of orders.

Future research can be pursued in the following directions:

- Analytical models for One- Many Model and Many- Many Model are required. In this research, analytical model is applied to only One-One Model. Thus, for other models, analytical model should be developed in order to make comparisons with the result of simulation model.
- Order configurations can be varied. For instance, 120-1 order combination is worth to examine in order to contemplate the behavior of sortation strategies clearly.
- Other operational parameters such as, conveyor speed, order assignment to specific lane before sorting, wave algorithm need to be conducted to see their effects.
- Other design parameters such as, circular and non-circular conveyor and length of circulation conveyor are necessary to analyze.

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APPENDIX

Table A.1 Data Set

<i>Number of Snap</i>	<i>One-Many Model</i>		
	<i>Sortation Time FPR</i>	<i>Sortation Time NAR</i>	<i>Sortation Time ECR</i>
Sortation Time for Snap 1	7398,839	sc 7093,839	sc 6803,839
Sortation Time for Snap 2	6562,875	sc 6457,875	sc 5964,557
Sortation Time for Snap 3	6277,654	sc 5564,336	sc 6224,336
Sortation Time for Snap 4	6746,027	sc 7261,027	sc 6091,027
Sortation Time for Snap 5	7228,298	sc 6573,298	sc 6898,298
Sortation Time for Snap 6	6743,044	sc 6993,044	sc 6144,726
Sortation Time for Snap 7	6234,419	sc 6739,419	sc 6169,419
Sortation Time for Snap 8	6744,872	sc 6124,872	sc 6239,872
Sortation Time for Snap 9	6294,288	sc 6584,288	sc 6239,288
Sortation Time for Snap 10	6302,028	sc 6197,028	sc 6052,028
Sortation Time for Snap 11	5953,435	sc 6753,435	sc 6153,435
Sortation Time for Snap 12	6226,874	sc 5861,874	sc 6425,192
Sortation Time for Snap 13	6698,174	sc 6018,174	sc 6538,174
Sortation Time for Snap 14	6804,482	sc 7094,482	sc 7064,482
Sortation Time for Snap 15	6975,505	sc 6515,505	sc 6610,505
Sortation Time for Snap 16	6529,482	sc 6854,482	sc 6564,482
Sortation Time for Snap 17	6367,725	sc 6422,725	sc 6132,725
Sortation Time for Snap 18	6635,669	sc 5970,669	sc 6215,669
Sortation Time for Snap 19	6964,423	sc 6930,213	sc 6250,213
Sortation Time for Snap 20	6362,816	sc 6134,498	sc 6427,816
Sortation Time for Snap 21	6988,234	sc 7438,234	sc 6888,234
Sortation Time for Snap 22	6385,344	sc 7030,344	sc 6265,344
Sortation Time for Snap 23	7020,731	sc 7175,731	sc 7015,731
Sortation Time for Snap 24	6061,759	sc 7075,078	sc 6031,759
Sortation Time for Snap 25	7212,218	sc 5563,899	sc 6212,218
Sortation Time for Snap 26	6971,068	sc 6061,068	sc 5927,749
Sortation Time for Snap 27	6509,965	sc 5621,646	sc 6146,646
Sortation Time for Snap 28	6895,016	sc 8513,335	sc 6410,016
Sortation Time for Snap 29	7210,516	sc 6810,516	sc 6875,516
Sortation Time for Snap 30	7196,3	sc 6607,318	sc 7201,3
Sortation Time for Snap 31	6635,132	sc 5601,813	sc 6220,132
Sortation Time for Snap 32	6236,689	sc 5776,689	sc 6021,689
Sortation Time for Snap 33	6352,43	sc 6857,43	sc 6257,43
Sortation Time for Snap 34	6229,098	sc 6444,098	sc 6080,779
Sortation Time for Snap 35	6483,743	sc 7123,743	sc 6068,743
Sortation Time for Snap 36	6366,18	sc 6611,18	sc 6206,18
Sortation Time for Snap 37	7078,483	sc 7168,483	sc 6618,483
Sortation Time for Snap 38	7237,713	sc 7887,713	sc 6847,713
Sortation Time for Snap 39	6849,26	sc 5760,942	sc 6180,942
Sortation Time for Snap 40	6928,644	sc 6633,644	sc 6733,644
Sortation Time for Snap 41	6093,917	sc 6758,917	sc 6223,917
Sortation Time for Snap 42	6070,676	sc 6845,676	sc 6115,676
Sortation Time for Snap 43	6031,029	sc 6671,029	sc 6071,029
Sortation Time for Snap 44	6328,504	sc 6848,504	sc 6213,504
Sortation Time for Snap 45	7191,476	sc 6146,476	sc 6161,476

Sortation Time for Snap 46	6492,873	sc	7077,873	sc	6154,555	sc
Sortation Time for Snap 47	6903,957	sc	6503,957	sc	6538,957	sc
Sortation Time for Snap 48	6397,296	sc	6297,296	sc	6332,296	sc
Sortation Time for Snap 49	6912,825	sc	5832,825	sc	6777,825	sc
Sortation Time for Snap 50	7317,276	sc	6717,276	sc	6622,276	sc
Sortation Time for Snap 51	6116,285	sc	5881,285	sc	6197,966	sc
Sortation Time for Snap 52	7202,058	sc	6292,058	sc	5967,058	sc
Sortation Time for Snap 53	7198,883	sc	6838,883	sc	6873,883	sc
Sortation Time for Snap 54	7152,309	sc	6492,309	sc	6687,309	sc
Sortation Time for Snap 55	6501,864	sc	6566,864	sc	6796,864	sc
Sortation Time for Snap 56	6006,652	sc	6476,652	sc	6006,652	sc
Sortation Time for Snap 57	7084,864	sc	6416,546	sc	6681,546	sc
Sortation Time for Snap 58	7108,198	sc	6443,198	sc	6283,198	sc
Sortation Time for Snap 59	6058,657	sc	5668,657	sc	6038,657	sc
Sortation Time for Snap 60	7555,929	sc	6115,929	sc	6865,929	sc
Sortation Time for Snap 61	6425,184	sc	6850,184	sc	6395,184	sc
Sortation Time for Snap 62	6235,443	sc	6260,443	sc	6210,443	sc
Sortation Time for Snap 63	6467,738	sc	6662,738	sc	6112,738	sc
Sortation Time for Snap 64	6142,476	sc	5967,476	sc	6047,476	sc
Sortation Time for Snap 65	6968,503	sc	6846,875	sc	7003,503	sc
Sortation Time for Snap 66	6264,284	sc	6149,284	sc	6134,284	sc
Sortation Time for Snap 67	6452,769	sc	7447,769	sc	6507,769	sc
Sortation Time for Snap 68	6663,714	sc	6028,714	sc	6143,714	sc
Sortation Time for Snap 69	5991,614	sc	6896,614	sc	6161,614	sc
Sortation Time for Snap 70	6998,41	sc	6040,091	sc	6163,41	sc
Sortation Time for Snap 71	6201,75	sc	5653,432	sc	6106,75	sc
Sortation Time for Snap 72	6562,142	sc	6562,142	sc	6272,142	sc
Sortation Time for Snap 73	7064,726	sc	7019,726	sc	6559,726	sc
Sortation Time for Snap 74	6470,354	sc	6845,354	sc	6180,354	sc
Sortation Time for Snap 75	6769,772	sc	5456,702	sc	6290,021	sc
Sortation Time for Snap 76	6866,489	sc	6296,489	sc	6266,489	sc
Sortation Time for Snap 77	7072,644	sc	7162,644	sc	6872,644	sc
Sortation Time for Snap 78	6303,558	sc	6818,558	sc	5970,239	sc
Sortation Time for Snap 79	6181,166	sc	5626,166	sc	6234,485	sc
Sortation Time for Snap 80	6433,433	sc	6453,433	sc	6273,433	sc
Sortation Time for Snap 81	6984,931	sc	7269,931	sc	6719,931	sc
Sortation Time for Snap 82	6899,576	sc	5591,258	sc	6197,45	sc
Sortation Time for Snap 83	6322,765	sc	5697,765	sc	6512,765	sc
Sortation Time for Snap 84	6482,452	sc	6667,452	sc	6079,134	sc
Sortation Time for Snap 85	6940,348	sc	6210,348	sc	6440,348	sc
Sortation Time for Snap 86	6746,932	sc	6411,932	sc	6166,932	sc
Sortation Time for Snap 87	7017,735	sc	6687,735	sc	6164,416	sc
Sortation Time for Snap 88	6456,036	sc	5606,036	sc	6057,717	sc
Sortation Time for Snap 89	7160,229	sc	6851,91	sc	6216,91	sc
Sortation Time for Snap 90	6726,55	sc	6686,55	sc	6081,55	sc
Sortation Time for Snap 91	6379,379	sc	5809,379	sc	6279,379	sc
Sortation Time for Snap 92	7246,627	sc	7116,852	sc	6986,852	sc
Sortation Time for Snap 93	7486,659	sc	7196,659	sc	7031,659	sc
Sortation Time for Snap 94	6847,671	sc	6547,671	sc	6077,671	sc
Sortation Time for Snap 95	7024,527	sc	6924,527	sc	6699,527	sc
Sortation Time for Snap 96	7404,469	sc	6529,469	sc	6789,469	sc
Sortation Time for Snap 97	7442,987	sc	6514,668	sc	6224,668	sc
Sortation Time for Snap 98	6881,091	sc	6481,091	sc	6481,091	sc
Sortation Time for Snap 99	7400,642	sc	5432,323	sc	6067,323	sc
Sortation Time for Snap 100	5941,158	sc	5961,158	sc	6256,158	sc
Average	6689,539	sc	6500,397	sc	6364,683	sc