INBOUND AND OUTBOUND TRUCK SCHEDULING AT CROSSDOCK

by

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ABSTRACT OF THE THESIS

Inbound and Outbound Trucks Scheduling at Crossdocks

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In today's customer driven economy, moving products quickly, efficiently, and cost effectively offers crucial advantages to companies. To achieve these goals, more and more companies are finding that cross-docking can play an integral part in their distribution model by partially replacing or complementing existing warehousing facilities. Crossdocking is a material handling and distribution operation, which moves products quickly and directly from inbound trucks (ITs) to outbound trucks (OTs) through the crossdock facility where products are being resorted or consolidated, without being stored or only with a short-term storage, usually within 24 hours or sometimes only within one hour.

This research deals with the scheduling of both ITs and OTs at a crossdocking facility where three objectives are considered: The first objective is to minimize the starting and handling time of all ITs; the second objective is to minimize the total weighted distance of pallets traveled inside the crossdock facility; and the third objective is to minimize the total departure time of all OTs. Multi-objective mixed-integer program formulations are built in order to address the problem. Justification for the use of these objectives in optimizing cross-dock operations is given. Different models are built for three different door layouts at crossdocking facility.

Since the problems are NP-hard, we consider the problem size limitations to obtain an exact solution. In addition, a restriction-approximation approach to solve the models is proposed and the efficiency of our approximation method is proved based on generated data. Finally, numerical examples are provided using the mathematical models built and the approximation approaches. Results for different layouts and scenarios are compared to evaluate the characteristics of different crossdock layouts.

Acknowledgement

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Chapter 1

Introduction

In today's customer driven economy, moving products quickly, efficiently and cost effectively offers crucial advantages to businesses. Distribution plays an important role, as a main component of Logistics, along with supply and materials management [1]. A distributor ships products from origins, such as points of manufacture, (named "suppliers" for all types of origins in this thesis) to different levels of destinations, such as points of retailer, shops, and residences, (named "customers" for all types of destinations in this thesis). Transportation and warehousing are critical services in the distribution system and the study of trade-offs between the two is an ongoing issue. Achieving economies of scale (EOS), by consolidating products into one shipment in warehousing operation, may reduce transportation costs per unit of product. Warehousing, however, typically requires high levels of inventory, which increases the costs for holding and handling products. Therefore, it is desirable to have a facility that can not only act as a consolidating point to achieve EOS in transportation, but also eliminate the high inventory costs of storing products. Crossdock operations, studied in this research, have the potential to reach both of these goals.

1.1. Types of distribution channels and facilities

1.1.1. Distribution channels

There are many different methods by which a product or a group of products can be distributed from supplier to final customer. A list of main physical alternative channels of distribution is given as follows:

Direct distribution: Products are delivered directly from suppliers to different customers. It takes a shorter amount of time for products to reach each customer because each order is treated separately and products are delivered without passing through a transfer facility. Direct distribution, without any value added process taking place during the delivery, can reduce delivery time. This channel is cost efficient only when full Truck-Loads (TL) are being delivered [1]. Due to the pressure of satisfying customers and the need to respond quickly to their demands, suppliers usually deliver products in smaller amounts, which cause Less-than-Truck-Load (LTL) deliveries (see Fig.1).

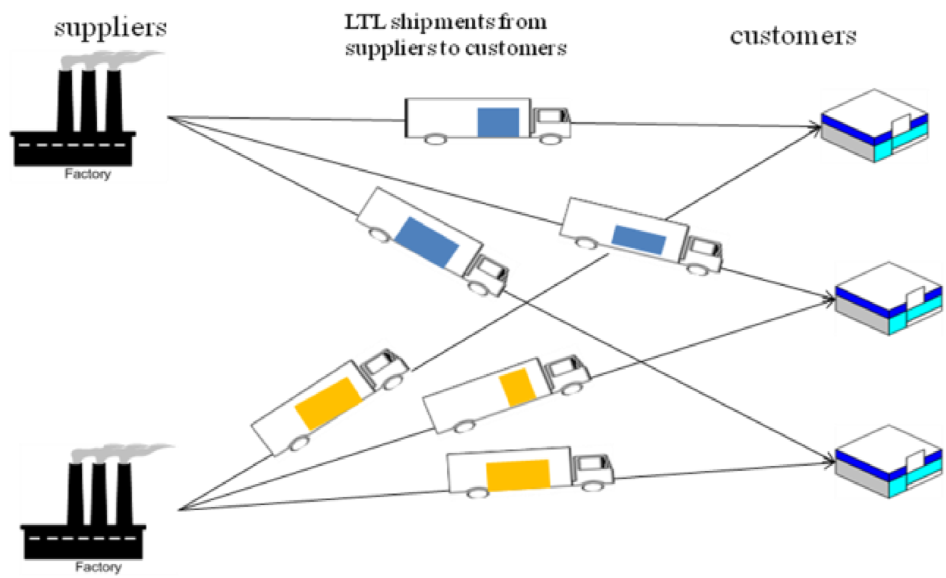
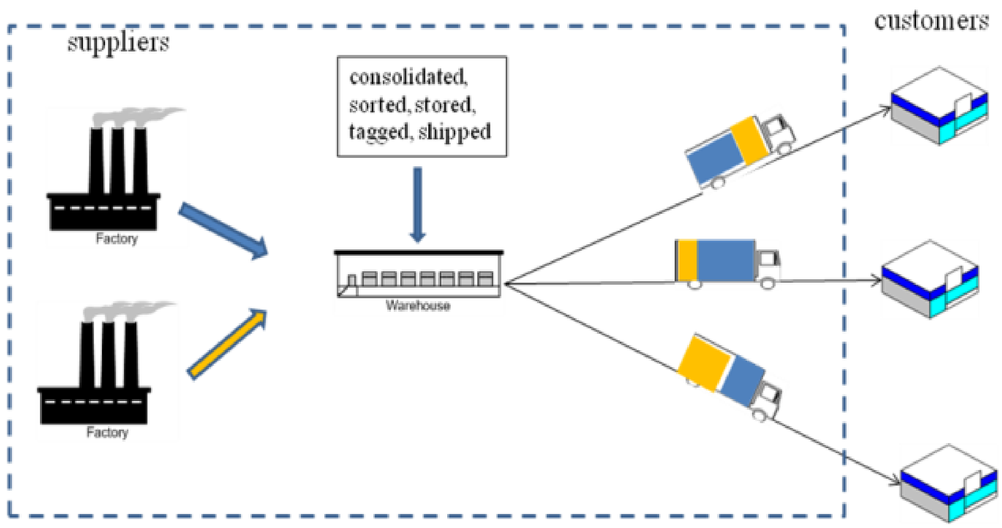


Figure 1 Direct Distribution

Warehousing distribution: Unlike direct distribution, warehousing distribution allows products to be transferred through a warehouse where products can be consolidated, sorted, stored, tagged, etc. This enables TL shipments, achieving lower transportation costs. Such warehouse centers belong to the supplier (e.g. manufacture) or the customer (e.g. retail store). The products are either broken down in a suppliers' warehouse according to separate customers' demands and delivered by suppliers to each customer (Fig.2.a) or consolidated in a customer's warehouse and then delivered to their stores (Fig. 2.b).



(a)

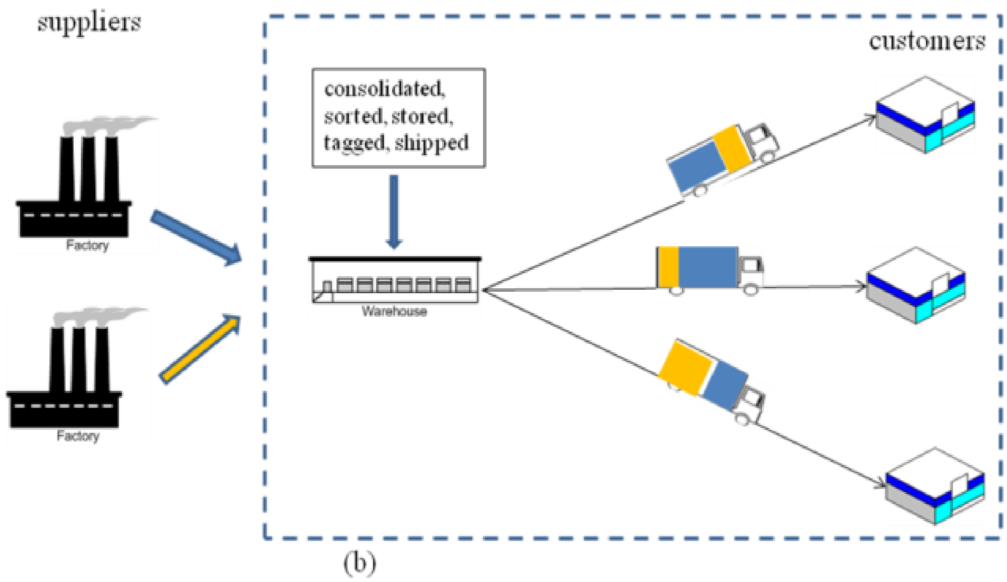


Figure 2 Warehousing Distribution
via Supplier's Warehouse (a) and Customer's Warehouse (b)

Third Party Logistics (3PL) distribution: The transportation and warehousing service in warehousing distribution is a high expense process and requires intensive labor work. Many companies prefer to give this work to 3PL companies which provide outsource services and many suppliers and customers are using 3PLs for their distribution operations (dashed box in Fig 2 represents the delivery operations handled by 3PL). 3PL distribution has similar networks with other distribution patterns, the difference lays on the operator of the services.

Crossdocking distribution: A new distribution strategy has been introduced recently. In the next section, crossdocking distribution will be explained in detail. By and large, instead of using warehouse which has high inventory levels, this distribution pattern uses crossdock facilities. Crossdocks do not hold stock, but act as intermediate transfer points in the distribution operation for transferring goods to customers (Fig 3a and 3b).

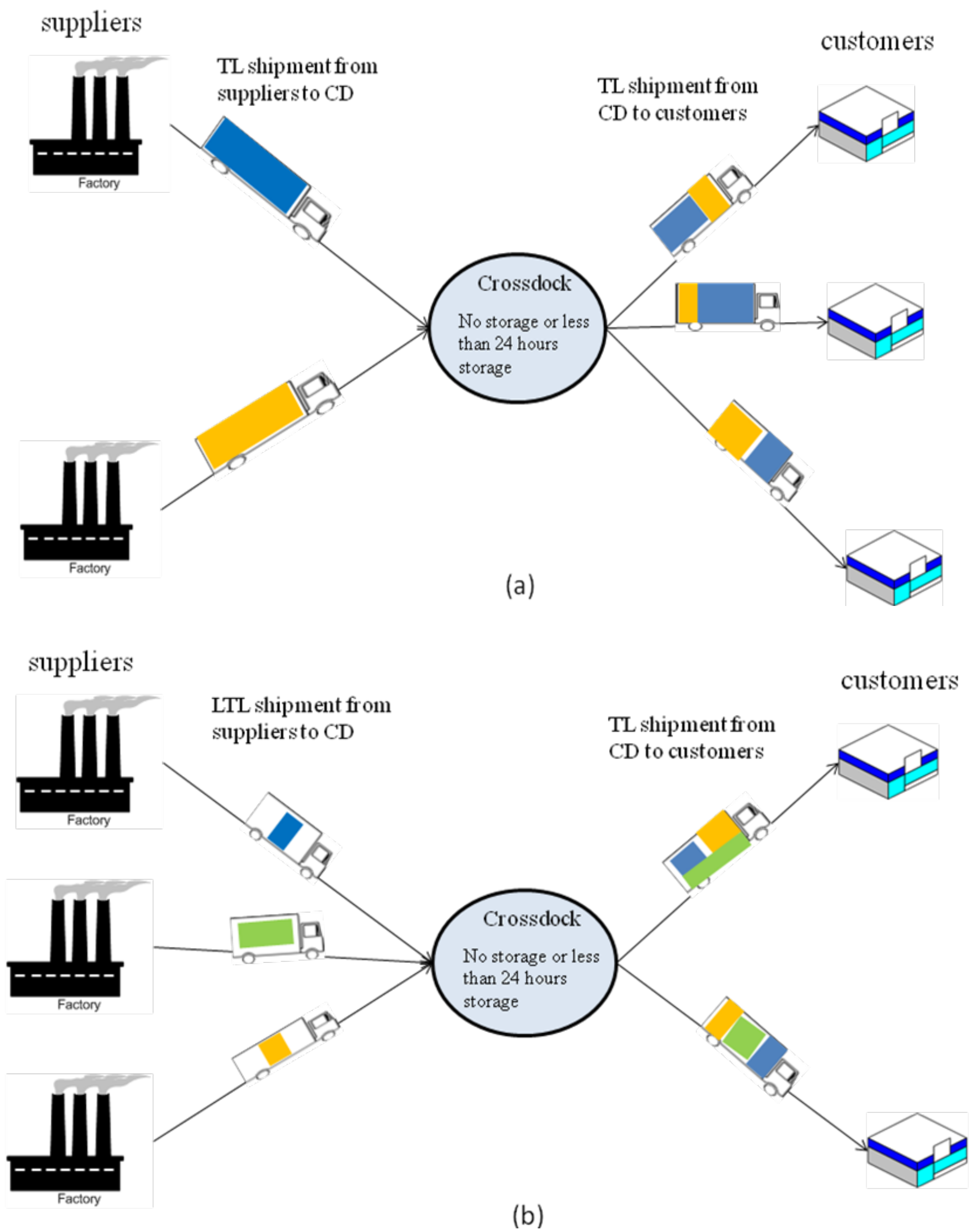


Figure 3 Crossdocking Distribution

Note that different channels may be suitable for different distribution cases and the issue of how to choose a suitable channel depends on the specific market. The distribution patterns discussed above can be classified into two big categories: direct distribution and indirect d istribution (warehousing distribution, c rossdocking d istribution, a nd 3 PL distribution). If there are no other parties involved in the distribution process, direct distribution might be used in the cases of fast and LTL shipments. For indirect distribution, 3PL companies typically use warehousing or crossdocking distribution. Figure 4 gives the guidelines for using crossdocking and warehousing distribution [2]. 1) When the unit stock-out costs are high and the order demand is unstable or fluctuating, traditional warehousing distribution should be employed to take advantage of holding inventory, because inventory is considered as a buffer to meet uncertainty and reduce unit stock-out cost [3]. 2) In contrast, if the unit stock-out costs are low and the demand is stable and remains constant, crossdocking is preferred. In such cases, inventory for preventing stock-out costs is not desirable as inventory itself is expensive. In addition, since the demand is stable, it can be forecasted based on historical data and therefore stock as a safety for uncertainty is not necessary. 3) If the unit stock-out costs are high but with stable demand or low with unstable demand, either crossdocking or warehousing distribution can be implemented with proper systems and planning.

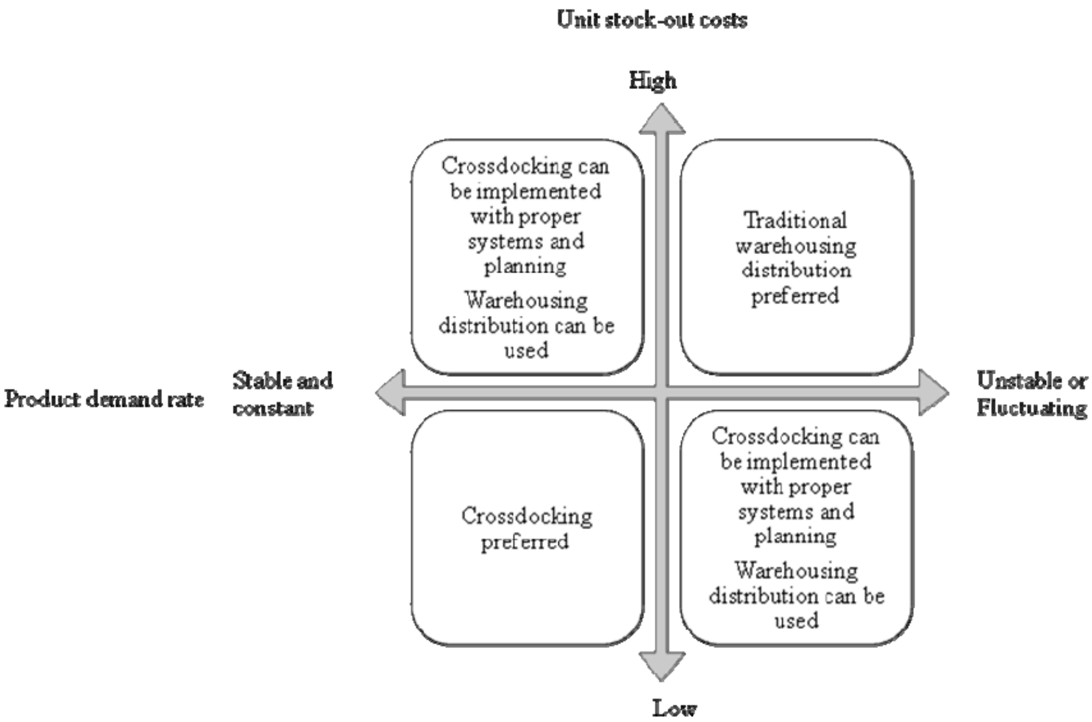


Figure 4 Guidelines for the Use of Crossdocking and Warehousing Distribution (adopted from [2])

1.1.2. Delivery facilities

The distribution center is a critical point of the distribution network. A distribution center can be a warehouse, a fulfillment center, a bulk break center, a package handling center or a crossdock facility.

The different distribution channels as presented above, show two sources of delivery [4] from which products can be shipped to customers: 1) Single product locations, such as manufacturing plants in direct distribution, where a single type of product is delivered from (Fig.1). These facilities are suitable when there is a predictable and high demand for products. This makes it possible to deliver in Truck-Load (TL) shipments, which can achieve EOS. 2) Distribution Centers (DC), which serve as facilities for shipments of products that arrive from various single product locations. Storing, retrieving, sorting and reconsolidating might be conducted to inbound products. After all these processes, the products are sent out to retailers upon request. Usually, suppliers are located far away from customers; by being located near the customers, DCs can provide EOS for shipment of products to each customer.

1.2. Operations in warehouses

Warehouses are facilities that keep inventories and sort and consolidate products. The main activities of warehouse operations are (Fig.5): receiving and handling products, holding inventories in storage locations, retrieving items from the storage locations, assembling customer orders and shipping them to customers [5].

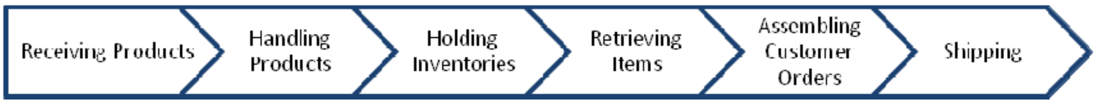


Figure 5 Main Activities in a Warehouse

In a typical warehouse, the products are unloaded, checked, stocked, sorted, picked up or retrieved, consolidated, and shipped after they arrive. The material flow in centered distribution centers (CDCs) is simple, while in regional distribution centers (RDCs) it is more complex [5]. In CDCs, the key activity is storing goods. The products are received, stored and then shipped in full pallets of the same type of product in each shipment (Fig.6a); In RDCs, products of different types are received and according to different destinations, shipments containing small quantities of each kind of product are formed and dispatched (Fig.6b).

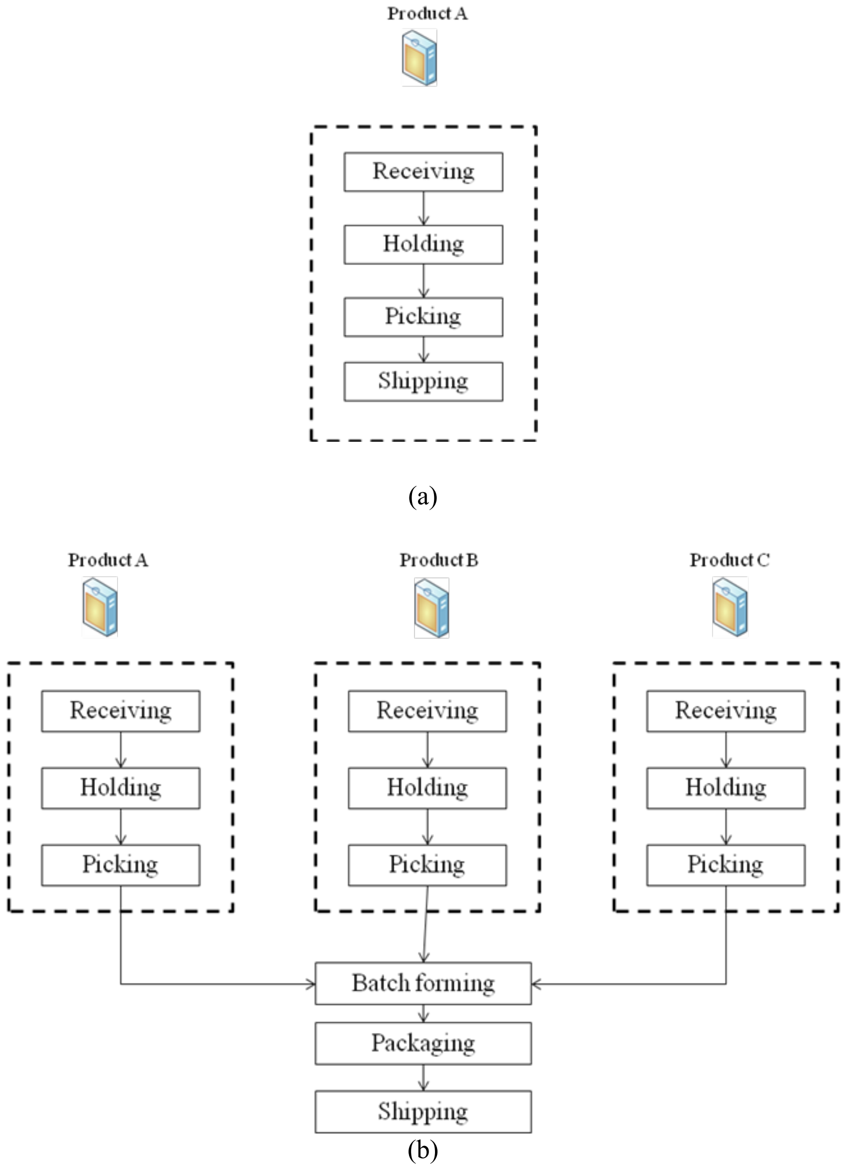


Figure 6 Material Flow through Warehouse
(a) the goods are received and shipped in TL; (b) the goods are received in full pallets and shipped in LTL (adopted from [5])

Several issues related to warehouse operations need to be addressed in modern logistics. Large inventory is used for storage. Processing of large inventory will slow down the speed of product flow through the warehouse. In consequence, this will slow down the supply chain and the response time to customers. Moreover, holding and handling costs for putting and retrieving products to and from storage are high, and the process is labor intensive for non-automatic warehouses. These problems result in high overall costs for warehouse operation and lower levels of customer service.

1.2.1. Common warehouse costs

As shown in Fig 7, holding costs take up to 15 percent of a common warehouse total costs [5]. Besides that, the handling costs, which account for most (up to 50 percent) of the total cost of the common warehouse, also depend on warehouse storage [6]. Handling operations in warehouses, such as moving products to storage area, tracking of materials, retrieving goods from storage and value-added processes are labor intensive. It is easy to see that handling costs are associated with the storing functions of a warehouse. The receiving processes, including getting advanced notification of truck arrival, unloading products from inbound trucks (ITs), and scanning and registering the products, make up the 17% of a common warehouse cost. Shipping processes, such as loading products to outbound trucks (OTs), and registering shipping trucks, make up the 18% of cost [7]. Receiving and shipping together make up less than half of the total warehouse cost. Storage related costs in a warehouse, make up a significant part of the total costs, which may be reduced by eliminating storage.

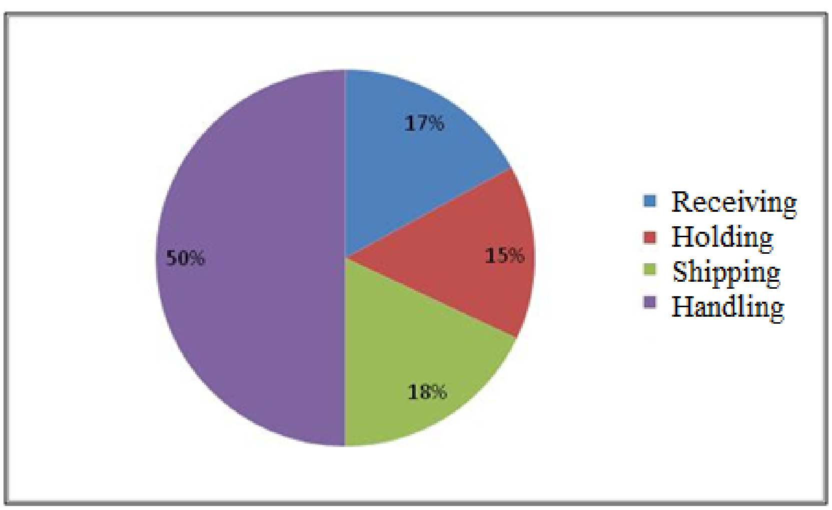


Figure 7 Common warehouse costs
(adopted from[5])

1.2.2. Role of warehouses

Warehouse operations vary depending on the type of companies and their business nature [1]. Although holding inventory in warehouses is associated with high costs, it does have some benefits (Fig.8). Warehouse holding inventory enables long production runs, decouples demand requirements for production capabilities, caters large seasonal demands and provides good customer services. Long production runs reduce production costs by reducing time for machine set-up and changeover. When customers' demand exceeds the production capability, inventory in warehouses is used as a "back up". Thus, inventory smoothes the flow of products in supply chains and improves service level. This, in turn, gives quicker and more accurate response to customer demands. This is also the case for seasonal products during peak season, when demand typically exceeds the production capability. Moreover, warehouses enable cost trade-offs by allowing TL shipments.

However, such traditional warehousing is declining in some cases as it cannot satisfy a Just-In-Time (JIT) strategy. JIT is an inventory strategy to improve the investment return of business by reducing in-process inventory and its associated carrying costs [8]. The strategy emphasizes on reducing input buffer inventory to zero and requires elimination of inventory while maintaining the other functions of a warehouse system. In this case, crossdocking operation is a good substitution.

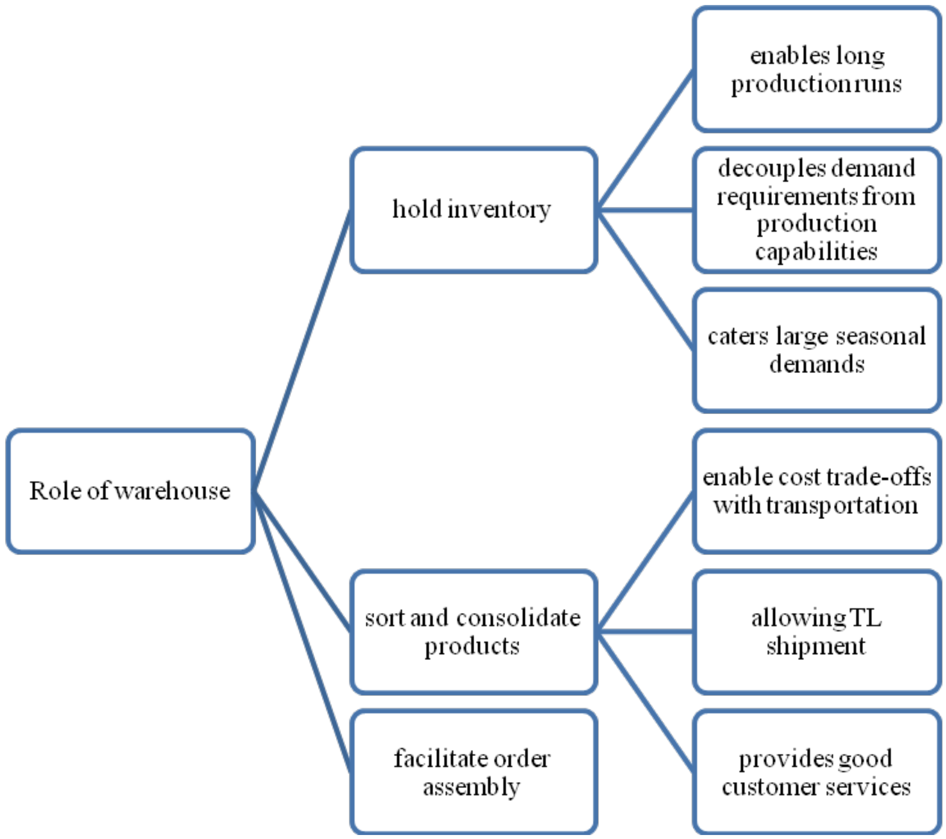


Figure 8 Role of Warehouse

1.3. Crossdocking background

To achieve the goals of moving products quickly, efficiently, and cost effectively, more and more companies are using crossdocking facilities, which can play an important role in their distribution model by partially replacing or complementing existing warehousing facilities. A survey of 547 logistics professionals performed by Saddle Creek's [9] showed that more than 52% of the respondents have somehow already used crossdocking in their distribution operations; and 13% are planning to add crossdocking to their logistics plan in the next one to two years. Unlike warehousing, crossdocking eliminates the process of storage and thus reduces the inventory costs.

Crossdocking is a material handling and distribution operation, which moves products quickly, directly from ITs to OTs through the crossdock facility where products will be resorted or consolidated, without being stored or only with a short-term storage usually within 24 hours or sometimes only within one hour [10]. It is actually not a new practice and has been used by a few companies for several decades, but has been recently rehashed and merged up for more applications due to its significance in today's business world.

Wal-mart pioneers the use of crossdocking operations and run 85% of their products through crossdocking systems. By using crossdocking, Wal-mart is able to reduce its costs of sales by 2-3% and can thus offer lower prices than its competitors [11]. Belk, the largest privately held department store chain in the United States, transfer 90% of its inbound products through crossdock. This results in increasing the throughput, as it needs 21 days to move products from vendor to store before crossdocking, but only eight days after crossdocking the products [12]. Crossdocking also stabilizes an item's price, and in turn, makes sales more predictable.

1.3.1. Reasons for crossdocking

The key reason for which crossdocking is implemented is to improve customer service [13]. Manufacturers and retailers are trying to achieve a trade-off between transportation and inventory, reduce per unit transportation cost, and accelerate the products' flow speed to increase customer service levels [14]. The following table (table 1) presents results of a survey of 547 professionals who work in the area of supply chain and lists their top ten reasons of why crossdocking was adopted [9].

Table 1 Top Ten Reasons for Crossdocking
(adopted from [9])

Reasons for adopting a crossdocking	Percentage of professionals
Improved service level	23%
Reduced transportation costs	17%
Reduced need for warehouse space	14%
Consolidated shipments to destination	11%
Savings from reduced inventory carrying costs	9%
Get products to market more quickly	5%
Improved inventory management	5%
Reduced labor costs	5%
Increased demand for just-in-time service	3%
Accommodate company growth	2%

As shown in Fig. 4, crossdocking distribution holds the advantage of TL shipment both from supplier to crossdocks and from crossdocks to customers. This addresses the disadvantage of LTL shipments, which usually occur in direct shipments. In addition, crossdocking does not have a storing function and therefore eliminates the high inventory costs. Because products are not warehoused as inventory, using crossdocking also leads to elimination of storage-related labor costs. However, warehousing, which holds anticipated inventory, is essential in some cases, managing production (as presented in Fig 8) under uncertain product demand from the market and allocating items to customers. Crossdocking should be used if the arriving products have already been ordered by customers since there is no need to store these products for future order as safety stocks.

Overall, some main benefits of crossdocking operations are: to reduce inventory; reduce handling costs and operating costs; reduce or eliminate warehousing costs; accelerate product delivery speed to the distributor or customers; increase perspective sale space and enable retailers to streamline the supply chain from point of origin to point of sale. Crossdocking is used for minimizing warehousing and achieving fewer inventories [15]. A crossdocking center located near its customers would make the distribution process much faster and more efficient, as well as save money on transportation costs. This would minimize the product handling costs by reducing the number of “touches” to the products. The benefits of reducing costs and improving service levels by shifting to crossdocking encourage companies to use this practice more actively [16].

Finally, crossdocking allows companies to meet customers’ specific needs when time is of the essence [17]. Some requirements from customers include product promotions or other timed marketing strategies, support of JIT practices, and consolidation of multiple supplier networks. Fig. 9 summarizes the reasons and benefits discussed above.

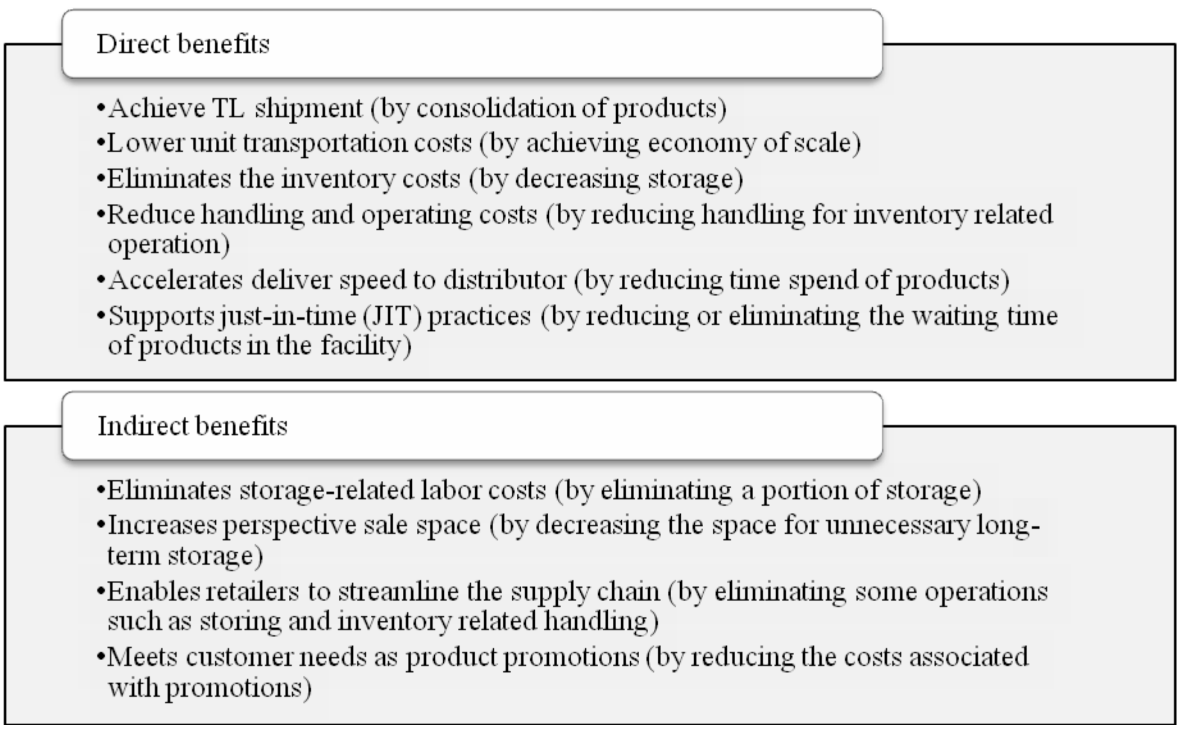


Figure 9 Benefits of Crossdocking

1.3.2. Material flow through crossdocking

Crossdocking is really a speedy mechanism. Similar to a warehousing facility, products are received at the inbound doors (IDs) and unloaded, sorted and consolidated. But unlike warehousing, the products are immediately shipped out at outbound doors (ODs) without ever going into long-term storage [4].

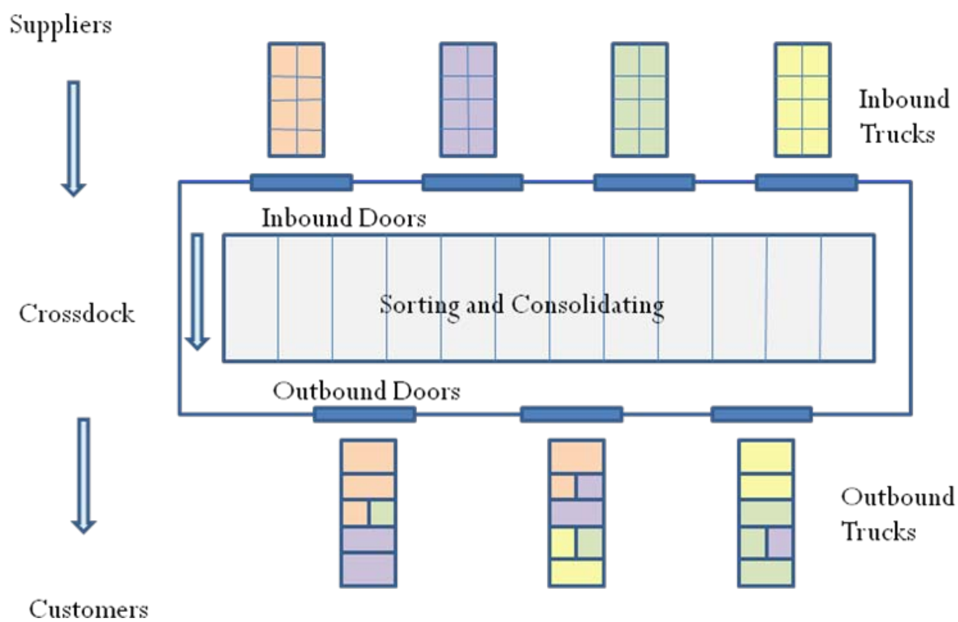


Figure 10 Material Flow through Crossdocking

Figure 10 shows a general products flow via a crossdock facility. The crossdocking system operates as follows:

a) Inbound trailers/trucks (ITs) from suppliers arrive at the crossdock, usually with different types of products in TL on different ITs.

b) ITs are assigned to IDs and there might be some queues at the IDs where the ITs are assigned. Therefore, an IT may have to wait until other ITs assigned to the same dock has been unloaded.

c) Once an IT goes into service, the products from the IT are unloaded at the ID.

d) Products are broken down into smaller lots and are combined with small lots of other products according to their destinations.

e) After finishing the above process, the reconsolidated products are moved to ODs and loaded onto the outbound trucks (OTs).

f) OTs will wait at the ODs untill all the different types of products have been loaded.

g) OTs depart for the final destination in TL shipments.

1.3.3. Crossdocking characters

a. Type of crossdocking

Based on the time when products are assigned to customers, there are two types of crossdocking, as shown in figure 11: pre-distribution crossdocking and post-distribution crossdocking [18]. If products are already allocated, tagged and packed for each customer before they are shipped out from the supplier, we have a pre-distribution crossdocking. For pre-distribution crossdocking, suppliers need to know the exact amount of products needed for each customer; this requires suppliers to have accurate information on the products demand by each customer. In this case, crossdocking operators do not need to assign products to each OT nor tag or label the product, which requires additional labor work. Furthermore, the products can be transferred directly from ITs to OTs without temporary storage. If products are not pre-allocated by the suppliers, and they have to be assigned and tagged at the crossdock, we have post-distribution crossdocking. Post-distribution crossdocking reduces the work for suppliers, but the burden will be undertaken by the crossdock operators. After the products are received, workers inside the crossdock facility will need to allocate and label the products to each customer according to their receipt from customer orders. This requires that products are put in the temporary storage first, and then picked out according to their allocation to customers. Pre-distribution crossdocking is more difficult to complement than post-distribution crossdocking because it requires better information transfer in an integrated supply chain system, and coordination of suppliers, distributors and customers.

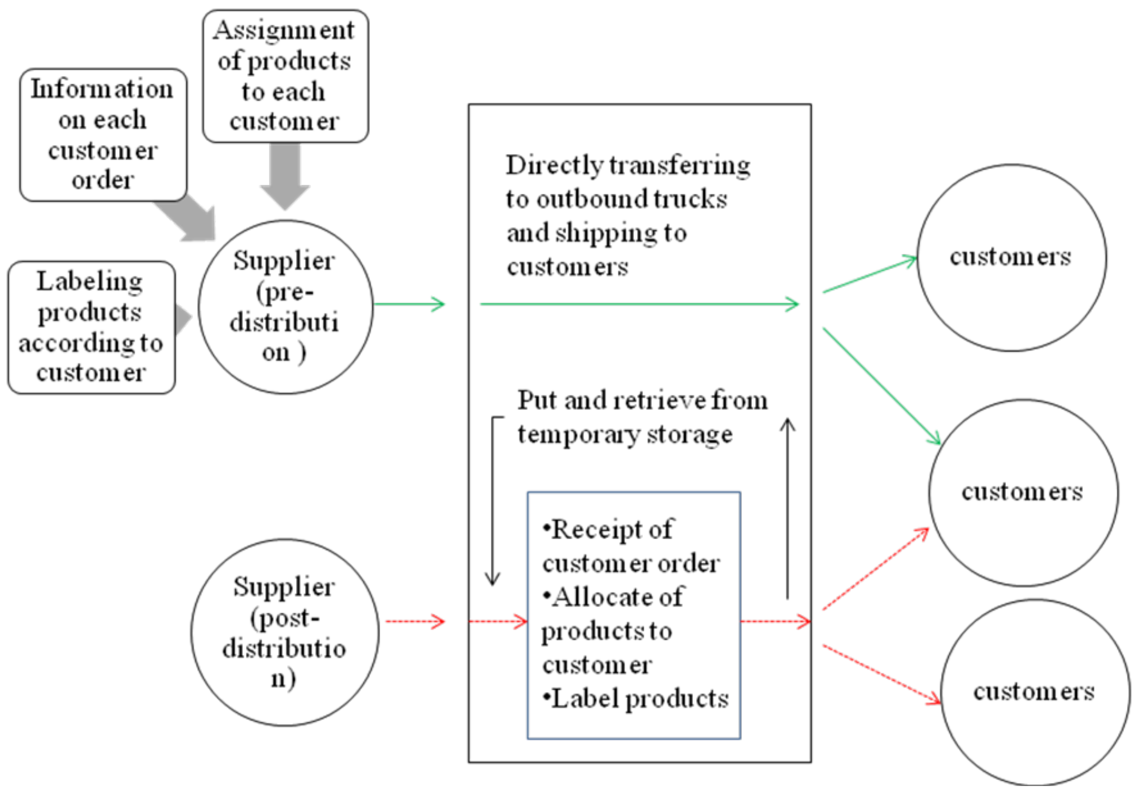


Figure 11 Pre (solid arrow) and Post (dashed arrow) Distribution Crossdocking Network

Based on the type and use of crossdocking, there are manufacturing, distribution, transportation, retail, and opportunistic crossdocking [19, 20]: For manufacturing crossdocking, the facility receives inbound products from manufacturing and prepares for the production orders such as sub-assembly lines [19]. Crossdocks receive, consolidate and ship out a pre-known quantity of products, raw materials, or components for producing a product. Typically, products are from different suppliers but shipped to one plant. For distribution crossdocking, crossdocks receive inbound products from different suppliers. Products or product parts are consolidated on a multi-SKU pallet or integrated to final products and delivered by OTs after the loading process. Products shipped out from distribution crossdocking are delivered to customers, instead of plants as is the case in manufacturing crossdocking. For transportation crossdocking, the main goal of a transportation company is to sort and consolidate the products into a TL shipment from LTL arrivals. This reduces the unit transportation cost, achieving EOS. Transportation crossdocking also changes the structure of different LTL carrier networks by combining their shipments into TL, especially for carrying cargos from small package industries. For retail crossdocking, crossdocks support JIT assembly by sorting and consolidating the products from multiple vendors and shipping them out to retail stores as soon as OTs have all the required products loaded. Usually, products are received at a retailers' crossdock, and are moved across the facility to be combined with other products heading for the same retailer store. This retail crossdocking was introduced by Wal-Mart in the 1980's [19]. Opportunistic crossdocking can be used at any warehouse. A crossdock facility is not required to be built. Products are transferred directly from IDs to ODs to meet a prior-known demand such as a customer sales order. Crossdocking may have more than one of above applications, which is the case studied in this dissertation. A summary of the various types of crossdock facilities is shown in figure 12.

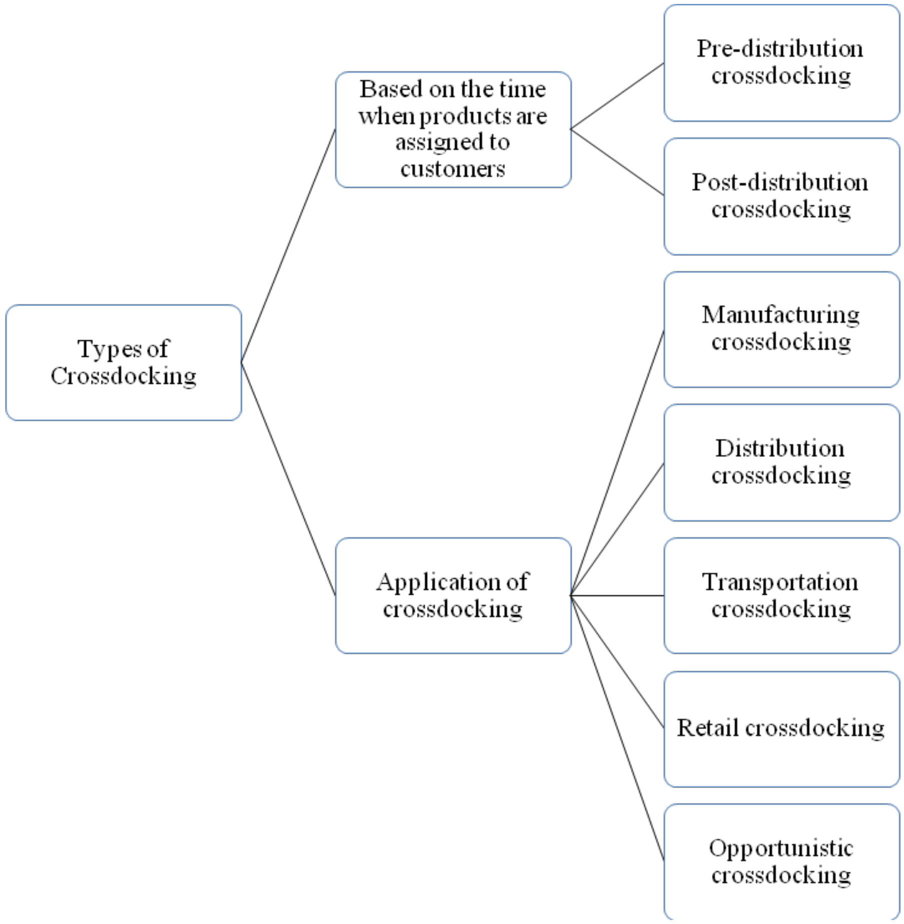
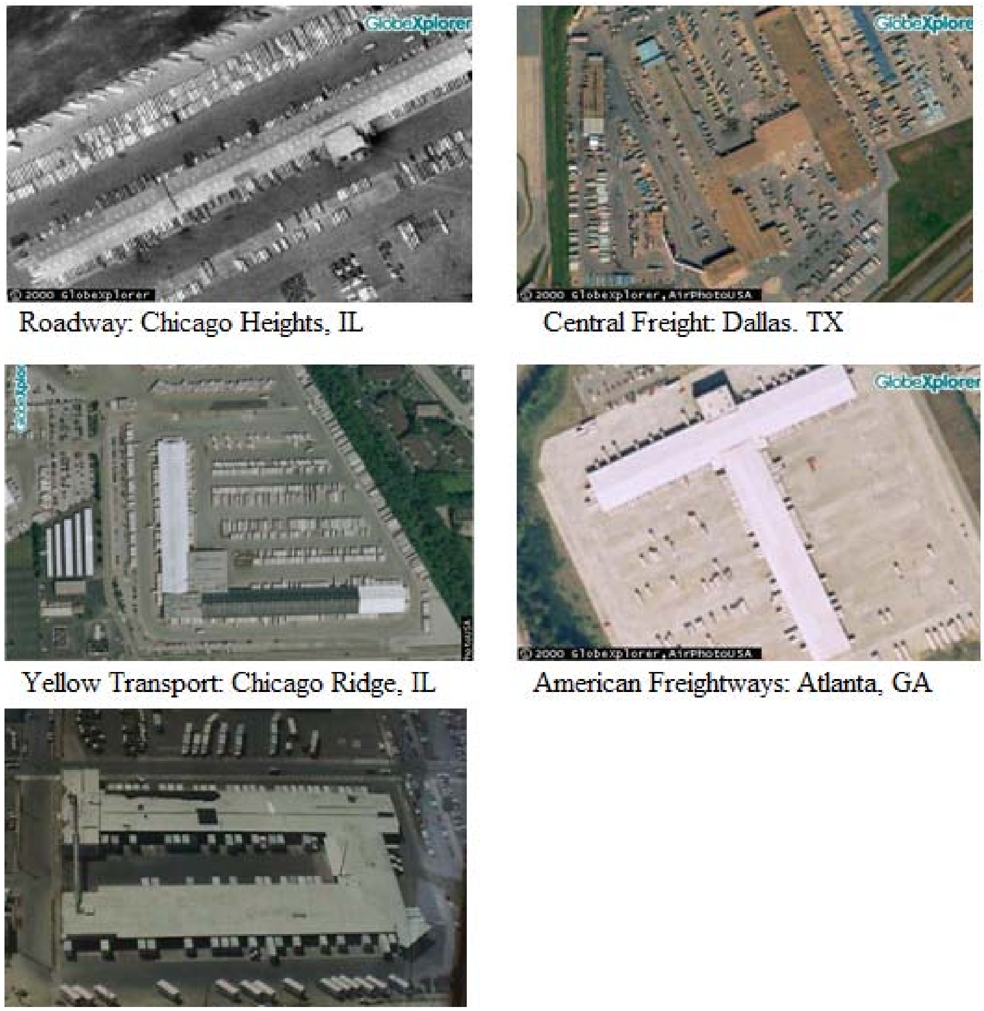


Figure 12 Types of Crossdocking

b. Shape of crossdocking

The shape and layout of a crossdocking facility is a strategic level decision. For existing facilities that have been converted to a crossdock, the shape usually depends on their previous use. [21]. For existing facilities it is unlikely to change the shape to optimize the operations of crossdocking. Even for newly built crossdocks, the shape of the facility depends on many factors such as existing land use, and parking area. The shape of crossdock facilities varies. While the traditional and most used shape is the "I" shape crossdocking, other shapes such as L (Yellow freight Chicago), T (American Freight in

Atlanta-), H (Center freight in Dallas), and U (Center freight in Portland) shapes also exists (see figure 13).



Roadway: Chicago Heights, IL

Central Freight: Dallas. TX

Yellow Transport: Chicago Ridge, IL

American Freightways: Atlanta, GA

U-Consolidated Freightways: Portland, OR

Figure 13 Different Shapes of Crossdock Facility

Besides the external factors discussed above, which affect the shape of a crossdock facility, some internal factors might also be considered in determining the facility shape. According to [21], the best shape depends on the distribution of flows and the fraction of doors devoted to receiving freight(ratio of number IDs to number of ODs). Based on the weighted distance traveled by pallets inside the facility, it has been concluded [21]that as the size increases, the best shapes for a crossdock facility are I, T and X respectively. An L shape is generally inferior to an "I" shape from an operational point of view, because L shape has more inside corners and outside corners than I shape. On the other hand, I shape spaces can accommodate fewer trucks and products at corners, compared to L shape ones. H shape performs better when it has a smaller center. According to their computation work, the center of H shape facility is better to have a distance of 16 door positions or 192 feet. The issue of optimal shapes of crossdock facilities is an open research topic, since there are several aspects that need to be considered such as the travel distance of freight across the facility, the amount of time freight needs to stay inside the facility, and the influence of staging and congestion.

c. Stage process in crossdocking

Jobs such as value-added process, waiting for products of an order to come, or reverse loading of multi-stop delivery take place in crossdocking. Therefore, although there is no long-term storage, space for conducting the above processes is needed. Based on how these processes are conducted, there are free-stage crossdocking, one-stage crossdocking and two-stage crossdocking facilities (as shown in Fig 14). Studies on the staging of crossdocking have been limited to I shape facilities. For free-stage crossdocking, products are unloaded from ITs, and some (named A part) of them are transferred directly on to the OTs, while the others (named B part) are temporarily put inside the facility wherever convenient. This usually creates confusion when trying to locate the product later in a free-stage crossdocking. To deal with this issue, free-stage crossdocking, one-stage crossdocking and two-stage crossdocking can be used. For one-stage crossdocking, such temporary area is usually right inside the receiving docks. The B part products are unloaded into the area nearer to the IDs, and later picked up on the other end of the blocks for loading on to OTs. The processing of products right inside receiving docks is more efficient than the unloading work at the other end of the stage, because the unloading area to OTs may cause conflicts. For a two-stage crossdocking, the first stage acts similarly to the one-stage crossdocking, while instead of picking products and loading them directly to OTs, products are moved into the second stage according to their destinations, and finally loaded on to OTs from the second stage. Such staging strategy reduces the mess often created at the ODs area in one-stage crossdocking. It has been found, however, [22] that a two-stage system offers lower throughput than a single-stage system, because between the two stages freight may block the passageway.

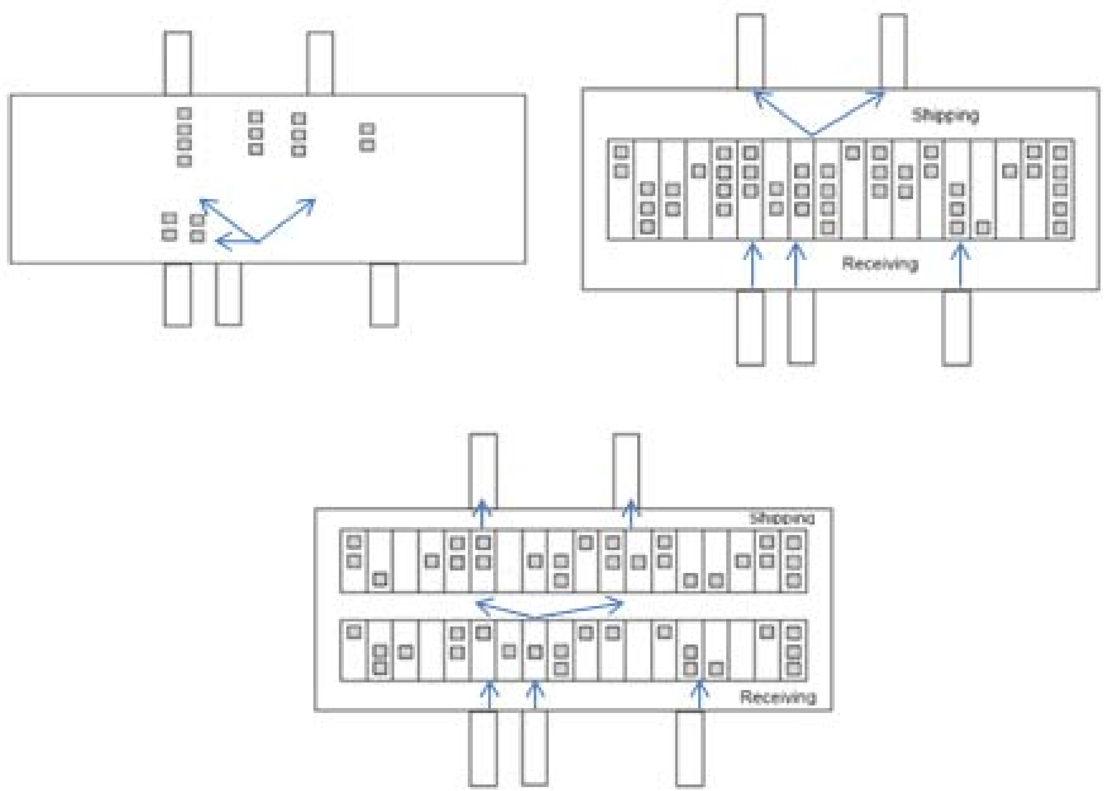


Figure 14 Free-Stage Crossdocking, One-Stage Crossdocking and Two-Stage Crossdocking (adopted from [23] and [21])

1.3.4. Issues and operations in crossdocking

The benefits of crossdocking are obvious, but supporting techniques and tools are needed to realize the operation efficiency and coordination between inbound and outbound shipments. This can only be achieved by solving a set of issues effectively. Such issues include: handling of physical and information flow, utilizing of TL shipments and conducting proper planning and management [2].

To utilize crossdocking operation, operators need advance information on the incoming products such as the products' destination. The vendor should pack the products in a form required by the final receiver [24]. The right information management system is a critical component for coordinating data in the whole process. The real-time and paperless information flow is preferred, since electronic data captured using bar coding and radio frequency (RF) devices can automatically direct the workers to move products to ODs. In addition, it enables real-time order tracking and reduces the error rates caused by manual paper work. A more advanced technology used in crossdocking is the radio frequency identification (RFID), which reduces the labor scanning work and captures pallet information automatically as products pass by RFID portals located on the docks.

Because not all products can be transferred directly from ITs to OTs, part of them need to be put into the yard either in front of IDs (in one stage crossdocking and two stage crossdocking) or somewhere inside the crossdock (free stage crossdocking). Crossdocks need proper capacity for temporary storage.

In addition to "hardware" issues in crossdock operations, "software" issues are very important, requiring further study. Hardware usually depends on the fixed costs and investments made to crossdocking systems. Improving the operations of a crossdocking system, will enable the operators of the facility to improve the facility's productivity.

Crossdocking operations include docking and 'undocking' ITs and OTs, unloading and loading products from ITs and to OTs. Once the products are unloaded from ITs, several subsequent operations are typically conducted before the products are loaded onto the OTs. These subsequent operations include recording all units of product information into the information system, checking the product quality and quantity, collecting and sorting the products, reconsolidating and packing products from different ITs and combining into loads for OTs.

1.3.5. Strategic, tactical and operational levels in crossdocking management

Like warehouse design and planning problems, crossdocking design and planning problems can be divided into three levels of decisions—strategic, tactical and operational [25].

At the strategic level, decisions range from strategic network planning including numbers of crossdock facilities, location and size of crossdocks, system designing and material handling systems. Designing crossdocks also includes determining the shape, stages and parking areas of the facility and the type of the information technology system. At the tactical level, the main concerns include determination of labor force, capacity, lane arrangement and layout. At the operational level, the concerns include the truck scheduling, ID assignment, work assignments, and the positions of products in the facility for temporary storage.

Although the OD assignment to destinations is considered at the tactical level, once it is determined it will influence the ID assignment and the scheduling of trucks arriving and leaving the facility. Thus, a joint solution of layout determination, IT door assignment and scheduling is desirable.

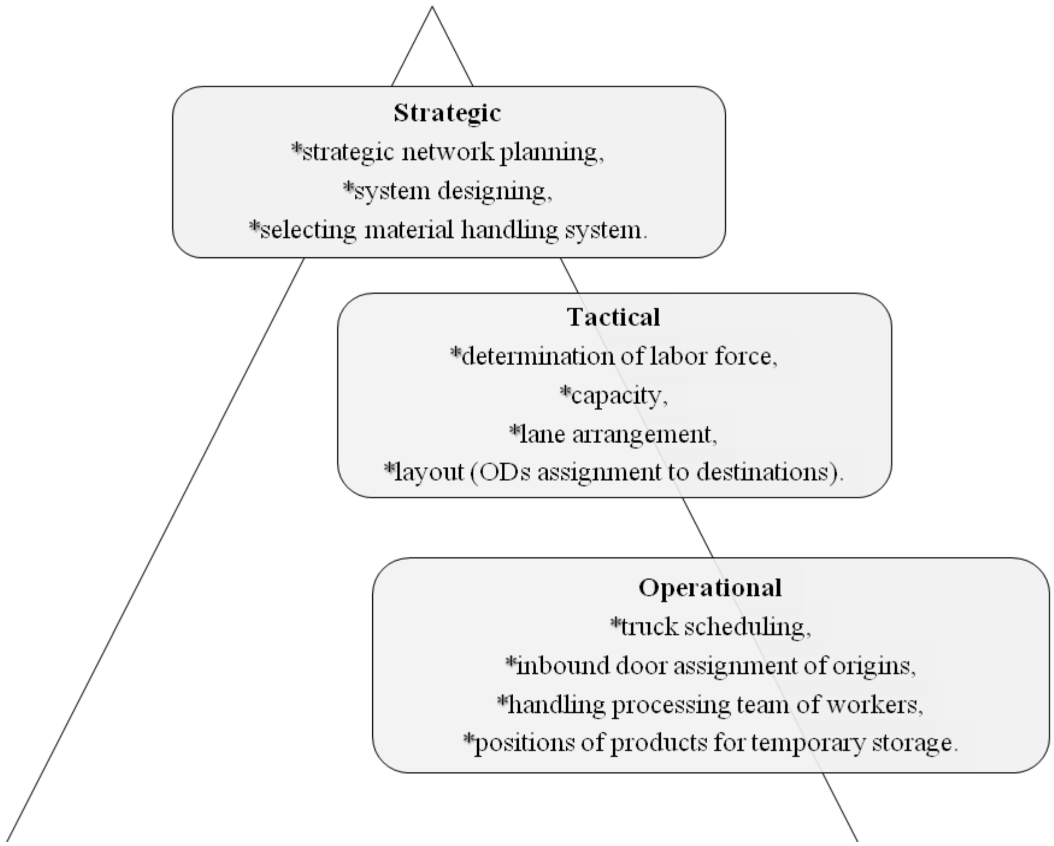


Figure 15 Strategic, Tactical and Operational Levels of Crossdocking

Figure 15 summarizes the three levels discussed above. Strategic level decisions are the highest level of crossdocking planning and management. This level has the longest planning horizon, and decision cannot be easily changed. Decisions at a tactical level are mid-term decisions and at an operational level short term decisions.

1.4. Summary and conclusions

This chapter first introduced the different distribution channels including direct distribution, warehousing distribution, 3PL distribution and crossdocking distribution. Given the characteristics of the distribution channels, decisions on how to choose a proper distribution pattern is discussed. Different distribution channels might involve different delivery facilities such as manufacturing plants in direct distribution, and distribution centers in indirect distribution. Typical distribution centers like warehouses are discussed in detail regarding their operations, main activities, material flow, common costs and their role in a supply chain.

The main objective of this chapter is to introduce the crossdock facility concept and the operations taking place at these facilities. Crossdocking is a material handling operation where products are moved directly from ITs to OTs without storage or with a temporary storage of less than 24 hours. Materials are received at the IDs, unloaded, sorted, consolidated and finally shipped out to OTs through crossdocking. Crossdocking is an operation that moves products quickly and directly through the crossdock facility and meets the needs for quick and efficient movements of products.

Reasons for crossdocking were stated in this chapter. As discussed earlier, the first reason for using crossdocking is that it eliminates storing, which directly eliminates the inventory costs. In addition, crossdocking reduces handling costs, achieves EOS for transporting products, and reduces the unit transportation cost by achieving TL shipments.

Crossdocking characteristics are also discussed depending on the type of crossdocking, shape, and staging. Based on the time when products are assigned to customers, crossdocking can be categorized as pre-distribution crossdocking or post-distribution crossdocking. Based on their different applications, crossdocking facilities can be categorized as: manufacturing, distribution, transportation, retail, or opportunistic crossdocking. In practice, a crossdocking may have more than one application, or combine different operations in one facility. Crossdock facilities also vary in their shape. A study on the shape of crossdock facilities concludes that the choice of the best shape depends on the distribution of flow and the fraction of doors devoted to receiving shipments. Different staging strategies were discussed: free-stage, one-stage and two-stage. One-stage and two-stage crossdocking result in better organization of products when the products need reverse loading onto OTs and improve the efficiency in picking and moving of products. On the other hand, free-stage crossdocking may decrease the blockage caused in fixed staging areas in one-stage and two-stage strategies.

The importance of utilizing crossdocking lies in the fact that it reduces unit transportation costs, reduces handling costs and eliminates inventory costs at the same time. In addition, advantages such as increasing delivery speed, reducing labor costs, and supporting JIT practice help crossdocking to achieve a higher level of customer service, which is a first-line goal in the market.

Chapter 2

Literature Review

2.1. Introduction

In today's market environment, businesses are competing for speed, customer satisfaction, and cost efficiency. For example, the retailer who first gets a product on the floor is considered as the winner [12]. Delivering the same amount and types of products from the same vendors may mean different delivery time for different retailers. This is usually due to the method involved in operation. Speeding up the logistics chain without increasing cost is an operational goal of most retailers and logistics service providers. Inventory holding time is a big part of total operational time and cost. Improving the efficiency by reducing the inventory-related costs is an important objective. By using crossdocking efficiently, these goals may be achieved. Research topics on crossdocking vary widely, but for each topic there are a limited number of papers.

One of the earliest papers on crossdocking systems stated the importance of simulation techniques for determining the configuration of crossdocking. The paper also considered modeling methods for crossdocking [26]. Another paper illustrates the development of mathematical models and algorithms to provide suggestions on optimizing crossdocking operations [27]. The paper also deals with the issue of building networks with a crossdocking environment and designing such facilities. Based on a review of literature and field visits of warehouses, [2] addressed and developed a framework for understanding and designing crossdocking facilities. The authors discussed the techniques which can improve the efficiency of distribution. The paper studied the distribution of network structure and the design of physical and information flow, and analyzed the management systems for crossdocking.

Studies related to crossdocking can be categorized into two large groups: a) studies that consider the crossdock facility as a node within a larger distribution network, and b) studies that focus on the operations of the crossdocking as a system itself. The former problem includes: routing of vehicles in the network with crossdocking facility [28, 29], the location and the demand allocation of the crossdocking facility [30], the effects of crossdocking on the supply chain [31] and manufacturing industry [32], network study of crossdocks with delivery and pickup time windows and capacity constraints [33], network design and distribution systems with crossdocks [34, 35] etc. The emphasis of this review is on the second category, and the pertinent literature is reviewed in the following sections.

2.2. Design and handling system

Crossdocking receives more attention nowadays than ever before, even though it is not a new practice. The first issue in realizing crossdocking operations is the design of the facility and the selection of equipment for handling systems. Existing distribution centers can be converted to crossdocking facilities as long as they can meet the crossdocking requirements (material handling systems, adequate yard space, truck docks, parking space etc.). Moreover, crossdocking operations can be achieved partially inside a typical distribution facility like a warehouse, that is, parts of the products are crossdocked while the others are not. Another option is to find a facility with good potential for crossdocking and modify its layout and design. [15].

Most commonly used crossdocks are narrow, long rectangular (“I” shape) facilities with dock doors surrounding their perimeter. The direct distance of each pair of IDs and

ODs [36] or the sum of two straight lines orthogonal with each other can be considered in the analysis. Besides the "I" shape, other shapes also exist as it was discussed in the previous chapter. The shapes of crossdocks in some way determine the distance workers have to travel inside the facility. Thus, a study on the best shape of crossdock facility [21] focuses on the internal performance of crossdocking such as distance travelled, freight flows and congestion. Two observations are raised: "1) for a given number of doors, a narrower dock realizes a smaller average distance between doors. 2) If a dock is *w* door positions wide, then each outside corner loses *w/2* doors' worth of floor space". By computing the weighted average distance of uniform freight flows and exponential freight flows between ITs and OTs of I, L, T, H, and X-shapes, the authors concluded that "as size increases, the most labor-efficient shapes for crossdock are I, T and X, respectively" [21]. For these three different shapes of a crossdock facility, the authors examined the use of the internal corners, and concluded that some space is not usable because of the conflict of arrangement between trucks at the orthogonal doors. For example, if a trailer is 48-foot long and the door is 12-foot long, the trailer, which is assigned to the door at one side of the corner closest to another door at the other side of the corner, will take up the space in front of the other side. Calculations on the unusable space of each shape are shown in the following table. The relationship between number of doors and shapes of crossdock facilities is stated (Table 2).

Table 2 Shapes and Number of Doors
(summarized from[21])

Shape	Number of Doors
"I": there is no inside corner	less than 150 doors
"T": two inside corners (for standard 48 foot trailers at 12-foot door, 48/12*4=16 doors are unusable)	between 150 and 250 doors
"X": four inside corners (for standard 48-foot trailers at 12-foot doors, 48/12*8=32 doors are unusable)	more than 250 doors

In designing a crossdock facility, the parking space in front of each ID should also be taken into account. As the number of ITs for different sizes of crossdocks varies largely, there is no specific study on parking space for different crossdock facilities. The parking space is a buffer for queues in front of each ID. A suggestion [18, 21] is that two trailers' space for parking in front of each dock door can accommodate most flow surges of ITs without major problems.

Although narrow shapes can reduce the average labor travel distance inside the facility [21], it should be noted that the facility cannot be too narrow, otherwise congestion will increase. In addition, enough space for staging the products is required.

The material handling system is one of the factors that influence the freight flow inside a crossdock. Proper use of the material handling system will accelerate the freight flow speed. The material handling system for small size products would be manual carts. Pallet jacks and forklifts can be used for pallet loads. Cart draglines are also employed since they can reduce the labor walking time [18].

2.3. Crossdock layout

Typically, doors surround the perimeter of a crossdocking facility. Some of the doors are used for receiving products from ITs (referred to as inbound doors (IDs), receiving doors or strip doors according to different studies) and the other doors are used for shipping and unloading products to OTs (referred to as outbound doors (ODs), shipping doors or stack doors). Crossdock layout means the specification of doors used as either IDs or ODs as well as the assignment of destinations to the shipping doors [37]. Bartholdi and Gue studied the IT/OT door assignment to improve the working efficiency of workers. They used a simulated annealing approach to interchange designations of dock doors, and the goal is to minimize the labor cost. The labor costs are presented by models of travel cost, moreover, three types of congestion typically experienced are considered to construct layouts. The assignment of ODs to destinations is usually considered as a medium term decision because an OD is normally used for certain customers. In order to prevent mistakes made by workers by frequently changing doors, the destination of an OD does not change very often. On another aspect, based on the study of an existing crossdocking area layout of a Toyota motor manufacturing plant and of another three tested shapes (I, T and V), it was concluded that a lane arrangement of crossdocking area can improve efficiency [38]. By rearranging the sequence of lanes through genetic algorithm, the workload could be improved by nearly 34% [38].

Another study by Gue [39] considered the material flow through a crossdock facility which is affected by the assignment of ITs to dock doors. A Linear Programming (LP) model was constructed for the material flow and a parameter was used to capture the influences. No statistics for calculation time of the algorithm which combines swap heuristics and queuing analysis was reported. Gue [40] examined the effects of trailer scheduling on the layout of freight terminals. A look-ahead scheduling strategy (usually assign ITs to the IDs with the most outgoing freight closest to the ODs) was used to develop a material flow model to minimize worker travel. The authors used the LP model to assign trailers to doors and then ran simulations by interchanging pairs of assignments of shipping doors to determine the layout with the lowest expected cost.

Bartholdi et. al [41] categorized crossdocking into single-stage, two-stage and free-stage. They discussed methods for pallet queuing and crossdock design, and found that staging pallets in a flow rack was more efficient than staging them on the floor.

Gue and Kang [22] studied the staging queuing problem using equal number of IDs and ODs. They checked single and parallel staging queues and by using random choice rules, they concluded that it is better to have one long queue than two shorter queues. Later, Sandal [42] also used a door ratio of one to study the staging queuing problem. He developed a simulation approach to imitate the staging and analyzed five different staging scenarios in a LTL crossdock facility. The analysis suggests that loading OTs simultaneously while using a zoned staging strategy performs better than the other four strategies (all staged with random staging, all staged with zoned staging, all staged simultaneously with random staging and direct loading) studied. Taylor and Noble [43] examined material staging in different situations with door ratios of one half for IDs to ODs and they concluded that the layout only mattered for makespan determination. Vis et. al [44] focused on the locations for incoming products temporarily stored, and the goal was to minimize travel distance in a crossdock when pallets cannot be staged along the shortest path between IDs and ODs. The problem was modeled as a network problem and solved as a cost flow problem.

Masel and Goldsmith [45] studied a freight consolidation terminal's layout, which is also the assignment of destinations to ODs in the parcel delivery industry (PDI). They evaluated terminal layouts based on congestion and time span of the transferring operation using a simulation method. The objective was to find a layout that would balance the static workloads on the loading docks based on historical parcel mix (a mix of parcel products). Masel [46] used a list-scheduling heuristic to generate assignment lists based on longest processing time scheduling heuristic [47] and studied the shipping dock assignment of a freight consolidation terminal with consideration of historical demands.

2.4. Truck door assignment and scheduling

The truck door assignment problem includes ITs and OTs assignments, but it usually emphasizes on the ITs assignment to IDs problem. Tsui and Chang [48] proposed a microcomputer based tool using a bilinear program to assign IDs to the origins/ITs and ODs to destinations/OTs in freight yards. They aimed to minimize the distance traveled by forklifts in the freight yard and found a local optimal solution for the problem. However, the local optimal solution heavily depended on the initial solution. Therefore, later, they proposed a new branch and bound algorithm for global optimal solution by converting the original formulation into a new formulation whose objective value is the lower bound for the original model [48]. In contrast to the above work, Aickelin and Adewunmi [49] proposed a simulation optimization method in order to find the optimal arrangement of IDs and ODs and the assignment of ODs to destinations, on the measurement of minimizing distance travelled by forklifts in a crossdock.

Bozer and Carlo [36] considered a static door assignment problem and presented a mixed integer program (MIP) model for a LTL crossdocking to minimize travel time of freight from IDs to ODs. To avoid congestion, they restricted the maximum number of subsequent trucks assigned to the same door to two. A simulated Annealing (SA) based heuristic was presented. However, the proposed approach is only suitable when the number of trailers and doors are equal.

Miao and Lim [50, 51] claimed that the arrival/departure time of each truck, the operational time of shipment, and the capacity of the crossdock are factors affecting the system feasibility. Therefore, they considered an over-constrained truck dock assignment problem with a time window, an operational time, and a capacity constraint, in a transshipment network through crossdocks. The crossdocks had trucks exceeding the number of docks available, and the capacity of the crossdock was limited. Two studies with different objectives were conducted; the first minimized the operational cost of the cargo shipments and total number of unfulfilled shipments [50], while the other minimized the total shipping distance inside the crossdock [51]. Both cases were formulated as integer programming (IP) models aiming to find an optimal assignment of trucks to minimize the total operational cost of cargo shipments and unfulfilled shipments [50] and shipping distance of cargos [51]. As the problem size grows, the number of decision variables and constraints in the IP model quickly increases. Thus, two meta-heuristic approaches, Tabu Search and Genetic Algorithm are proposed to solve these problems.

Bermudez [52] presented a Genetic Algorithm for assigning trailers to doors in order to minimize the total weighted travel distance in a crossdock facility, thus, to minimize the freight travel time. He formulated the problem as a Quadratic Assignment Problem (QAP) and experimented on real data obtained from the industry. He analyzed crossdocks with 16 doors, 43 doors and 195 doors separately and found the GA approach gave results comparable to the results obtained from a steepest-descent pair wise exchange algorithm. Extensions of this work were presented as experiment with different IDs and

ODs ratios, diverse truck load, and calculations based on trips instead of weight for travel distance.

The number of papers published on truck scheduling at crossdocking is very limited. Yu, W. and P.J. Egbelu [53] discussed the ITs and OTs scheduling problem in crossdock with temporary storage. Their objective was to find the best truck scheduling sequence to minimize total operation time while a temporary storage buffer is located at the shipping dock. They built a MIP model to solve the crossdocking problem based on assumptions that there is only one receiving dock and one shipping dock, which is not necessarily the case in practice.

Li et. al [54] modeled the crossdocking scheduling as a machine scheduling problem by the nature of considering each incoming and outgoing container for processing as jobs and the limited number of workers as machines. Two heuristics were implemented to solve this NP-hard problem and small experiments were conducted using CPLEX for examining the accuracy of the heuristics. Based on their work, Alvarez-Perez et. al [55] proposed a new solution approach by combining two meta heuristics, Reactive GRASP and Tabu Search (RGTS), and testing the performance of this approach by comparing the results of 16 problem instances. The model in these two papers was based on a given schedule of ITs/OTs, i.e., the trucks are already docked before scheduling the unloading and loading work, which means that door assignment was not considered. Chen and Song [56] studied the crossdocking scheduling problem with total completion time in JIT logistics. Several heuristics and branch and bound algorithms were proposed based on different characteristics of the problem. Ma and Chen [57] designed a dynamic programming model to solve the problem with total weighted completion time and Chen and Lee [58] showed in strong sense that the problem is NP-hard, and they proposed a branch and bound algorithm to minimize the makespan (which is equivalent to the completion time of the last job to leave the system in machine scheduling [59] and showed its efficiency with up to 60 jobs. There are two stages in their model; however, it is assumed that only one machine exists at each stage. Later, Song and Chen [60] minimized the total scheduling makespan at a two stage crossdock by building an MIP model. Two heuristic methods-Johnson's rule-based heuristic and dynamic Johnson's rule-based heuristic-were presented considering two lower bounds of large number of jobs. However, the model was limited to one OT with multiple ITs.

McWilliams [61] studied the scheduling of ITs to IDs at a freight consolidation terminal as parcel hub scheduling problem (PHSP) and studied this problem aiming to optimize the time span of the transfer operation (unloading the ITs, sorting parcels and loading to OTs). They proposed a simulation-based optimization approach using GA to drive the schedules. Later, a mathematical model for solving small-size PHSP and a GA approach for solving large-size PHSP were proposed with minimum computational time compared to other competing approaches [62]. One thing we should note on these two studies of scheduling ITs is the difference between transferring terminals and crossdock facilities. In a transferring terminal, the products are not assigned to each destination, while in a crossdock facility the products on ITs have specified destinations. Wang et. al [23] claimed that minimizing labor costs such as costs for moving products is not necessarily the only goal in crossdock operations due to the need to decrease transportation lead-time in coordination to JIT, make-to-order or merge-in-transit strategies. They tried to minimize the time freight spends in a crossdock and they used a dynamic simulation model to get the conclusion a Leave-early algorithm can save time for OTs. Wang and Regan [63] scheduled trailers based on real-time information using simulation. They developed time-oriented scheduling algorithms to measure the average time freight spends at crossdocks. The above studies used simulation approaches and no mathematical formulations were provided.

2.5. Comparison of studies

A comparison of the papers reviewed above, focusing on crossdocking door assignment and scheduling is presented herein. The papers are compared in four categories: crossdocking system optimization objectives; crossdocking scheduling with focus on the IT and OT scheduling; crossdocking door assignment problem, which contains door assignments to origins and destination as well as ITs and OTs assignment to doors; and simulation solutions.

2.5.1. Crossdocking systems optimization

Crossdocking is employed mainly to reduce transportation costs, unnecessary inventory and handling costs, and delivery speed, to achieve a better customer service level. Research focusing on the crossdocking operation as a system mostly tried to optimize the system performance by optimizing different aspects of crossdocking operations.

Many research works related to crossdock truck assignment or door arrangement tried to optimize travel distance inside the crossdock facility. Aickelin and Adewunmi [49] aimed to find the optimal arrangement of a crossdock centre's IDs and ODs and the most efficient assignment of destinations to ODs, in order to minimize the material handling equipment travelling distance. Bartholdi and Gue [21, 37] stated that the crossdocking operation is labor intensive therefore of high labor cost. They studied the trailer assignment problem and the best crossdock shape to reduce travel distances with consideration to congestion in order to minimize the labor cost of transferring freight. Bermudez [52] assign trailer to doors in order to minimize weighted travel distances in a crossdock, a surrogate for labor cost and cycle time. Peck [64] seek to improve terminal productivity by door assignment, to minimize total distance material handlers travel during a transfer operation. Tsui and Chang [48, 65] tended to improve the efficiency of the crossdocking operation by minimizing the distance traveled by forklifts and Vis and Roodbergen [44, 66] tried to minimize distance traveled by forklifts with loads in order to find the proper location of products in a crossdock facility. Bozer and Carlo [36] claimed that the crossdocking performance is measured by the rate at which freight is processed (loaded, moved, and unloaded). The rate equals the ratio of total tonnage of freight and the total processing time with a given labor force. With a given tonnage of freight, it is optimal to reduce the time. On the other hand, the processing time primarily depends on the travel time. Again, the travel time can be measured by travel distance, therefore, the paper tried to minimize the overall material handling workload travel distance. Gue [40] used travel distance by freight to measure the cost of a given layout and tried to minimize the weighted freight travel distance.

Several studies aimed to optimize service time. Li and Alvarez-Perez [54, 55] claimed that in a JIT environment, having the jobs finished by the exact time requested by the customer is desirable and thus the objective of JIT scheduling is to minimize penalties for finishing late. Boysen et. al [67] claimed that the efficiency of a crossdocking system depends mostly on the coordination of inbound and outbound flows. Therefore, they solve a sequencing problem by reducing the delay of shipments at the crossdock, minimizing the total completion time of the operation (referring to as makespan in scheduling). By holding the same objective of minimizing the total completion time, Chen et. al [56, 58, 68] tried to minimize the makespan of the crossdocking scheduling problem and Ma and Chen [57] minimized the weighted completion time. Similarly, Yu and Egbelu[53] minimized total operation time to find the best truck door assignment and scheduling sequences. Wang and Regan [63] tried to minimize the time freight spends in a crossdock by studying the truck scheduling problem. Wang and Regan [23] scheduled ITs to minimize departure of OTs, a surrogate for minimizing the time freight spends in crossdock. Lim et. al [51] minimized the total shipping distance of freight inside a crossdock facility. Miao et. al [50] aimed to find an optimal assignment of trucks that minimizes the operational cost of the cargo shipments and the total number of unfulfilled shipments at the same time. The two objectives were combined to one term, the total cost -- by transferring the unfulfilled shipments into penalty cost.

Figure 16 and Table 3 summarize the primary optimization objectives considered in the reviewed literature. In summary, to reduce the operating cost, which is primarily affected by the labor cost of crossdocking, we need to reduce the travel distance by workers, forklifts, weighted freight movements etc. From the JIT environment point of view, the freight should be handled on time. One of the handling processes is moving freight from IDs to ODs, and this traveling time is determined by the (weighted) travel distance. Other than that, we also seek to minimize the makespan of the crossdocking scheduling that is required by the JIT philosophy.

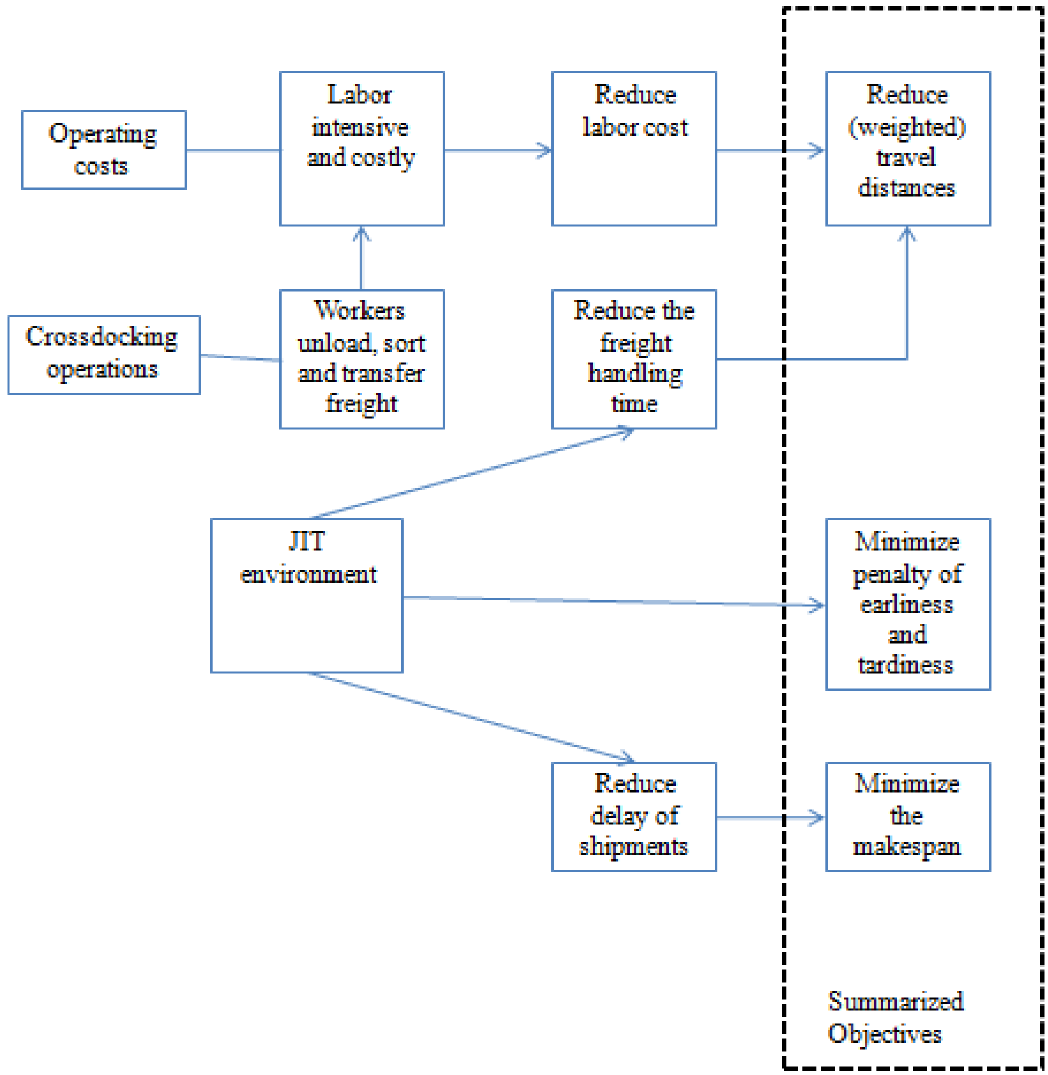


Figure 16 Primary Optimization Objectives and Reason

Table 3 Optimization Objectives of Existing Crossdocking Research Papers

Author	Year	Objective
Aickelin and Adewunmi	2006	minimize the material handling equipment travelling distance
Alvarez-Perez et al.	2008	minimize the penalty of earliness and tardiness for both incoming containers and outgoing containers
Bartholdi III and Gue	2000	minimize travel distance with congestion constraints thus reduce labor costs
Bartholdi III and Gue	2004	minimize travel distance between inbound and outbound trailers weighted by the intensity of freight flow
Bermudez	2002	minimize the total travel distance weighted by freight flow
Boysen et al.	2008	minimize the total completion time of operations (makespan)
Bozer and Carlo	2007	minimize overall material handling workload travel distance
Chen and Lee	2007	minimize the scheduling makespan
Gue	1999	minimize the weighted freight travel distance
Li et al.	2004	minimize the penalty of earliness and tardiness for both incoming containers and outgoing containers
Ma and Chen	2007	minimize weighted completion time
Miao et al.	2006	minimize the operational cost of the cargo shipments and minimize the total number of unfulfilled shipments
Lim et al.	2006	minimize the total shipping distance of freights
Peck	1983	minimize the total travel time/distance
Song and Chen	2007	minimize the scheduling makespan
Tsui and Chang	1990	minimize the distance traveled by the forklifts
Tsui and Chang	1992	minimize the distance traveled by the forklifts
Vis and Roodbergen	2002	minimize travel distance of the forklift trucks with loads
Vis and Roodbergen	2007	minimize travel distance of the forklift trucks with loads
Wang and Regan	2008	minimize the time freight spends in a crossdock
Wang et al	2008	minimize departure time for outgoing trucks in a crossdock
Yu and Egbelu	2008	minimize total operation time

2.5.2. Crossdocking scheduling modeling approaches

Truck scheduling at crossdocking terminals is similar to machine scheduling. There are studies on single machine scheduling of crossdocking, which is the simplest scheduling problem and a special case which considers that all jobs (products, loading/unloading service, or containers/pallets etc) are processed on a single machine (team of worker, dock door, etc). Also, there are studies on multi-machines scheduling of crossdocking truck scheduling. In this case, there are three categories of machines: identical machines in parallel, machines in parallel in different speeds, and unrelated machines in parallel [59]. For identical machines in parallel, there are more than one machine (teams, doors etc.) available, and jobs can be processed at any machine since all machines are identical. For machines in parallel in different speeds, teams of workers at dock doors of crossdocking have different processing speeds for the jobs. If the speed of all machines is considered the same, we have a special case of identical machines in parallel. For unrelated machines in parallel, the processing speeds not only depend on the machines but also depend on the different jobs (for different products, sizes, pallets, containers etc.). If the speeds only depend on the machines, it is a special case of machines in parallel in different speeds.

Li et. al [54] considered timing as the crucial objective for crossdocking operation which need JIT scheduling for starting breakdown and completing buildup of cargos. They considered each incoming container and each outgoing container as a job to be processed by teams (which are regarded as machines). There are limited numbers of teams (machines) available. Containers are processed in two phases: breakdown and buildup, and the teams for breakdown and buildup are identical. Each job has a due date for processing and the processing time is known as well as the release time of incoming containers. They did not consider the transport of products inside the crossdock facility from the inbound area to the outbound area as they claimed that the time is negligible compared to the processing time. As the problem is NP-hard, they proposed two algorithms, namely Squeaky Wheel Optimization embedded in a Genetic Algorithm (SWOGA), and Linear Programming within a Genetic Algorithm (LPGA) to solve the problem. Based on this model, Alvarez-Perez et. al [55] studied the scheduling problem as parallel machine with job dependent due dates, and proposed an alternative solution approach to [54]'s work by combining two meta-heuristics: Reactive GRASP and Tabu Search, abbreviated as RGTS.

Boysen et. al [67] tended to provide a base model for scheduling trucks—Truck Scheduling Problem (TRSP) at crossdocking terminals. In order to serve as a base model, many assumptions were made: the handling times are merged into a service slot (a slot comprises unloading time of ITs and complete loading time for OTs), and the service time for each job is equal as well as the movement time between doors. The basic model in this paper only decided the sequence of ITs at a single ID and OTs at a single OD. An IP formulation was built and upper and lower bounds were found. The model was decomposed into sub-problems and a Dynamic Programming approach and a heuristic starting procedure were introduced to solve the sub-problems.

Chen and Lee [58] studied a two-machine crossdocking flow shop scheduling problem with two stages: a) download and unpack the inbound products, b) collect those products with the same destination into an OT. However, only one machine exists at each stage, and this was a special case of a later study [60]. They studied the two-stage crossdocking optimization problem as a two machine flow shop scheduling problem. The vehicles for inbound and outbound are considered as machines and the products are considered as jobs. In this paper, there are multiple parallel machines in the first stage and one machine in the second stage.

Table 4 summarizes the literature studied on the crossdocking scheduling as a machine scheduling problem and the information presented. The first two rows in the table state the author and year of publication. The third and fourth rows state the relations between crossdocking scheduling and the machine scheduling while the next two rows present the model and formulation. Since the formulations are all NP-hard, the last row states the adopted solution approach.

2.5.3. Crossdocking door assignment modeling approaches

Other than IT/OT scheduling, the door assignment problem also affects cooperation of inbound and outbound freight flow through crossdocking, which in turn, affects the performance of crossdocking operations. Most papers on the crossdocking door assignment problem are aiming to minimize the travel distance or weighted distance of freight and formulate the problem as quadratic assignment problem (QAP). In a typical QAP, there is a set of locations and facilities, and the facilities need to be assigned to each location [69]. To measure the cost of the assignment, a weight function and a distance function are introduced and the cost is the summation over all the pairs of production of weight and distance. The aim is to find the assignment that minimizes this cost, which is presented by the summation of all productions.

Tsui and Chang [48, 65] defined a basic mathematical model for the truck door assignment problem. The weight function was the number of forklift trips required, and the distance function was the distance between ID and OD. The initial approach [65] was very sensitive to the starting solution. They realized that the computation time increases dramatically with the problem size and recognized the need to develop an algorithm for large size problems. Bermudez [52] also formulated the crossdocking door assignment as QAP. The door assignment required assigning doors to origins and destinations of products. The weight of loads from each origin to each destination was considered as weight function, and the travel distances between doors were considered as a distance function. He proposed a GA based tool to solve the problem. Bozer and Carlo [36] formulated a MIP formulation for the QAP with rectilinear distances. Instead of putting distance directly in the formulation, they consider an "I" shape crossdocking where the distance between doors can be calculated using coordinates. The weight function was the frequency of shipment going from ITs to OTs.

Table 5 summarizes the crossdocking door assignment problem formulations presented above. The first two rows state the author and year of publication. The third and fourth rows state the relations between crossdocking door assignment problem and QAP while the next two rows present the model and the formulation. The last row states the adopted solution approach.

Additional formulations of the crossdock door assignment problem include the following. Gue [40] assigned ITs and OTs to doors under look-ahead scheduling. A LP model was used for door assignment and was solved using a steepest-descent algorithm and the LP was used as part of a two-way exchange. Bartholdi and Gue [37] built a cost model that consist of workers' travel time and workers' waiting time for assigning trailers to doors. Lim et. al [51] considered a dock assignment problem with time windows and capacity constraint. They formulated the problem as an IP model and proposed Tabu Search and Genetic Algorithm with good testing performance. Miao et. al [50] considered an over-constrained truck dock assignment problem and formulated an IP model aiming to find an optimal assignment of trucks. As the size of the problem grows the number of decision variables and constraints in the IP model increases substantially. Thus, two meta-heuristic approaches, TS and GA were proposed to solve this problem.

Table 6 summarizes the modeling approaches (other than QAP) for crossdocking door assignment problem presented above. The first two columns state the author and year of publication. The third presents the model and the fourth states the solution approach. The last column presents the conclusions given in these papers.

Table 4 Crossdocking Scheduling as Machine Scheduling Problem

Author	Year	Machines	Jobs	Model	Formulation	Solution Approach
Li et al.	2004	teams of workers	incoming and outgoing container	two-phase parallel machine scheduling	IP	SWOGA,LPGA
Alvarez-Perez et al.	2008	teams of workers	incoming and outgoing container	parallel machine scheduling with job-dependent due dates	IP	combination of Reactive GRASP and Tubu Search--RGTS
Boysen et al.	2008	inbound door and outbound door	inbound trucks and outbound trucks	two phase single machine scheduling	IP	dynamic programming and heuristic starting procedure
Song and Chen	2007	vehicles in the inbound and outbound	inbound and outbound products	two-machine crossdocking flow shop problem	MIP	heuristics with lower bounds
Chen and Lee	2007	vehicle in the inbound and outbound	inbound and outbound products	two-machine crossdocking flow shop problem	MIP	approximation algorithm and branch-and-bound algorithm

Table 5 Crossdocking Door Assignment Modeled as QAP

Author	Year	Weight Function (w)	Distance Function (d)	Model	Formulation	Solution Approach
Tsui and Chang	1990	number of forklift trips required	distance between receiving door and shipping door	QAP	IP	bilinear program, find local optimal
Tsui and Chang	1992	number of forklift trips required	distance between receiving door and shipping door	QAP	IP	branch and bound algorithm
Bermudez	2002	weight of loads from each origin to each destination	travel distance between doors	QAP	MIP	genetic algorithm
Bozer and Carlo	2008	frequency of shipment going from ITs to OTs	rectilinear distances between doors	QAP	MIP	SA-based heuristic

Table 6 Other Modeling Approaches on Crossdocking Door Assignment Problem

Author	Year	Model	Solution Approach	Conclusion
Peck	1983	IP model	Greedy Balance Algorithm	assigning ITs and OTs to docks efficiently will improve terminal productivity
Gue	1999	LP model	steepest-descent procedure	look-ahead scheduling can reduce labor cost compared to FCFS scheduling
Bartholdi III and Gue	2000	cost model similar in structure to QAP	SA	changing layout effectively reduces labor costs by balancing travel distances an congestion
Lim et al.	2006	IP model	TS and GA	the TS and GA works better than CPLEX solver within shorter running times
Miao et al	2006	IP model	TS and GA	the TS and GA works better than CPLEX solver within shorter running times

2.5.4. Simulation approaches

Rohrer [26] discussed methods and issues as they apply to crossdocking systems, how simulation can be used to determine optimal hardware configuration and software control, and whether and how it ensures success in crossdocking design. He also developed failure management strategies. Aickelin and Adewunmi [49] tried to optimize the results of simulation models by optimizing the door assignment from the simulation models that performed the best against a set of predetermined criteria. Wang et. al [23] used detailed simulation models built in the Arena simulation package, to compare the performance of a first-come-first-served algorithm, a look-ahead algorithm and a leave-early algorithm.

2.6. Summary

This section reviewed articles pertinent to crossdocking design and operations. The articles reviewed relate to the design and handling systems and crossdock layout. In addition, articles focusing on crossdocking operations, including the truck/trailer door assignment, and truck/trailer scheduling at the IDs and ODs have been reviewed and compared. Chapter 3 presents modeling approaches and assumptions, with different scenarios, to study the truck assignment and scheduling problem, which is the main subject of this dissertation.

Chapter 3

Model Approach and Assumptions

3.1. Problem description

3.1.1. Decisions to be made

Material flow through crossdocking is illustrated in Chapter 2. The general idea is that ITs arrive at the crossdocking facility and need to be assigned to IDs. Those ITs assigned to the same door will need a sequence for unloading products. Assigning and sequencing ITs are the main part of inbound operation for crossdocking. Inbound operation is one of the three main operations of crossdocking, along with outbound operation and inside operation. Inbound operations consist of the assignment of a time slot, door and unloading and transferring equipment to the ITs, recording of the data on incoming products and their characteristics, and assignment of temporary storage location if needed [70]. Outbound operations consist of the assignment of a time slot, door and loading to the OTs, generation of manifests, and recording of the information on the shipment and the vehicle [70]. At the IDs, the unloaded products from ITs will be moved either directly or after some reconfiguration to those ODs where OTs requiring these products is assigned. The traveling of products inside the facility is part of inside operation of crossdocking. For truck scheduling studied in this research, we consider the integration of inbound operations, outbound operations and inside operations. The problem of truck door assignment and truck sequencing after being assigned is notated as truck scheduling problem in this research.

3.1.2. Problem objectives

As discussed in the literature review chapter, minimization of total travel distance or weighted distance within the crossdock facility are the main objectives for the truck door assignment problem. The main objectives for the truck sequencing problem studied so far are minimization of total service time, departure time, and tardiness. There are some publications available on each of problem, however, all of them consider each objective individually and did not consider the problem of truck door assignment and sequencing simultaneously. Thus the truck scheduling models in this thesis consider three objectives specified as follows. (1) Minimize total starting and handling time of serving ITs at the IDs. (2) Minimize total weighted travel distance freight traveled inside the crossdock facility. (3) Minimize total departure time of all OTs from the ODs. The first objective is an objective of the inbound operation, the second objective is an objective related to the inside operation of crossdocking, and the last objective deal with the outbound operation. Reasons and benefits of optimizing these three objectives are discussed in the following sections.

3.1.2.1. Minimize total starting and handling time of serving ITs

Crossdocking starts when ITS with products arrive at the facility and ends when the products are loaded onto the OTs [2]. The main physical handing operations at crossdocking doors include receiving and shipping. Successful operations at IDs/ODs depend on the coordination of both operations. In this section, we discuss the objective of optimizing inbound operation.

Receiving of commodities into a crossdock needs to be carefully planned [71]. For typical pre-distribution crossdocking, before the arrival of ITs, an ID is usually allocated to an IT. By means of real-time information technology, the arrival time of ITs are known to crossdocking operators before its occurrence. ITs carrying various products from different suppliers arrive at the IDs of the crossdocking facility. Upon their arrival, drivers of ITs report to the gatehouse, and staff working at the gatehouse will check the vehicle documentation and direct the drivers where to go. All these trucks are either directly assigned to an ID or need to wait in line in the parking space in front of the IDs they are assigned to [67]. The facility cannot handle all the ITs arrive at the same time due to the limited resource of equipments, workers and doors. IT scheduling ideally begins before its arrival. As a static problem, the scheduling of all ITs is assumed to start at time zero. For all these ITs, late starting time means long waiting time. Therefore, we want to minimize the total starting time plus the total waiting time of all ITs.

The performance of inbound operation can be measured by how fast the ITs are served, given fixed resources. Since the ITs will leave as soon as they finish unloading all its commodities, the earlier the ITs depart and the less waiting and handling time they have, the faster are serviced. There are three reasons to minimize total starting and handling time of all ITs: First, an efficient IT schedule reduces the makespan of the whole operation and links to the departure of OTs. At this starting point of crossdocking operation, objectives such as minimizing the total waiting time of the ITs can be covered by the objective of minimizing the starting and handling time of serving IT. Second, those ITs not served directly at the IDs need to wait at the parking area in front of the crossdocking facility. One way to keep the number of ITs waiting from exceeding the parking area capacity is to increase the capacity of the parking area. But this causes huge fixed costs. On the operational level, a better way is to reduce the number of ITs waiting at the same time or the ITs' waiting time at the parking area. Since minimizing the starting and handling time of serving ITs reduce the waiting time of all the ITs, this objective, in consequence, can help relief the congestion that may occur at the parking area in front of the crossdock facility. Last but not least, if ITs can start their service as early as possible, the drivers can take some rest during the unloading service of the ITs. On the other hand, late starting time of service challenges the drivers' patience. However, it should be noted that early starting time does not link to short unloading time; therefore, the objective is to minimize the summation of both.

Minimizing the total starting and handling time of ITs offers many benefits. However, it should be noted that, only minimizing this objective will lead to the degradation in the other performances of crossdocking operations. By only minimizing the starting and handling time of the ITs, the ITs will be assigned without considering the physical location. This will greatly increase travel distance from the ITs to the OTs. While minimizing travel distance degrades the optimality of total starting and handling time as discussed in previous section, these two objectives are confliction with each other. The following section will discuss the objective to optimize inside operation of crossdocking, and to minimize the total weighted distance traveled by freight inside the facility.

3.1.2.2. Minimize total weighted travel distance

Commodities unloaded from ITs at IDs need to be moved to ODs by equipment inside the facility and loaded onto OTs by workers. This can be done either directly or after being staged on the dock for some time or after reconfiguration on the staged dock. There are several ways to measure the performance of crossdocking operation. One way is to estimate the total distance travel between IDs and ODs [21]. In their work, two methods for evaluating performance of crossdocking operations were provided, one is simply to look at the distances between each pair of ID/OD and the other method is to look at the weighted distance traveled by freight between pairs of doors. In the past, those studies on evaluating crossdocking performance focused mainly on the former evaluation criteria because of lack of real-time information about the freight flows between doors. Nowadays, the improvement of modern technology allows the implement of pre-distribution crossdocking, which will provide the crossdocking operator with the knowledge of product flow between supplier and customers and even freight flow from each IT to each OT. Minimizing the total weighted travel distance gives more reasonable assumptions and is better than measuring travel distance between doors. In this research, one of the objectives for the truck scheduling problem is to minimize the total weighted distance traveled by all pallets across the crossdock facility.

The use of crossdocking is effective as long as its total operating cost is less than the savings from inventory cost and transportation cost. More savings from eliminating inventory cost, reducing transportation cost, lowering operating cost helps to obtain more benefits for operators. Among all kinds of crossdocking operating costs, labor costs are high due to intensive labor work. Because commodities delivered through crossdocking are not in uniformed shape and require flexibility in the material handling process, crossdocking operation needs labor to move products from IDs to ODs instead of using automatic equipments. While labor costs depend highly on their travel distance inside the facility, it is affected by the door assignment of ITs/OTs. Therefore, we could reduce the labor cost by minimizing the total weighted travel distance when we make the truck door assignment.

On the other hand, it is important to reduce the total handling time of products inside crossdocks by decreasing the transportation lead time and improving the speed of products movement inside the crossdocking facility in order to coordinate with other requirements such as just-in-time, make-to-order and merge-in-transit [63]. In practice, the time duration freight spends inside a crossdocking facility depends heavily on the travel time. Particularly, some of the products unloaded from the ITs will be moved directly to the ODs to be loaded, the time spent by those products inside the crossdocking facility mainly depends on the travel distance from IDs to ODs. While the other part of the products from ITs will be first staged on the dock and then moved to the ODs after sorting or reconsolidation. The travel distance of these products still have an impact on the transferring time through the crossdocking facility. Therefore, by minimizing the total weighted travel distance, we can minimize the time spent on those products which are moved directly from IDs to ODs and at least reduce the time spent on of the rest of the products inside the facility.

Minimizing total weighted travel distance is a surrogate of minimizing labor cost or cycle time of moving products between doors [52]. Reducing cycle time of transferring products inside crossdocking improves crossdocking productivity, thus, minimizing total weighted travel distance can help to improve productivity[64]. However, if minimization of total weighted distance is set as the only objective for the crossdocking operations, it will exacerbate congestion inside the facility and increase the waiting time of service for both ITs and OTs. Only minimizing total weighted distance will make the assignment of ITs and OTs to a few numbers of centered doors or only one pair of doors with the minimum distance or the same door with zero distance. As a result, all products from ITs to OTs will have to go through these doors, and this will increase the equipments travelling. Once the numbers of equipments between the centered doors are greater than the appropriate volume, congestion will occur, especially for the manual cart operated by workers. Another disadvantage associated with only minimizing the weighted travel distance is that such an objective will be achieved by scarifying the service level of inbound and outbound operations. The service level could be measured by the waiting time and loading/unloading time of ITs and OTs. Only minimizing travel distance will cause longer waiting time for both ITs and OTs to be served. Long waiting time for ITs and OTs causes late starting time of service, while causes late finishing time. For ITs, long queues outside the crossdocking facility can causes dissatisfaction of drivers as well as congestion in front of IDs due to limited parking area. For OTs, late starting time of ITs service delays the starting time of loading products to OTs given fixed labor and equipments. Similar to the assignment of ITs, the assignments from only minimizing the travel distance also delays the starting time of serving OTs. And these will cause delay for the departure time of OTs. On the other hand, the objective of minimizing total starting and handling time of ITs assigns the ITs to all the available IDs respectively, and this increases the distance from each IT to each OT. Therefore, in order to achieve a good ITs/OTs schedule, it is necessary to find a way to balance to reach an optimal solution.

Considering the OTs assignment resulting from optimizing the starting and handling time of ITs, it gives a better plan than the resulted assignment from minimizing the total travel distance. Since the OD operation starts after the ID operation and inside operation, both the assignment and scheduling of ITs and the travel distance of products affect the performance of the OD operation. Above all, in order to save transferring time of products inside crossdocking facility and reduce labor cost in crossdocking operation, minimizing total weighted travel distance should be considered as an important objective.

However, such objective should be combined with other objectives or constraints to avoid congestion inside and outside the facility or delays of the ITs/OTs schedule.

3.1.2.3. Minimize total departure time of OTs

Other than the above two objectives concerning inbound and inside operation in crossdocking, a third objective is to minimize the total departure time of OTs. If the starting time of the first IT arrival is set as time zero, then the departure time of the last OT could be regarded as the makespan of crossdocking operation. A lot of research has been done on minimizing the makespan of the whole crossdocking operations [58, 60, 67, 68]. However, most research on minimizing the makespan focus mainly on the travel time of freight inside the facility to minimize the total processing time. It should be noted that, in addition to travel time of products inside the facility and handling time at the facility doors, freight waiting time takes a big fraction of the whole period freight spends inside the facility. From a practical point of view, the travel time of freight between ID and OD take approximately less than five minutes for directly transferred products, but the waiting time for one unit of product in an IT to be unloaded and for the OT to be loaded might take more than 60 minutes [23, 63]. Therefore, other than minimizing travel time of freight inside crossdocking facility, the wait time of freight should be taken into account [23, 63]. In [23], they identified the relationship between the departure of OTs and freight waiting time, that is, accelerating the departure time of OTs causes the decreasing of freight spending time inside the facility. Therefore, by minimizing departure time of OTs, the freight waiting time could be reduced. Departure time of OTs is affected by the combined process including: inbound operations such as waiting time of ITs and unloading time of the products; inside operations such as freight waiting time at IDs and ODs and traveling time of freight through the facility; outbound operations such as waiting time of OTs, and loading time of products, etc. Thus, minimizing departure time of OTs can help improve all three operations of crossdocking.

Moreover, in JIT philosophy, it is highly recommended to have the jobs done by exact time or time windows. If a job is done before the required time, the time difference is considered as earliness. On the other hand, if a job is done after the required time, the time difference is regarded as tardiness. Although neither earliness nor tardiness is desirable in JIT environment, tardiness is an implication for late delivery, implies penalty costs, and this will lead to unsatisfied customers [55]. Therefore, tardiness will usually causes more penalties than earliness, and it is necessary to avoid tardiness in scheduling jobs. For crossdocking truck scheduling problems, tardiness can be considered as the late departure of OTs. Usually, the delivery to customers should be within a certain time window; therefore, in order to deliver products to customers on time, the OTs are required to leave crossdocking facility as early as possible. Early departure time of OTs is desirable given difficultly in estimating trucks travel time in various traffic conditions. Although the minimization of departure time cannot guarantee the minimum tardiness by the fact that it may cause longer tardiness for a few OTs, minimizing total departure time can indirectly guaranty to reduce tardiness of most trucks. Moreover, together with the other two objectives: minimizing the total service time of ITs and minimizing the total weighted travel distance within the facility, the objective of minimizing the OTs departure time helps to optimize the throughput of the crossdocking operation.

In addition, similar to scheduling of ITs at IDs [72], long waiting time of OT will make the truck drivers tired and discontent. Also, long waiting time of OTs increases labor cost in shipping company or retailers. In case of OTs from retailers, long waiting time and late departure may have the potential to lose existing or potential customers. Assuming the OD can be used for loading next OT as soon as the previous OT departs, minimizing the departure time of the previous OT can thus indirectly reduce the waiting time of its immediate successor. Therefore, this objective helps to reduce waiting time of OTs.

Above all, departure time is one of the crucial measurements of the throughput of crossdocking operation. Minimizing the total departure time of the OTs pushes back to the optimization of the outbound operations for crossdocking.

3.2. Mathematical model

The mathematical formulation in this study supports several door layouts considerations at crossdocking facility and different operating assumptions. The model considers the ITs and OTs scheduling at an "I" shape crossdocking facility with IDs/IDs along the long side of the rectangular parameter. As crossdocks can be classified into pre-distribution and post-distribution [41], with the development of modern technology, this study assumes a pre-distribution crossdocking, which means the freight flow from each IT to each OT is known as a priori. Other assumptions are listed as follow.

1) Each door is pre-defined as ID or OD.
2) The equipment for moving products can transfer a fixed number of pallets per time from an ID to an OD (e.g. one pallet per time).
3) Assuming that the handling time of pallets depends on only the volume and is independent from the type of the commodity.
4) After finishing unloading products from ITs, the products are available just inside the ID to be transferred to OD.

5) After all the products for an OD are ready to be loaded at the OD, the OT starts loading.
6) Travel time per unit distance between every pair of ID and OD is same. (e.g. 0.005 time unit per feet per pallet distance)
7) There is an adequate number of internal equipments and labors moving products.

In order to take into account different door layouts of crossdocks, the mathematical model is built for two scenarios: with assumption 1) (scenario 1) or without assumption 1) (scenarios 2). Crossdocks with IDs/ODs pre-defined and with free doors are studied. Pre-defined doors means at the crossdock, it is already defined whether a door is used as an ID or an OD and this will not change during the studying period. Free door crossdock in our assumption means that, a door at the crossdocking facility can be used either as an ID or an OD in the scheduling horizon. The set up time/cost of a door for changing from an ID to an OD or the opposite way in scenarios 2 is not considered in the model. If this needs to be taken into account, it can easily be achieved by adding a constant for each change. Assumption 2) and 3) transfers the unit of products into time unit, and these do not loose generality for the model. Assumption 4) and 5) are reasonable for two reasons: first, this prevents workers from making mistakes and avoiding masses and congestions inside the facility. Second, this actually happens in the favor of recording the commodities and information. In assumption 6), in order to transfer the travel instance into travel time, parameter *speed* is introduced.

3.2.1. Formulation

3.2.1.1. Model for pre-defined ODIDs and ODs

Index

i	All IDs $i = 1, 2, \ldots I$
j	All ITs $j = 1, 2, \ldots J$
m	All ODs $m = 1, 2, \ldots M$
l	All OTs $l = 1, 2, \ldots L$
k	Serving order for trucks $k = 1, 2, \ldots K$

Parameters

$ITAT_j$	Arrival time of IT j
$OTAT_l$	Arrival time of OT l
$C_{j,i}$	Handling time for IT j at ID i
$H_{l,m}$	Handling time for OT l at OD m
$V_{j,l}$	Freight flow (number of pallets) from IT j to OT l
$DV_{j,l}$	Binary matrix, if $V_{j,l} > 0$, $DV_{j,l} = 1$, otherwise 0
$d_{i,m}$	Distance between door i and door m
$speed$	Time need to move per unit pallet per feet (mins)
M	Big positive number

Decision Variables

$x_{j,i,k}$	Binary variable, $x_{j,i,k} = 1$ if IT j is served at door i as the kth truck, 0 otherwise
$y_{l,m,k}$	Binary variable, $y_{l,m,k} = 1$ if OT l is served at door m as the kth truck, 0 otherwise

$f_{j,i,m,l}$	Non-negative variable, pallet flow between i and m when IT j is assigned at door i and OT l is assigned at door m
$ITTS_{j,i,k}$	Non-negative variable, starting time of unloading IT j at door i as the kth truck if j is served at door i as the kth truck, otherwise 0
$OTTS_{l,m,k}$	Non-negative variable, starting time of loading OT l at door m as the kth truck if l is served at door m as the kth truck, otherwise 0
TD_l	Departure time of OT l

Objectives

Minimize the total starting time and the handling time of all ITs.

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{k=1}^{K}(ITTS_{j,i,k} + C_{j,i} \cdot x_{j,i,k}) \tag{3.1}$$

Minimize the total travel distance weighted by freight flow

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{m=1}^{M} f_{j,i,m,l} \cdot d_{i,m} \tag{3.2a}$$

Minimize the total departure time of OTs

$$\sum_{l=1}^{L} TD_l \tag{3.3}$$

Constraints

1) Every IT will be served and only served once

$$\sum_{i=1}^{I}\sum_{k=1}^{K} x_{j,i,k} = 1, \quad \forall j \tag{3.4}$$

2) Every OT will be served and only served once

$$\sum_{m=1}^{M}\sum_{k=1}^{K} y_{l,m,k} = 1, \quad \forall l \tag{3.5}$$

3) Each ID cannot serve more than one IT as the same order

$$-M \times (1 - x_{j,i,k}) + x_{n \neq j,i,k} \leq 0, \quad \forall n \neq j,i,k \tag{3.6}$$

4) Each OD cannot serve more than one OT as the same order

$$-M \times (1 - y_{l,m,k}) + y_{o \neq l,m,k} \leq 0, \quad \forall o \neq l,m,k \tag{3.7}$$

5) Freight flow constraint, the flow from i to m when j is assigned to i and l is assigne d to m equals to the flow $V_{j,l}$. For all other $f_{j,i,m,l}$ it is zero.

$$V_{j,l} - f_{j,i,m,l} \leq M(2 - x_{j,i,k} - y_{l,m,k'}), \quad \forall j,i,k,l,m,k' \tag{3.8}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} f_{j,i,m,l} = V_{j,l}, \quad \forall j,l \tag{3.9}$$

6) Starting time of serving IT j at i as the kth truck should be later than the arrival tim e and should be zero if j is not served at door i

$$ITAT_j \cdot x_{j,i,k} \leq ITTS_{j,i,k} \leq Mx_{j,i,k}\ , \quad \forall i,j,k \tag{3.10}$$

7) Starting time of serving OT l at m as the kth truck should be later than the arrival t ime and should be zero if l is not served at door m

$$OTAT_l \cdot y_{l,m,k} \leq OTTS_{l,m,k} \leq My_{l,m,k}\ , \quad \forall l,m,k \tag{3.11}$$

8) The starting time of loading outoubnd truck l at m as the kth truck should be after the time the last commodity is ready to be loaded.

$$OTTS_{l,m,k'} \geq (ITTS_{j,i,k} + C_{j,i} \cdot x_{j,i,k})DV_{j,l} + speed \cdot f_{j,i,m,l} \cdot d_{i,m} - M(1 - y_{l,m,k'})$$

$$\forall j,i,l,m,k,k' \tag{3.12}$$

9) The starting time of serving IT n (n≠j) at door i as the (k+1)th truck should be no earlier than the service finish time of its predecessor.

$$ITTS_{n \neq j,i,k+1} \geq ITTS_{j,i,k} + C_{j,i} \cdot x_{j,i,k} + M(x_{j,i,k} + x_{n \neq j,i,k+1} - 2), \quad \forall n \neq j,i,k$$

(3.13)

10) The starting time of serving OT o (o≠l) at door m as the (k+1)th truck should be no earlier than the service finish time of its predecessor.

$$OTTS_{o \neq l,m,k+1} \geq OTTS_{l,m,k} + H_{l,m} \cdot y_{l,m,k} + M(y_{l,m,k} + y_{o \neq l,m,k+1} - 2), \forall o \neq l,m,k$$

(3.14)

11) The order at the ID has to be consecutive.

$$k \times x_{j,i,k} \leq \sum_{n \neq j}^{J} \sum_{h<k}^{K} x_{n,i,h}, \quad \forall j,i,k > 1 \tag{3.15}$$

12) The order at the OD has to be consecutive.

$$k \times y_{l,m,k} \leq \sum_{o \neq l}^{L} \sum_{h<k}^{K} y_{o,m,h}, \quad \forall l,m,k > 1 \tag{3.16}$$

13) Define the departure of OT l.

$$TD_l \geq OTTS_{l,m,k} + H_{l,m} \times y_{l,m,k} - M \times (1 - y_{l,m,k}), \quad \forall l,m,k \tag{3.17}$$

$$TD_l \geq 0, \quad \forall l \tag{3.18}$$

3.2.1.2. Model for free doors

Index

Instead of having two indexes for the doors: i as the IDs and m as the ODs, only one index is introduced to present all doors (index i)

i All doors $i = 1,2,...I$

Parameters

Same parameters are used here except those parameters associated with door index, as the doors are not defined for inbound or outbound, changes for some of the parameters are changed as follows:

$C_{j,i}$	Handling time for IT j at ID i
$H_{l,i}$	Handling time for OT l at OD i
$d_{i,i'}$	Distance between door i and door i'

Decision Variables

Same decision variables are used as in the first model, but the variables related to the doors are changed with the door index as follows:

$y_{l,i,k}$	Binary variable, $y_{l,i,k} = 1$ if OT l is served at door i as the kth truck, 0 otherwise
$f_{j,i,i',l}$	Non-negative variable, flow between i and i' when IT j is assigned at door i and OT l is assigned at door i'
$OTTS_{l,i,k}$	Non-negative variable, starting time of loading OT l at door i as the kth truck if l is served at door m as the kth truck, otherwise 0

Objectives:

The expression for objectives (3.1) and (3.3) are same as the first model and objective (3.2a) is changed as:

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{i'=1}^{I} f_{j,i,i',l} \cdot d_{i,i'} \tag{3.2b}$$

Constraints for the free door model would be:

$$\sum_{i=1}^{I}\sum_{k=1}^{K} x_{j,i,k} = 1, \quad \forall j \tag{3.4}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} y_{l,i,k} = 1, \quad \forall l \tag{3.19}$$

$$-M(1-x_{j,i,k}) + x_{n\neq j,i,k} \leq 0, \quad \forall n \neq j,i,k \tag{3.6}$$

$$-M(1-y_{l,i,k}) + y_{o\neq l,i,k} \leq 0, \quad \forall o \neq l,i,k \tag{3.20}$$

$$-M(1-y_{l,i,k}) + x_{j,i,k} \leq 0, \quad \forall j,l,i,k \tag{3.21}$$

$$V_{j,l} - f_{j,i,i',l} \leq M(2-x_{j,i,k} - y_{l,i',k'}), \quad \forall j,i,k,l,i',k' \tag{3.22}$$

$$\sum_{i=1}^{I}\sum_{i'=1}^{I} f_{j,i,i',l} = V_{j,l}, \quad \forall j,l \tag{3.23}$$

$$ITAT_j \cdot x_{j,i,k} \leq ITTS_{j,i,k} \leq Mx_{j,i,k} \quad \forall j,i,k \tag{3.10}$$

$$OTAT_l \cdot y_{l,i,k} \leq OTTS_{l,i,k} \leq My_{l,i,k} \quad \forall l,i,k \tag{3.24}$$

$$OTTS_{l,i',k'} \geq (ITTS_{j,i,k} + C_{j,i} \cdot x_{j,i,k})DV_{j,l} + speed \cdot f_{j,i,i',l} \cdot d_{i,i'} - M(1-y_{l,i',k'}) \quad \forall j,i,k,l,i',k' \tag{3.25}$$

$$ITTS_{n\neq j,i,k+1} \geq ITTS_{j,i,k} + C_{j,i} \cdot x_{j,i,k} + M(x_{j,i,k} + x_{n\neq j,i,k+1} - 2), \quad \forall n \neq j,i,k \tag{3.13}$$

$$ITTS_{j,i,k+1} \geq OTTS_{l,i,k} + H_{l,i} \cdot y_{l,i,k} + M(y_{l,i,k} + x_{j,i,k+1} - 2), \quad \forall j,l,i,k \tag{3.26}$$

$$OTTS_{o\neq l,i,k+1} \geq OTTS_{l,i,k} + H_{l,i} \cdot y_{l,i,k} + M(y_{l,i,k} + y_{o\neq l,i,k+1} - 2), \quad \forall o \neq l,i,k \tag{3.27}$$

$$OTTS_{l,i,k+1} \geq ITTS_{j,i,k} + C_{j,i} \cdot x_{j,i,k} + M(x_{j,i,k} + y_{l,i,k+1} - 2), \quad \forall j,l,i,k \tag{3.28}$$

$$k \cdot (x_{j,i,k} + y_{l,i,k}) \leq \sum_{h<k}^{K}(\sum_{n\neq j}^{J} x_{n,i,h} + \sum_{o\neq l}^{L} y_{o,i,h}), \quad \forall j,l,i,k > 1 \tag{3.29}$$

$$TD_l \geq OTTS_{l,i,k} + H_{l,i} \cdot y_{l,i,k} - M(1-y_{l,i,k}), \quad \forall l,i,k \tag{3.30}$$

$$TD_l \geq 0, \quad \forall l \tag{3.18}$$

Again, (3.4) and (3.19) ensures every IT and OT will be served and only served once. (3.6) (3.20) and (3.21) ensures each door cannot serve more than one truck as the same order. (3.22) and (3.23) defines the freight flow constraint: the flow from i to m when j is assigned to i and l is assigned to m equals to the flow $V_{j,l}$. For all other $f_{j,i,m,l}$ it is zero. (3.10) and (3.24) ensures the starting time of serving IT and OT at any door i should be later than the arrival, and should be zero if the truck is not served at door i. (3.25) ensures the starting time of serving OT l at i with order k should be after the time the last commodity is ready to be loaded. (3.13) and (3.26-28) make sure that the starting time of serving IT and OT at door i as the (k+1)th truck should be no earlier than the service finish time of its predecessor. (3.29) force the order at the each door to be consecutive. (3.30) and (3.18) define the departure time of OT.

3.3. Summary

This chapter starts with description of the problem studied in this research. The main goal is to scheduling both ITs and OTs to crossdocking doors with different objectives. Multi-objective mixed-integer program formulations are built in order to address the problem. There are three objectives in the model: The first objective is to minimize the starting and handling time of all ITs; the second objective is to minimize the total weighted distance of pallets traveled inside the crossdock facility; and the third objective is to minimize the total departure time of all OTs. Two models were built based on two scenarios, where in the first scenario, the doors at crossdock facility are predefined as either IDs or ODs; and in the second scenario, the doors at crossdock facility are not predefined, i.e. there is no restriction on the function of each door that every door could be used as ID or OD. Both of these two scenarios models are MIP models. The following chapter will discuss the solution approaches to solve the models with different objectives separately and will take numerical examples to study the behavior of three objectives.

Chapter 4

Solution Approach and Numerical Examples

4.1. Scenarios and Data

In order to compare the proposed models for different scenarios and objectives, 42 test datasets are created as computational examples. As stated in Chapter 3, there are two scenarios in total: The first scenario has predefined IDs and ODs corresponding to the first model above. In this scenario, two different ID/OD layouts (Layout 1 and Layout 2) are created in order to cover different crossdock door arrangements. Layout 1 has IDs along one side of the crossdock and ODs on the other side of the "I" shape crossdock and Layout 2 has IDs/ODs on both sides of the rectangular (Fig 17, 18 respectively). According to [23], Layout 2 in our example has IDs close to the center of the facility. In Fig. 17 and Fig. 18, green doors represent the ODs and the red doors represent the IDs. The second scenario has free doors where IDs/ODs are not pre-defined and the free door layout is Layout 3 in the test dataset. Layout 3 (Fig 19) corresponds to the second model above that has 10 free doors.

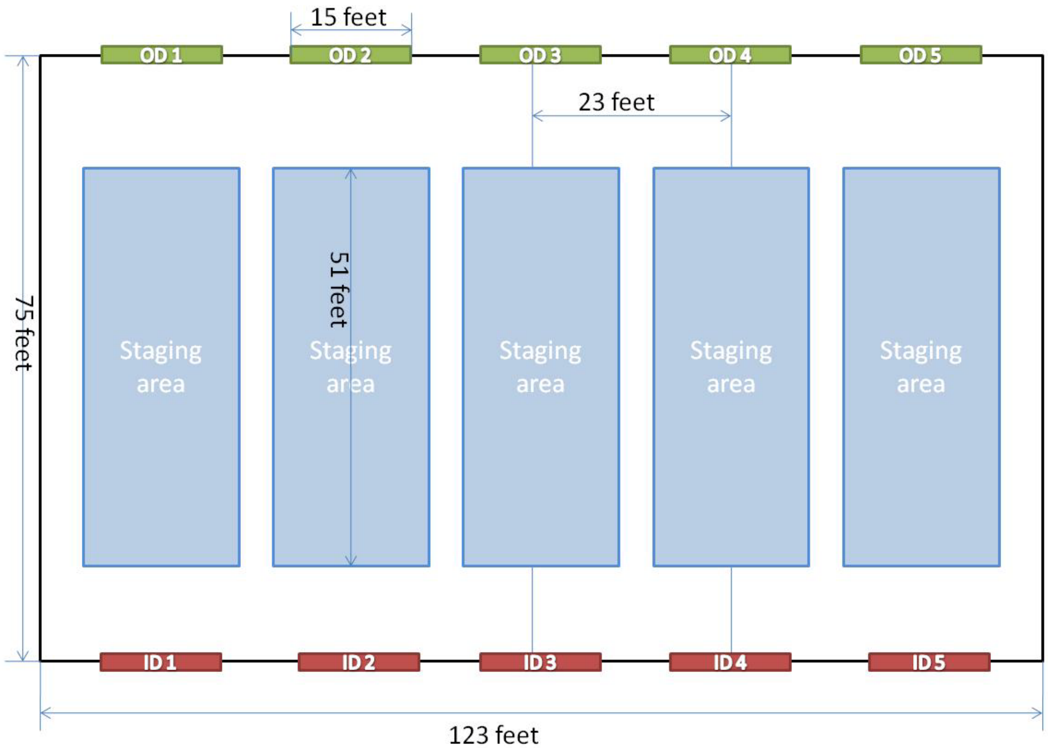


Figure 17 Door Layout 1 of Crossdock

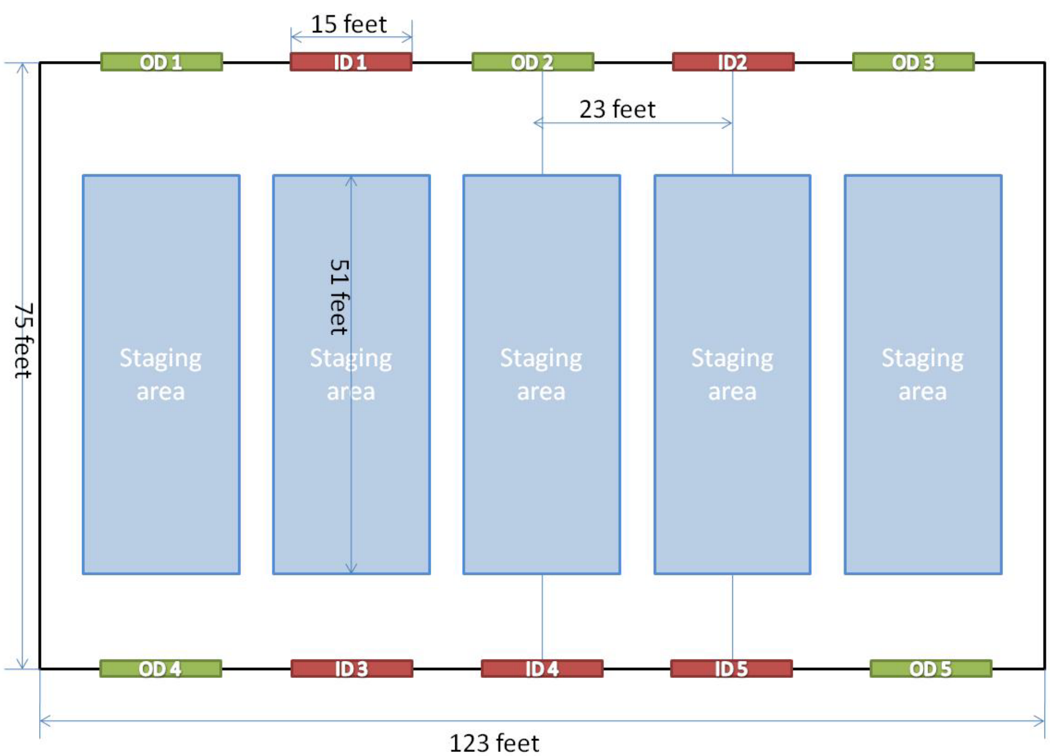


Figure 18 Door Layout 2 of Crossdock

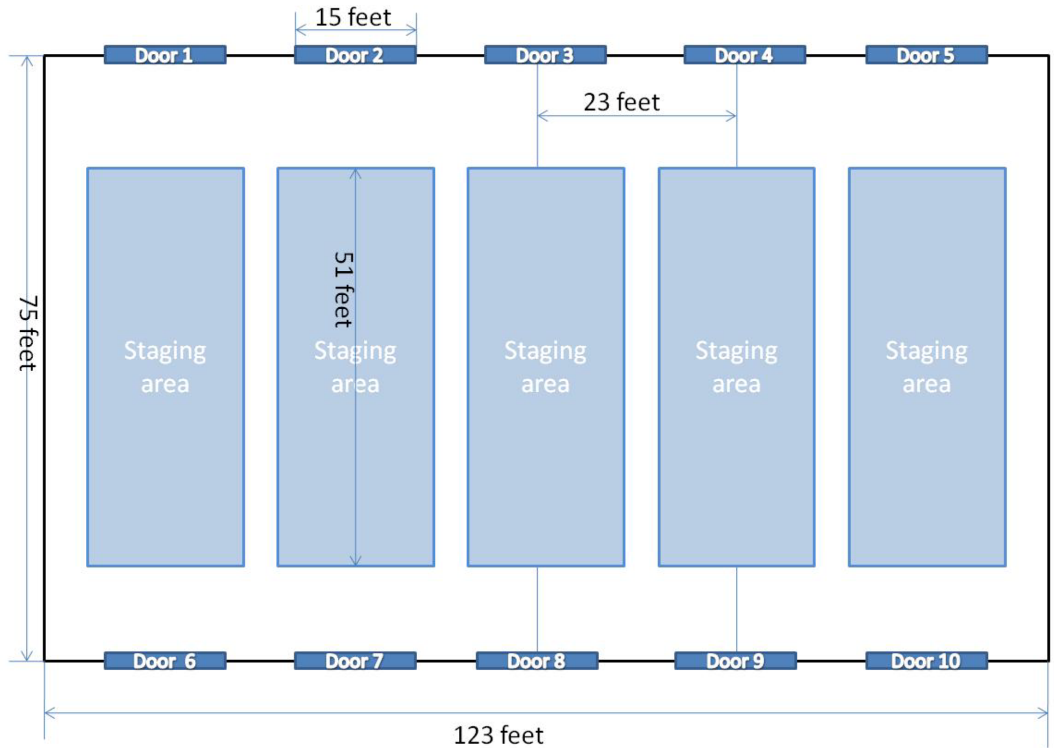


Figure 19 Door Layout 3 of Crossdock

a. Dimensions and distance

The crossdock dimensions are based on the work of [42] and [23]: The width of the crossdock is 75 feet, each door has a width of 15 feet with 8 feet distance between every neighboring doors. With 5 doors on each side of the crossdock, the length of crossdock is 123 feet. Based on this dimension, the distance between each pair of door is shown in Appendix I (Table 12 and Table 13). Table 12 shows the distance between each pair of doors for layout 3 and the shaded area is the distance matrix for layout 1. Table 13 shows the distance matrix between each pair of doors for layout 2.

b. Arrival time

Our objective is to introduce real numerical examples, a small size crossdock facility in practice is found to have 10 doors (5 IDs and 5 O Ds), the number of trucks served everyday should be greater than the number of doors, for this reason we optimize the schedule for 20 trucks (10 ITs and 10 OTs). In each dataset, there are 10 ITs and 10 OTs. The arrival time for ITs are exponentially distributed with different inter-arrival time of parameters five, ten, fifteen, twenty, twenty-five, thirty, thirty-five minutes respectively. The arrival time for all OTs is carefully generated based on the arrival time of ITs. Data for arrival time of ITs and OTs are shown in Appendix I (Table 14).

c. Handling time

Two different datasets are created for the handling time given the three layouts. The first dataset (Dataset A, Appendix I, Table 15) has the unloading time of each truck at each door randomly generated between 30 minutes and 60 minutes (except for Dataset 4, Dataset 5, Dataset 18, Dataset 19, Dataset 32 and Dataset 33). In order to see the behavior of extreme cases in the computational results, we give unloading time of 60 minutes to one of the IDs (ID 1) for dataset 4, 18 and 32. And for dataset 5, 19 and 33, we also give 60 minutes unloading time to ID1 and give unloading time of 20 minutes to another ID (ID2). That is, in dataset 4, 18 and 32, ID 1 has unloading time of 60 minutes and in dataset 5, 19 and 33, ID 1 has unloading time of 60 minutes while ID 2 has unloading time of 20 minutes. According to [7] the loading time is usually longer than the unloading time (approximately 1.5 to 2 times), therefore, the loading time of each truck at each door is randomly generated from 45 to 90 minutes (Dataset A, Appendix I, Table 16). The second dataset (Dataset B, Appendix I, Table 17) has different handling time for the preferred doors and non-preferred doors among all the ten doors. Door 2, 4, 6, 7, 8, 9, 10 are preferred doors for ITs and Door 1, 2, 3, 4, 5, 6,10 are preferred doors for OTs. The unloading time of the preferred IDs is generated between 30 minutes and 50 minutes and unloading time of the non-preferred IDs is generated randomly from 40 minutes to 60 minutes. The loading time of the preferred ODs is generated randomly from 45 minutes to 75 minutes and the loading time of the non-preferred OD is generated randomly from 60 minutes to 90 minutes. The data for handling time is shown in Appendix I (Table 18).

d. Freight Flow

According to [23], all ITs and OTs in our examples carry 28 pallets. Assuming the OTs are going to different destinations and the freight flow is generated since it is known as prior for pre-distribution crossdocking. The binary matrix associated with the freight flow is also generated. Both matrixes are shown in Appendix I (Table 19, 20).

4.2. Difficulties with exact solution approach

The problem studied in the research is of the category “flexible flow shop (FFc)” in typical scheduling problem [59]. There are two stages in series in such problem, with at each stage, a number of unrelated machines in parallel. Each job has to be processed first at stage 1, then at stage 2. In relation to our problem studied, the first stage is the inbound operation and the second stage is the outbound operation. At the inbound stage, there are a number of IDs which are unrelated in parallel. While at the outbound stage, there are a number of ODs also unrelated in parallel. Each ID and OD can process the pallets from ITs and OTs at a speed dependent on both the trucks and the doors themselves. At each stage, job (pallet) requires to be processed on only one door and any door can do, which means each IT will only be served at one ID and same with OTs which will be served at only one OD. Therefore, the pallets from ITs will be handled at only one ID and the pallets to OTs will be handled at only one OD. The constraint of the problem ensures all pallets from the same IT be handled at the same ID, so does the pallets to the same OT.

As many scheduling problems, the problem under study is NP-hard [36, 60, 73]. The problem is solvable only for small instances. However, when the problem size (the number of doors and trucks) increases, the computational time increases exponentially. Therefore, when increasing the problem size to a larger number over a certain point, the computational time dramatically increase or the software is even not possible to solve the problem. The experiments show that the mixed integer programming (MIP) solver of ILOG CPLEX 10.1 takes a long time to reach an optimal solution (when possible) for large problem instances using the formulation of chapter 3.

4.3. Limitations and solution approximation

In the following, limitations of the exact solution for solving each objective are shown. For each objective function, the maximum size of the problem which is solvable using exact solution approach in reasonable time is found. After that we try to find the optimal solution using an approximation approach for each one of the objectives. All the computation results are obtained by using the MIP solver of ILOG CPLEX 10.1. The computer for running CPLEX is equipped with AMD Athlon 64 Processor 2.39 GHz, 1.37 GB of RAM.

4.3.1. Minimization of starting and handling time for all ITs (Objective I)

The illustration takes part of the example data based on Dataset 1(see Table 11), the original problem size in the dataset with 10 ITs and 10 OTs with 5 IDs and 5 ODs is not solvable by using exact solution approach. For this objective, maximum solvable size by using exact approach in reasonable CPU time is found (for the example tested) to be 5 IDs and 5 ODs with 6 ITs and 6 OTs respectively. The optimal value for such limitation was found in 885.25 sec. As we have 5 doors in Dataset 1, the number of ITs and OTs is increased from 3 trucks until 6 trucks, and it is found that 6 trucks are the limitation for the first objective. When running 7 ITs and 7 OTs with 5 doors, the gap is about 2.59% after eight hours. In this case, it is also found that the speed of finding optimal after a gap of 3.85% (after about 3.5 hours) dramatically decreased.

Since the problem is difficult to solve and in order to restrict the dimension of the problem, and not just restrict the solution space, an approximation solution is proposed to solve the model. The suggested approximation restricts the maximum number of k in the model, where k is the order of trucks served at each door (k also represents the maximum number of trucks served at each door in the model).

Actually, we know that for the numerical examples presented herein for 10 trucks and 5 doors and based on the idea that all the doors are going to be used at least one time, the maximum k could be restricted by the following equation:

$$k = number\ of\ \ trucks - number\ of\ \ doors + 1 \tag{4.1}$$

This means that the valid upper bound of k is much less than the maximum number of trucks. The value of k could be restricted further, assuming that each door will serve an equal number of trucks, if the following equation is applied:

$$k = {number\ of\ \ trucks} \big/ {number\ of\ \ doors} \tag{4.2}$$

In the numerical example used herein, there are 10 trucks for each inbound and outbound, 5 doors for inbound and outbound, therefore, k=10/5=2.

In order to show k=2 is a reasonable restriction, we run different examples for k=2, k=3 ...until k=6 (defined by equation 1) or until we get the same objective function value for k and k+1 or the CPU time exceeds 24 hours, the k where we stop running is notated as K*. First, running examples for k=1, 2, 3… 6 shows the trend of the relationship between

CPU time and the optimal value of different k. Second, if objective values for k and k+1 are equal, it means that by further increasing the value of k the value of the objective function will not increase. Third, if the CPU time of solving example using larger k exceeds 24 hours and little improvement in the optimal value of the objective function is observed for previous k values, it is not worth further increasing k. 12 datasets (2 arrival times*2 handling time*3 layouts=12) are picked from the total 42 datasets to test the use of k, following table shows the results of the test (Table 7). The second and third column shows the CPU time spent and value of the objective function when using k=2. The fourth and fifth column shows the CPU time spent and value of the objective function when using k=3. The sixth and seventh column shows the CPU time spent and value of the objective function when using k=4, etc. If the CPU time exceeds 24 hours, the program is stopped without getting the final results. The last column shows the relative difference of objective function value between k=2 and K*. The relative difference is calculated using the following equation:

$$relative\ difference\ between\ objective\ function\ (OF)\ value = \frac{Value\ of\ \ OF(k=2) - Value\ of\ \ OF\ \ (k=K^*)}{Value\ of\ \ OF(k=2)} \times 100\% \qquad (4.3)$$

Table 7 Test for Different k Value

Dataset	k=2		k=3		k=4		k=5	relative difference
	CPU (sec)	Value	CPU (sec)	Value	CPU (sec)	Value	CPU (sec)	
dataset 1	33	688.13	4935	675.17	19096	665.29	>=24 hrs	3.32%
dataset 7	71	2386.89	1765	2364.58	7862	2346.53	>=24 hrs	1.69%
dataset 8	169	635.06	1233	627.55	>=24 hrs	----	----	1.20%
dataset 14	79	2341.04	25337	2333.56	>=24 hrs	----	----	0.32%
dataset 15	1782	662.21	75326	657.99	>=24 hrs	----	----	0.64%
dataset 21	11	2359.61	9635	2357.34	12000	2357.34	----	0.10%
dataset 22	317	624.9	72091	612.44	>=24 hrs	----	----	1.99%
dataset 28	17	2337.65	979	2329.25	12822	2325.82	>=24 hrs	0.51%
dataset 29	746	606.76	35747	604.93	>=24 hrs	----	----	0.30%
dataset 35	62	2333.89	85751	2325.54	39138	2325.54	----	0.36%
dataset 36	77	596.38	50720	594.70	>=24 hrs	----	----	0.28%
dataset 42	60	2325.34	14906	2323.66	78886	2323.66	----	0.07%

From the table above (Table 7), we found that when we increase the value of k, the computational time increases dramatically. However, the value of the objective function decreases marginally. None of the examples need to run until k=6. For most of the examples, CPU time exceeds 24 hours when k=4 (e.g. dataset 8, 14, 15, 22, 29, 36), for dataset 1, 2 and 28, CPU time exceeds 24 hours when using k=5. For dataset 21, 35 and 42, the value of objective function is same when using k=3 and k=4. The maximum relative difference is 3.32% (dataset 1) and the minimum relative difference is 0.07% (dataset 42). Most of the relative differences are less than 1%. This means when increasing the value of k, the objective function value decrease relatively small. In order to show the trend of relationship between CPU time and the optimal value of objective function for different k, we take dataset 7 above as an example: when use k=2, the CPU time is about 71seconds and the value of objective function is 2386.89. If k is increased to k=3, the CPU time is about 1765 seconds and the value of objective function is 2364.58. This means when k=3, the CPU time is increased by 2379.3%, while the value of objective function is only improved by 0.93%. If k is increased to k=4, the CPU time is about 7862 seconds and the value of objective function is 2346.53. Comparing to k=3, the CPU time is increased by 430.5% while the value of the objective function is only improved by 0.81%. And the relative difference of objective function value for using k=2 and k=4 is 1.69%. There is no reason to improve the objective value of less than 2% by sacrificing the CPU time so much. The large increase in the CPU time and the minor improvement in the OF value do not justify the use of a larger k value. Therefore, the k=2 restriction-approximation for the first objective is reasonable and realistic.

When using this k=2 restriction-approximation, to obtain realistic assignments for the OTs, one more constraint is added in addition to the original model presented in Chapter 3. This is because by using k=2, we force each door to serve two trucks, and herein we try to minimize the services of ITs, this might make the planning results for OTs unreasonable. For example, the starting time of serving OTs are not considered when minimizing the staring and handling time of ITs, neither the waiting time of the OTs. In such situation, the planning results of the starting time for OTs might be extremely late and some of them are shown as infinity. In order to prevent this situation from happening, we add a constraint to the waiting time of OTs for k=2 approximations, i.e. the waiting time of each OT should be within certain time limits. The constraint is as follows:

$$\textit{starting time of serving OT} \leq \textit{arrival time} + t \qquad (4.4)$$

Practically, the time limit ***t*** in the above equation should be within 30~40 minutes. This means that the OTs should not wait more than 30 to 40 minutes to be served. The question here is to find reasonable value of ***t*** for every example dataset. Ideally, the value of

t for every dataset should be as small as possible, for the OTs to be served as early as possible. For this reason, we hope to use small value of ***t*** for every example dataset. However, the value of ***t*** influences the feasibility of the example problems. If the value of ***t*** is set to be too small, it will make the example infeasible. Therefore, we find the minimum ***t*** values that make the examples feasible for every dataset. In order to find the minimum ***t*** values that make the examples feasible (notated as ***minimum feasible t***), different ***t*** values are tested for every example dataset. For each dataset, the value of ***t*** is tested from 0 minutes, and increased by every 5 minutes (i.e., 0 min, 5 min, 10min, 15 min,….), until the example has a feasible solution. In this way, the ***minimum feasible t*** is found for every example dataset and shown in Table 8 column seven.

When designing the value of ***t***, in addition to considering the feasibility of the problem, we also notice that the added constraint should not affect objective function value we are trying to minimize here. We found that by using the ***minimum feasible t***, the objective value of minimizing starting and handling time of all ITs could be different from the objective value without the added constraint (eq. 4.4). In order to eliminate the influence of adding this constraint (eq. 4.4), another ***t*** value (notated as ***t***', which does not impact the first objective value) need to be found for each of the example dataset. The ***t***' we need is found in following steps, and the values of ***t'*** are shown in Table 8 column six.

Step 0: Initialize ***t*=*minimum feasible t***.

Step 1: Solve each example dataset, get the objective function value (OF1*) for every example by not adding constraint (eq. 4.4).

Step 2: Solve each example dataset, get the objective function value (OF1) for every example by adding constraint (eq.4.4) using ***t***.

Step 3: Compare the value of OF1* and OF1 of every example dataset.

Step 3 a: If OF1*=OF1, then ***minimum feasible t*** =***t'*** we need, output ***t'***.

Step 3 b: If OF1*<OF1, go to step 4.

Step 4: Increase the value of ***t***, ***t***=***t***+5 minutes, go to step 2.

For all the examples solved, it is found that all OTs could be served within 40 minutes after their arrival. The sixth column of Table 8 shows the ***t*** used for solving the first objective function. By using these values, we avoid affecting the first objective when adding one more constraint for the OTs.

Following table (Table 8) shows the results of minimizing starting and handling time of all ITs by using k=2 approximation. The second column of the table is CPU time spent to solve the example. The third, fourth and fifth column gives the value of the first, second and third objective function respectively when minimizing the first objective. The sixth column is the ***t*** value we used in the added constraint and the seventh column is the value of ***minimum feasible t***.

Table 8 Computational Results for Minimizing Objective I

	CPU time	Value OF1	Value OF2	Value OF3	t used	min feasible t
dataset 1	1237.03 sec	672.11	31764	1919.81	30 min	25 min
dataset 2	165.44 sec	890.72	32408	2185.60	20 min	15 min
dataset 3	64.55 sec	1532.36	32684	3607.79	30 min	30 min
dataset 4	39.86 sec	1619.49	29924	3685.80	35 min	35 min
dataset 5	12.17 sec	1754.52	31764	3660.91	20 min	20 min
dataset 6	27.8 sec	1997.74	31212	3505.03	10 min	10 min
dataset 7	1.19 sec	2386.89	32960	4868.56	20 min	15 min
dataset 8	169.11 sec	635.06	30200	1790.54	35 min	35 min
dataset 9	98.73 sec	844.27	30476	2146.69	20 min	20 min
dataset 10	1606.24 sec	1486.34	31120	3528.05	30 min	30 min
dataset 11	12.80 sec	1523.22	30844	3585.88	15 min	15 min
dataset 12	30.19 sec	1693.45	30660	3548.06	20 min	20 min
dataset 13	30.25 sec	1951.89	31396	3540.99	10 min	10 min
dataset 14	79.23 sec	2341.04	29464	4841.24	25 min	20 min
dataset 15	1782.48 sec	662.21	30752	1731.61	30 min	30 min
dataset 16	112.44 sec	882.2	30752	2202.99	25 min	25 min
dataset 17	176.31 sec	1517.19	31672	3538.33	35 min	35 min
dataset 18	10.54 sec	1594.16	32500	3840.38	40 min	40 min
dataset 19	123.22 sec	1729.93	29556	3670.05	20 min	20 min
dataset 20	16.20 sec	1979.49	31028	3580.09	20 min	15 min
dataset 21	11.47 sec	2359.61	29924	4801.33	30 min	25 min
dataset 22	317.36 sec	624.9	31580	1811.99	25 min	25 min
dataset 23	91.94 sec	849.2	30016	2112.72	20 min	20 min
dataset 24	322.81 sec	1481.2	33604	3532.84	30 min	30 min
dataset 25	79.23 sec	1519.83	29188	3594.16	20 min	15 min
dataset 26	10.44 sec	1687.65	33604	3527.04	10 min	10 min
dataset 27	42.89 sec	1949.1	32868	3478.35	15 min	10 min
dataset 28	17.03 sec	2337.65	31580	4750.79	25 min	20 min
dataset 29	746.31 sec	606.76	22724	1712.78	10 min	10 min
dataset 30	85.92 sec	837.83	23412	2214.11	10 min	10 min
dataset 31	69.94 sec	1479.71	17096	3599.54	30 min	20 min
dataset 32	102.17 sec	1516.07	19536	3591.26	15 min	15 min
dataset 33	69.80 sec	1652.35	17460	3601.56	5 min	5 min
dataset 34	103.08 sec	1945.26	21564	3558.31	10 min	5 min
dataset 35	61.98 sec	2333.89	22764	4889.70	20 min	20 min
dataset 36	76.56 sec	596.38	27076	1659.64	10 min	10 min
dataset 37	67.72 sec	827.49	21060	2209.79	15 min	15 min
dataset 38	84.64 sec	1470.64	25972	3424.66	15 min	10 min
dataset 39	57.83 sec	1507.52	22812	3592.77	20 min	10 min
dataset 40	74.64 sec	1677.75	24056	3563.03	5 min	5 min
dataset 41	66.64 sec	1936.19	22764	3524.58	15 min	15 min
dataset 42	60.38 sec	2325.34	23964	4784.41	20 min	10 min

4.3.2. Minimizing total weighted distance (Objective II)

For the objective of minimizing the total weighted distance traveled inside the crossdock facility, taking part of the example data based on Dataset 1(see Table 11), limitations are found to be 5 IDs and 5 ODs with 9 ITs and 9 OTs (data used are the first 9 ITs and OTs from Dataset 1) . This optimal was found in 4,245 sec (about 12 minutes). If we run 5 IDs and 5 ODs with 10 ITs and 10 OTS, after eight hours, the gap is about 6.93%. It is also noticed that the speed of finding the optimal solution after 84 minutes decreased substantially at a gap of 8.40%. Besides the limitation of problem size for this objective, it should be noticed that the results of optimizing this objective alone are not realistic as well. It is important to minimize the weighted distance, but in order to be realistic we have to take under consideration also other measure of performance like for example the waiting time. Optimizing only the weighted distance and for Layout 1, the results show that all ITs are arranged to be served at the same ID while all the OTs are served at the same OD which is facing the working ID. In this way, the distance between ID and OD is always 75 feet which is the minimum. For Layout 2, it is found that all the ITs are served at the same ID and the OTs are served at the same OD which is besides the working ID. In this way, the distance between ID and OD is always 23 feet which is the minimum. For Layout 3, it is found that all the ITs and OTs are served at the same door. In this way, the distance is theoretically zero which is the minimum in this case. These outcomes are expected, since the truck service time is not considered.

In order to solve the model with the second objective, we first use k=10 with additional constraint. k=10 can relax the model, which means gives the model more flexibility to assign the trucks. However, since it is beyond the limitation of solving the second objective, as presented above, one more constraint is added. We use the same constraint added as that in solving the first objective (eq. 4.4). In this equation, ***t*** is set to be 40 minutes, which is the largest ***t*** found in the sixth column of Table 8, and this is a realistic number in practice. However, this approximation does not work at all. Similar to solving the model with second objective by using exact solution approach, even one more constraint is added, the problem size is still too big to solve, since it does not produce any feasible solution in 24 hours.

Therefore, a second approximation is tried -- the approximation of k=2 for solving the first objective. k=2 is used in order to avoid assigning all ITs and OTs to one single door. By using k=2, we assign equal number of trucks to each door and make equilibrium to each door in order to have a realistic solution which means to have also good values for the other performance of the crossdocking. This may not always happen in practice, but it is realistic when the number of trucks is much more than the number of doors. Since the teams of workers in crossdocking are usually assigned to certain doors, this equilibrium can help prevent unequal work between different teams. But with 10 ITs and 10 OTs, k=2 does not gives results after even 24 hours. After we tried several examples, we realize that optimizing the second objective requires a lot of CPU time and the speed of solving model with k=2 slows down significantly after certain time point (normally within 2 hours). In addition, several examples show that after 12 hours of running of CPLEX, the gap between the best integer objective and the objective of the best node remaining is between 10% and 20%. Therefore, in order to solve the examples in reasonable time and gives relatively good performance, we force the program to stop after either four hours or when the gap is below 10%, which means either CPU time of solving the examples exceeds four hours or the gap is below 10%, it will stop running and print out the results. Reducing the value of k to k=2 results in assigning equal number of trucks to each door and restricts the model from assigning all the ITs and OTs to a single ID or OD, producing a more realistic solution.

Following table (Table 9) shows the result of optimizing the second objective function by using k=2. The second, third, and fourth column of the table are the values of first, second and third objective respectively when optimizing the second objective. The fourth column is the CPU time and the last column is the gap obtained after 4 hours.

Table 9 Computational Results for Minimizing Objective II

	Value OF1	Value OF2	Value OF3	CPU Time	Gap
dataset 1	795.39	26060	1831.20	4 hrs	13.86%
dataset 2	1046.63	25232	2298.14	4 hrs	13.60%
dataset 3	1740.15	24220	3648.29	3146.16 sec	10.00%
dataset 4	1987.04	24750	3668.45	4hrs	13.97%
dataset 5	1931.65	25600	3643.38	4hrs	13.15%
dataset 6	2340.95	24882	3828.17	4hrs	13.83%
dataset 7	2628.45	24036	4900.78	12785 sec	10.00%
dataset 8	787.2	25416	1814.62	4hrs	10.96%
dataset 9	1054.1	25048	2156.65	4hrs	12.00%
dataset 10	1749.11	24680	3541.50	5778.63 sec	10.00%
dataset 11	1750.99	24312	3682.12	14180.00 sec	10.00%
dataset 12	1859.98	25232	3673.34	4hrs	10.45%
dataset 13	2064.15	25416	3664.23	4hrs	11.88%
dataset 14	2527.16	23760	4882.72	11960.22 sec	9.29%
dataset 15	778.5	26704	1951.07	4hrs	17.96%
dataset 16	1080.5	26060	2266.69	4hrs	15.27%
dataset 17	1745.48	25692	3623.32	4hrs	14.20%
dataset 18	1836.27	26470	3958.28	4hrs	18.76%
dataset 19	1932.19	25140	3747.64	4hrs	11.34%
dataset 20	2221.36	25508	3588.20	4hrs	13.44%
dataset 21	2565.95	23392	4856.51	3476.66 sec	7.90%
dataset 22	830.72	26060	1870.03	4hrs	16.84%
dataset 23	1001.9	25508	2372.44	4hrs	15.55%
dataset 24	1615.03	25784	3511.68	4hrs	15.33%
dataset 25	1654.29	25784	3660.18	4hrs	16.35%
dataset 26	1799.55	25416	3652.67	4hrs	13.60%
dataset 27	2022.21	25416	3506.32	4hrs	13.36%
dataset 28	2528.2	23528	4823.63	4hrs	14.57%
dataset 29	747.87	12828	1875.5	4hrs	98.44%
dataset 30	935.75	9252	2177.93	4hrs	97.03%
dataset 31	1681.75	10172	3623.36	4hrs	97.70%
dataset 32	1705	6860	3716.98	4hrs	95.59%
dataset 33	1803.37	9700	3655.09	4hrs	95.56%
dataset 34	2048.33	10356	3528.11	4hrs	97.09%
dataset 35	2526.35	9712	4889.6	4hrs	97.68%
dataset 36	714.02	10316	1806.5	4hrs	97.77%
dataset 37	967.91	12180	2212.92	4hrs	98.29%
dataset 38	1647.61	13068	3503.57	4hrs	98.40%
dataset 39	1743.58	12088	3717.82	4hrs	98,46%
dataset 40	1783.65	8872	3693.04	4hrs	96.87%
dataset 41	2031.68	10264	3574.79	4hrs	97.52%
dataset 42	2612.6	9988	4921.24	4hrs	97.57%

4.3.3. Minimizing the total departure time of all OTs (Objective III)

Part of example data based on Dataset 1(see Table 11) is taken as illustration for the third objective which is minimizing the total departure time of all OTs, limitations are found to be 4 IDs and 4 ODs with 5 ITs and 5 OTs respectively. And the optimal value of this objective is found in about 3.4 hours. The dataset used has 5 doors for both inbound and outbound and 10 trucks for both inbound and outbound. However, it is not solvable for using 5 IDs and ODs with even 3 ITs and 3 OTs. In order to be more reasonable, the number of trucks should be bigger than the number of doors. Therefore, both the number of trucks and number of doors used to find the limitation is reduced. During the computations, it is found that problem size with 3 doors and 4 trucks for both inbound and outbound is solved in 180 sec. If the numbers of doors and trucks are both increased by one from the limitation, saying 5 doors and 6 trucks, the optimal is not obtained in reasonable time, and the gap is about 92.97% after 8 hours.

Since the minimum realistic number of doors at a crossdocking facility in practice is found to be 5 IDs and 5 ODs, the limitation of solving the third objective is not realistic. It is also found that the approximation restriction used for the first and second objective does not work for minimizing the total departure time of all OTs. The problem cannot be solved by using k=2 approximation for the problem of 5 IDs and 5 ODs with 10 ITs and 10 OTs with third objective, When using the k=2 approximation, after 24 hours, the relative gap is still more than 90% for most example datasets. Therefore, two more constraints are added combined with the k=2 approximation method to solve the problem. One constraint is that OTs should start service within certain time limits after arrival (eq.4.4); the other constraint is that ITs should also start service within certain time limits after ITs arrival. Different maximum waiting time of ITs and OTs are tried between 20 and 50 minutes, however, the method does not give optimal solution within reasonable CPU time. The relative gap after 24 hours does not change much, still more than 90% for example dataset tested.

By realizing that departure time of an OT is the sum of the starting time and the service time of the OT. The starting time of serving an OT is affected by the starting time of serving ITs, the service time of ITs and the transferring time of pallets, all of which have been optimized by the first and second objective. Thus, to minimize the total departure time of all OTs, we use an approximation, which minimizes the service time of all OTs. In addition we add an additional constraint for minimizing the service time to be more accurate in approximating the departure time: the starting time of serving an OT should be less than the arrival time of OTs plus certain time limits (eq. 4.4). By adding this constraint, we make sure that the OTs will not waiting too long time for being served at the optimal door. The time limits are no more than 40 minutes, the actual minimum feasible time limit for different datasets are found and shown in Table 10, as stated in section 4.3.1.

Following table (Table 10) shows the result of minimizing the service time of all OTs at the OD by using the ***minimum feasible t***. The second column of the table is the CPU time for solving the example, the third, fourth and fifth columns are the values of first, second and third objective respectively when minimizing the service time of all OTs. The sixth column is the value of the minimized service time of OTs. The last column shows the value of ***t*** (minimum feasible) used in solving the examples.

Table 10 Computational Results for Minimizing Objective III

	CPU time	Value OF1	Value OF2	Value OF3	min feasible t
dataset 1	167.75 sec	813.36	33328	1714.42	25 min
dataset 2	303.20 sec1	1020.37	32408	2139.89	15 min
dataset 3	40.00 sec	1737.1	32408	3481.35	30 min
dataset 4	62.69 sec	1695.48	32776	3510.13	35 min
dataset 5	344.03 sec	1772.5	28544	3578.80	20 min
dataset 6	120.30 sec	2049.91	30016	3411.45	10 min
dataset 7	140.00 sec	2423.5	31396	4723.88	15 min
dataset 8	17.36 sec	731.131	31028	1729.73	35 min
dataset 9	120.63 sec	993.33	30200	2081.60	20 min
dataset 10	292.92 sec	1693.52	31948	3508.66	30 min
dataset 11	1.13 sec	1662.38	29372	3501.87	15 min
dataset 12	19.14 sec	1862.65	30936	3506.62	20 min
dataset 13	80.00 sec	2021.6	33512	3414.28	10 min
dataset 14	78.00 sec	2535.56	31028	4741.77	20 min
dataset 15	72.11 sec	783.8	30200	1769.04	30 min
dataset 16	2103.94 sec	1016.44	31580	2180.01	25 min
dataset 17	56.29 sec	1720.02	31580	3512.96	35 min
dataset 18	231.27 sec	1872.56	33880	3814.58	40 min
dataset 19	74.52 sec	2126.38	30292	3635.29	20 min
dataset 20	2.43 sec	2173.83	29556	3449.08	15 min
dataset 21	20.25 sec	2551.93	31212	4823.03	25 min
dataset 22	152.45 sec	701.81	31672	1758.95	25 min
dataset 23	56.45 sec	972.65	31488	2081.03	20 min
dataset 24	29.25 sec	1694.19	31672	3468.47	30 min
dataset 25	30.00 sec	1809.91	32500	3479.90	15 min
dataset 26	31.14 sec	1823.81	31580	3508.15	10 min
dataset 27	8.33 sec	2038.25	28820	3397.31	10 min
dataset 28	9.31 sec	2422.62	31948	4701.71	20 min
dataset 29	6652.08 sec	714.88	23916	1713.14	10 min
dataset 30	1562.91 sec	1020.11	22664	2059.36	10 min
dataset 31	9122.41 sec	1590.98	17396	3379.79	20 min
dataset 32	55.91 sec	1638.18	22528	2493.58	15 min
dataset 33	8900.70 sec	1775.53	23116	3441.67	5 min
dataset 34	219.27 sec	2183.95	25480	3431.62	5 min
dataset 35	23.52 sec	2909.88	25732	4705.13	20 min
dataset 36	229.73 sec	764.27	22720	1620.90	10 min
dataset 37	1383.56 sec	964.69	24108	2063.36	15 min
dataset 38	3999.99 sec	1665.44	23060	3350.98	10 min
dataset 39	2174.05 sec	1627.38	23528	3353.78	10 min
dataset 40	172.16 sec	1868.77	23732	3429.45	5 min
dataset 41	108.19 sec	2228.44	22672	3381.19	15 min
dataset 42	238.56 sec	2542.14	23664	4568.15	10 min

4.4. Analysis of results

4.4.1. Sensitivity analysis

Table 8 first shows that for all three layouts, when the arrival time interval of ITs increases, the total starting and handling time of serving ITs increases as expected (see Figure. 20). Take dataset 1~7 as an example, the objective value is 688.13 minutes for 5 minutes arrival time interval (dataset 1) and 890.72 minutes for 10 minutes arrival time interval (dataset 2), and when the arrival time interval increases to 30 minutes (dataset 6) and 35 minutes (dataset 7), the total starting and handling time are 1998.74 minutes and 2386.89 minutes respectively.

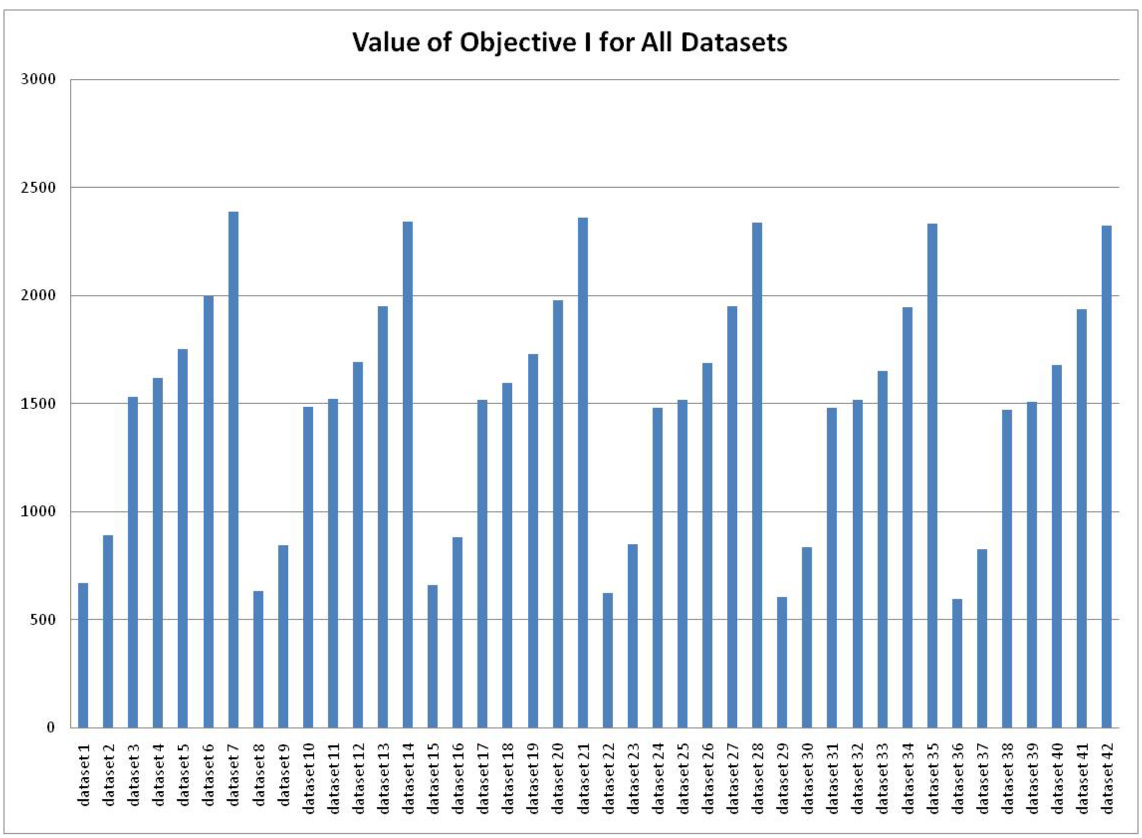
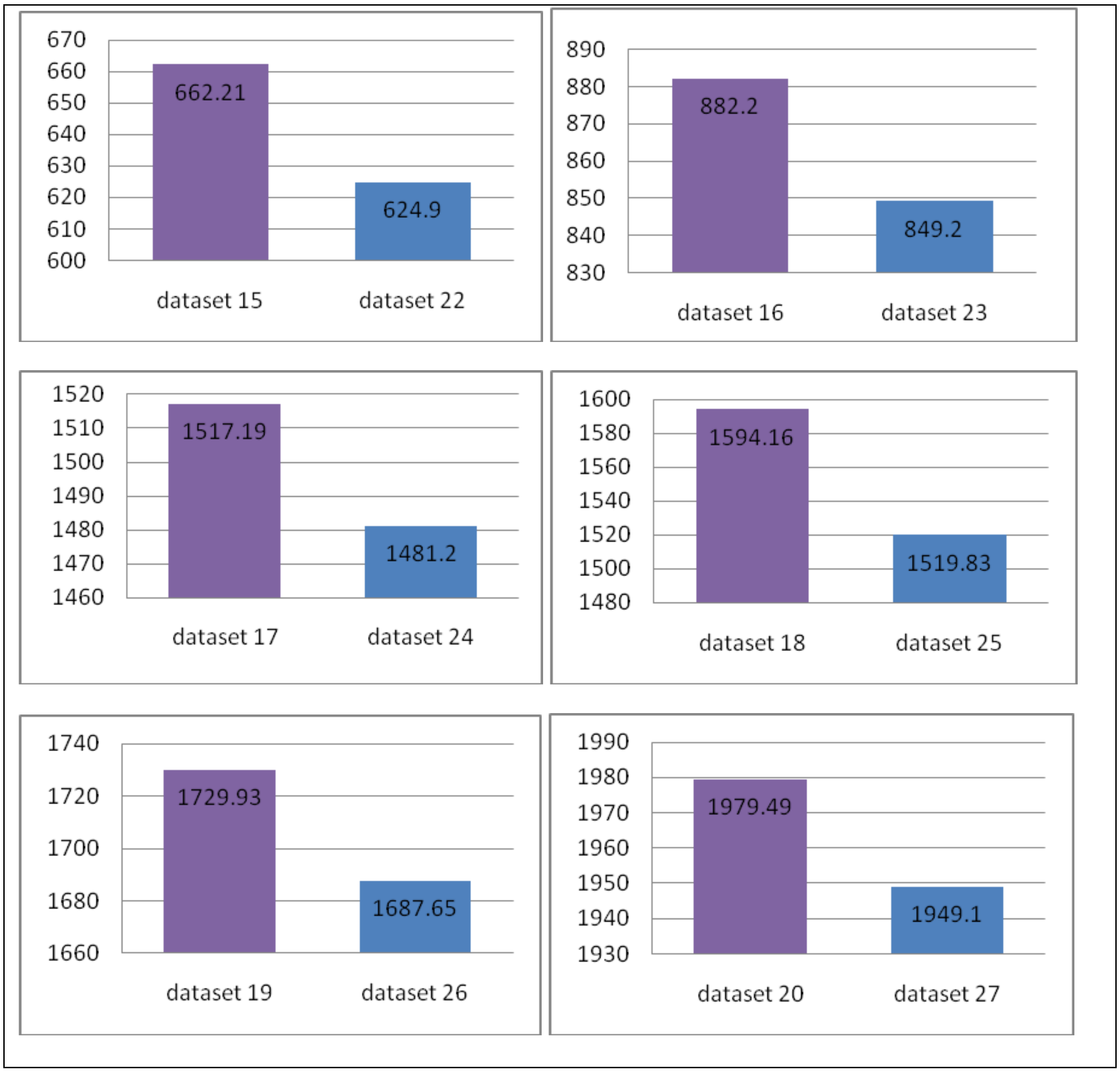


Figure 20 Total Starting and Handling Time of ITs

Second, for each layout, when the handling time for preferred doors and non-preferred doors are different, there is gain in the objective of minimizing total starting and handling time. For example, comparing datasets 15~21 with datasets 22~28 (see Figure 21), the objective value are smaller for datasets 15~21. This means crossdocking with preferred doors which have differences in unloading time between doors performs more efficiently for the ID operations.



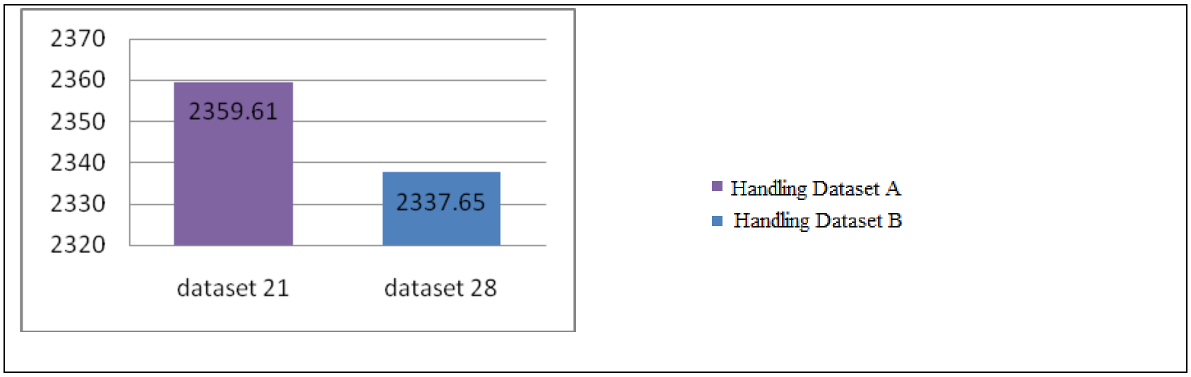
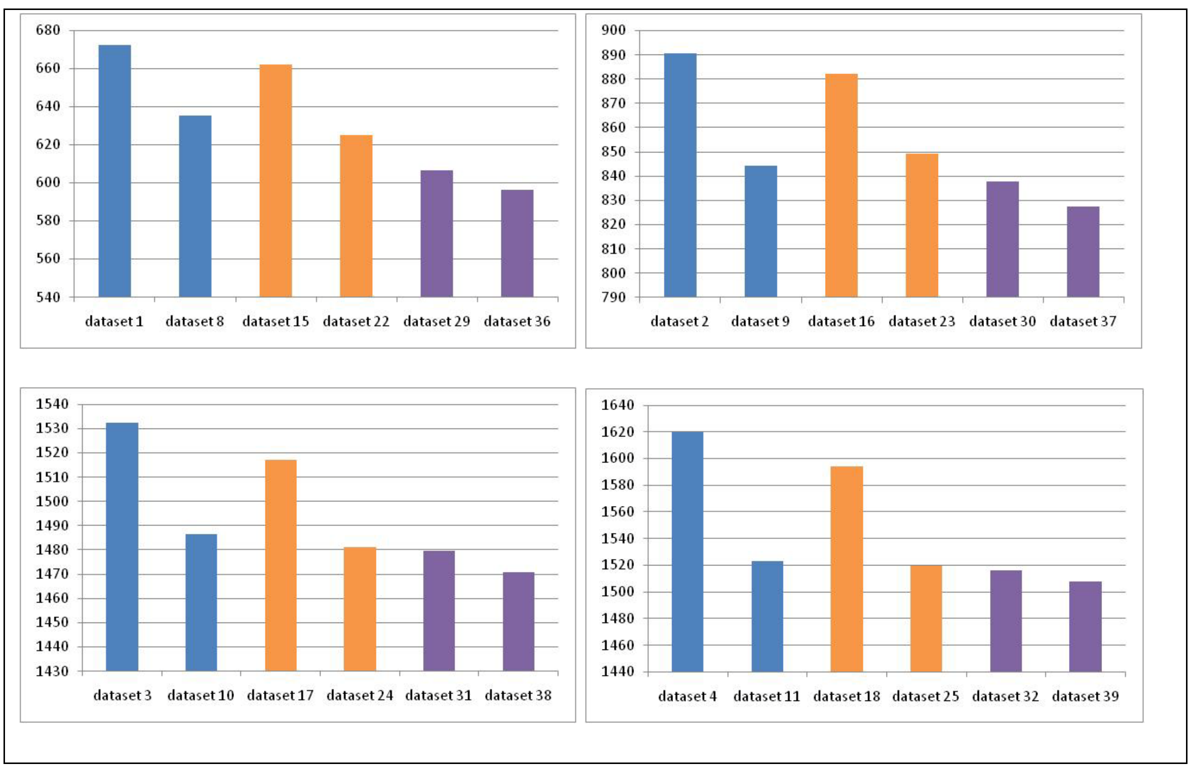


Figure 21 Performance of First Objective Function with Different Handling Time Data

Third, from Table 8 and Figure 22 we can see layout 3 (crossdock with free doors, datasets 29~42) gives better value for the total starting and handling time of all ITs for each dataset with same arrival time of trucks and handling time for trucks at each door. In addition, the figures show that Layout 2 works better in terms of total starting and handling time of ITs than Layout 1 in general (comparing blue bars with yellow ones).



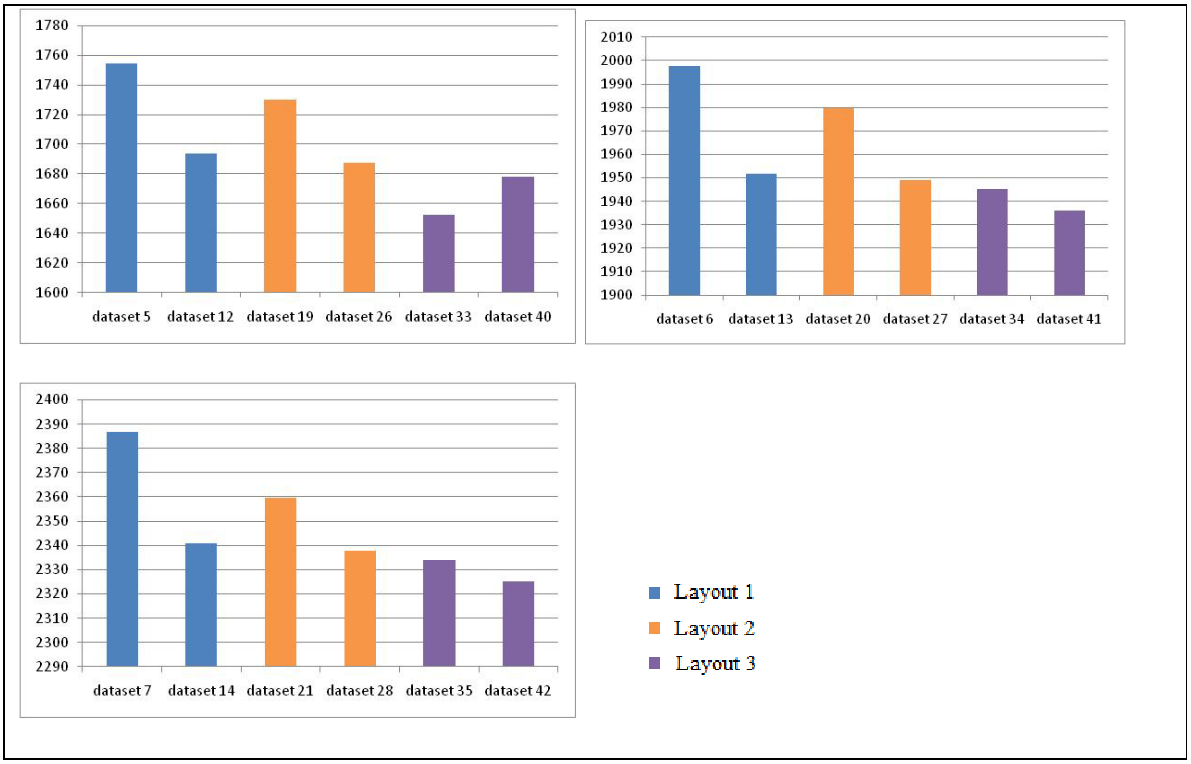


Figure 22 Value of First Objective Function with Different Layouts

Table 9 shows that neither the arrival time of trucks nor the handling time affect the total weighted distance very much. But even the objective is to minimize the total weighted distance; the arrival time and handling time still impact the total starting and handling time of ITs and the departure time of OTs. Different door layouts perform different in terms of total weighted distance travelled inside the crossdock facility. Layout 3 gives much smaller objective value than both Layout 1 and Layout 2, which means crossdock with free doors can help to save a lot in travel distance of all pallets through the facility (see Figure 23), while at the same time such gain in travel distance does not influence the total starting and handling time of ITs or the total departure time of OTs (Table 9). For all examples datasets in layout 3, the results show that the savings in total weighted distance are more than 50% on average comparing to the other two layouts. However, we should notice that there might be cost for frequent changeovers between served for inbound and outbound operations for the same door. In practice, a door first used as an ID will have some costs when it changes into an OD and vice versa. Therefore, the savings from our second objective need to be compared with such changeover costs. From most of the results, it seems Layout 1 provides better objective function value comparing to Layout 2. This might because the relative gaps for the results from Layout 1 are smaller than the gaps for the results from Layout 2 since neither of the results are global optimal. It is hard to see which layout is better between Layout 1 and 2, but it is reasonable to believe layout 1 performs better for our data than layout 2 at saving the total weighted travel distance. For instances, comparing dataset 6 with dataset 20, which have exactly the same data in arrival time and handling time, dataset 6 have higher gap (13.83%) than dataset 20 (13.44%) but dataset 6 of Layout 1 gives smaller objective value than dataset 20. This might be because our example crossdock facility size is small (5 IDs and 5 ODs), for large crossdock facility, Layout 2 might performs better for the total weighted distance since the average distance between each pair of doors is shorter than Layout 1. We notice that the relative gaps of the second scenario (Layout 3) are relatively high comparing to the first scenario (Layout 1 and 2). The converging process is relatively slow, which indicates that this is not solvable in practice in reasonable time, however, even the gaps are such high, we are still able to see the advantages of using Layout 3 by the results (see Figure 23) (as discussed earlier which gives us more than 50% gain).

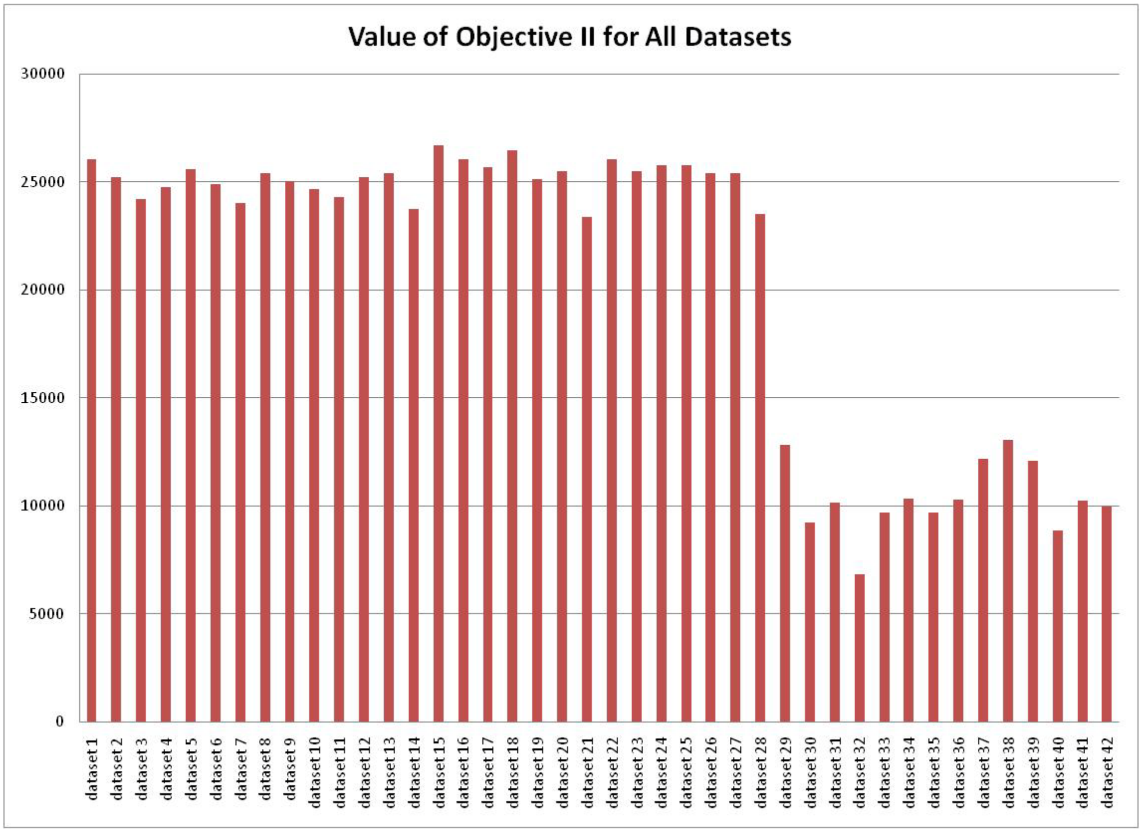


Figure 23 Total Weighted Distance

Table 10 first shows that for all three layouts, when the arrival interval of trucks increases, the total departure time increases as expected (See Figure 24). Take dataset 1~7 as an example, the third objective value is 1714.42 minutes for 5 minutes arrival time interval (dataset 1) and 2139.89 minutes for 10 minutes arrival time interval (dataset 2), and when the arrival time interval increases to 30 minutes and 35 minutes, the total departure time are 3411.45 minutes (dataset 6) and 4723.88 minutes (dataset 7) respectively. This is mainly because the total starting time increases for all ITs when the trucks arrive late, and the service starting time of OTs partially depends on the starting time of serving ITs. But we also notice that the difference of departure time among dataset 3~6 is not that obvious, this is because the departure time is not only depending on the arrival time of trucks but also depending on the travel time of pallets inside the facility. When the arrival time interval of trucks is between15~30 minutes, the departure time of OTs does not change very much.

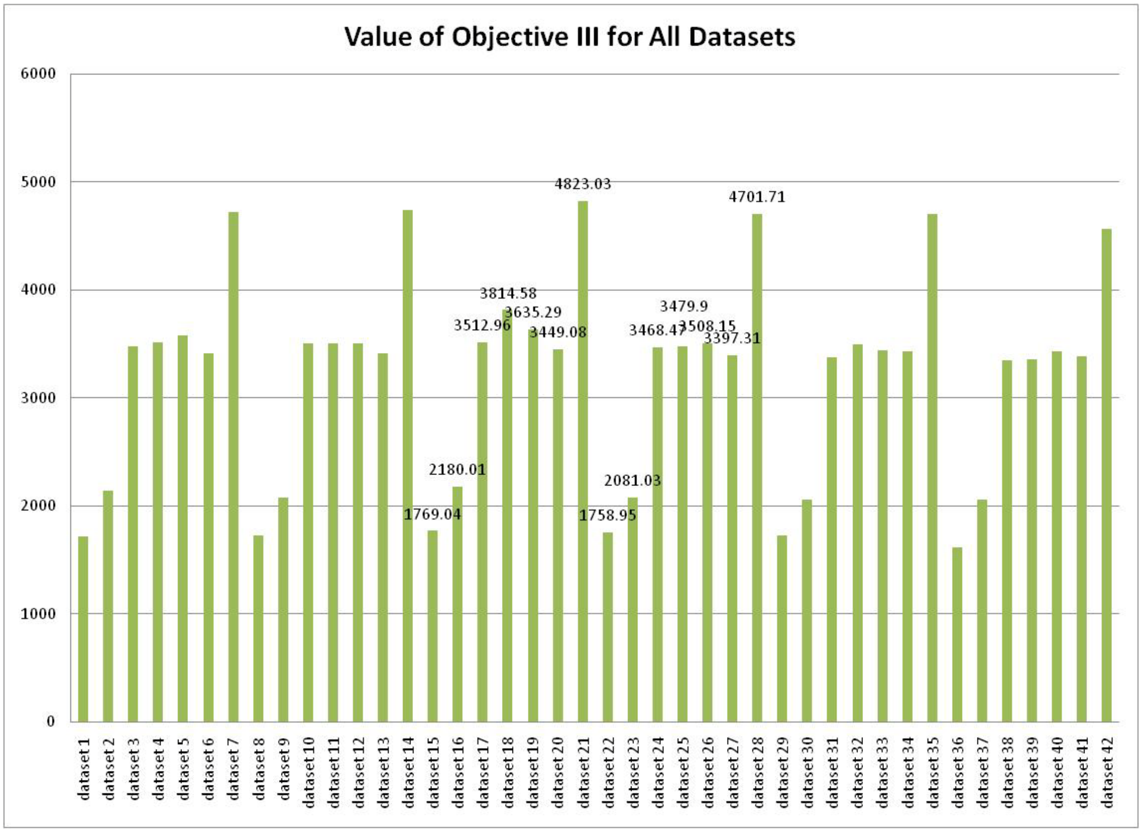


Figure 24 Total Departure Time for OTs

Second, f or each l ayout, when t he handling time for pr eferred doors a nd non-preferred doors a re different, there i s ga in in th e obj ective o f m inimizing total departure time for OTs. For example, comparing datasets 15~21 with datasets 22~28, the objective value are smaller for datasets 22~28 (see Figure 25). This means crossdocking with preferred doors which have differences in loading time between doors performs more efficiently for the OD operations.

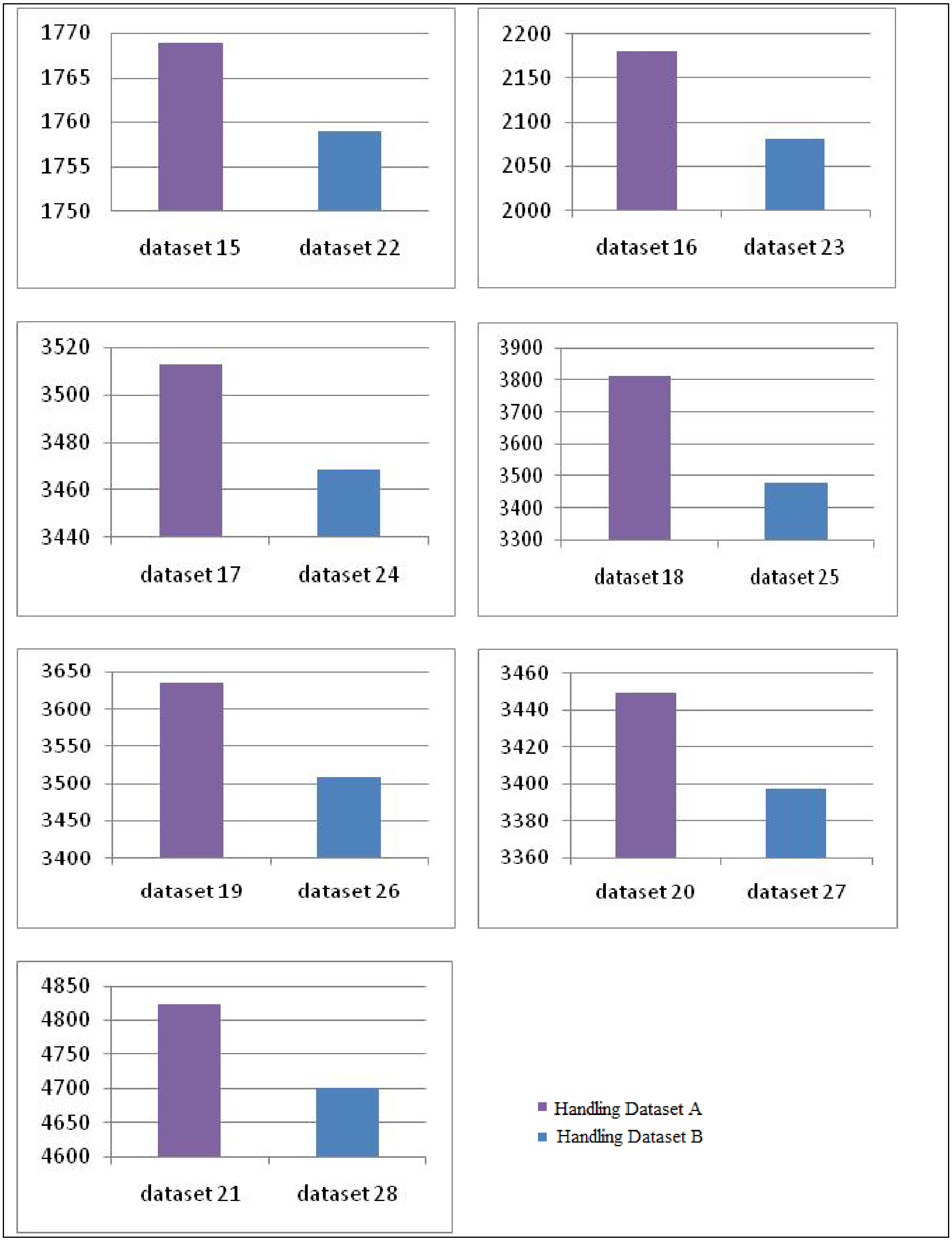
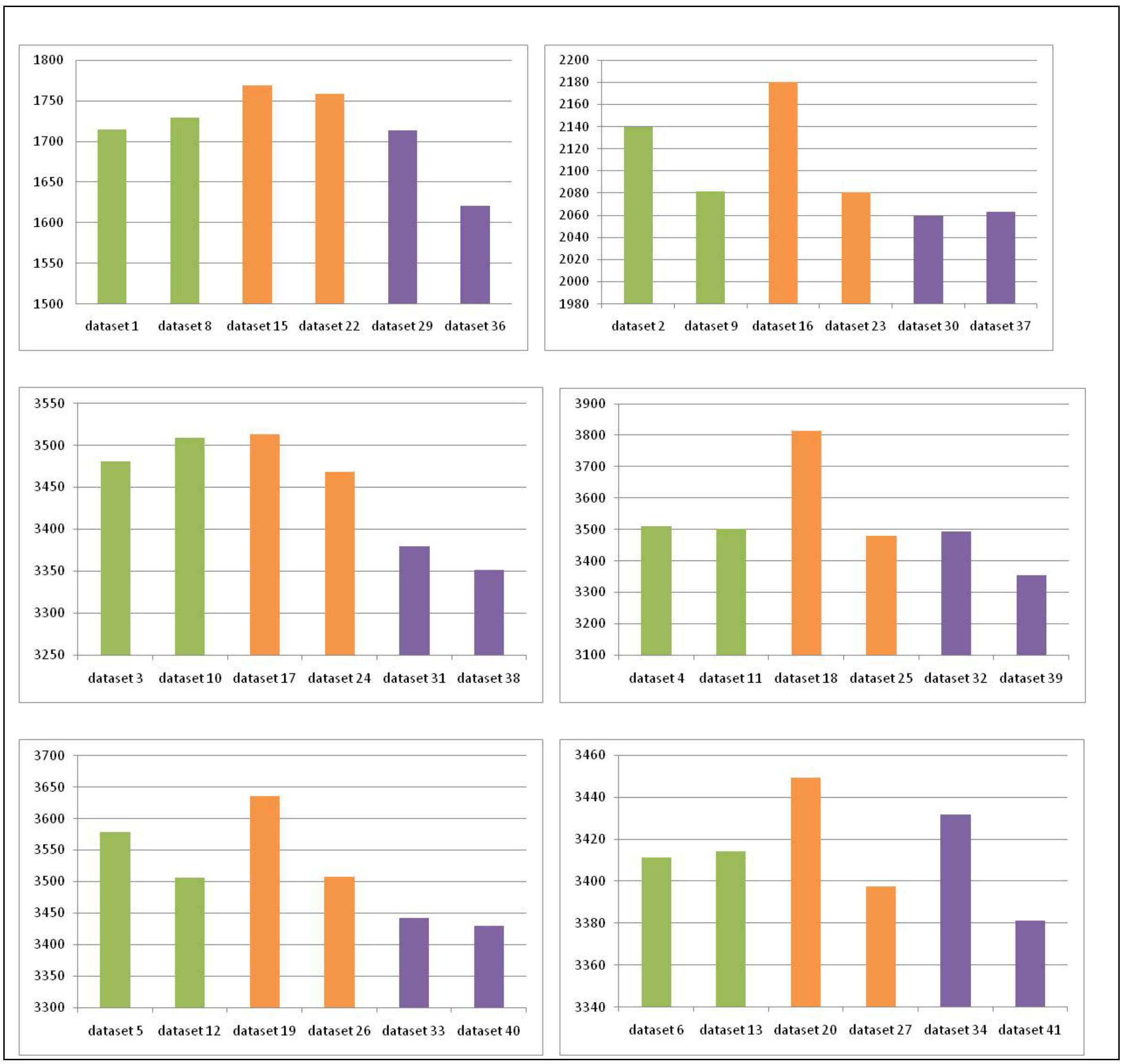


Figure 25 Values of the Third Objective Function with Different Handling Time Data

Third, layout 3 (crossdock with free doors) gives better value for total departure time of OTs for each dataset when they have the same arrival time and handling time (see Figure 26). And from this figure we also notice that layout 1 works better than layout 2 when the trucks arrives more frequently in terms of total departure time (This could be seen when comparing every first dataset of layout 1 and layout 2). With the conclusion from Figure 22, Layout 1 works better than Layout 2 for ID operation, we can conclude that the total weighted travel distance of Layout 1 is much less than the total weighted travel distance of Layout 2 in general.



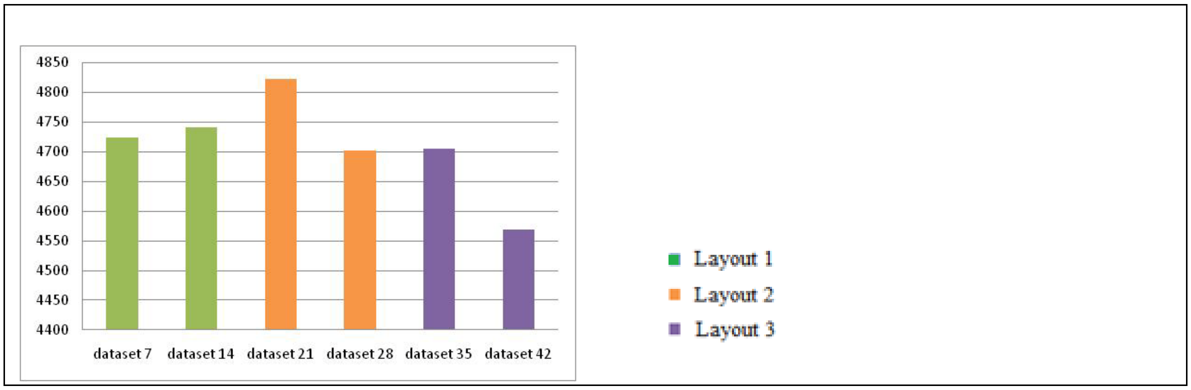
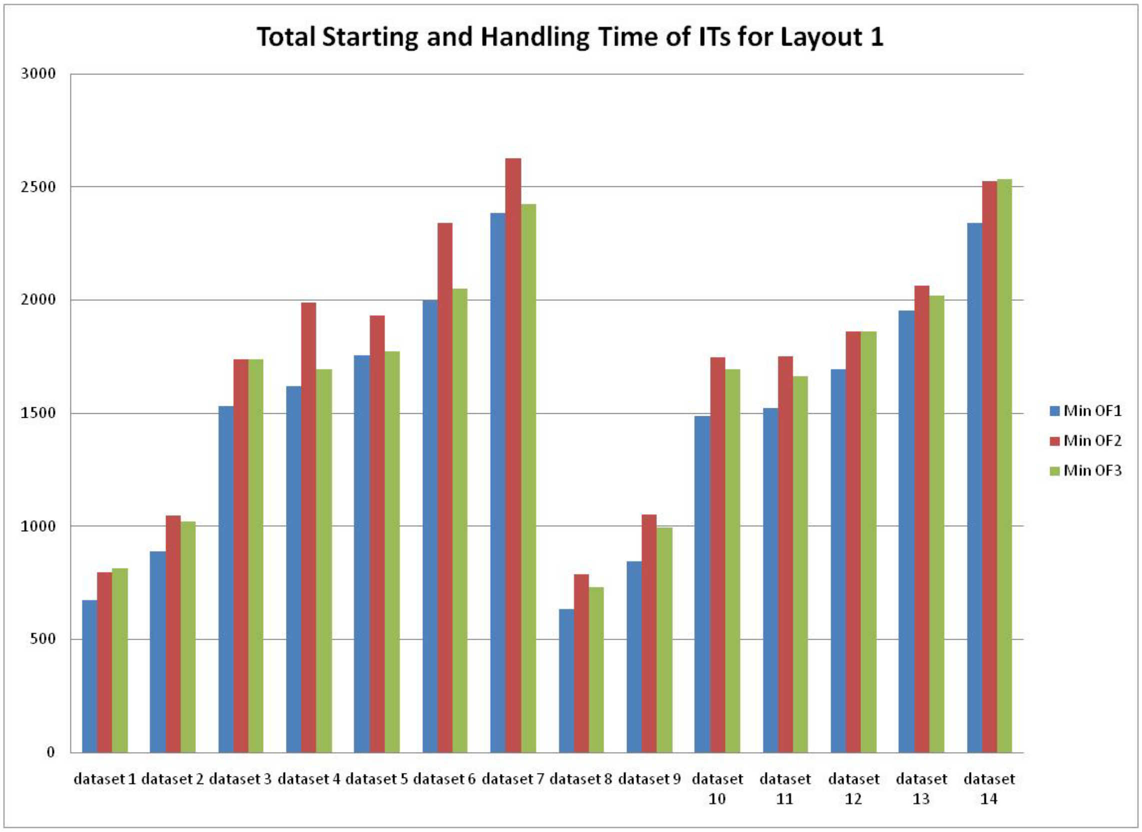
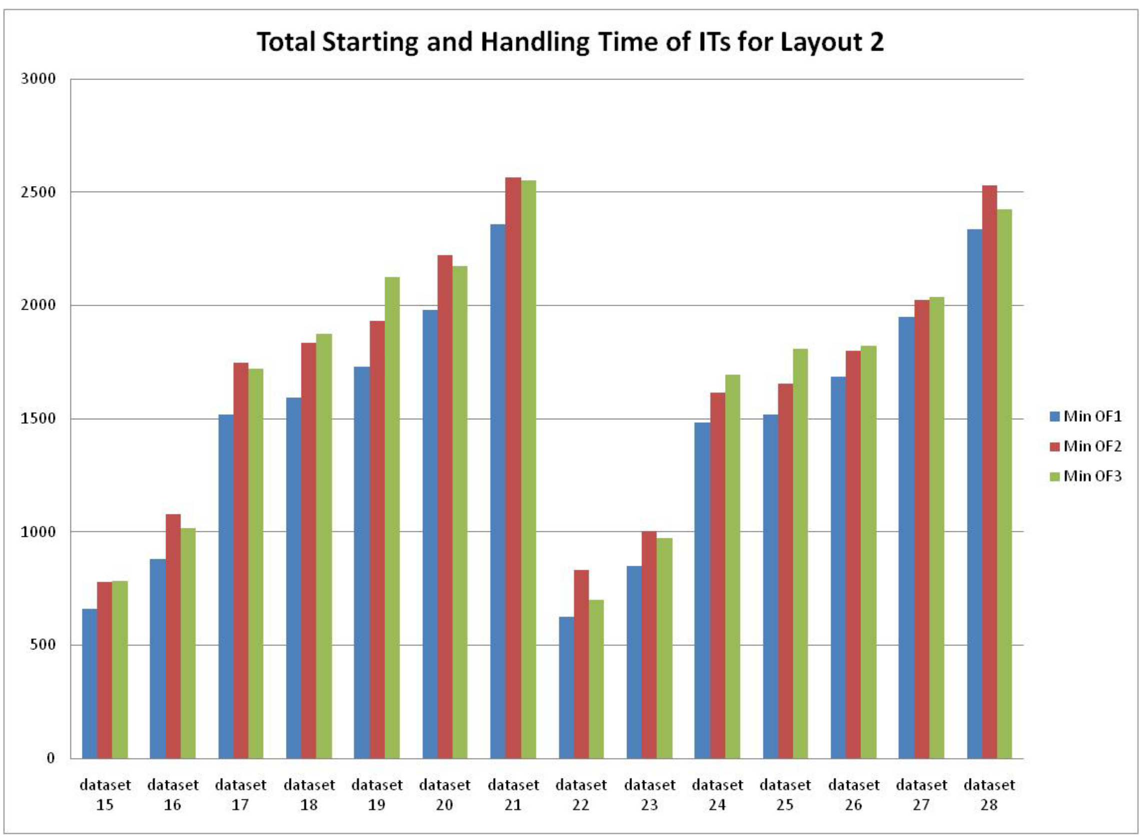


Figure 26 Values of the Third Objective Function with Different Layouts

4.4.2. Comparison of results

In this section, we compare the performance of crossdocking operation. The performance is measured by those values of three objectives. The values of each objective function are compared when optimizing different objectives. Figure 27 shows the values of total starting and handling time of ITs when optimizing OF1 (total starting and handling time of ITs), OF2 (total weighted distance), and OF3 (total departure time of OTs). From the figure we see that by minimizing OF2 and OF3 the value of OF1 increases in general, when the inter-arrival time of trucks increases as well. This increase, however, is not proportional and in some instances we observe a decrease of the OF1 value for higher inter-arrival times. Meanwhile, optimizing OF3 gives better values of OF1 compared to optimizing OF2, and this can be seen easily in Layout 1. This is because minimizing the total departure of OTs directly impacts the service time of ITs, while minimizing OF2 does not consider the performance of the starting and handling time of ITs. However, the value of OF1 from optimizing OF2 in our results gives also reasonable plans for ITs. This is because of our assumption— every door serves two trucks, spreads the services of ITs to all the IDs.


Total Starting and Handling Time of ITs for Layout 1
3000
2500
2000
1500
1000
500
0
dataset 1
dataset 2
dataset 3
dataset 4
dataset 5
dataset 6
dataset 7
dataset 8
dataset 9
dataset 10
dataset 11
dataset 12
dataset 13
dataset 14
Min OF1
Min OF2
Min OF3


Total Starting and Handling Time of ITs for Layout 2
3000
2500
2000
1500
1000
500
0
dataset 15
dataset 16
dataset 17
dataset 18
dataset 19
dataset 20
dataset 21
dataset 22
dataset 23
dataset 24
dataset 25
dataset 26
dataset 27
dataset 28
Min OF1
Min OF2
Min OF3

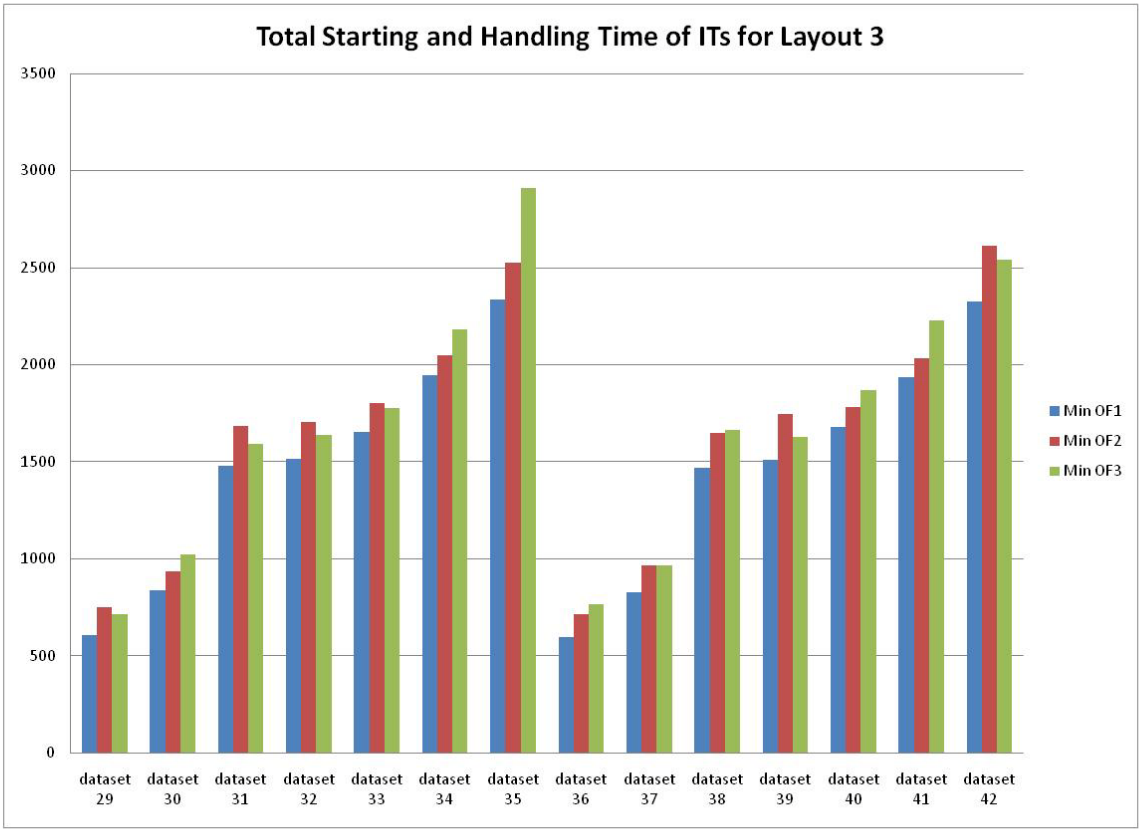
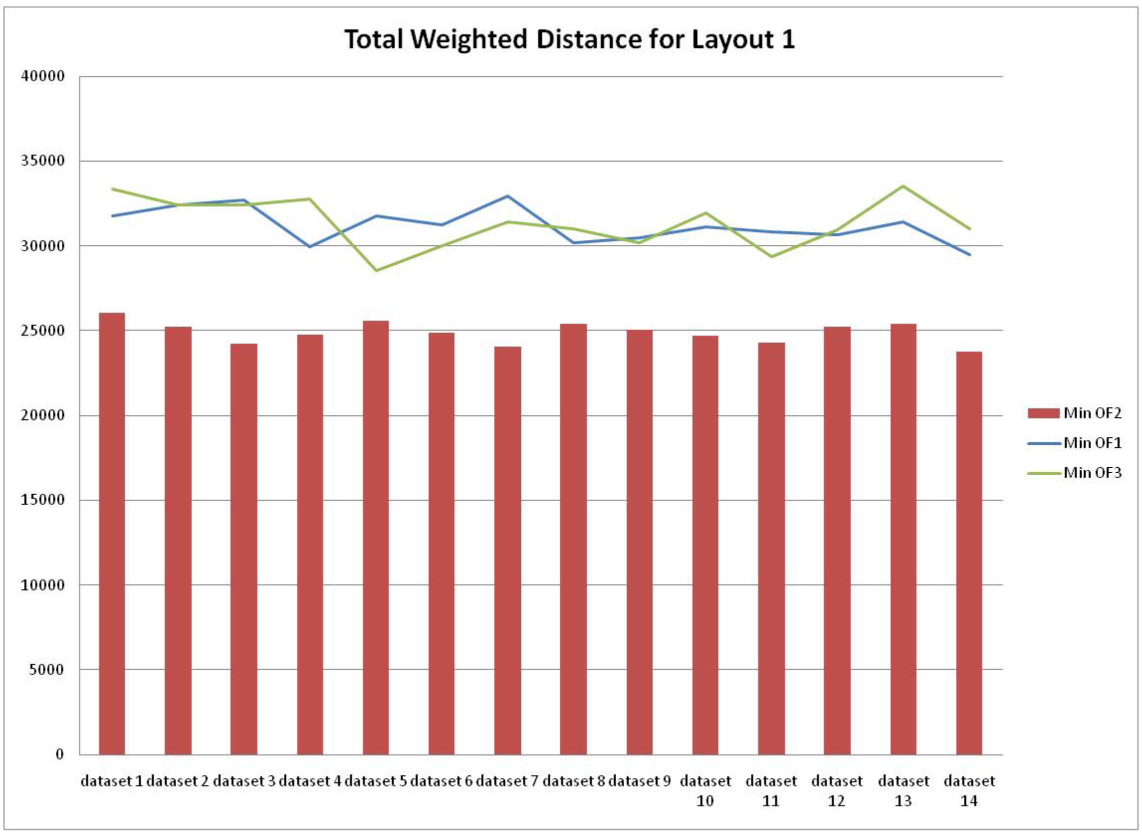


Figure 27 Total Starting and Handling Time

Figure 28 are the resulting values for total weighted distance of pallets traveled inside crossdock facility when optimizing OF1, OF2, and OF3. From the figure we can see that for both Layout 1 and Layout 2, the values of total weighted travel distance from optimizing OF1 and OF3 are mostly between 30000~34000 feet, while the optimal value obtained from minimizing OF2 is around 25000. This means when minimizing OF1 and OF3, the results for OF2 is about 20%~36% worse than minimizing OF2. While for Layout 3, when minimizing OF1 and OF3, the values of total weighted distance are around 23000 on average, and optimal values of OF2 are around 10000 on average. This means, for Layout 3, optimizing OF1 or OF3 does not give good results for the weighted distance. Figure for Layout 3 with free doors rather than pre-defined doors especially shows us that minimizing OF1 and OF3 gives bad results for the value of OF2, which is about 2.3 times the minimum. Since the total departure time of OTs depends on both the service of ITs and the travel time of pallets inside the crossdock facility, the results of Figure 28 shows that for a our crossdock facility, the total departure time of OTs mostly depends on the service starting time and handling time of ITs. This is because for our crossdock facility, the travel time of pallets inside the facility is small comparing to the service time of trucks at the doors.



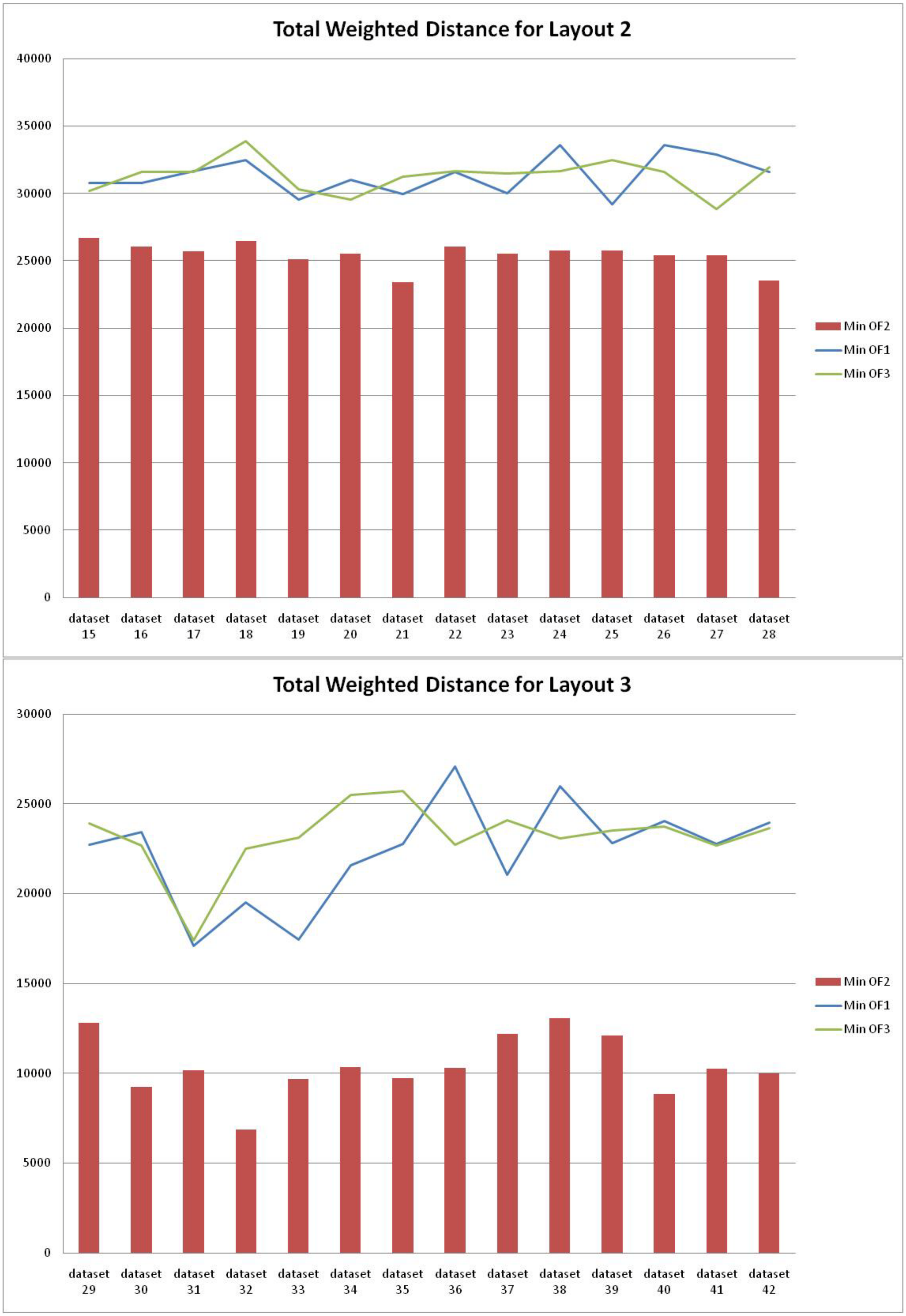
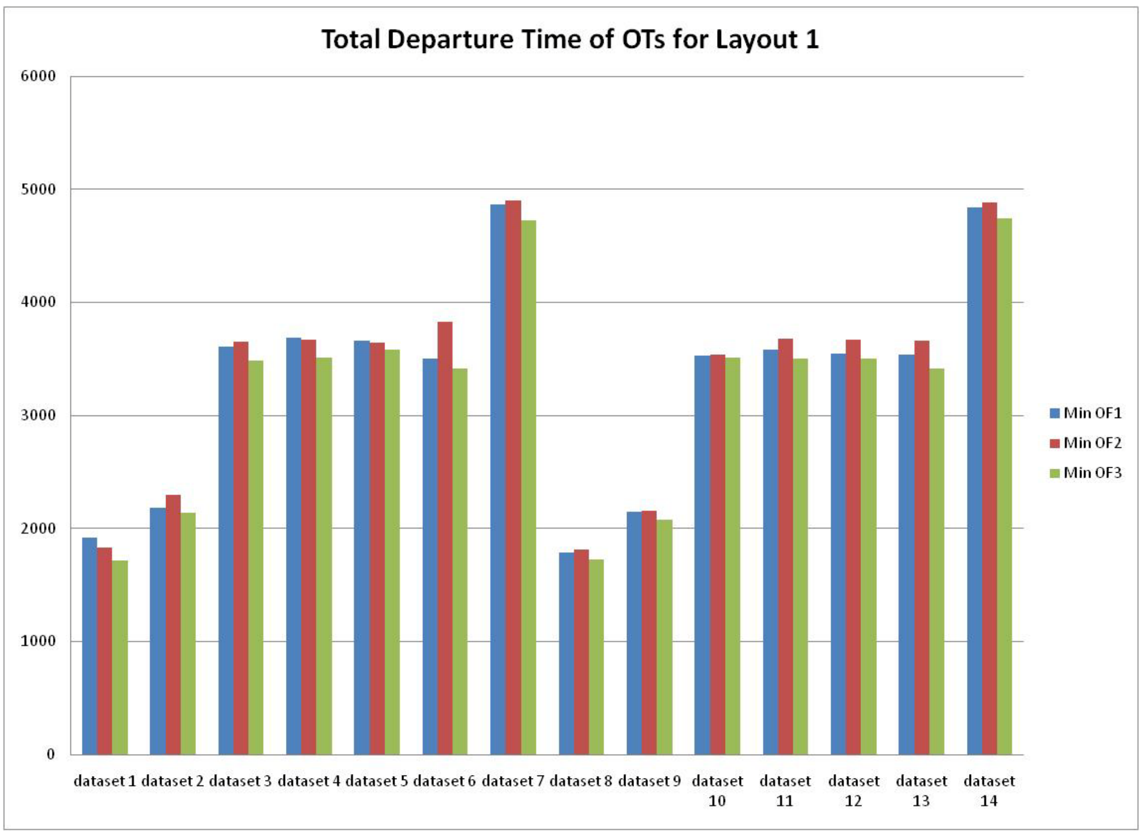
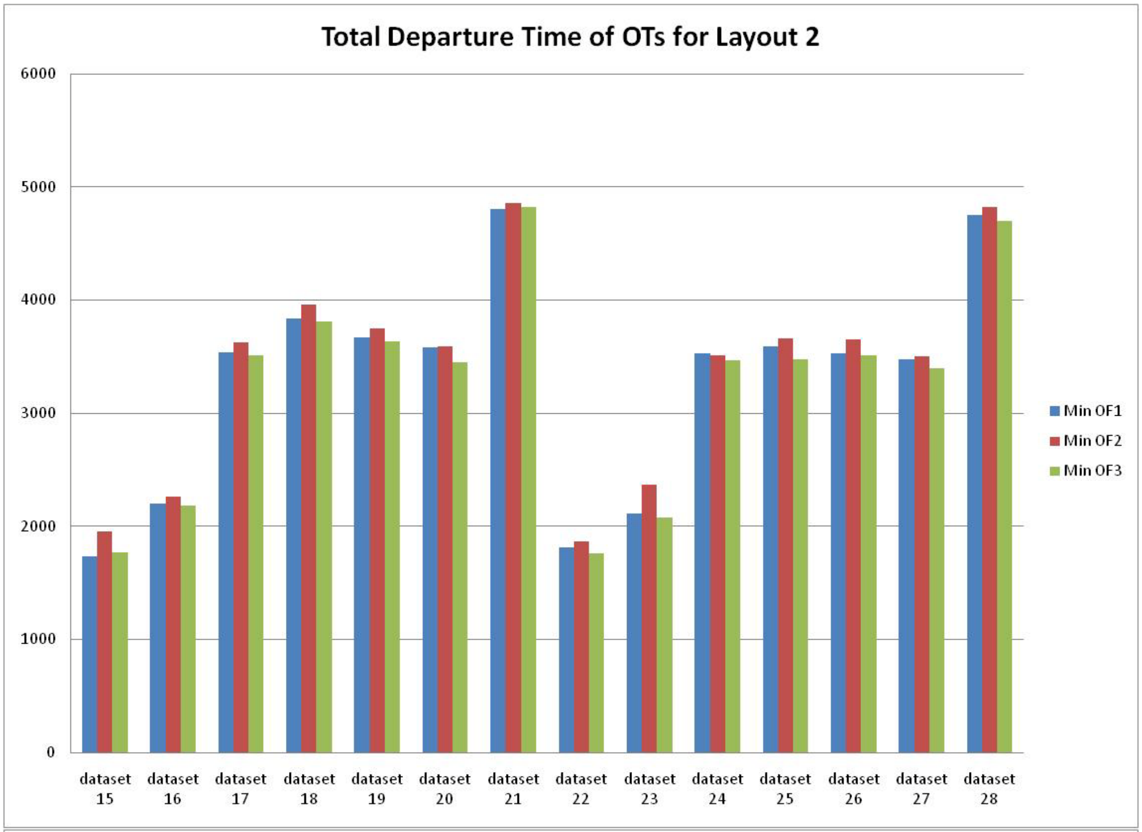


Figure 28 Total Weighted Distance

Figure 29 are the values of total departure time of all OTs when optimizing OF1, OF2 and OF3. The results indicate that both OF1 and OF2 produce good results for OF3. This is anticipated, as the departure time of OTs depends on the values of both OF1 and OF2 and, as discussed earlier, the starting and handling time of ITs almost determines the starting time for serving OTs. Therefore, it may be concluded that, at least for crossdocking facility of our size, minimizing the total starting and handling time of ITs produces good results for the departure time of OTs as well.





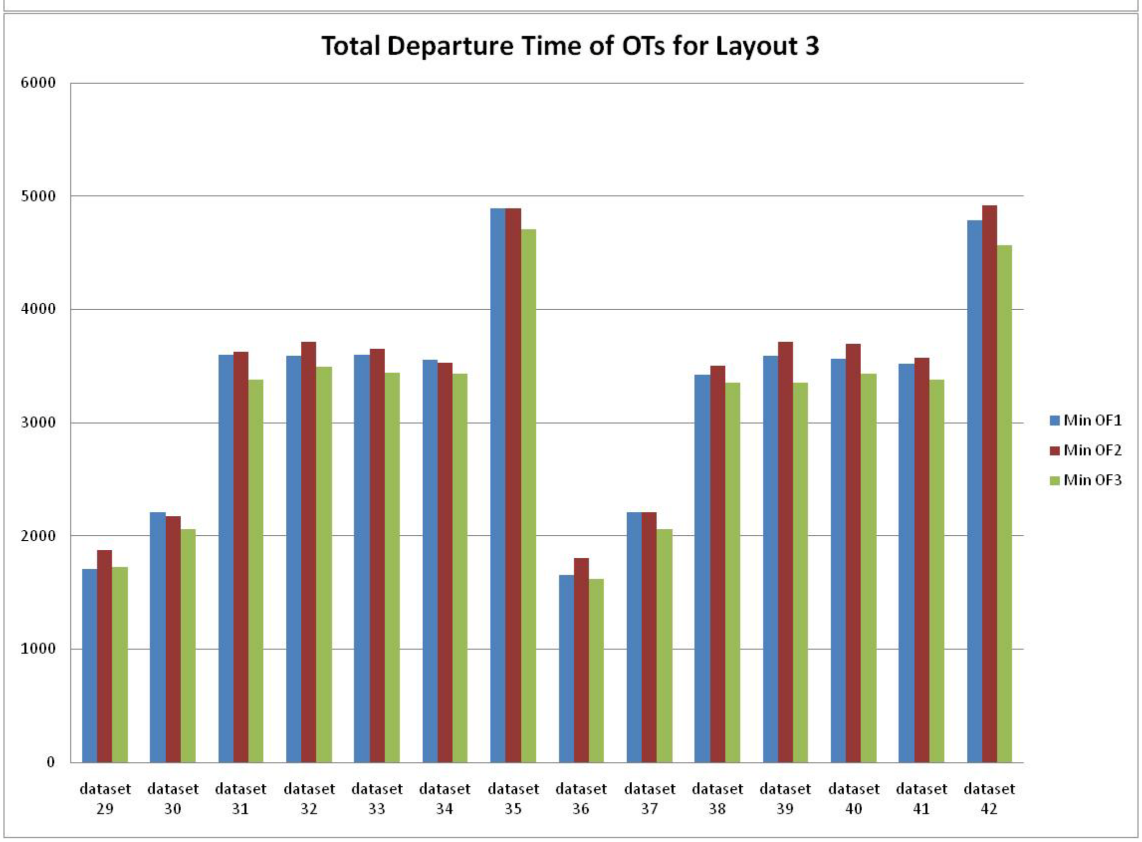


Figure 29 Total Departure Time of OTs

4.4.3. Pareto and post-Pareto analysis

The general *N*-objective optimization problem (or in general the multi-objective optimization problem) can be defined in the following way: Find the vector of decision variables $\boldsymbol{x}=[x_1, x_2, \ldots, x_n]$ that optimizes (minimizes or maximizes) a vector of objective functions: $\boldsymbol{f}(\boldsymbol{x})=[f_1(\boldsymbol{x}), f_2(\boldsymbol{x}),\ldots, f_N(\boldsymbol{x})]$, subject to m inequality constraints $G_i(\boldsymbol{x}),$ $i=(1,2,3\ldots,m)$ and k equality constraints $H_j(\boldsymbol{x}),$ $j=(1,2,3,\ldots,k)$. Due to the conflicting nature of the objectives it is usually the case that there is no unique optimal solution. It is possible to improve separately at least one (but not all) objective function of a given solution but this will usually cause the declining of its remaining objective functions (or at least one of them). Thus, several different solutions could be thought of as "optimal", because no one dominates the other. Since the model presented in this thesis have three objectives and optimizing one of the objectives causes degrading the performance on the other objectives, our problem is a multi-objective problem [74]. Like most real-world scheduling problems which are implicitly or explicitly multi-objective, this paper develops a model with three objectives from the crossdocking operators' point of view—minimizing total starting and handling time of ITs, minimizing the total weighted distance of pallets traveled inside the crossdock facility and minimizing the total departure time of all OTs.

In general the most famous approaches for solving multi-objective problems are: a) the weighted approach [75], b) the monotony approach [76], c) the goal programming approach, as the ε -constraint method [77], d) the balance approach [78, 79], and e) evolutionary algorithms [75]. From these approaches the most common resolution approach is the use of evolutionary algorithms [80]. The difficulty and at the same time main advantage of using the latter approach is that the modeler needs to develop a custom made (meta)heuristic and takes advantage of the problems' domain and special properties. In this paper the weighted approach is selected. The weighted approach consists of using a weighted aggregate function according to preferences set by decision-makers, and its complexity and accuracy lies in the proper selection of the weights used to depict the decision-maker preferences. In practice, it can be very difficult to precisely and accurately select these weights, even for someone familiar with the problem domain [81]. For this reason in this thesis different weight combinations are used to generate different weighted objective functions and each model is solved using the k=2 approximation with the additional constraint (eq. 4.4). The solutions from all the optimization problems with the different weights form, what is known from the literature, as the Pareto front. All points in the Pareto front satisfy the Pareto dominance criterion (Definition I).

Definition I: dominate, Pareto-optimal, non-dominated

Vector $F(a)$ ***dominates*** vector $F(b)$, ($F(a) \prec F(b)$) if and only if

(1) $f_i(a) \leq f_i(b)$ for all i;

(2) $f_i(a) < f_i(b)$ for at least one i.

If $F(a)$ dominates vector $F(b)$, vector $F(a)$ is considered ***Pareto-optimal*** or ***non-dominated*** if there exists no other vector $F(b)$ such that $F(b) \prec F(a)$.

All the Pareto-optimal solutions compose a certain boundary between the space, which contains dominated solutions and the space where no solutions exist. This boundary is called the trade-off surface or Pareto Front or Pareto-set and can be depicted as a surface in the N-dimensional space, where N is the number of objectives. The use of exact methods to solve multi-objective optimization problems is time consuming and is often infeasible [75].

In total, 45 different weight combinations are applied and the resulting models are solved. The values of each objective function for each weight combination are shown in Table 11 for one of the datasets (Dataset 1, Appendix I, Table 13). As we observe in table 11 we notice that not all the points satisfy the Pareto Dominance Criterion (PDC). This is attributed to the application of an approximation method as a resolution approach (as opposed to an exact method). If an exact solution method had been used, all points satisfying $\sum_{i=1}^{3} w_i = 1$ and $w > 0$ would satisfy the PDC [82].

Table 11 OF Values with Different Weights

no.	weights			Value OF1	Value OF2	Value OF3
	OF1	OF2	OF3			
1	0	0.9	0.1	672.11	31948	1788.38
2	0	1	0	795.39	26060	2298.14
3	0	0.1	0.9	810.39	34708	1756.51
4	0	0	1	813.36	33328	1714.42
5	0.1	0.7	0.2	672.11	31948	1801.4
6	0.1	0.8	0.1	672.11	31948	1764.53
7	0.1	0.9	0	672.11	29464	1947.06
8	0.1	0.3	0.6	673.49	31764	1732.59
9	0.1	0.1	0.8	687.21	32776	1724.03
10	0.1	0.2	0.7	687.21	32776	1778.38
11	0.1	0.4	0.5	687.21	32776	1727.27
12	0.1	0.5	0.4	687.21	32776	1743.41
13	0.1	0.6	0.3	687.21	32776	1717.93
14	0.1	0	0.9	801.05	32316	1759.46
15	0.2	0.4	0.4	672.11	31948	1771.57
16	0.2	0.5	0.3	672.11	31948	1750.41
17	0.2	0.6	0.2	672.11	31948	1788.38
18	0.2	0.7	0.1	672.11	31948	1767.22
19	0.2	0.3	0.5	684.17	32776	1750.77
20	0.2	0.1	0.7	685.94	32316	1773.71
21	0.2	0.2	0.6	687.21	32776	1724.03
22	0.3	0.1	0.6	672.11	31948	1774.92
23	0.3	0.2	0.5	672.11	31948	1753.76
24	0.3	0.3	0.4	672.11	31948	1769.62
25	0.3	0.4	0.3	672.11	31948	1769.83
26	0.3	0.5	0.2	672.11	31948	1758.11
27	0.3	0.6	0.1	672.11	31948	1783.08
28	0.4	0.1	0.5	672.11	31948	1765.27
29	0.4	0.2	0.4	672.11	31948	1753.76
30	0.4	0.3	0.3	672.11	31948	1753.76
31	0.4	0.4	0.2	672.11	31948	1774.92
32	0.4	0.5	0.1	672.11	31948	1753.76
33	0.5	0.1	0.4	672.11	31948	1753.76
34	0.5	0.2	0.3	672.11	31948	1788.38
35	0.5	0.3	0.2	672.11	31948	1788.38
36	0.5	0.4	0.1	672.11	31948	1753.76
37	0.6	0.1	0.3	672.11	31948	1778.73
38	0.6	0.2	0.2	672.11	31948	1774.92
39	0.6	0.3	0.1	672.11	31948	1779.8
40	0.7	0.1	0.2	672.11	31948	1764.53
41	0.7	0.2	0.1	672.11	31948	1801.4
42	0.8	0.1	0.1	672.11	31948	1786.43
43	0.9	0	0.1	672.11	32776	1883.45
44	0.9	0.1	0	687.21	32776	1764.23
45	1	0	0	672.11	31764	1919.81

Table 12 Pareto Front Points

no.	weights OF1	weights OF2	weights OF3	Value OF1	Value OF2	Value OF3
2	0	1	0	795.39	26060	2298.14
4	0	0	1	813.36	33328	1714.42
7	0.1	0.9	0	672.11	29464	1947.06
8	0.1	0.3	0.6	673.49	31764	1732.59
9	0.1	0.1	0.8	687.21	32776	1724.03
16	0.2	0.5	0.3	672.11	31948	1750.41
45	1	0	0	672.11	31764	1919.81

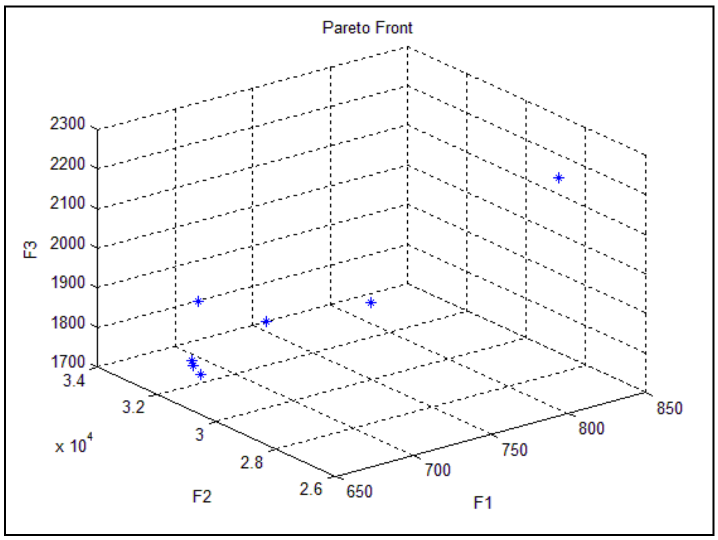


Figure 30 Pareto Front

Once the Pareto front is obtained, we need to decide which one of the non-dominated points to choose as the final solution to the problem. This follow up step known as post-Pareto analysis helps in the decision-making process. However, post-Pareto analysis can be quite a challenging task since, in the absence of subjective or judgmental information, none of the corresponding trade-offs can be said to be better than the others. In this thesis a post-Pareto analysis algorithm developed at the CAIT-FMP lab at Rutgers University is used to score all 7 Pareto points [74]. The algorithm is based on non-numerical ranking preference method (NRPM) The non-numerical ranking preferences method (NRPM) ranks the objective functions non-numerically and in order of relative importance, without selecting specific numerical weight values for each objective function. Initially, an uncertain weight function is generated based on the decision-maker objective function preferences. The weight values used are systematically generated using an uncertain weight function and, this uncertain weight function is obtained with the simple information of the decision-maker objective function preferences. Then, possible weight combinations reflecting the decision-makers preferences are generated numerous times from the uncertain weight function. For instance, without loss of generality consider the case in which the first objective is more important than the second objective and the second objective is more important than the third objective: f1 f2 f3. Then, random but ranked weights are generated using Monte Carlo simulation methods. These weights are uniformly sampled from the region of interest that satisfies the following: w1>w3>w2 and w1 + w2 + w3 = 1. After obtaining the set of ranked weights, a substantially large set of weights is generated (in the range of thousands). Then, each of the weight sets is multiplied by each of the solutions found in the Pareto front as in: f '= w1f1(x) + w2f2(x) + w3f3(x). Then, without loss of generality, for minimization multiple objective problems, the solution that yields the minimum value for f ' for each weight combination is recorded and gets a counter of 1. At the end, the solutions that have a counter of 1 are those solutions that form the pruned or reduced Pareto front. Simply explained, in this approach the objectives prioritization adds constraints that effectively remove most of the possible weight combinations, and this leads to a dramatic solution space reduction. The solutions that this method yields have been reported to be those that clearly satisfied the given objective functions preferences [83]. The proposed NRPM is also applicable in cases where the decision maker is also uncertain or unable to provide the priorities of the different objective functions (from now on called the E-NRPM). In this case the pruning methodology is applied to all the possible combinations of the objective functions preference order.

Tables 13 shows the Pareto front solutions along with their score using the NRPM and the E-NRPM. The first column shows the number of the solution, columns 2 through 4 show the values of each objective function and the last two columns show the NRPM and E-NRPM score as percentages. For example solution 7 was the dominant one 54% and 58% of the times the simulation was performed using the NRPM and E-NRPM respectively. Solutions from the Pareto front (Table 12) not shown in Table 13 have a score of zero. From Table 13, we conclude that the solution no.8 with highest score is the best solution to our example Dataset 1. The total starting and handling time of all ITs is 673.49 minutes; the total weighted distance traveled of all pallets inside the facility is 31,764 feet; and the total departure time of all OTs is at 1732.59 minutes started from time zero. The detailed scheduling plan of ITs and OTs is shown in Figure 31. As a result from our restriction-approximation, each door serve two trucks; the starting time of serving ITs and OTs are shown on the top of each truck. Sequence of serving ITs and OTs are presented in the figure.

Table 13 Ranked Pareto Front Solutions

	Objective Function Values			Scores	
Pareto Front Solution	F1	F2	F3	NRPM Score	E-NRPM Score
7	672.11	29464	1947.1	12%	12%
8	673.49	31764	1732.6	54%	58%
9	687.21	32776	1724	9%	7%
16	672.11	31948	1750.4	25%	23%

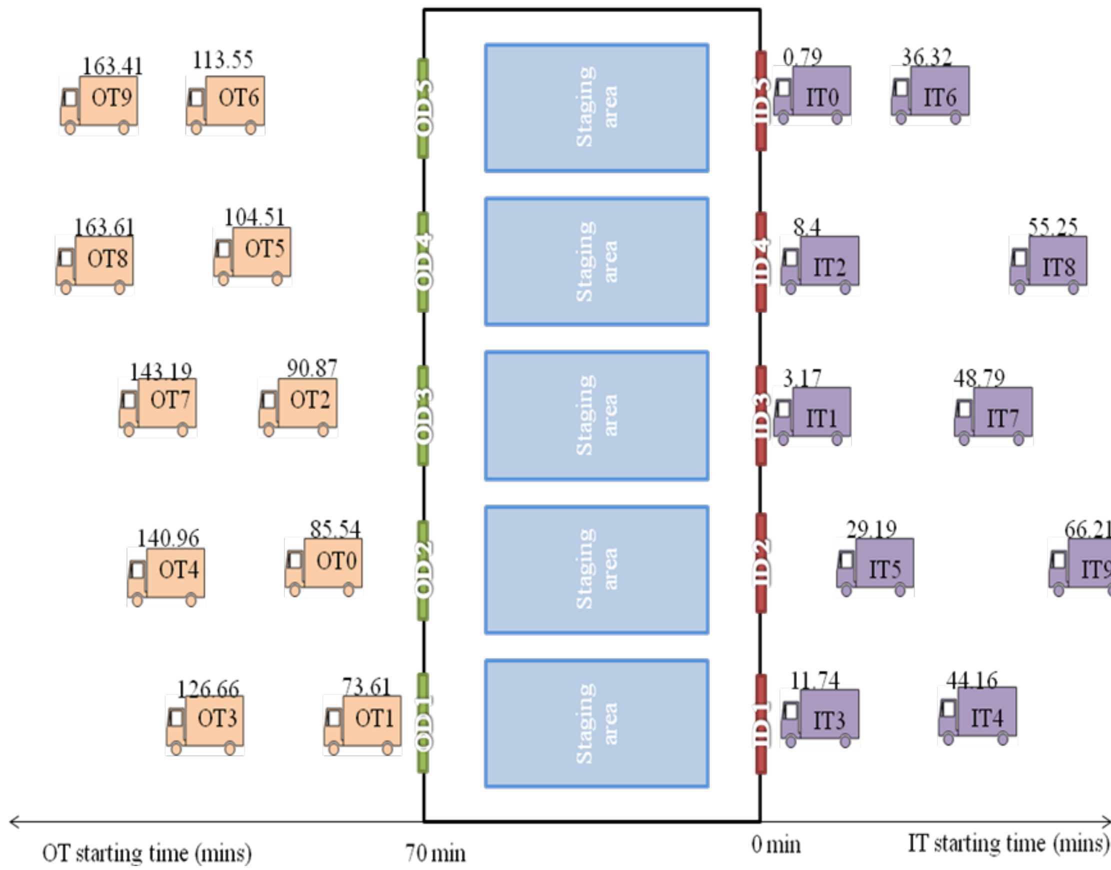


Figure 31 Scheduling Results of ITs and OTs for Example 1

4.5. Conclusion

As c onclusion, all exa mples p resented for t he lim itation using e xact s olution approach are not realistic. For the first objective, only 5 doors and 6 trucks can be arranged, and for the last objective only 4 doors and 5 trucks can be arranged. The minimum realistic number of doors at a crossdocking facility is found to be 5 IDs and 5 ODs. The results of the second objective give extreme cases where only one ID and one OD would be used while other doors are idling. Therefore, the limitation of the exact solution does not give the opportunities to solve realistic problem, either in realistic size or reasonable CPU time or the plan results. In order to make realistic analysis of the crossdocking operation, we need to develop a good heuristic approach which would give us a good quality solution in a reasonable CPU time.

Therefore, we use approximation approaches, which is k=2 approximation, for the solving all the objectives with different restrictions. This chapter shows that by using k=2, for the first objective function, it gives enough good objective value within little computational time; and for the second objective, this approximation avoids assigning the trucks to the same door. For the third objective, the objective of minimizing departure time of all ITs is approximated by minimizing the service time of all OTs with additional constraint that forces the OTs to be served within certain time limits after their arrival. The behaviors of different objectives are shown in Table 8, 9 and 10 when optimizing the first, second and third objectives respectively.

Finally, numerical examples are provided in order to show the objective values with different arrival time interval and handling time with different layouts. It is found that both total starting and handling time of ITs and total departure time of OTs increase with the increase of arrival time interval, but not the weighted travel distance. In addition, crossdocking with preferred doors which has shorter handling time, either unloading time or loading time, performs better for both ID and OD operations. Moreover, crossdock with free doors layout rather than predefined doors improves the performance of crossdocking operations, especially for the total weighted travel distance. This might benefit more for large crossdock facility rather than small size crossdock facility when taking the changeover costs into account. This chapter also shows the performance of crossdocking operation when optimizing different objectives. Different objective function values are compared. From the comparison, we learn that with our approximation approaches, minimizing departure time of OTs and minimizing travel distance give reasonable scheduling plan for trucks in terms of total starting and handling time of ITs. In addition, neither minimization of starting and handling time nor the minimization of total departure time of OTs gives good scheduling plan for trucks in terms of minimizing the total weighted distance. At last, for small size crossdock facility, departure time of OTs mainly depends on the service stating and handling time of ITs. Finally, a Pareto analysis is conducted using example dataset 1 and a best solution is picked from the Pareto front by applying post-Pareto analysis algorithm.

Chapter 5

Summary, Contributions and Future Research

This research deals with the scheduling of ITs and OTs at a crossdocking facility where three objectives are considered. Three different layouts are compared based on our MIP model developed. A restriction-approximation approach is developed and used to solve the MIP model. The following section summarizes this thesis and draws general conclusions. The last section in this chapter recommends future researches.

5.1. Summary and Contributions

The research provides a detailed introduction to crossdocking operations in practice, a full description to problems that need to be solved for current crossdocking operations and comprehensive review of up to date literatures.

The scheduling of trucks to doors in a crossdocking environment is a reality that needs to be planned for in order to maximize profits and efficiency. This research aims to schedule ITs and OTs to doors at a crossdock facility, while considering three objectives a crossdocking operator might have (minimizing total starting and handling time of ITs, minimizing the total weighted distance traveled inside the crossdock and minimizing total departure time of OTs).

Two mixed-integer models are developed to schedule ITs and OTs. The first model deals with crossdock with predefined doors and the second model deal with crossdock with non-predefined doors (free doors). The models aim to provide effective scheduling plan for trucks, while it also provide the opportunity to compare the different layouts of crossdock facility. Since the problem is a NP-hard problem, a restriction-approximation approach with additional constraint is developed to solve our model and the efficiency of the approximation is proved. The approximation approach forces each door to serve a fixed number of trucks at most, the number is obtained by dividing the number of trucks by the number of doors. For the numerical example studied where 10 ITs are assigned to 5 IDs and 10 OTs are assigned to 5 ODs, the maximum number of trucks served at each door is forced to be 2. Numerical examples are conducted for analyzing the performance of crossdocking operation, and comparing the different layouts for a given crossdock facility size. Finally, behaviors and relationships of three objectives are analyzed. As the three objectives this research tries to optimize cannot get to the optimality at the same time, a Pareto analysis is conducted based on one of the examples and a post-Pareto analysis algorithm is used for picking the best solution from obtained Pareto front points.

In conclusion from the research and numerical example results, the research makes the following contributions:

- Provides a detailed introduction to crossdock facility (type, layout, size, etc) and problems related to crossdocking (levels of crossdocking management, operations characteristics, issues of inbound, inside and outbound operations)
- Conducts a comprehensive review of up-to-date literatures related to crossdocking operations.
- Develops general scheduling models for trucks to crossdock doors for both a predefined door and non-predefined door crossdock facility.
- Develops an efficient and effective approximation approach that solves the scheduling model presented.
- Compares different layouts of a small size rectangular crossdocking facility.

- Analyzes behavior and relations of multi-objectives for a small size rectangular crossdocking facility

A major contribution of this research is that it develops the model for the truck assignment and scheduling of both ITs and OTs than the ones that currently only considers partial problems of our study. Trying to reach these goals raises other questions for future research in a crossdocking operation.

5.2. Future research

Scheduling of trucks for crossdocking operation is a rich area for future research. This is due to both the requirements of high efficiency and the low cost of crossdocking operations and the lack of previous research.

Scheduling of trucks in our model needs to be further examined for bigger crossdocks having more number of doors and ITs/OTs. Crossdocks of rectangular shape with more than 10 doors (e.g. 20-150 doors) should be considered and different objectives should be studied under more complex conditions.

By examining all inbound, inside and outbound operations, more conditions should be considered for each operation. For inside operations, the model developed in this research does not take the temporary storage into account. Direct shipping without storage could happen in small size crossdock, but in bigger size crossdock there are usually staging processes for at least part of the pallets going through the facility. Therefore, the time spent storage and operations for staging of inside operations could be built into the model for future research. In addition, when considering the scheduling of OTs, the model developed in this thesis assumes the starting time of serving an OTs is after when all the pallets for this OT are ready to be loaded, while this helps to prevent mistakes and masses from loading but this delays the starting time of serving OTs. Future research might also study the cases where pallets could be loaded before all of them are ready to be handled.

Other than I shape crossdock, U shape, H shape, T shape and X shapes are also commonly used for large size crossdock in practice. Traveling and storage of pallets in different shapes of crossdocks give rise to difficulties in modeling of scheduling trucks. A more detailed distance matrix between each pair of doors should be carefully calculated and the determination of doors' layout in crossdocks of different shapes is also a difficult task.

In all the research reviewed, the stochastic characteristic of the process was not considered as an option. By the nature of crossdocking operations, the trucks arrival time, the handling time of pallet, and the travel time of pallets inside the facility sometimes are not certain. For instance, although the use of information technology provides information of expected arrival time of trucks, the trucks arrival time might change due to the change of the road and weather conditions. Moreover, the handling time for each truck at each door and travel time of pallets inside the facility are not fixed since both of them are affected by the team of workers and equipments used. Therefore, the stochastic nature could be taken into account into our model for future research.

Appendix I

Computational Data

I.1. Datasets

In to tal, there a re 3 (layouts)*7(arrival times)*2(handling t imes) = 42 da tasets for computational example. For example, Dataset 1 has the second column of Table 15 as the arrival time and the handling time at IDs for all ITs are the last five columns of Table 16 and the handling time at ODs for all OTs are from the second to the sixth columns of Table 17. Dataset 28 has the arrival time of the eighth column from Table 15, the handling time at the IDs for all ITs are the third, fifth, eighth, ninth and tenth columns of Table 18 and the handling time at the ODs for all OTs are the second, fourth, sixth, seventh and eleventh columns of Table 19. Dataset 33 has the arrival time of the sixth column of Table 15, the handling time for all ITs at each door is shown entirely in Table 16 and the handling time for all OTs at each door is shown entirely in Table17. The combination and datasets are illustrated in the following table (Table 12).

Table 14 Datasets

Scenarios	Layout	Handling Time	Datasets	Arrival Time
Scenario 1	Layout 1	Dataset A	Dataset 1	Arrival Time 1
			Dataset 2	Arrival Time 2
			Dataset 3	Arrival Time 3
			Dataset 4	Arrival Time 4
			Dataset 5	Arrival Time 5
			Dataset 6	Arrival Time 6
			Dataset 7	Arrival Time 7
		Dataset B (with preferred doors)	Dataset 8	Arrival Time 1
			Dataset 9	Arrival Time 2
			Dataset 10	Arrival Time 3
			Dataset 11	Arrival Time 4
			Dataset 12	Arrival Time 5
			Dataset 13	Arrival Time 6
			Dataset 14	Arrival Time 7
	Layout 2	Dataset A	Dataset 15	Arrival Time 1
			Dataset 16	Arrival Time 2
			Dataset 17	Arrival Time 3
			Dataset 18	Arrival Time 4
			Dataset 19	Arrival Time 5
			Dataset 20	Arrival Time 6
			Dataset 21	Arrival Time 7
		Dataset B (with preferred doors)	Dataset 22	Arrival Time 1
			Dataset 23	Arrival Time 2
			Dataset 24	Arrival Time 3
			Dataset 25	Arrival Time 4
			Dataset 26	Arrival Time 5
			Dataset 27	Arrival Time 6
			Dataset 28	Arrival Time 7

Table 12 Datasets (continued)

Scenarios	Layout	Handling Time	Datasets	Arrival Time
Scenario 2	Layout 3	Dataset A	Dataset 29	Arrival Time 1
			Dataset 30	Arrival Time 2
			Dataset 31	Arrival Time 3
			Dataset 32	Arrival Time 4
			Dataset 33	Arrival Time 5
			Dataset 34	Arrival Time 6
			Dataset 35	Arrival Time 7
		Dataset B (with preferred doors)	Dataset 36	Arrival Time 1
			Dataset 37	Arrival Time 2
			Dataset 38	Arrival Time 3
			Dataset 39	Arrival Time 4
			Dataset 40	Arrival Time 5
			Dataset 41	Arrival Time 6
			Dataset 42	Arrival Time 7

I.2. Distances between doors

Table 15 Distance Matrix for Layout 1 and 3

Distance between doors for layout 1 and layout 3 (feet)										
	Door 1	Door 2	Door 3	Door 4	Door 5	Door 6	Door 7	Door 8	Door 9	Door 10
Door 1	0	23	46	69	92	75	98	121	144	167
Door 2	23	0	23	46	69	98	75	98	121	144
Door 3	46	23	0	23	46	121	98	75	98	121
Door 4	69	46	23	0	23	144	121	98	75	98
Door 5	92	69	46	23	0	167	144	121	98	75
Door 6	75	98	121	144	167	0	23	46	69	92
Door 7	98	75	98	121	144	23	0	23	46	69
Door 8	121	98	75	98	121	46	23	0	23	46
Door 9	144	121	98	75	98	69	46	23	0	23
Door 10	167	144	121	98	75	92	69	46	23	0

Table 16 Distance Matrix for Layout 2

Distance between doors for layout 2 (feet)					
	Door 1 (OD1)	Door 3 (OD2)	Door 5 (OD3)	Door 6 (OD4)	Door 10 (OD5)
Door 2 (ID1)	23	23	69	98	144
Door 4 (ID2)	69	23	23	144	98
Door 7 (ID3)	98	98	144	23	69
Door 8 (ID4)	121	75	121	46	46
Door 9 (ID5)	144	98	98	69	23

I.3. Arrival time for ITs and OTs

Table 17 Arrival Time for ITs and OTs

	Arrival Time of ITs (mins)						
	Arrival 1	Arrival 2	Arrival 3	Arrival 4	Arrival 5	Arrival 5	Arrival 7
IT1	0.79	6.03	5.22	16.81	3.97	26.22	8.68
IT2	3.17	18.20	56.93	18.69	15.84	116.30	41.66
IT3	8.40	21.14	76.19	52.78	42.02	119.37	91.37
IT4	11.74	37.81	122.32	79.43	58.69	121.08	123.10
IT5	16.30	41.56	157.30	117.97	81.49	142.42	204.95
IT6	29.19	58.52	160.21	157.87	145.93	163.87	275.83
IT7	36.32	68.50	165.67	160.67	181.61	196.44	277.92
IT8	46.79	73.19	182.90	171.57	233.94	199.59	279.49
IT9	55.25	75.67	183.67	183.53	276.27	229.48	298.85
IT10	62.39	100.79	234.19	222.16	311.95	295.38	397.45

	Arrival Time of OTs (mins)						
	Arrival 1	Arrival 2	Arrival 3	Arrival 4	Arrival 5	Arrival 5	Arrival 7
OT1	72.31	79.71	250.78	176.46	189.47	187.64	290.72
OT2	73.61	94.68	251.64	190.28	197.27	205.21	298.74
OT3	85.17	102.03	263.78	202.57	207.38	207.05	347.87
OT4	93.46	104.07	275.91	264.77	292.40	228.34	376.81
OT5	100.97	122.96	275.97	275.53	302.99	228.73	314.10
OT6	104.51	136	282.84	307.50	325.09	344.88	532.50
OT7	113.55	157.84	283.49	344.48	349.43	346.94	556.21
OT8	129.03	209.16	289.89	388.87	349.58	361.05	465.95
OT9	137.07	239.35	308.47	390.70	343.15	363.03	519.41
OT10	139.55	242.95	313.59	392.77	353.47	368.47	436.52

I.3. Arrival time for ITs and OTs

Table 17 Arrival Time for ITs and OTs

	Arrival Time of ITs (mins)						
	Arrival 1	Arrival 2	Arrival 3	Arrival 4	Arrival 5	Arrival 5	Arrival 7
IT1	0.79	6.03	5.22	16.81	3.97	26.22	8.68
IT2	3.17	18.20	56.93	18.69	15.84	116.30	41.66
IT3	8.40	21.14	76.19	52.78	42.02	119.37	91.37
IT4	11.74	37.81	122.32	79.43	58.69	121.08	123.10
IT5	16.30	41.56	157.30	117.97	81.49	142.42	204.95
IT6	29.19	58.52	160.21	157.87	145.93	163.87	275.83
IT7	36.32	68.50	165.67	160.67	181.61	196.44	277.92
IT8	46.79	73.19	182.90	171.57	233.94	199.59	279.49
IT9	55.25	75.67	183.67	183.53	276.27	229.48	298.85
IT10	62.39	100.79	234.19	222.16	311.95	295.38	397.45

	Arrival Time of OTs (mins)						
	Arrival 1	Arrival 2	Arrival 3	Arrival 4	Arrival 5	Arrival 5	Arrival 7
OT1	72.31	79.71	250.78	176.46	189.47	187.64	290.72
OT2	73.61	94.68	251.64	190.28	197.27	205.21	298.74
OT3	85.17	102.03	263.78	202.57	207.38	207.05	347.87
OT4	93.46	104.07	275.91	264.77	292.40	228.34	376.81
OT5	100.97	122.96	275.97	275.53	302.99	228.73	314.10
OT6	104.51	136	282.84	307.50	325.09	344.88	532.50
OT7	113.55	157.84	283.49	344.48	349.43	346.94	556.21
OT8	129.03	209.16	289.89	388.87	349.58	361.05	465.95
OT9	137.07	239.35	308.47	390.70	343.15	363.03	519.41
OT10	139.55	242.95	313.59	392.77	353.47	368.47	436.52

I.4. Handling Time

Table 18 Unloading Time for Dataset A

Lay-out	Door 1	Door 2	Door 3	Door 4	Door 5	Door 6	Door 7	Door 8	Door 9	Door 10
	unloading time (mins) (30,60)									
Lay-out 1						ID 1	ID 2	ID 3	ID 4	ID 5
Lay-out 2		ID 1		ID 2			ID 3	ID 4	ID 5	
Lay-out 3	ID/O D1	ID/O D2	ID/O D3	ID/O D4	ID/O D5	ID/O D6	ID/O D7	ID/O D8	ID/O D9	ID/OD 10
IT 1	58.75	42.37	45.77	32.32	42.20	55.09	52.30	40.39	32.42	46.72
IT 2	46.17	57.31	46.70	44.92	50.22	54.43	51.36	42.01	50.53	54.11
IT 3	42.53	39.96	59.20	36.91	57.87	37.02	45.62	51.82	36.61	57.26
IT 4	47.47	42.48	36.03	55.66	35.51	37.69	41.92	46.37	50.95	57.17
IT 5	34.28	34.42	58.33	46.51	31.92	32.44	42.67	46.08	55.37	59.16
IT 6	55.67	55.95	41.27	55.66	53.73	49.02	30.47	39.78	45.30	41.78
IT 7	58.99	37.13	49.65	38.95	35.98	36.66	38.28	41.22	40.50	30.08
IT 8	34.86	31.78	35.93	42.04	41.47	39.58	46.11	40.61	37.39	55.88
IT 9	34.21	59.28	59.81	52.27	39.66	31.09	37.58	34.80	32.40	41.18
IT 10	35.72	55.69	56.96	37.16	48.30	32.80	40.44	54.39	59.66	47.02

Table 19 Loading Time for Dataset A

Lay-out	Door 1	Door 2	Door 3	Door 4	Door 5	Door 6	Door 7	Door 8	Door 9	Door 10
	Loading time (mins) (45,90)									
Lay-out 1	OD 1	OD 2	OD 3	OD 4	OD 5					
Lay-out 2	OD 1		OD 2		OD 3	OD 4				OD 5
Lay-out 3	ID/O D1	ID/O D2	ID/O D3	ID/O D4	ID/O D5	ID/O D6	ID/O D7	ID/O D8	ID/O D9	ID/O D10
OT 1	59.86	53.05	57.15	64.06	62.60	88.77	81.32	66.00	68.48	50.18
OT 2	55.43	50.55	68.50	50.99	57.86	80.60	84.07	88.14	71.55	55.73
OT 3	78.23	80.65	52.31	69.69	80.59	69.59	78.25	59.93	79.64	53.57
OT 4	55.64	89.24	81.00	55.45	80.40	85.17	79.00	85.59	72.70	75.13
OT 5	59.10	49.16	80.10	70.61	88.05	74.85	50.32	74.31	75.12	54.78
OT 6	80.25	49.86	75.95	47.48	79.87	49.69	56.10	77.61	67.80	68.33
OT 7	77.09	53.62	67.49	77.76	59.48	52.07	82.54	79.96	75.33	48.90
OT 8	47.68	57.88	47.27	59.87	57.78	79.28	70.07	52.60	72.63	58.07
OT 9	62.17	86.66	61.45	57.66	74.39	53.95	64.32	54.44	49.17	70.64
OT 10	71.23	87.39	87.22	61.48	49.18	76.74	58.22	75.93	74.43	65.54

I.5. Freight flow

Table 22 Freight Flow Matrix

Freight flow from each IT to each OT											
	OT 1	OT 2	OT 3	OT 4	OT 5	OT 6	OT 7	OT 8	OT 9	OT 10	Total
IT 1	8	12		8							28
IT 2	4	6		18							28
IT 3		10	12	2		4					28
IT 4			12		16						28
IT 5	8		4		8			8			28
IT 6	8				4	10	6				28
IT 7						6	6	6	10		28
IT 8						8	8	12			28
IT 9							8	2	10	8	28
IT 10									8	20	28
Total	28	28	28	28	28	28	28	28	28	28	280

Table 23 Binary Matrix for Freight Flow

Freight flow from each IT to each OT										
	OT 1	OT 2	OT 3	OT 4	OT 5	OT 6	OT 7	OT 8	OT 9	OT 10
IT 1	1	1		1						
IT 2	1	1		1						
IT 3		1	1	1		1				
IT 4			1		1					
IT 5	1		1		1			1		
IT 6	1				1	1	1			
IT 7						1	1	1	1	
IT 8						1	1	1		
IT 9							1	1	1	1
IT 10									1	1

Bibliography

1. Rushton, A., P. Croucher, and P. Baker, *Handbook of Logistics and Distribution Management*. 3rd ed ed. 2000.
2. Apte, U .M. a nd S . Viswanathan, *Effective Cross Docking for Improving Distribution Efficiencies.* International Jou rnal of L ogistics Research and Applications, 2000. **3**(3): p. 291-302.
3. Tempelmeier, H., *Inventory Management in Supply Networks*. 2006, Norderstedi.
4. Hugos, M., *Essentials of supply chain management*, ed. I. John Wiley & Sons. 2003.
5. Ghiani, G ., G . L aporte, a nd M . Roberto, *Introduction to Logistics Systems Planning and Control*. 2004.
6. Chopra, S. and P. Meindl, *Supply Chain Management: Strategy, Planning, and Operation*. 2002, Upper Saddle River, New Jersey: Prentice-Hall, Inc.
7. Bartholdi III , J .J. a nd S.T. H ackman, *Warehouse&Distribution Science*. 2008 : Atlanta.
8. *A study of the Toyota Production System*, in *Productivity Press*. 1989 : Shigeo Shingo. p. p187.
9. Saddle Creek, *By the numbers: Crossdocking*, in *Supply Chain and Logistics*. 2008.
10. Saxena, R., *Cross-docking demystified*, in *Industrial Engineer*. Sunday,2007
11. Howard, R . and R.D. H aas, *The Learning Imperative: Managing People for Continuous Innovation (Harvard Business Review Book)*. 1993: Harvard Business School Press.
12. Trebilcock, B., *Crossdock for productivity*, in *Modern Materials Handling*. 2006.
13. *2008 Cross-docking Trends report.* Outsourced Logistics, Aug, 2008. **1**(3).
14. Napolitano, M ., *Warehousing and Distribution Center Management: The cross-dock revolution--are you in or out?*, in *Logistics Management*. 2008.
15. Saxena, R., *Cross-docking demystified*, in *Industrial Engineer*. 2007
16. KoLman, D.A., *Cross-Docking: Logistics technique reduces costs, improves service*, in *Refrigerated Transporter* 2008.
17. Napolitano, M., *Warehouse Management: How to be a lean, mean cross-docking machine*, in *Logistics Management*. 2007.
18. Gue, K ., *Crossdocking-Just in time for distribution*. 2001 , Graduate School of Business & Public Policy, Naval Postgraduate School: Monterey.
19. Murray, M. *Cross Docking in the Warehouse*. About.com [cited.
20. *Cross Docking & Cross Dock Applications*. [cited.
21. Bartholdi III, J.J. and K.R. Gue, *The best shape for a crossdock.* Transportation Science, 2004. **38**(2): p. 235-244.
22. Gue, K.R. and K. Kang. *Staging Queues in Material Handling and Transportation Systems*. in *Winter Simulation Conference*. 2001. Arlington, VA.
23. Wang, J.-F., A. Regan, and M.-T. Tsai. *Minimizing departure time for outgoing trucks in a crossdock*. in *Transportation Research Board*. 2008. Wanshington DC.
24. Shanahan, J ., *Cross docking spruces up Urban Outfitters*, in *Logistics Management*. 2004.
25. Heragu, S.S., *Facilities Design*. second ed. 1997: PWS Publishing Company.

26. Rohrer, M. *Simulation and cross docking*. in *1995 Winter Simulation Conference*. 1995.
27. Galbreth, M.R., J.A. Hill, and S. Handley, *AN INVESTIGATION OF THE VALUE OF CROSS-DOCKING FOR SUPPLY CHAIN MANAGEMENT.* Journal of Business Logistics 2008.
28. Lee, Y.H., J.W. Jung, and K.M. Lee, *Vehicle routing scheduling for cross-docking in the supply chain.* Comput. Ind. Eng., 2006. **51**(2): p. 247-256.
29. Wen, M. , et al ., *Vehicle routing with cross-docking*, in http://neumann.hec.ca/chairedistributique/common/VRPCD.pdf. 2007.
30. Sung, C. and S. Song, *Integrated service network design for a cross-docking supply chain network.* Journal of the Opertional Research Society, 2003. **54**: p. 1283-1295.
31. Waller, M.A., C.R. Cassady, and J. Ozment, *Impact of cross-docking on inventory in a decentralized retail supply chain.* Transportation Research Part E: Logistics and Transportation Review, 2006. **42**(5): p. 359-382.
32. Reeves, K.A., *Supply Chain Governance: A Case of Cross Dock Management in the Automotive Industry.* Engineering Management, IEEE Transactions on, 2007. **54**(3): p. 455-467.
33. Ping, C., et al., *Multiple crossdocks with inventory and time windows.* Comput. Oper. Res., 2006. **33**(1): p. 43-63.
34. Donald, R.H., J.V. Vate, and M. Zhang, *Network Design for Load-driven Cross-docking Systems*. 1999, The Logistics Institute, Georgia Institute of Technology, Atlanta, GA.
35. Gumus, M. and B.J. H., *Cross-docking and its implications in location-distribution systems.* Journal Of Business Logistics, 2004. **25**(2): p. 199-228.
36. Bozer, Y.A. and H.J. Carlo, *Optimizing inbound and outbound door assignments in less-than-truckload crossdocks.* IIE Transactions, 2008. **40**(11): p. 1007-1018.
37. Bartholdi III, J.J. and K.R. Gue, *Reducing labor costs in an LTL crossdocking terminal.* Operation Research, 2000. **48**(6): p. 823-832.
38. Hauser, K. and C.H. Chuang *Genetic algorithms for layout optimization in crossdocking operations of a manufacturing plant.* International Journal of Production Research, 2006. **44**(21): p. 4663-4680.
39. Gue, K.R., *Freight terminal layout and operations*, in *Industrial and Systems Engineering*. 1995, Georgia Institute of Technology: Atlanta.
40. Gue, K., R. , *The Effects of Trailer Scheduling on the Layout of Freight Terminals.* Transportation Science, 1999. **33**(4): p. 419-428.
41. Bartholdi III, J.J., K.R. Gue, and K. Kang. *Staging Freight in a crossdock.* in *International conference on Industrial Engineering and Production Management*. 2001.
42. Sandal, S., *Staging approaches to reduce overall cost in a crossdock environment*, in *Industrial Engineering*. 2005, University of Missouri-Columbia: Columbia. p. 81.
43. Taylor, G.D. and J.S. Noble. *Determination of Staging Needs in a Crossdock Environment*. in *Annual Conference and Exhibition*. 2004.
44. Vis, I., F.A. and K.J. Roodbergen, *Short term storage of goods in cross-docking operations.* Material Handling Research, 2002: p. 441-451.

45. Masel, D. and D. Goldsmith. *Using a simulation model to evaluate the configuration of a sortation facility*. in *Winter simulation conference*. 1997.
46. Masel, D., *Adapting the longest processing time heuristic (LPT) for output station assignment in a sortation facility* in *seventh industrial engineering research conference*. 1998.
47. Baker, K., *Introduction to sequencing and scheduling*. 1974, New York: Wiley.
48. Tsui, L.Y. and C.-H. Chang, *An optimal solution to a dock door assignment problem.* Computers & Industrial Engineering, 1992. **23**(1-4): p. 283-286.
49. Aickelin, U. and A. Adewunmi, *Simulation optimization of the crossdock door assignment problem*, in *UK Operational Research Society Simulation Workshop* 2006: Leamington Spa, UK.
50. Miao, Z., A. Lim, and H. Ma, *Truck Dock Assignment Problem with Operational Time Constraint Within Crossdocks.* European Journal of Operational Research, 2006. **4031**: p. 262-271.
51. Lim, A., H. Ma, and Z. Miao, *Truck Dock Assignment Problem with Time Windows and Capacity Constraint in Transshipment Network Through Crossdocks*, in *Computational Science and Its Applications - ICCSA 2006*. 2006. p. 688-697.
52. Bermudez, R.A., *A genetic algorithm approach to LTL break-bulk terminal door assignment*. 2002, University of Arkansas.
53. Yu, W. and P.J. Egbelu, *Scheduling of inbound and outbound trucks in cross docking systems with temporary storage.* European Journal of Operational Research, 2008. **184**: p. 377–396.
54. Li, Y., A. Lim, and B. Rodrigues, *Crossdocking-JIT scheduling with time windows.* Journal of the Operational Research Society 2004. **55**: p. 1342-1351.
55. Alvarez-Perez, G., J. Gonzalez-Velarde, and J. Fowler, *Crossdocking-Just in Time scheduling: an alternative solution approach.* Journal of Operational Research Society, 2008. **I**(11).
56. Chen, F. and K.L. Song, *Cross docking logistics scheduling problem and its approximation and exact algorithms.* Industrial Engineering and Management, 2006. **6**: p. 53-58 (In Chinese).
57. Ma, D.Y. and F. Chen, *Dynamic programming algorithm on two machines cross docking schuduling.* Journal of Shanghai Jiao Tong University, 2007. **36**(6): p. 2066-2073 (In Chinese).
58. Chen, F. and C.-Y. Lee, *Minimizing the Makespan in a Two-Machine Cross-Docking Flow Shop. Problem.* European Journal of Operational Research, 2009. **193**(1): p. 59-72.
59. Pinedo, M.L., *Scheduling: theory, algorithms, and systems*, ed. thrid. 2008, Springer.
60. Song, K. and F. Chen. *Scheduling Cross Docking Logistics Optimization Problem with Multiple Inbound Vehicles and One Outbound Vehicle*. in *Automation and Logistics, 2007 IEEE International Conference on*. 2007.
61. McWilliams, D.L., P.M. Stanfield, and C.D. Geiger, *The parcel hub scheduling problem: A simulation-based solution approach.* Computers & Industrial Engineering, 2005. **49**(3): p. 393-412.
62. McWilliams, D.L., *Genetic-based scheduling to solve the parcel hub scheduling problem.* Computers & Industrial Engineering. **In Press, Corrected Proof**.

63. Wang, J.-F. and A. Regan, *Real-Time Trailer Scheduling for Crossdock Operations.* Transportation Journal, 2008. **47**(2): p. 5-20.
64. Peck, K.E., *operational analysis of freight terminals handling less than container load shipments*. 1983, University of Illinois at Urbana-Champaign.
65. Tsui, L.Y. and C.-H. Chang, *A microcomputer based decision support tool for assigning dock doors in freight yards.* Comput. Ind. Eng., 1990. **19**(1-4): p. 309-312.
66. Vis, I.F.A. and K.J. Roodbergen, *Positioning of goods in a cross-docking environment.* Computers & Industrial Engineering, 2007.
67. Boysen, N., M. Fliedner, and A. Scholl, *Scheduling inbound and outbound trucks at cross docking terminals.* OR Spectrum, 2008.
68. Chen, P., et al., *Multiple crossdocks with inventory and time windows.* Comput. Oper. Res., 2006. **33**(1): p. 43-63.
69. Cela, E., *The Quadratic Assignment Problem: Theory and Algorithms* Combinatorial Optimization. 1998: Springer. 304.
70. Golias, M., et al., *Scheduling Inbound Trucks at a Cross-Docking Facility: A Multi-objective and a Hierarchical Approach*, in *International Conference on Industrial Engineering and Systems Management* 2009: Montreal, Canada.
71. Rushton, A., P. Croucher, and P. Baker, *The handbook of logistics and distribution management*. 2006.
72. GOLIAS, M., et al., *Scheduling Inbound Trucks at a Cross-Docking Facility: A Multi-objective and a Hierarchical Approach*, in *Industrial Engineering and Systems Management*. 2009: Montreal, Canada.
73. Miao, Z., A. Lim, and H. Ma, *Truck dock assignment problem with operational time constraint within crossdocks.* European Journal of Operational Research, 2009. **192**(1): p. 105-115.
74. Golias, M.M., et al., *A multi-objective decision and analysis approach for the berth scheduling problem.* International Journal of Information Technology Project Management (Forthcoming), 2009.
75. Taboada, H., *Multi-objective optimization algorithms considering objective preferences and solution clusters.* PhD Dissertation. Rutgers University, 2007.
76. Rao, J. and P. Papalambros, *A Non-linear Programming Continuation Strategy for One Parameter Design Optimization Problems.* Proceedings of ASME Design Automation Conference, Montreal, Quebec, Canada, 1989: p. 77-89.
77. Chankong, V. and Y. Haimes, *Multi-objective decision making theory and methodology*. North-Holland Amsterdam, 1983.
78. Simaan, M. and J. Cruz, *On the Stackelberg strategy in non-zero-sum games.* Journal of optimization theory and applications, 1973. **11**: p. 533-555.
79. Galperin, E.A., *Pareto analysis vis-à-vis balance space approach in multi-objective global optimization.* Journal of optimization theory and applications, 1997. **93**(3): p. 533-545.
80. Golias, M., *The discrete and continuous berth allocation problem: Models and algorithms.* Ph.D. Dissertation. Rutgers University, 2007.
81. Coello, C.A.C. and N. Laboratorio, *Treating Constraints As Objectives For Single-Objective Evolutionary optimization.* Engineering Optimization, 1999. **32**(3): p. 275-308.

82. Nedjah, N. and L.D.M. Mourelle, *Real-world multi-objective system engineering*. 2005 Nova Publishers.
83. Taboada, H. and D. Coit, *Multi-objective scheduling problems: Determination of pruned Pareto sets*. IIE TRANSACTIONS, 2008. **40**(5): p. 552-564.