AN INTEGRATED MODEL OF CROSS DOCKING

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

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An Integrated Model of Cross docking

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ABSTRACT

Cross docking is a relatively new logistics technique used in the retail and trucking industries with operations seeking to move materials from inbound locations to outbound locations as quickly as possible. As the high-speed warehouse, short-term staging can still be used to consolidate shipments from disparate sources and realize economies of scale in outbound transportation. In this research, the layout design, short term staging strategy and shipping trailer assignment issues are integrated with the objective of increasing shipping trailer utilization while still satisfying the time-efficiency requirement of the cross docking facility. The problem is modeled as a non-linear mixed integer programming model. Small-scale problems are solved using Lingo 8.0. The tabu search meta-heuristic is also applied in order to solve large-scale problems.

TABLE OF CONTENTS

List of Figures

List of Tables

Chapter 1 Introduction

1.1 Cross docking

A traditional warehouse has four major functions – receiving, storage, order picking and shipping. Among the four major functions, storage and order picking are the most costly: storage because of inventory holding costs, and order picking because it is labor intensive.

Cross docking, as a relatively new logistics technique that was first used by Wal-Mart, is widely applied in the retail and trucking industries to rapidly consolidate shipments from disparate sources and realize economies of scale in outbound transportation. Cross docking essentially eliminates the storage function of a warehouse while still allowing it to serve its consolidation and shipping functions. The idea is to transfer incoming shipments directly to outgoing trailers without storing them in between. Based on this, shipments typically spend less than 24 hours at the facility, sometimes less than an hour.

Cross docks are essentially transshipment facilities to which trucks arrive with goods that must be sorted, consolidated with other products and loaded onto outbound trucks. Outbound trucks may be loaded for a manufacturing site, a retail outlet, or another cross dock, depending on the application.

In a warehouse, goods are received from vendors and stored in devices like pallet racks or shelving. When a customer requests an item, workers pick it from the shelves and send it to the destination. In a cross dock, goods arriving from the vendor already have a customer assigned, so workers need only move the shipment from the inbound trailer to an outbound trailer bound for the appropriate destination.

The term “cross docking” can be used to describe a range of different types of operations, Napolitano (2000) proposes the following classifications scheme:

Manufacturing cross docking – receiving and consolidating inbound supplies to support Just-In-Time manufacturing. For example, a manufacturer might lease a warehouse close to its plant, and use it to consolidate kits of parts. Since demand for the parts is known, there is no need to maintain stock.

Distributor cross docking – consolidating inbound products from different vendors into a multi-SKU pallet, which is delivered as soon as the last product is received. For example, computer distributors often source components from different manufacturers and consolidate them into one shipment in merge-in-transit centers, before delivering them to the customer.

Transportation cross docking – consolidating shipments from different shippers in the Less-than-truckload (LTL) and small package industries to gain economics of scale. For small package carriers, material movement in the cross dock is by a network of conveyors and sorters; for LTL carriers it is mostly by manual handling and forklifts.

Retail cross docking – receiving product from multiple vendors and sorting onto outbound trucks for different stores. Cross docking has been cited as a major reason Wal-Mart surpassed Kmart in retail sales in the 1980's (Stalk et al., 1992).

Opportunistic cross docking – in any warehouse, transferring an item directly from the receiving dock to the shipping dock to meet a known demand.

Another way to classify cross docking operations is according to when the customer is assigned to an individual pallet or product. In pre-distribution, the customer is assigned before the shipment leaves the vendor, so it arrives to the cross dock bagged and tagged for transfer. In post-distribution cross docking, the cross dock itself allocates material to its stores.

The end product of a cross dock operation is a loaded container bound to its intermediary or terminal destination. Thus the cost of the overall logistics operation can be reduced if the space in the outbound trailer is utilized to its maximum.

1.2 Motivation

The initial motivation for this study is provided by the issues and ideas related to staging strategies raised by Taylor and Noble (2004). They suggested that staging needs can vary depending on different staging methods and the scenarios considering different factors (demand type in their case).

Shipments in the trucking industry are classified into two major categories: Less-than-Truck-Load (LTL<10000 pounds) and Truck-Load (TL>10000 pounds). It has been observed that the average LTL container utilization is less than 50%. Low container utilization means that each container is carrying fewer loads which translate into a greater number of trips. In order to reduce the logistics costs, companies are increasingly moving towards consolidation which is a way to increase the container utilization. Looking at the three major components of the cross dock operation: inbound, staging, and outbound, it is the staging and outbound operations that have the most impact on the overall profit of an operation, and it is an ideal way to achieve the goal of higher cube utilization.

Iris and Kees (2004) focus on a process of short-term storage which can be interpreted as the staging of unit-loads in a cross docking environment to determine temporary storage locations. In their work, it can be noticed that the layout of the cross dock is assumed to be known before using the model to determine the short term storage locations. This provides a potential research field to explore since the layout and staging locations might be affected by each other and both layout design and short-term storage location problems can be integrated.

Taylor and Noble's research (2004) is continued by Sandal (2006) who examined specific staging strategies and their impact on overall system performance. In this work, staging plays a role to increase the shipping trailer utilization; the results show that a simultaneous loading scenario with a zoned strategy results in high container volume utilization (90%).

It is known that the objective in cross docking operations is to move materials from inbound locations to outbound locations as soon as possible. When staging is used as a tool to increase shipping trailer utilization, cargo stays for a longer time compared to direct loading without staging. Therefore, it is possible that staging can help to increase container utilization while at the same time cause tardiness, which is not desired. Based on Sandal's work (2006), an additional factor – Time is considered.

The rest of this thesis is organized as follows. Chapter 2 reviews the literature in the area of cross docking applications in logistics and manufacturing systems, dock door assignment problems, staging operations, and scheduling problems of cross docking. Chapter 3 presents two mathematical models built during this research. Chapter 4 presents two approaches we used for solving our model: LINGO model and Tabu search program. And chapter 5 presents a summary of this research and future research directions.

Chapter 2 Literature Review

Cross docking, as a dynamic Just-In-Time distribution center, has been widely applied in both logistics and manufacturing systems. The current literature on cross docking can be classified into three major areas: layout design or the door assignment problem, staging location assignment, and scheduling.

2.1 Cross docking

2.1.1 Cross docking in logistics systems

Cross docking is a warehousing strategy that involves movement of material directly from the receiving dock to the shipping dock with a minimum dwell time in between. Uday and Viswanathan (2000) provide a framework for understanding and designing cross docking systems and discuss techniques that can improve the overall efficiency of the logistics and distribution operation. The cross dock is essentially similar to a mixed warehouse that combines unloading and consolidation. The difference between a traditional warehouse and a cross dock is that in the cross dock cargo stays only for a short time. Full Truck Load shipments are used whenever possible to achieve the objective of minimizing the transportation costs and simultaneously minimizing the inventory holding cost. Cross docking can also reduce the cycle time. As a material handling system, cross docking is also an information handling system -- the operations in a cross docking heavily depends on the information technology which can coordinate the physical product flow and information flow. Physical product flows can be improved through proper selection of layout design, manpower and equipment. Information flows can be improved by technologies such as EDI, SCM, bar-coding with UPC and bar code readers. Cross docking can be ideally implemented for products with stable and constant rate and low unit stock-out cost.

The operations in a cross dock facility mainly include:

- Assigning receiving trucks to receiving docks
- Unloading the receiving trailers
- Delivering cargo to the shipping trailer directly or placing them on the staging area to be loaded later

Magableh, Rossetti and Mason (2005) developed a simulation model of a generic cross docking facility, which provides a good understanding of cross docking operations. This model incorporates five aspects including resource contention for dock doors, flexible assignment of loads to inbound and outbound doors, worker resource requirements, material handling contention and outbound load building. The cross docking procedure starts from the entering of Less Than Truck Loads (LTLs), once an LTL enters the cross dock, it will be placed in a queue waiting for a free dock. When a door in the cross docking becomes available, the yard driver is assigned to bring the LTL to the specific door, then a worker in the cross dock is assigned the task of unloading the trailer. The unloaded goods are either directly delivered to an outbound trailer or placed on the staging area to be loaded later. When there are enough goods in the staging area to fill a truckload to a specific destination, the yard driver is assigned to bring an empty trailer to the specific dock doors. However, sometimes the number of purchase orders does not form a Truck Load (TL), these PO will wait for more POs to arrive or they will be directly delivered to destinations if threshold of waiting time has come.

2.1.2 Cross docking in manufacturing systems:

Though cross docking is well known as a distribution center application in a logistics network, the same idea can also be applied in a manufacturing environment. Kondo, Tamai and Vining (2004) propose an cross docking application in a manufacturing system: in a manufacturing environment, in the case that plants receive supplies directly from suppliers, suppliers may need to make a stopover to more than one assembly line, and each stopover can add cost. Therefore, in order to reduce cost, the number of stopovers of each supplier should be reduced. Warehouse and cross dock or a similar type of facility are used instead of delivering directly from suppliers to assembly plant. Staging at assembly plants is also costly to a manufacturer. So moving the staging from assembly plants to facility can also reduce the cost. Cross dock and staging are combined in one facility super-cross-dock. Supplies from multiple suppliers are stored in this facility for less than one day for distribution to the assembly plants. Hauser and Chung (2003) also compare an actual layout of a cross docking operation at a major automotive JIT manufacturing plant with a newly designed layout. It is mentioned that, in a ideal JIT situation, the suppliers would deliver the needed parts directly to the workstation at the assembly line in the exact quantity at the exact time and in the sequence needed. In this ideal case, the inventory level at and between all workstations would be zero. In reality, only a few parts are delivered directly in sequence to the assembly line, thus different intermediate storage solutions have been developed: flow racks or floor staging areas, internal sequencing areas and lane storage/cross docking area. In the lane storage area the incoming parts are sorted by line and are immediately delivered to the line. This sorting process is called cross docking.

2.2 Layout and Dock door assignment problem

Bartholdi and Gue (2004) discuss in detail the best shape of a cross dock. They found that as size increases, the most labor-efficient shapes for a cross dock are I, T and X shapes. Based on experimental results, the best shape for small and mid-sized (less than 150 doors) cross docks is a narrow rectangle or I-shape. For larger docks (150-

200 doors), a T-shape is more attractive. For docks larger than 200 doors, the X-shape is the best.

Handling freight in a cross docking terminal is labor intensive and therefore costly because workers must unload, sort, and transfer a wide variety of freight from incoming to outgoing trailers. The efficiency of workers depends in large part on how trailers are assigned to doors around the dock; that is, on its layout. A good layout design reduces travel distances without creating congestion.

In an early work on the dock door assignment problem, Tusi and Chang (1992) propose a binary integer programming model with the objective of minimizing the weighted distance between incoming and outgoing trailers. While Bartholdi and Gue (2000) propose some other measures of performance, they mention that minimizing weighted door-to-door distances can exacerbate congestion. As more activity is squeezed into a smaller area of the dock delays will occur. (For example, forklifts interfere with each other.) Congestion on the dock leads to excessive labor cost and can result in shipments missing service commitments. Distinctive features of their layout models include:

- Models of the standard types of material handling systems in LTL terminals;
- Models of several types of congestion to which a dock is susceptible;
- Explicit effort to minimize the total labor costs, accounting for both travel and

congestion cost.

Also, Bartz-Beielatein, et al. (2006) also consider another measure -- waiting time for trucks between arrival at the terminal and being assigned to a gate besides the transportation volume inside of cross docking terminals. Trucks should be allocated to a gate as soon as possible after their arrival at the terminal. Each truck has an individual time table indicating the earliest arrival time and the latest departure time from the terminal. The planner has to reserve a time slot within this period of time that is long enough for discharging and charging the booked number of load units. If a truck is not allocated right after its arrival, the driver has to wait in a parking zone until he gets further information. Therefore, minimizing waiting times leads to less crowded yards. In addition, trucks should be charged and discharged as soon as possible to reserve dock gates for time critical or very late trucks.

Though several different mathematical models have been built based on different measures of performance, we notice that their objective functions are nonlinear, which precludes the use of established integer programming methods. For this reason, meta-heuristics are widely applied to the dock door assignment problem. Bartholdi and Gue (2000) construct an effective cross docking layout by a simulated annealing procedure. Bermudez and Cole (2001) present a genetic algorithm for assigning doors in LTL break-bulk terminals to minimize the total weighted travel distance, a surrogate for labor cost and cycle time. Also, Hauser and Chung (2006) propose a genetic algorithm to optimize the lane layout associated with the cross docking operation at an automotive manufacturing plant.

2.3 Staging operations

Though cross docking is desired to be a high speed warehouse without a long-term storage function, there are still some times where short-term storage is required. This is also known as staging operations inside the cross docking facility. Staging operations are critical for sorting and consolidation processes. Gue and Keebom (2001) discuss in detail the staging queues in material handling and transportation systems: in most physical queuing applications, customers join a queue and move forward after each service, leaving room for others to join behind them. However, some queues found in material handling and transportation systems do not operate like this because the queued entities are incapable of moving forward autonomously. The results of their model suggests that for systems of parallel staging queues, it is better to have more short queues than fewer long ones. For a single stage system, the firm can stage by the receiving door or stage by the shipping door. The advantage to staging by receiving is that the destination needs not to be known when the worker unloads the freight from the trailer. This relieves the vendor of the burden of labeling pallets before shipping them. The advantage of staging by shipping is that workers in shipping have a better view of what freight is available for loading, and so can achieve a tighter pack of freight while loading, thus reducing transportation costs in the long run. A two-stage system achieves both advantages, but the results illustrate that a two-stage staging system has significantly lower throughput than a single-stage system when entities block between stages. Therefore, it was concluded that a single stage system would be a better choice for a cross dock if the necessary information links have been established rather than a two-stage cross docking systems, though a two stage cross docking system has some important operational advantages.

Iris and Kees (2004) discuss the process of short-term storage of unit-loads in a cross-docking environment. The goal of their research is to determine temporary storage locations for incoming unit loads such that the travel distances of the forklift trucks are minimized. They model this problem as a minimum cost flow problem and correlate the traveling path of material handling equipment with storage locations using the idea of "shortest and extra distance". The shortest distance, as named, is the shortest distance between one receiving door and one shipping door. Extra distance is interpreted as the cost required to store the unit load. If the storage location is on the shortest path the cost is zero, if not, and an extra distance has to be traveled. Taylor and Noble (2004) used simulation examine three material staging alternatives in various cross docking environments, mainly looking at layout method (door assignment), outbound demand scenario, and staging method (flow rack, single queue and double queue). One unique aspect of their research is the concept of a common overflow queue when the outbound queues fill, which is similar to the two stage queue used by Gue and Kang (2001) but it is centrally located near the inbound doors in the center of the facility. Based on their simulation results, they conclude that demand type is more important than either the facility layout in terms of inbound and outbound assignments, or the type of staging made available, and layout only matters for make-span determination.

2.4 Scheduling

Another interesting area of cross dock research is scheduling. Ting, Chen and Weng (2004) focus on the vehicle schedule coordination problem. It is mentioned that a reduction in overall service levels can result if the cross dock timing is not matched. Therefore, integrated vehicle scheduling is very important for a cross-docking system. The inbound and outbound vehicle schedules that meet at the cross dock is optimized in their study. They consider three different schedule strategies: uncoordinated strategy, coordinated operation with common headway strategy and coordinated operation with integer ratio headway strategy. Their tests results illustrate that both coordinated operation strategy results in a decrease in the total system cost and the integer ratio headway strategy yields the lowest total cost. Also, at low inventory carrying cost the uncoordinated operation strategy yields the lowest total system cost. When inventory carrying cost increases the integer ratio headway strategy performs the best, which indicates that cross docking is a better way for high value products.

2.5 Summary

The current literature on cross-docking can be classified into three major areas: layout design or the door assignment problem, staging location assignment, and scheduling. Even though these three areas of research are full of opportunities to be explored separately, there is no literature published that address all three from an integrated perspective.

Chapter 3 Modeling

As mentioned in chapter 1, staging operations can be used to increase shipping trailer utilization. Cargo stays in the cross docking facility for a period of time to wait for later cargo so that it can be shipped out in one shipping trailer. However, longer staging time also means less time-efficiency, the objective of the proposed model is to increase shipping trailer utilization while still satisfying the time-efficiency requirement of the cross docking facility.

The problem is formulated as a nonlinear mixed integer problem, it involves continuous and binary variables, and the objective function is nonlinear.

3.1 Problem Description

The model is based on a common cross docking layout. Figure 3.1 is a layout example.

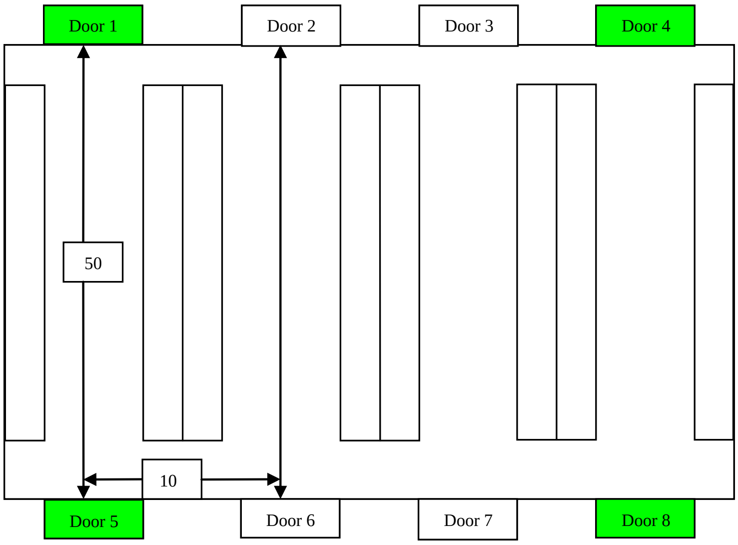


Figure 3.1 Cross dock layout example

Doors 2, 3, 6, 7 are receiving doors and Doors 1, 4, 5, 8 are shipping doors. The inside blocks represent several storage lanes for short-term staging.

Each receiving door is assigned an origin. The receiving trailer from that origin is unloaded in the assigned receiving door. Similarly, each shipping door is assigned to a destination. The shipping trailer assigned to that specific destination is loaded with cargo from different receiving trailers.

Many times, shipments from different vendors to a specific retail outlet are not large enough to justify a FTL shipment. In such a situation, the shipments from different vendors can be sent through a cross docking warehouse to take advantage of consolidation. Figure 3.2 illustrates such a scenario where both retailer 1 and 2 place an order for three different products: A, B and C. All three vendors ship two orders for retailers 1 and 2 together to a cross docking center. In the cross docking center, three receiving trailers are unloaded and three kinds of products are consolidated and shipped out to different retailers.

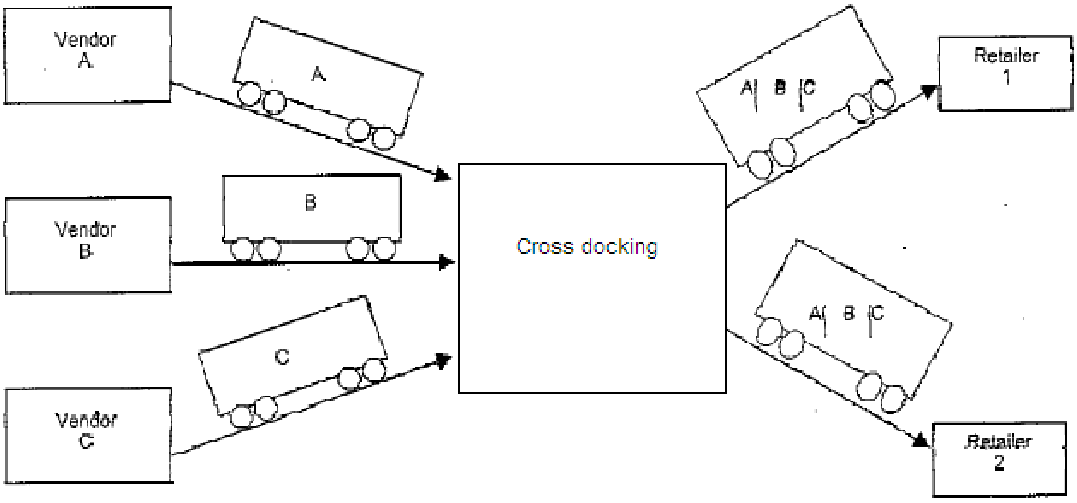


Figure 3.2 Cross docking operations

3.2 Problem Notation

The following notation is used to model the problem:

1). Decision variables:

X_{im} : = 1 if the incoming trailer *i* is assigned to receiving door *m*,

= 0 otherwise

Y_{jn} : = 1 if destination *j* is assigned to shipping door *n*

= 0 otherwise

Z_{ijk} : = 1 if cargo from origin *i* to destination *j* are stored in storage lane *k*

= 0 otherwise

U_{ijh} : = 1 if cargo from *i* to destination *j* are shipped out in the trailer *h* in destination *j*

= 0 otherwise

D_{jh} : departure time of the trailer *h* to destination *j*

2). Parameters:

d_{mn} : shortest distance between of dock doors *m* and *n*

q_{ij} : quantity of cargo need delivered from incoming trailer *i* to destination *j*

v_{ij} : volume of cargo from origin i to destination j

q_k : capacity of each storage lane *k*

y_{kmn} : extra distance the cargo travel from door *m* to door n will travel if it is stored or travel in the storage lane *k*

a_{ij} : arrival time of cargos from origin *i* to destination *j*

t_{ij} : length of interval time cargo from origin *i* to destination *j* can stays in the cross dock

s_{jh} : container size of the trailer *h* for destination *j*

e_{jh} : container weight limit of trailer *h* for destination *j*

r_{jh} : revenue generated by trailer *h* for destination *j* per mile

n_j : average number of miles per trip

c: cost to move cargo per foot

c_t : time related cost of unit item staying in the facility per time unit

M: a large integer

The five sets of decision variables included in this model, X_{im}, Y_{jn}, Z_{ijk}, U_{ijh} are all binary variables and D_{jh} is a set of continuous variables.

The shortest distance between any pair of dock doors is represented to d_{mn}. For example, as shown in Figure 3.1 the shortest distance from door 1 to door 6 is 60 = 50

+ 10. Also in figure 3.1, there are 4 storage lanes; each lane has the storage capacity q_k which is defined as the number of unit loads in this model.

y_{kmn} is the extra distance cargo travels from door *m* to door *n* if it is stored or travels in storage lane *k*. In figure 3.1, if cargo from door 1 to door 6 are stored in storage lane 3, then the total travel distance is 80, while the shortest distance between door 1 and 6 is 60, so this extra distance is 20 = 80 – 60.

3.3 Problem Formulation

Model:

Maximize

$$\sum_j \sum_h \left(\frac{(\sum_i q_{ij} v_{ij} U_{ijh})^2}{(s_{jh})^2} r_{jh} n_j \right) - c \sum_i \sum_j \sum_m \sum_n q_{ij} X_{im} Y_{jn} (d_{mn} + \sum_k y_{kmn} Z_{ijk})$$
$$- c_t \sum_i \sum_j (q_{ij} (\sum_h D_{jh} U_{ijh}) - a_{ij})$$

S.T. $\sum_m X_{im} = 1$ (1)

$$\sum_n Y_{jn} = 1 \quad (2)$$

$$\sum_i X_{im} = 1 \quad (3)$$

$$\sum_j Y_{jn} = 1 \quad (4)$$

$$\sum_i \sum_j q_{ij} Z_{ijk} \leq q_k \quad (5)$$

$$a_{ij} + t_{ij} - \sum_h D_{jh} U_{ijh} \geq 0 \quad (6)$$

$$a_{ij} \cdot U_{ijh} \leq D_{jh} \quad (7)$$

$$\sum_i q_{ij} v_{ij} U_{ijh} \leq s_{jh} \quad (8)$$

$$\sum_i q_{ij} w_{ij} U_{ijh} \leq e_{jh} \quad (9)$$

$$\frac{\sum_h (D_{jh} U_{ijh} - a_{ij})}{M} \leq \sum_k Z_{ijk} \quad (10)$$

$$\sum_h (D_{jh} U_{ijh} - a_{ij}) \geq 0 \quad (11)$$

$$\sum_k Z_{ijk} \leq 1 \quad (12)$$

$$\sum_h U_{ijh} = 1 \quad (13)$$

$$X_{im}, Y_{jn}, U_{ijh}, Z_{ijk} \in (0,1) \quad (14)$$

3.3.1 Objective Function:

The first part in the objective function $\sum_j \sum_h (\frac{(\sum_i q_{ij} v_{ij} X_{ijh})^2}{(s_{jh})^2} r_{jh} n_j)$ is the revenue relating to trailer utilization.

The revenue is positively correlated to trailer utilization; higher utilization will generate higher revenue. Consider the following example of how the revenue is calculated:

- Revenue per mile made by full truck load = $1.5/mile

  Two batches of cargo need to be shipped out, each with the quantity of 4

  Trailer capacity is 10

  Shipping truck travel distance is 500

In the first case, if two batches are shipped out in two trucks, the revenue is

1.5*0.4*0.4*500 + 1.5*0.4*0.4*500=240

In the second case, if the two batches of cargo are shipped out in just one truck, the revenue is 1.5*0.8*0.8*500=480.

So, as the utilization of the trailer increases, the revenue increases.

The second and third part is the cargo staging related cost.

$c \cdot \sum q_{ij} X_{im} Y_{jn} (d_{mn} + y_{kmn} Z_{ijk})$ is the distance related cost, a different storage location may cause different travel distance. $(d_{mn} + y_{kmn} Z_{ijk})$ represents the traveling distance which is the shortest distance between one pair of receiving and shipping doors plus the extra distance if the cargo is stored in a specific storage lane.

$c_t \sum_i \sum_j q_{ij} (\sum_h D_{jh} U_{ijh} - a_{ij})$ is the time related penalty cost, more staging time results in increased cost.

Therefore, the objective seeks to use a staging process to maximize the cube utilization, while minimizing the staging time if possible.

3.3.2 Constraints

Constraint (1) $\sum_m X_{im} = 1$ ensures that each origin trailer *i* is assigned to only one receiving door *m*.

Constraint (2) $\sum_n Y_{jn} = 1$ ensures that each destination trailer *j* is assigned to only one outgoing door *n*.

Constraint (3) $\sum_i X_{im} = 1$ ensures that each receiving door *m* is assigned to only one origin *i*.

Constraint (4) $\sum_j Y_{jn} = 1$ ensures that each outgoing door *n* is assigned to only one destination *j*.

Constraint (5) $\sum_i \sum_j q_{ij} Z_{ijk} \le q_k$ enforces the storage capacity q_k of each storage row *k* in the cross dock. Since the storage lane assignment to each transshipping cargo will affect the moving distance inside the cross dock, the storage lane on the shortest path is the best choice. It is possible the storage lane on the shortest path is already assigned, then cargos will be assigned to nearby storage lanes with the least extra travel distance.

Constraints (6), (7), (8) and (9)

$$a_{ij} + t_{ij} - \sum_h D_{jh} U_{ijh} \geq 0 \qquad (6)$$

$$a_{ij} \cdot U_{ijh} \leq D_{jh} \qquad (7)$$

$$\sum_i q_{ij} v_{ij} U_{ijh} \leq s_{jh} \qquad (8)$$

$$\sum_i q_{ij} w_{ij} U_{ijh} \leq e_{jh} \qquad (9)$$

These four constraints are used to determine which outgoing trailer the cargo is shipped out to destination *j*. With the objective of minimizing the time penalty cost, these four constraints also determine the departure time.

Constraint (6) $a_{ij} + t_{ij} - \sum_h D_{jh} U_{ijh} \geq 0$ determines the latest departure time of cargo from origin *i* to destination *j* and prevents tardiness.

Constraint (7) $a_{ij} \cdot U_{ijh} \leq D_{jh}$ enforces that the departure time of cargo from origin *i* to destination *j* is later than its arrival time.

Constraint (8) $\sum_i q_{ij} v_{ij} U_{ijh} \leq s_{jh}$ ensures that cargo loaded to trailer *h* to destination *j* does not exceed the trailer's space limit.

Constraint (9) $\sum_i q_{ij} w_{ij} U_{ijh} \leq e_{jh}$ ensures that cargo loaded to trailer *h* to destination *j* does not exceed the trailer's weight limit.

Here is a simple example illustrating how constraints (6), (7), (8) and (9) work:

One part of a cross dock is considered. Dock door 4 is a shipping door, which has 3 incoming receiving doors 1, 2 and 3.

Figure 3.3 illustrate the problem and Table 3.1 provides the related data:

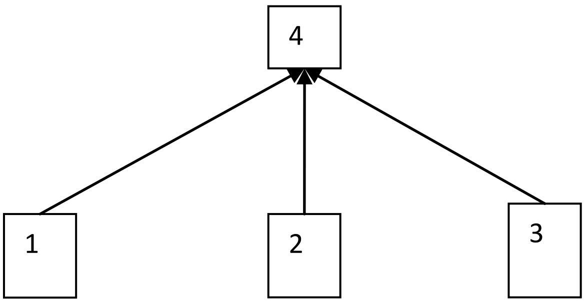


Figure 3.3 A small problem with 4 doors, Door 1,2, and 3 are incoming doors, Door 4 are an outgoing door

Table 3.1 Sample data for a 4 doors problem

	D1 to D4	D2 to d4	D3 to D4
Quantity	3	4	3
Cargo Size	24	36	48
Available Time	2	2	2
Arrival Time	4	8	5

Notation: ***D1: Door 1***

From constraint (6), we obtain:

$$\left.\begin{array}{l} D_{41} \le 4+2=6 \\ D_{41} \le 8+2=10 \\ D_{41} \le 5+2=7 \end{array}\right\} \Rightarrow D_{41} \le 6$$

Constraint (7) determines the possible value of U_{ijh}

From constraint (7): $\left.\begin{array}{l} a_{14} \cdot U_{141} \le D_{41} \\ a_{24} \cdot U_{241} \le D_{41} \\ a_{34} \cdot U_{341} \le D_{41} \end{array}\right\} \Rightarrow \left.\begin{array}{l} 4 \cdot U_{141} \le D_{41} \\ 8 \cdot U_{241} \le D_{41} \\ 5 \cdot U_{341} \le D_{41} \end{array}\right\}$

With $D_{41} \le 6$

$$\Rightarrow \begin{cases} U_{141} = 0 or 1 \\ U_{241} = 0 \\ U_{341} = 0 or 1 \end{cases}$$

Since it is a max problem, we can set $\begin{cases} U_{141} = 1 \\ U_{241} = 0 \\ U_{341} = 1 \end{cases}$ in the size and weight constraints.

If the size and weight constraints are satisfied, the results are:

> Cargo from incoming trailer 1 and 3 should be shipped out in the 1st outgoing trailer to destination 4.

If the size and weight constraints cannot be satisfied:

> The total volume of cargo from incoming trailer 1 and trailer 3 is 216 the volume capacity of the outgoing trailer in shipping door 4 is 200.
>
> Therefore, cargo from trailer 1 and 3 cannot be shipped out in a same outgoing trailer, since the objective of the model is to maximize the trailer cube utilization, the model will force cargo from receiving trailer 3 to be shipped out in the first outgoing trailer as it has a larger volume, which will cause the cargo from trailer 1 to be tardy.

In order to prevent tardiness, constraint (6) is included in this model. If cargo from trailer 3 is shipped out in the first outgoing trailer, constraint (10) is not satisfied. Cargo from trailer 1 would be the better choice.

With the objective of minimizing the time penalty cost $c_t \sum_i \sum_j q_{ij} (\sum_h D_{jh} U_{ijh} - a_{ij})$, the departure time is determined. The additional staging time within the available time slot cannot increase the cube utilization, i.e. there is not an incoming trailer with the same destination between the current time and the end of available time slot, that point of time should be the departure time.

In addition, if staging during the whole available time slot does not increase the cube utilization for the same reason explained above, then $\sum_h D_{jh} U_{ijh} - a_{ij}$ will be 0. This determines whether staging is needed or not. It is assumed that material handling time is included in the arrival time a_{ij}.

Determining whether staging is needed is very important in this model, if staging is not needed, the time related penalty cost, $c_t \sum_i \sum_j q_{ij} (\sum_h D_{jh} U_{ijh} - a_{ij})$ is 0, and since no storage location is needed, the items can travel directly through the shortest path from their origin to destination door.

Constraints (10), (11) and (12)

$$\frac{\sum_h (D_{jh} U_{ijh} - a_{ij})}{M} \le \sum_k Z_{ijk} \tag{10}$$

$$\sum_h (D_{jh} U_{ijh} - a_{ij}) \ge 0 \tag{11}$$

$$\sum_k Z_{ijk} \le 1 \tag{12}$$

determine whether staging is needed or not. $\sum_h (D_{jh} U_{ijh} - a_{ij})$ in constraint (10) is the staging time spent in the facility.

If $\sum_h (D_{jh} U_{ijh} - a_{ij}) > 0$, then $\frac{\sum_h (D_{jh} U_{ijh} - a_{ij})}{M} < 1$.

Since $\sum_k Z_{ijk} \le 1$ (12), from constraint (10) we can get $\sum_k Z_{ijk} = 1$, which means cargo from *i* to *j* is stored in only one of the storage lanes.

If $\sum_h (D_{jh}U_{ijh} - a_{ij}) = 0$, then $\frac{\sum_h (D_{jh}U_{ijh} - a_{ij})}{M} = 0$.

Since $\sum_k Z_{ijk} \leq 1$, from constraint (10) we get $\sum_k Z_{ijk} = 1$ or 0. Since the objective seeks to minimize the staging cost, the model will force $\sum_k Z_{ijk} = 0$, which means that no staging process will be included.

Constraint (13) $\sum_h Z_{ijh} = 1$ ensures that cargo from origin *i* to destination *j* will be shipped out in an outgoing trailer to destination *j*.

3.4 A model with predetermine shipment times

Considering the fact that there exist two transshipment scenarios in cross-docking operations:

Scenario 1: Transshipment cargo has a flexible schedule, without losing the time efficiency of cross-docking; each cargo is assigned a time window. Within this time window, cargo can be staged shortly waiting for later arriving cargo so they can be shipped out in a same outgoing truck. This scenario is modeled and described in section 3.3.

Scenario 2: All transshipment cargo has a fixed and strict schedule, their arrival and departure times are determined beforehand within the overall logistics systems. Since the schedule is not flexible, we cannot use the time window of each cargo to help to consolidate cargo as we do in scenario 1. Therefore, in this case, in order to reduce costs, we focus on material handling equipment traveling distance in the facility considering the door assignment and staging location assignment. The model shown below is based on this scenario, for convenience we name this model Model 2, and we call the model described in section 3.3 Model 1.

Model 2:

Minimize

$$c\sum_i\sum_j\sum_m\sum_n q_{ij}X_{im}Y_{jn}(d_{mn}+\sum_k y_{kmn}Z_{ijk})$$

S.T. $\sum_m X_{im}=1$ (1)

$\sum_n Y_{jn}=1$ (2)

$\sum_i X_{im}=1$ (3)

$\sum_j Y_{jn}=1$ (4)

$\sum_i\sum_j q_{ij}Z_{ijk}\le q_k$ (5)

$\sum_k Z_{ijk}=1$ (6)

$X_{im}, Y_{jn}, Z_{ijk}\in(0,1)$ (7)

The following notation is used in Model 2:

1). Decision variables:

X_{im} : = 1 if the incoming trailer *i* is assigned to receiving door *m*,

= 0 otherwise

Y_{jn} : = 1 if destination *j* is assigned to shipping door *n*

= 0 otherwise

Z_{ijk} : = 1 if cargo from origin *i* to destination *j* are stored in storage lane *k*

= 0 otherwise

2). Parameters:

d_{mn}: shortest distance between of dock doors *m* and *n*

q_{ij}: quantity of cargo need delivered from incoming trailer *i* to destination *j*

q_k: capacity of each storage lane *k*

y_{kmn}: extra distance the cargo travel from door *m* to door n will travel if it is stored or travel in the storage lane *k*

c: cost to move cargo per foot

Model 2 is a simplified model based on Model 1. The objective of this model is to minimize the traveling cost inside the cross-docking facility considering door assignment and staging location assignment, while the time factor is excluded.

Objective Function:

$c \cdot \sum q_{ij} X_{im} Y_{jn} (d_{mn} + y_{kmn} Z_{ijk})$ is the distance related cost, a different storage location may cause different travel distance. $(d_{mn} + y_{kmn} Z_{ijk})$ represents the traveling distance which is the shortest distance between one pair of receiving and shipping doors plus the extra distance if the cargo is stored in a specific storage lane.

Constraints:

Constraint (1) $\sum_m X_{im} = 1$ ensures that each origin trailer *i* is assigned to only one receiving door *m*.

Constraint (2) $\sum_n Y_{jn} = 1$ ensures that each destination trailer *j* is assigned to only one outgoing door *n*.

Constraint (3) $\sum_i X_{im} = 1$ ensures that each receiving door *m* is assigned to only one origin i.

Constraint (4) $\sum_j Y_{jn} = 1$ ensures that each outgoing door n is assigned to only to only one destination j.

Constraint (5) $\sum_i \sum_j q_{ij} Z_{ijk} \le q_k$ enforces the storage capacity q_k of each storage row k in the cross docking. Since the storage lane assignment to each transshipping cargo will affect the moving distance inside the cross dock, the storage lane on the shortest path is the best choice. It is possible the storage lane on the shortest path is already full, and then cargo will be assigned to nearby storage lanes with enough space and the least extra travel distance.

Constraint (6) $\sum_k Z_{ijk} = 1$ ensures that cargo from i to j is stored in one and only one storage lane k.

Chapter 4 Methodology

Two approaches are adopted in this research. For small scale problems, LINGO was used to obtain the optimal solution. However, as the size of problems increases the computation time for LINGO increases exponentially. In order to tackle larger problems, a Tabu Search heuristics algorithm program was developed based on a JAVA tabu search framework OpenTS.

4.1 Optimal solution approach

In order to explore the models we mentioned in Chapter 3, optimal solution were obtained for small scale cross docking problems with 8 doors or less. LINGO was selected to achieve this purpose. LINGO allows a user to quickly input a model formulation, solve it, assess the correctness or appropriateness of the formulation based on the solution, quickly make minor modifications to the formulation, and repeat the process.

The most powerful feature of LINGO is its ability to model large systems. The key concept that provides this power is the idea of a set of similar objects. When we are modeling situations in real life, there will typically be one or more groups of similar objects. LINGO allows you to group similar objects together into sets. Once the objects in the model are grouped into sets, you can make single statements in LINGO that apply to all members of a set.

LINGO models of a large system will typically have three sections: 1) SETS, 2) DATA, and 3) Model equations.

4.1.1 The SETS section

The SETS section describes the data structures used for solving problems. These defined sets have two types: primitive sets and derived sets. A primitive set is a set composed only of objects that can’t be further reduced. They include several groups of similar objects such as Origins, Destinations, Receiving Doors, Shipping Doors, etc. A derived set is some product defined from one or more other sets. The key concept is that a derived set derives its members from other pre-existing sets. In our model, for instance, there is a derived set “Distance between Doors” which is derived from two primitive sets, “Receiving Doors” and “Shipping Doors”. This derived set consists of the distance between every possible combination of a receiving door and a shipping door. Each member in a set may have one or more characteristics associated with it. In LINGO, we call these characteristics attributes. All members of the same set have the same set of attribute types. Attribute values can be known in advance or unknowns for which LINGO solves. The figure shown below is all the sets defined in our LINGO model:

```
model:
sets:
Origin;
Destination;
ReceivingDoors;
ShippingDoors;
StorageLane:Q;
Trailers;
TravelDistance(Destination):Distance;
RevenuePerMile(Destination):RPM;
DistanceBetweenDoors(ReceivingDoors,ShippingDoors):Dmn;
ExtraDistance(ReceivingDoors,ShippingDoors,StorageLane):Ymnk;
TrailerProperty(Destination,Trailers):TS,DT,E;
Variable1(Origin,ReceivingDoors):Xim;
Variable2(Destination,ShippingDoors):Xjn;
Variable3(Origin,Destination,StorageLane):Xijk;
Variable4(Origin,Destination,Trailers):Xijh;
Link(Origin,Destination):Qij,AT,AVT,Size,Weight;
endsets
```

Figure 4.1 SETS section in Lingo model

4.1.2 The DATA section

As previously mentioned, a SETS section describes the structure of the data for a particular class of problems. A DATA section provides the data to create a specific instance of this class of problems. The DATA section allows us to isolate things that are likely to change. This is a useful practice in that it leads to easier model maintenance and makes a model easier to scale up or down in dimension. The DATA section in our model includes the definition of members of primitive sets and data value of attributes. In general, data can reside in the DATA section, or a DATA section can have OLE links to Excel, ODBC links to databases and connections to other spreadsheet and text based data files. In order to maintain our model and scale up or down easily, we use OLE links to Excel spreadsheet in our model. Figure 4.2 presents the DATA section in LINGO model.

```
data:
CPF= 0.01;
Ct= 0.1;
M= 100;
Origin,Destination,ReceivingDoors,ShippingDoors,StorageLane,
Q,Dmn,Ymnk,Trailers,TS,E,Qij,AT,AVT,Size,Weight,Distance,RPM=@OLE();
enddata
```

Figure 4.2 DATA section in Lingo model

4.1.3 The model equations section

In the model equations section of the model, we state the relationships among various attributes. Any statements not in a SETS or DATA section are by default in the model equations section. The power of set based modeling comes from the ability to apply an operation to all members of a set using a single statement. The function in LINGO that allows us to do this are called *set looping functions*. The looping functions allow us to iterate through all the members of a set to perform some operation. Based on LINGO's syntax rules, it is straightforward to translate our mathematical model to LINGO. Figure 4.3 is the model equation section.

```
@for(Origin(i):@sum(ReceivingDoors(m):Xim(i,m))=1);
@for(Destination(j):@sum(ShippingDoors(n):Xjn(j,n))=1);
@for(ReceivingDoors(m):@sum(Origin(i):Xim(i,m))=1);
@for(ShippingDoors(n):@sum(Destination(j):Xjn(j,n))=1);
@for(StorageLane(k):@sum(Origin(i):@sum(Destination(j):
                    Qij(i,j)*Xijk(i,j,k)))<=Q(k));
@for(Origin(i):
 @for(Destination(j):AT(i,j)+AVT(i,j)-
                   @sum(Trailers(h):DT(j,h)*Xijh(i,j,h))>=0));
@for(Origin(i):
 @for(Destination(j):@for(Trailers(h):AT(i,j)*Xijh(i,j,h)<=DT(j,h))));
@for(Destination(j):@for(Trailers(h):@sum(Origin(i):
                         Qij(i,j)*Size(i,j)*Xijh(i,j,h))<=TS(j,h)));
@for(Destination(j):@for(Trailers(h):@sum(Origin(i):
                         Qij(i,j)*Weight(i,j)*Xijh(i,j,h))<=E(j,h)));
@for(Origin(i):
 @for(Destination(j):(@sum(Trailers(h):DT(j,h)*Xijh(i,j,h))-AT(i,j))/M
                           <=@sum(StorageLane(k):Xijk(i,j,k))));
@for(Origin(i):
 @for(Destination(j):@sum(Trailers(h):DT(j,h)*Xijh(i,j,h))-AT(i,j)>=0));
@for(Origin(i):
 @for(Destination(j):@sum(StorageLane(k):Xijk(i,j,k))<=1););
@for(Origin(i):
 @for(Destination(j):@sum(Trailers(h):Xijh(i,j,h))=1););
@for(Variable1:@bin(Xim));
@for(Variable2:@bin(Xjn));
@for(Variable3:@bin(Xijk));
@for(Variable4:@bin(Xijh));

max= @sum(Destination(j):@sum(Trailers(h):@sum(Origin(i):Qij(i,j)*Size(i,j)
     *Xijh(i,j,h))*@sum(Origin(i):Qij(i,j)*Size(i,j)*Xijh(i,j,h))*Distance(j)
     *RPM(j)/TS(j,h)/TS(j,h)))
    -@sum(Origin(i):@sum(Destination(j):@sum(ReceivingDoors(m):
     @sum(ShippingDoors(n):CPF*Qij(i,j)*(Dmn(m,n)+@sum(StorageLane(k):
      Ymnk(m,n,k)*Xijk(i,j,k)))*Xim(i,m)*Xjn(j,n)))))
    -@sum(Origin(i):@sum(Destination(j):Ct*Qij(i,j)*(@sum(Trailers(h):
      DT(j,h)*Xijh(i,j,h))-AT(i,j))));
```

Figure 4.3 Model equations section in Lingo model

4.2 Tabu Search approach

4.2.1 Introduction to tabu search algorithm

Tabu search is a metaheuristic algorithm that can be used for solving combinatorial optimization problems. Tabu search uses a local or neighborhood search procedure to iteratively move from a solution x to a solution x' in the neighborhood of x, until a stopping criterion has been satisfied. To explore regions of the search space that would be left unexplored by the local search procedure, tabu search modifies the neighborhood structure of each solution as the search progress. The solutions admitted to $N^*(x)$, the new neighborhood, are determined through the use of memory structures. The search then progresses by iteratively moving from a solution x to a solution $x^{'}$ in $N^*(x)$.

The most important type of memory structure used to determine the solutions admitted to $N^*(x)$, is the tabu list. In its simplest form, a tabu list is a short-term memory which contains the solutions that have been visited in the recent past (less than n iterations ago, where n is the number of previous solutions to be stored, n is also called the tabu tenure). Tabu search excludes solutions in the tabu list from $N^*(x)$. A variation of a tabu list prohibits solutions that have certain attributes or prevent certain moves. Selected attributes in solutions recently visited are labeled "tabu-active". Solutions that contain tabu-active elements are tabu. This type of short-term memory is also called "recnecy-based" memory.

Tabu lists containing attributes can be more effective for some domains, although they raise a new problem. When a single attribute is marked as tabu, this typically results in more than one solution being tabu. Some of these solutions that must now be avoided could be of excellent quality and might not have been visited. To mitigate this problem "aspiration criteria" are introduced. The "aspiration criteria" overrides a solution's tabu status, thereby including the otherwise-excluded solution in the allowed set. A commonly used aspiration criterion is to allow solutions which are better than the currently-known best solution.

4.2.2 OpenTS – Java Tabu Search

OpenTS is a Java tabu search framework that can help us implement the tabu search meta-heuristic in a well-defined, object-oriented design. OpenTS makes no assumptions about the type of problem to be solved. This advantage perfectly matched our need to develop a tabu search program to a new model.

OpenTS asks the user to define basic elements common to all tabu searches and then performs iterations based on these elements. The key element we defined are:

- Solution structure
- Objective function
- Tabu list
- Move
- Move manager

OpenTS uses these elements to search the solution space. Given a starting, or current, solution, the move manager is asked to generate a list of moves for the iteration. OpenTS uses the objective function to determine the value of the solution that would result from each of these moves. With the help of the tabu list, OpenTS determines which move is the best, and that move operates on the starting, or current solution which results in a new solution. Figure 4.4 below illustrates this process graphically. A detailed description of how it applies to our own problem will be discussed in the next section.

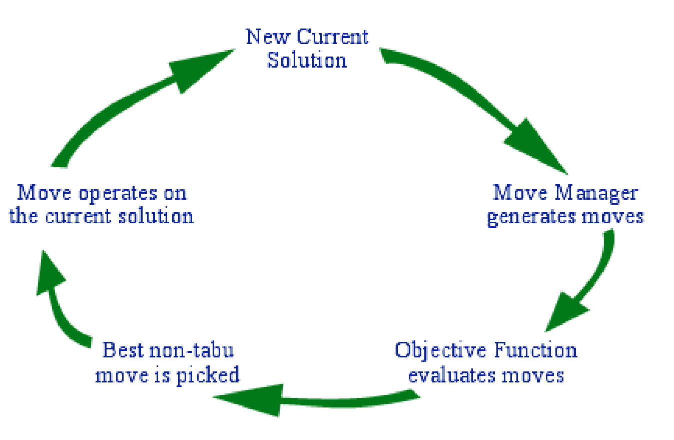


Figure 4.4 Tabu search structure

4.2.3 Tabu search program structure

Based on OpenTS tabu search program framework, our tabu search program is built with the following 6 classes: xdockingObjectiveFunction, xdockingSolution, xdockingMoveManager, XdockingBinaryMove, Main, and xdockingTabuList. As an objective oriented program, each class has its own function. They also cooperate with each other to achieve the objective of the whole program – solving problems based on our mathematical model. Figure 4.5 shows how these 6 classes cooperate with each other. Details of each class will be discussed in the following sections.

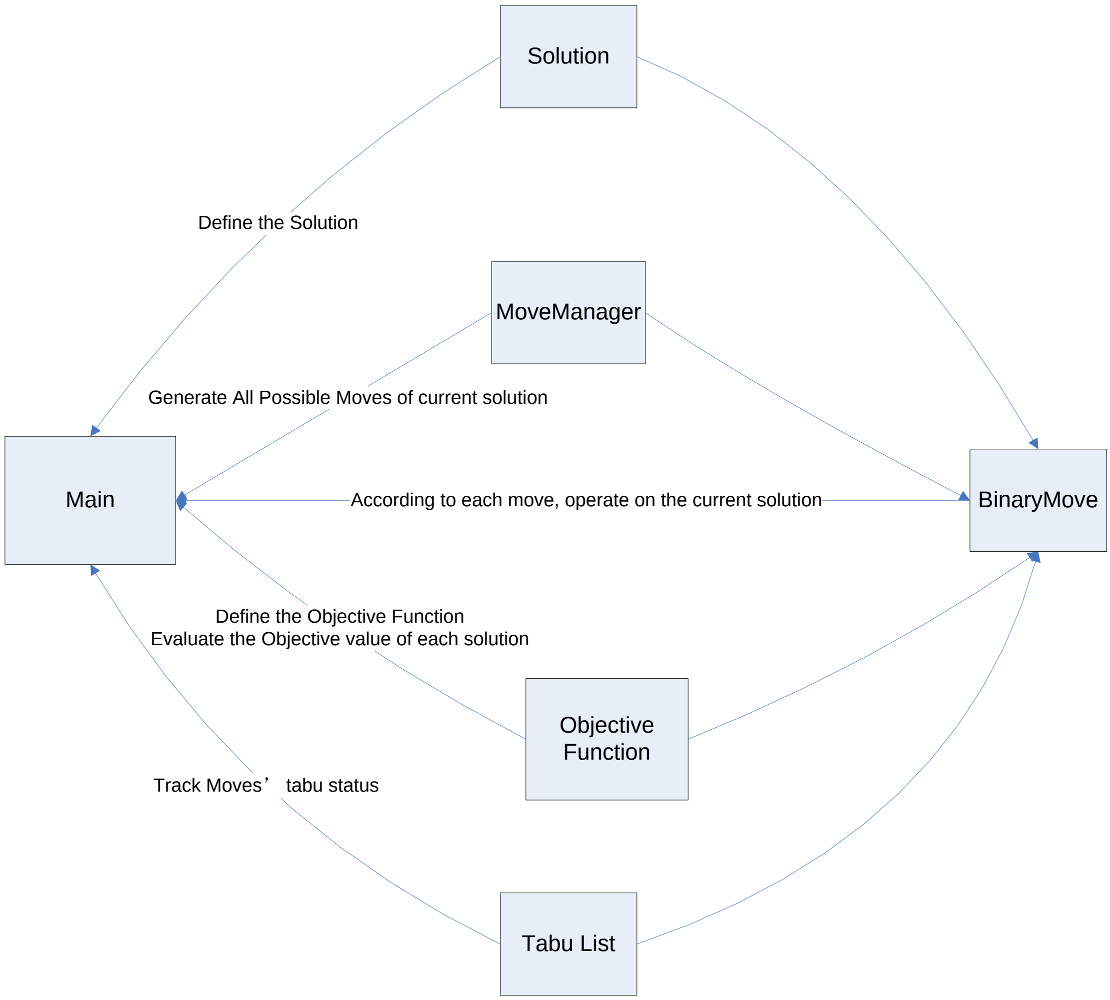


Figure 4.5 Tabu search program structure

Figure 4.6 is the flow chart of the Tabu search program. It starts from the initial solution; a set of Move Matrix is generated based on the current best solution. With the input of an element in this Move Matrix set together with the current solution matrix, a new possible solution is generated by calling the *Evaluate* method. At this step, we get the values of X_{im}, Y_{jn}, Z_{ijk}, U_{ijh} for the new possible solution, with which the values of the continuous variable can be calculated by the Djh Method. Then the program checks the feasibility and tabu status of these possible solutions to enforce that the final solution is feasible and the solution search process respects the tabu list. Finally, the program evaluates the objective function values of all these possible solutions and the best feasible solution is returned as the new current best solution. The details of these methods will be discussed in the following sections.

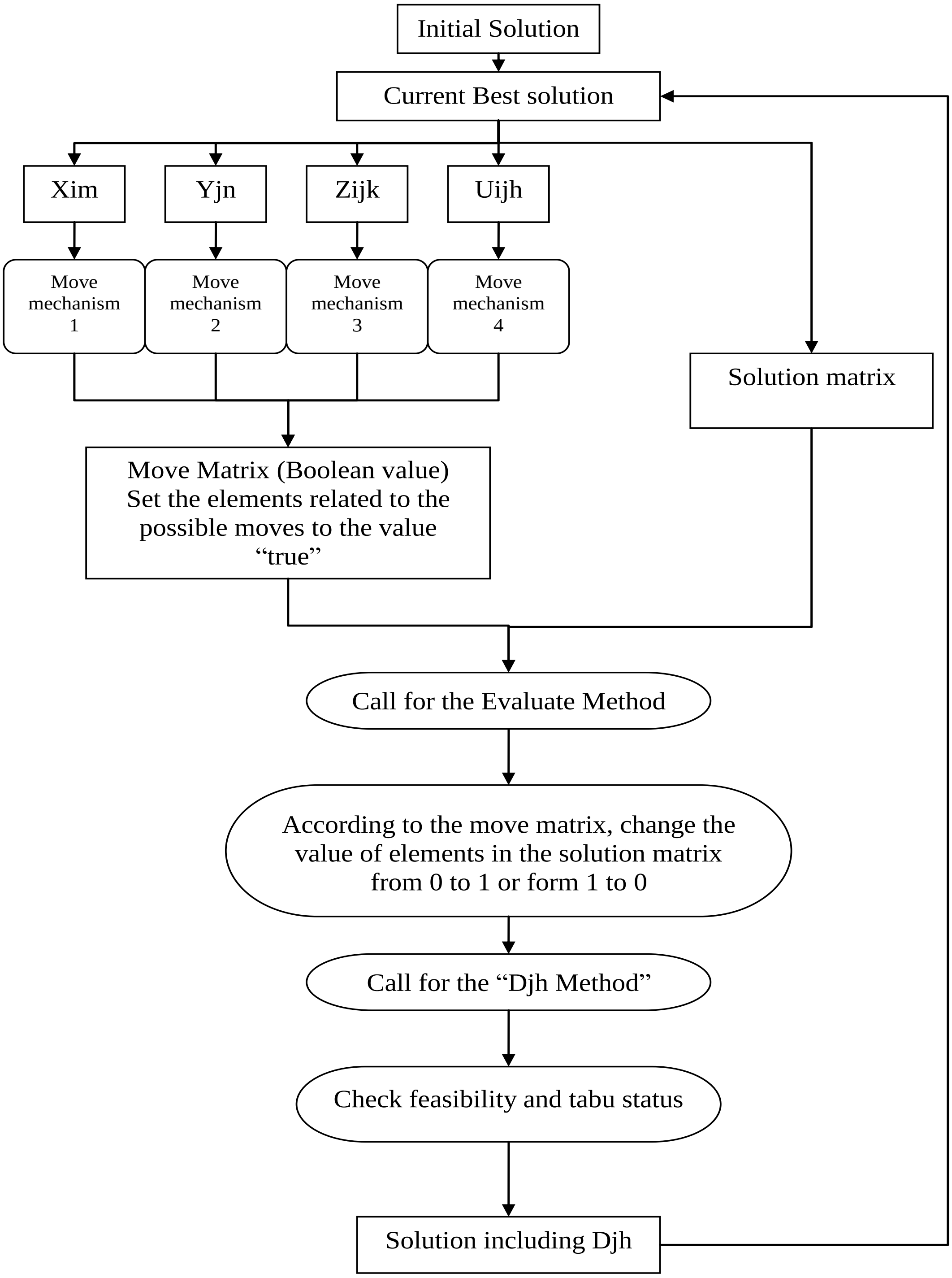


Figure 4.6 Program flow chart

4.2.3.1 xdockingObjectiveFunction class

The main function of this class is defining the objective function. A method named *evaluate* is constructed in this class, this method first checks the feasibility of a solution, we should notice here that this solution is just a member of a solution pool generated by the xdockingBinaryMove class which can be feasible or infeasible. If the solution is feasible, it calculates its objective value. If the solution is infeasible, it returns a big number as the objective value to make sure that the final solution is feasible.

4.2.3.2 xdockingSolution class

This class defines the components and structure of a solution. As mentioned in Chapter 3, there are five sets of variables in our model, X_{im}, Y_{jn}, Z_{ijk}, U_{ijh}, and D_{jh}. The first four sets are binary variables; the departure time D_{jh} is a set of continuous variables. A solution object is also defined in this class and contains these five sets of variables, X_{im}, Y_{jn}, Z_{ijk}, U_{ijh} are defined as Boolean-type multi-arrays, and D_{jh} is defined as a double-type 2-way array.

4.2.3.3 xdockingMoveManager class

xdockingMoveManager class determines which moves are available for any given solution. This function is achieved by a method named *getAllMoves.* This method returns an array of all possible moves to try at an iteration based on the most current solution.

Moves are generated by a multi-layer loop, which consists 4 layers:

- Loop 1: Move the location of each receiving trailer forward and backward to its neighboring 2 receiving doors;
- Loop 2: Move the location of each shipping trailer forward and backward to its neighboring 2 shipping doors;
- Loop 3: Move the storage location of each cargo forward and backward to its neighboring 2 trailers;
- Loop 4: Move each cargo from current assigned shipping trailer forward and backward to the neighbor 2 trailers;

One move is defined as an object including several Boolean arrays with the same size of solution arrays, in each array the TRUE value indicates the value of the solution arrays in the same position should be changed from 0 to 1 or 1 to 0.

For example, figure 4.7 is the X_{im} matrix of the current solution for a problem in which there are 4 receiving doors. This matrix indicates that origin 1, 2, 3, and 4 are sequentially assigned to receiving door 1, 2, 3, and 4. Figure 4.8 is a X_{im} move matrix with Boolean values. After this move is applied to X_{im} of the current solution, a new X_{im} is generated, which is shown in Figure 4.9.

1	0	0	0
0	1	0	0
0	0	1	0
0	0	0	1

Figure 4.7 Xim matrix of the current solution

TRUE	FALSE	**TRUE**	FALSE
FALSE	FALSE	FALSE	FALSE
TRUE	FALSE	**TRUE**	FALSE
FALSE	FALSE	FALSE	FALSE

Figure 4.8 Xim move matrix with Boolean values

0	0	1	0
0	1	0	0
1	0	0	0
0	0	0	1

Figure 4.9 Xim matrix of the new solution

The X_{im} matrix shown in Figure 4.9 indicates that origin 1 is assigned to receiving door 3, origin 2 is assigned to receiving door 2, origin 3 is assigned to door 1, and origin 4 is assigned to door 4.

4.2.3.4 xdockingBinaryMove class

For each move generated by xdockingMoveManager, this class operates on the current solution, evaluates it with respect to the objective function and then performs the *undoOperation*. A method with the name of *operationOn* is built in this class to perform the main function. Based on each move passed from xdockingMoveManager, this method operates on the current solution, which generates the value of all binary variables. Then based on the values of U_{ijh} this method goes through each shipping trailer and determines the departure time of each trailer as the latest arrival time of the cargo which is assigned to it.

4.2.3.5 xdockingTabuList class

This class performs the function of tracking which moves are tabu and for how long. A tabu list is constructed in this class, which includes several xdockingBinaryMove objects. Initially, all Boolean values in the tabu list are set to FALSE, as no moves are going to be tabu at the starting point. Then, once a move is made, the tabu list is updated by copying that move to the end of the list and deleting the first element of the list. A method named *allowMove* is built to determine whether this move has the same tabu criteria as the moves on the tabu list. For a potential move, we get the names of the origin and destination that are going to be moved from it, and then we compare them with the moves in the tabu list. If this potential move is trying to move the same origin or destination that already exists in the tabu list, it is placed on the tabu list.

4.2.3.6 Main class

The Main class reads data from text files, such as arrival time, quantity of cargo, available time, and so on. Tabu search objects of other classes mentioned previously are also instantiated in this class. Then the main class creates a tabu search engine (an object) with the parameters of all tabu search objects. The number of iterations to search and the tabu list length are also defined. In order to evaluate the solution obtained from this tabu search heuristic, an upper-bound calculation is included in this class. The details of how this upper-bound works will be mentioned in the next chapter.

Chapter 5 Results and Analysis

As mentioned in Chapter 4, we set up two approaches to solve the model 1. One way was using Lingo 8.0, through which we input our mathematical model and LINGO uses its built-in solver to solve the problem optimally. However, during our research, we found that when dealing with problems with 10 doors or more, the run time of Lingo 8.0 increases exponentially, as shown in Figure 5.1. Therefore, Lingo was used to solve small problems with 8 doors or less, and the analysis in this chapter is mainly based on the results from the Tabu Search program developed. Figure 5.2 presents the comparison of solutions obtained from both LINGO and the tabu search program.

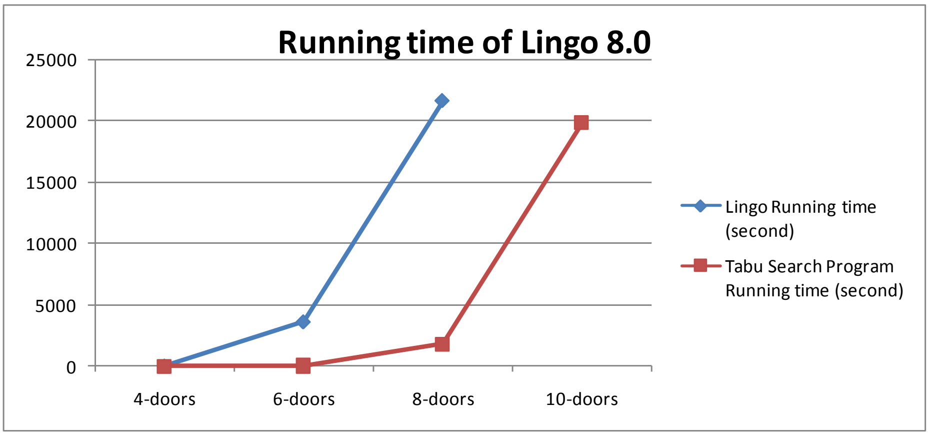


Figure 5.1 Running Time of Lingo as a function of problem size

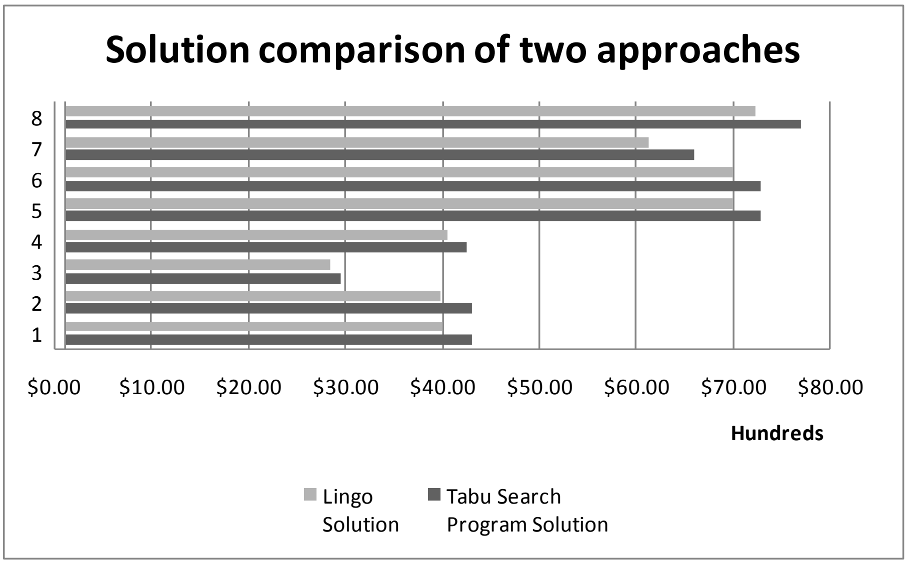


Figure 5.2 Solution Comparison of Two Approaches

5.1 Analysis of a small-scale problem

Consider a small problem with 4 doors, 3 of which are receiving doors and the fourth one is a shipping door. The layout of this problem is shown below:

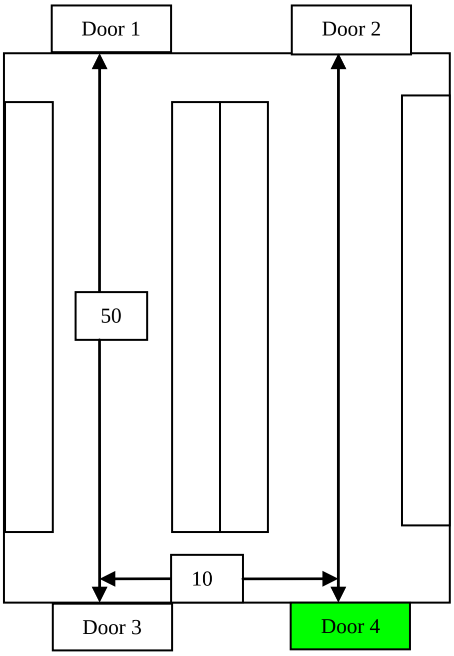


Figure 5.3 The layout of a 4-door problem, Door 1, 2, and 3 are receiving doors and Door 4 is a shipping door. The distance between Door 1 and 3 is 50, and 10 between Door 3 and 4.

There is one incoming trailer in each receiving door; cargo from each incoming trailer is sent to outgoing trailers through the cross-docking operation with or without staging process. The data used is listed in Table 5.1.

Table 5.1 Date of a 4-door problem

Shipping Quantity	40	20	10
Arrival Time	2	5	2
Available Time	2	2	2
Notation:	***O1:Origin 1*** ***D1:Destination 1***		
Trailer Capacity	80		

Recall that Model 1 in Chapter 3 optimizes the layout and staging locations which causes the least traveling cost, and also optimizes the shipping trailer assignment so as to maximize the shipping trailer utilization.

Since this is a small-scale problem we are able to solve it manually. We can notice that Origin 1 has the largest shipping quantity; therefore, in order to minimize the traveling distance, Origin 1 should be assigned to Door 3 which is closest to shipping Door 4. Also, Origin 3 has the least shipping quantity; it can be assigned to Door 1 which is farthest to Door 4. Cargo from both Origin 1 and 3 arrive at the cross-docking facility at the time 2, and both have an available time of 2 time units, so they can be shipped out in a same outgoing trailer. However, cargo from Origin 2 arrive at time 5, it is obvious that it must be shipped out in a different outgoing trailer. This problem was tested in Lingo which results in an optimal solution that is the same as the results discussed above.

5.2 Analysis of large-scale problems

For problems with 10 doors or more, we are not able to get the optimal solution in

Lingo within a reasonable time. For example, for a 10-door problem we tested during our research, a feasible solution can be found after 6 hours of run time, and no better solutions were found during the next 18 hours. Therefore, in order to tackle larger problems, we developed a tabu search program, and the results analysis below is mainly based on the solutions obtained from this program. Table 5.2 is part of a Tabu Search solution report for a 10-door problem.

Table 5.2 Part of a Tabu Search Solution Report

TS Solution	Revenue	Traveling Cost	Time Penalty Cost
7298.66	8213.66	874	41

The objective function value for this problem is 7298.66. We also test this problem in Lingo and a feasible solution was found with objective function value of 7011.34. We can tell that the solution from our tabu search program is better; however, there is no way to determine how good this solution is. Therefore, in order to evaluate the solutions we calculate the upper bound of the solution in our tabu search program, which is described in the next section.

5.2.1 Upper bound of solutions

Recall the objective function of Model 1:

$$\sum_j \sum_h \left(\frac{\sum_i q_{ij} v_{ij} U_{ijh}}{s_{jh}}\right)^2 U_{ijh} r_{jh} n_j - c \sum_i \sum_j \sum_m \sum_n q_{ij} X_{im} Y_{jn} (d_{mn} + \sum_k y_{kmn} Z_{ijk})$$
$$-c_t \sum_i \sum_j q_{ij} (\sum_h D_{jh} U_{ijh} - a_{ij})$$

It includes three parts:

$\sum_j \sum_h \left(\frac{\sum_i q_{ij} v_{ij} U_{ijh}}{s_{jh}}\right)^2 r_{jh} n_j$ is the revenue related to outgoing trailer utilization.

$c\sum_i \sum_j \sum_m \sum_n q_{ij} X_{im} Y_{jn} (d_{mn} + \sum_k y_{kmn} Z_{ijk})$ is the distance related cost, as different storage locations may cause different travel distance.

$c_t \sum_i \sum_j q_{ij} (\sum_h D_{jh} U_{ijh} - a_{ij})$ is the time related penalty cost, as more staging time will cause more related cost.

An upper bound for a solution will also contain three parts: 1) upper bound on revenue, 2) lower bound on traveling cost, and 3) lower bound on time penalty cost. We calculate these three parts separately.

For the upper bound on revenue, we simply assign cargo to as few as possible outgoing trailers without considering their time windows.

For the lower bound on traveling cost, it is found by taking the product of the total number of unit loads and the typical distance between two doors. Consider the layout shown in Figure 5.1.1, the lower bound distance is the average of distance between Door 1 and 3 and distance between Door 3 and 4 which is 30 = (10 + 50) / 2.

For the lower bound on time penalty cost, the best case is that no staging process is needed resulting in a lower bound for time penalty cost of 0.

Therefore, the Upper bound on Profit = Upper bound on revenue – Lower bound on traveling cost – Lower bound on time penalty cost.

We present here an example illustrating how the upper bound is calculated. Again we consider a small problem with 4 doors, 3 of which are receiving doors and the fourth one is a shipping door. The layout of this problem is in Figure 5.4. The data used is listed in Table 5.3.

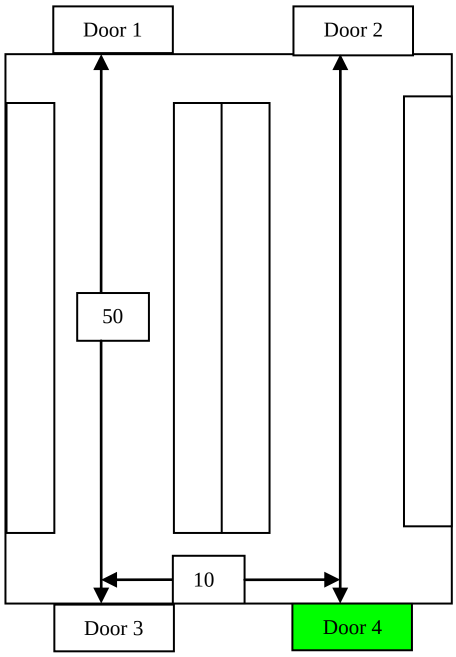


Figure 5.4 The layout of a 4-door problem, Door 1, 2, and 3 are receiving doors and Door 4 is a shipping door. The distance between Door 1 and 3 is 50, and 10 between Door 3 and 4.

Table 5.3 Data for a 4-door problem

	O1 to D1	O2 to D1	O3 to D1
Shipping Quantity	40	30	10
Arrival Time	2	5	1
Available Time	2	2	2
Cargo Size	10	20	40
Cargo Weight	20	30	40
Notations:	***O1: Origin 1*** ***D1: Destination 1***		
Trailer Size	1000		
Trailer Weight Limit	2500		
Revenue Per Mile	1.89		
Storage Lane Capacity	100		
Traveling cost per foot	0.01		
Time penalty cost per time unit	0.1		

1. Upper bound on revenue

   We notice that cargo from Origin 1 to Destination 1 and cargo from Origin 2 to Destination 1 have the total volume of $1000 = 40 * 10 + 30 * 20$, which is the maximum consolidation that can fit into one shipping trailer with size of 1000. Cargo from Origin 3 to Destination 1 is shipped out in a separate shipping trailer. Therefore, the upper bound on revenue is $1973.16 = 1^2 \times 1.89 \times 900 + 0.4^2 \times 1.89 \times 900$

2. Lower bound on travel cost

   As described above, Lower bound on travel cost is calculated as $0.01 \times 30 \times (40 + 30 + 10) = 24$

3. Lower bound on time penalty cost

The best case is that no staging is needed to consolidate cargo, therefore the Lower bound on time penalty cost is 0

Therefore, the Upper bound on Profit = Upper bound on revenue – Lower bound on traveling cost – Lower bound on time penalty cost = $1973.16 - 24 - 0 = 1949.16$. Table 5.5 gives us the comparison of upper bound and LINGO optimal solution.

Table 5.4 Comparison of upper bound and LINGO optimal solution

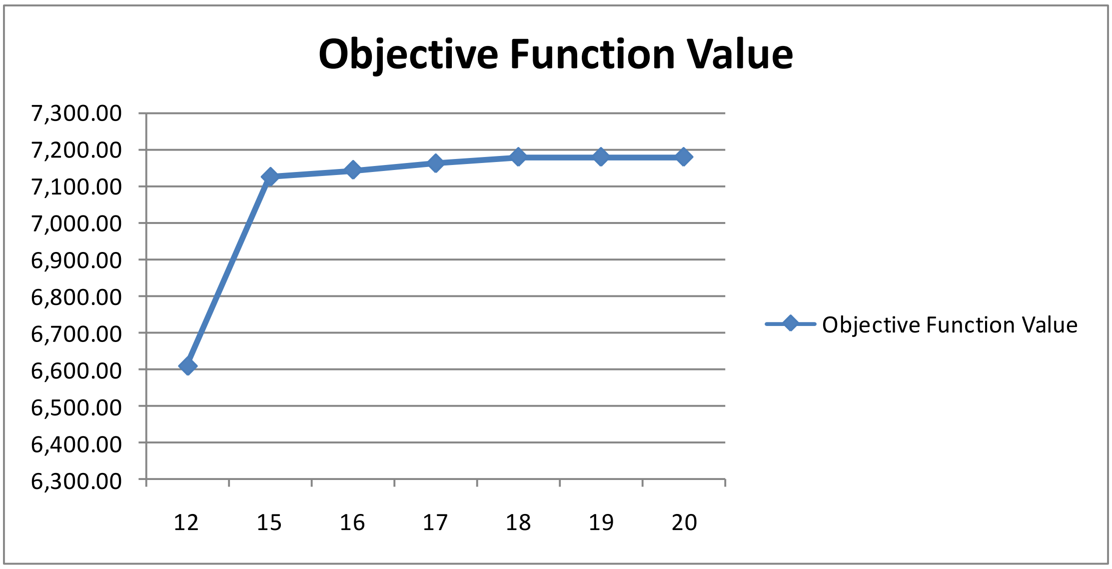
Revenue solution	Traveling cost solution	Time penalty cost solution	Profit solution
1701	25	1	1675
Upper bound on revenue	Lower bound on traveling cost	Lower bound on time penalty cost	Profit Upper bound
1973.16	24	0	1949.16

5.2.2 Tabu search iterations

Table 5.5 Objective Function Value for different number of iterations

Number of iterations	Objective Function Value (Dollars)
12	6,610.67
15	7,123.87
16	7,142.76
17	7,160.47
18	7,177.87
19	7,177.87
20	7,177.87

Table 5.6 Objective function value for different number of iterations



The tabu search program requires the user to set the number of iterations to run the search. For the problem with 10 doors, several tests were done to determine how many iterations are needed to get a good solution. The test results are shown in Table 5.4 and Figure 5.6.

From the tests results, we notice that as iterations increase from 12 to 18, the objective function value increases from 6610.67 to 7177.87. This trend stops when the number of iterations increased to 19 and 20. Several 10-door problems with different data sets are also tested using a different number of iterations, those results also show that the solution stops improving after 18 iterations.

5.2.3 Comparison of Model 1 and Model 2

As mentioned in Chapter 3, there exists another scenario for cross-docking operation: all transshipment cargo has a fixed and strict schedule, their arrival and departure times are determined beforehand within the overall logistics systems. Since the schedule is not flexible, we cannot use the time window of each cargo to help consolidate cargo. Therefore, in this case, in order to reduce costs, we only focus on material handling equipment traveling distance in the facility considering the door assignment and staging location assignment, as is mathematically modeled in Model 2. Table 5.7 and Table 5.8 present the results for a 10-door problem, which was tested in both models we notice that the MH travel cost of Model 1 is only 80.4% of the travel cost of Model 2, which is explained by some of the cargo traveling through the shortest distance without any staging process.

Table 5.7 Results of Model 1

Traveling Cost		Storage Lane Assignment	
874		Cargo between each pair of origin destination	Assig. Storage Lane
Origin	Assig. Door	O1 to D1	Not Assigned
O1	Door 2	O2 to D1	Lane 4
O2	Door 9	O3 to D1	Not Assigned
O3	Door 7	O4 to D1	Not Assigned
O4	Door 3	O5 to D1	Lane 3
O5	Door 8	O6 to D1	Not Assigned
O6	Door 4	O1 to D2	Lane 2
Destination	Assig. Door	O2 to D2	Not Assigned
D1	Door 1	O3 to D2	Not Assigned
D2	Door 6	O4 to D2	Not Assigned
D3	Door 5	O5 to D2	Lane 5
D4	Door 10	O6 to D2	Not Assigned
		O1 to D3	Lane 2
		O2 to D3	Not Assigned
		O3 to D3	Lane 2
		O4 to D3	Lane 3
		O5 to D3	Not Assigned
		O6 to D3	Not Assigned
		O1 to D4	Not Assigned
		O2 to D4	Lane 4
		O3 to D4	Lane 2
		O4 to D4	Not Assigned
		O5 to D4	Lane 3
		O6 to D4	Lane 4

Table 5.8 Results of Model 2

Traveling Cost		**Storage Lane Assignment**	
1087		Cargo between each pair of origin destination	Assig. Storage Lane
Origin	Assig. Door	O1 to D1	Lane 1
O1	Door 8	O2 to D1	Lane 1
O2	Door 3	O3 to D1	Lane 2
O3	Door 7	O4 to D1	Lane 2
O4	Door 2	O5 to D1	Lane 1
O5	Door 4	O6 to D1	Lane 1
O6	Door 9	O1 to D2	Lane 3
Destination	Assig. Door	O2 to D2	Lane 2
D1	Door 6	O3 to D2	Lane 2
D2	Door 5	O4 to D2	Lane 2
D3	Door 10	O5 to D2	Lane 4
D4	Door 1	O6 to D2	Lane 4
		O1 to D3	Lane 4
		O2 to D3	Lane 3
		O3 to D3	Lane 3
		O4 to D3	Lane 3
		O5 to D3	Lane 4
		O6 to D3	Lane 4
		O1 to D4	Lane 2
		O2 to D4	Lane 1
		O3 to D4	Lane 2
		O4 to D4	Lane 1
		O5 to D4	Lane 4
		O6 to D4	Lane 3

5.2.4 Design of Experiments

In order to get more insight into how different factors affect the profit level, a multi-factor experiment was designed in this research that includes 3 factors, each with 2 levels: flow profile, arrival time, and available time for transshipping cargo. Details of each factor are described below:

Factor A: Flow profile (for a 10-door problem)

To characterize the flow data, we consider the composition of the loads to each destination, which can be "pure, mixed or highly mixed."

These compositions are defined as: loads to a "pure" destination comes from 1 to 2 origins, a "mixed" destination receives loads from 3 to 4 origins, while a "highly mixed" destination receives loads from 5 to 6 origins.

The two levels of flow profile are shown in Table 5.9.

Table 5.9 Two levels of Flow Profile

	% Highly Mixed	*% Mixed*	*% Pure*
Level 1	---	50 (2 doors)	50 (2 doors)
Level 2	100 (4 doors)	---	---

Factor B: Arrival Time

If the variance of the arrival time of cargo for each receiving door is relatively small, then it is possible that more cargo from different receiving doors can be consolidated. The two levels adopted are listed in Table 5.10.

Table 5.10 Two levels of Arrival time

	Standard Deviation of Arrival Time
Level 1	0.585
Level 2	1.114

Factor C: Available Time

The available time is the time interval that cargo can stay in the facility. Longer available time indicates that they can stay in the facility for a longer period of time and it becomes easier to consolidate with cargo from other receiving doors.

Table 5.11 Two levels of Available Time

	Average of Available Time
Level 1	1.825
Level 2	3.55

Due to having 3 factors each with 2 levels it is a 2^3 factorial experiment, resulting in 8 trials. Table 5.12 lists the 8 trials adopted in this experiment. The result of each trial is listed in Table 5.13 to Table 5.20. First, we discuss each trial individually and then make some comparative comments for all of them.

Table 5.12 8 Trials adopted in the experiment

Trial	Flow Profile Level	Arrival Time Level	Available Time Level
111	Level 1=50%Mixed+50%Pure	Level 1=0.585	Level 1=1.825
112	Level 1=50%Mixed+50%Pure	Level 1=0.585	Level 2=3.55
121	Level 1=50%Mixed+50%Pure	Level 2=1.114	Level 1=1.825
122	Level 1=50%Mixed+50%Pure	Level 2=1.114	Level 2=3.55
211	Level 2=100%Highly Mixed	Level 1=0.585	Level 1=1.825
212	Level 2=100%Highly Mixed	Level 1=0.585	Level 2=3.55
221	Level 2=100%Highly Mixed	Level 2=1.114	Level 1=1.825
222	Level 2=100%Highly Mixed	Level 2=1.114	Level 2=3.55

Notation: ***111: trial with all level 1 for every factor***

Table 5.13 Test results of 10-door problem with level 1 in Flow profile, level 1 in Arrival time and level 1in Available time

General Solution

Initial Solution	Initial Revenue	Initial Traveling Cost	Initial Time Penalty Cost
2635.51	3053.51	418	0
Upper Bound of Profit	Upper Bound of Revenue	Lower Bound of Traveling Cost	Lower Bound of Time Penalty Cost
4423.88	4726.88	303	0
TS Solu.	Revenue	Traveling Cost	Time Penalty Cost
4301.38	4726.88	400	25.5
Proportion of Profit UB	Proportion of Revenue UB		
97.23%	100.00%		

Door assignment

Origin	Assig. Door
O1	Door 4
O2	Door 7
O3	Door 8
O4	Door 3
O5	Door 2
O6	Door 9
Destination	Assig. Door
D1	Door 5
D2	Door 10
D3	Door 1
D4	Door 6

Storage Lane Assignment		Outgoing Trailer Assignment			
Cargo between each pair of origin destination	Assig. Storage Lane	Assig. Truck	Arriving Time	Depart. Time	Staging Time
O1 to D1	Not Assigned	Truck 13	1	1	0
O2 to D1	Not Assigned	Truck 12	1.5	1.5	0
O3 to D1	Not Assigned	Truck 13	1	1	0
O4 to D1	Not Assigned	Truck 14	2	2	0
O5 to D1	Not Assigned	Truck 15	1.5	1.5	0
O6 to D1	Not Assigned	Truck 16	2.5	2.5	0
O1 to D2	Not Assigned	Truck 21	1	1	0
O2 to D2	Not Assigned	Truck 22	1.5	1.5	0
O3 to D2	Lane 3	Truck 26	1	2.5	1.5
O4 to D2	Not Assigned	Truck 24	2	2	0
O5 to D2	Lane 3	Truck 26	1.5	2.5	1
O6 to D2	Not Assigned	Truck 26	2.5	2.5	0
O1 to D3	Lane 4	Truck 31	1	1.5	0.5
O2 to D3	Not Assigned	Truck 31	1.5	1.5	0
O3 to D3	Not Assigned	Truck 33	1	1	0
O4 to D3	Not Assigned	Truck 34	2	2	0
O5 to D3	Lane 2	Truck 34	1.5	2	0.5
O6 to D3	Not Assigned	Truck 36	2.5	2.5	0
O1 to D4	Not Assigned	Truck 41	1	1	0
O2 to D4	Not Assigned	Truck 43	1.5	1.5	0
O3 to D4	Lane 3	Truck 43	1	1.5	0.5
O4 to D4	Not Assigned	Truck 44	2	2	0
O5 to D4	Not Assigned	Truck 45	1.5	1.5	0
O6 to D4	Not Assigned	Truck 46	2.5	2.5	0

Notations: ***O1: Origin 1***
D1: Destination 1
Truck 11: The #1 truck to Destination 1

Table 5.13 presents the result of a 10-door problem all with level 1 for each factor described above. Among the 4 shipping doors, 2 of them receive loads from 4 origins and the other 2 receive loads from 2 origins. The cargo arrival time from each receiving door has the standard deviation of 0.585, and the average available time of cargo is 1.825. For convenience, we call it *111* trial. The solution report has 4 main parts:

1. The general solution lists the initial solution, the final solution, the solution upper bound and the evaluation of the final solution.
2. The door assignment solution shows how origins are assigned to receiving doors as well as how destinations are assigned to shipping doors.
3. The storage lane assignment part contains how cargo is assigned to the staging lane, if a staging process is needed.
4. The outgoing trailer assignment part contains which outgoing trailer cargos are assigned, and the cargo which is consolidated highlighted.

After 18 iterations, the tabu search program improves the solution from an initial value of 2635.61 to 4301.38, is 97.23% of the Profit Upper Bound. We notice that the revenue of the tabu search solution is exactly equal the revenue upper bound. Therefore, we can tell that the tabu search solution is good and the trailer utilization has been optimized. As we have mentioned previously, whether the staging process for some specific cargo is needed depends on its trailer assignment. If the trailer to which it is assigned leaves some time after its arrival, the staging process is needed and a storage lane is assigned to this cargo. Consider for example Truck 26 (26 denotes this is #6 truck to destination 2), cargo from Origin 3, Origin 5 and Origin 6 are assigned to this truck. The departure time of Truck 26 is the arrival time of cargo from Origin 5 (we assumed that the material handling time is included in arrival time), therefore the early arrival cargo from Origin 3 and 5 must be stored for a short period of time in the facility, and the results show that storage lane 3 is assigned to them.

Table 5.14 lists us the results of a 10-door problem with level 1 in Flow profile, level 1 in Arrival time and level 2 in Available time (*112* trial). The total profit results are exactly the same as for the *111* trial. We can conclude here that the available time with an average 1.825 is long enough to consolidate all possible cargo.

The solution to the 10-door problem with level 1 in Flow profile, level 2 in Arrival time and level 1 in Available time (*121* trial) is shown in Table 5.15. We can see that even though it has the exact same Flow profile as the previous two trials, the objective function value only reaches 2952.97 which is only 66.75% of the upper bound. We also notice that only cargo from Origin 3 and 5 to Destination 2 are consolidated to Truck 23 and cargo from Origin 2 and 3 to Destination 4 are consolidated to Truck 43. Other cargo from different origins is shipped out in different outgoing trailers without consolidation. This can be explained by the decrease in the cargo's available time. A longer available time indicates that cargo can stay longer in the facility waiting for cargo arriving later, so they can be shipped out in the same outgoing trailer. When the available time decreases, the ability to consolidate fewer cargos causes the shipping trailer utilization to decrease.

Table 5.14 Test results of 10-door problem with level 1 in Flow profile, level 1 in Arrival time and level 2 in Available time

General Solution

Initial Solution	Initial Revenue	Initial Traveling Cost	Initial Time Penalty Cost
2635.51	3053.51	418	0
Upper Bound of Profit	Upper Bound of Revenue	Lower Bound of Traveling Cost	Lower Bound of Time Penalty Cost
4423.88	4726.88	303	0
TS Solu.	Revenue	Traveling Cost	Time Penalty Cost
4301.38	4726.88	400	25.5
Proportion of Profit UB	Proportion of Revenue UB		
97.23%	100.00%		

Door assignment

Origin	Assig. Door
O1	Door 4
O2	Door 7
O3	Door 8
O4	Door 3
O5	Door 2
O6	Door 9
Destination	**Assig. Door**
D1	Door 5
D2	Door 10
D3	Door 1
D4	Door 6

Storage Lane Assignment		Outgoing Trailer Assignment			
Cargo between each pair of origin destination	Assig. Storage Lane	Assig. Truck	Arriving Time	Depart. Time	Staging Time
O1 to D1	Not Assigned	Truck 13	1	1	0
O2 to D1	Not Assigned	Truck 12	1.5	1.5	0
O3 to D1	Not Assigned	Truck 13	1	1	0
O4 to D1	Not Assigned	Truck 14	2	2	0
O5 to D1	Not Assigned	Truck 15	1.5	1.5	0
O6 to D1	Not Assigned	Truck 16	2.5	2.5	0
O1 to D2	Not Assigned	Truck 21	1	1	0
O2 to D2	Not Assigned	Truck 22	1.5	1.5	0
O3 to D2	Lane 3	Truck 26	1	2.5	1.5
O4 to D2	Not Assigned	Truck 24	2	2	0
O5 to D2	Lane 3	Truck 26	1.5	2.5	1
O6 to D2	Not Assigned	Truck 26	2.5	2.5	0
O1 to D3	Lane 4	Truck 31	1	1.5	0.5
O2 to D3	Not Assigned	Truck 31	1.5	1.5	0
O3 to D3	Not Assigned	Truck 33	1	1	0
O4 to D3	Not Assigned	Truck 34	2	2	0
O5 to D3	Lane 2	Truck 34	1.5	2	0.5
O6 to D3	Not Assigned	Truck 36	2.5	2.5	0
O1 to D4	Not Assigned	Truck 41	1	1	0
O2 to D4	Not Assigned	Truck 43	1.5	1.5	0
O3 to D4	Lane 3	Truck 43	1	1.5	0.5
O4 to D4	Not Assigned	Truck 44	2	2	0
O5 to D4	Not Assigned	Truck 45	1.5	1.5	0
O6 to D4	Not Assigned	Truck 46	2.5	2.5	0

Notations:
O1: Origin 1
D1: Destination 1
Truck 11: The #1 truck to Destination 1

Table 5.15 Test results of 10-door problem with level 1 in Flow profile, level 2 in Arrival time and level 1 in Available time

General Solution

Initial Solution	Initial Revenue	Initial Traveling Cost	Initial Time Penalty Cost
2635.51	3053.51	418	0
Upper Bound of Profit	Upper Bound of Revenue	Lower Bound of Traveling Cost	Lower Bound of Time Penalty Cost
4423.88	4726.88	303	0
TS Solu.	Revenue	Traveling Cost	Time Penalty Cost
2952.97	3247.47	290	4.5
Proportion of Profit UB	Proportion of Revenue UB		
66.75%	68.70%		

Door assignment

Origin	Assig. Door
O1	Door 2
O2	Door 8
O3	Door 9
O4	Door 3
O5	Door 4
O6	Door 7
Destination	Assig. Door
D1	Door 1
D2	Door 10
D3	Door 5
D4	Door 6

Storage Lane Assignment		**Outgoing Trailer Assignment**			
Cargo between each pair of origin destination	Assig. Storage Lane	Assig. Truck	Arriving Time	Depart. Time	Staging Time
O1 to D1	Not Assigned	Truck 11	1	1	0
O2 to D1	Not Assigned	Truck 12	3	3	0
O3 to D1	Not Assigned	Truck 13	2	2	0
O4 to D1	Not Assigned	Truck 14	4	4	0
O5 to D1	Not Assigned	Truck 15	1.5	1.5	0
O6 to D1	Not Assigned	Truck 16	3	3	0
O1 to D2	Not Assigned	Truck 21	1	1	0
O2 to D2	Not Assigned	Truck 22	3	3	0
O3 to D2	Not Assigned	Truck 23	2	2	0
O4 to D2	Not Assigned	Truck 24	4	4	0
O5 to D2	Lane 4	Truck 23	1.5	2	0.5
O6 to D2	Not Assigned	Truck 26	3	3	0
O1 to D3	Not Assigned	Truck 31	1	1	0
O2 to D3	Not Assigned	Truck 32	3	3	0
O3 to D3	Lane 4	Truck 33	2	2	0
O4 to D3	Not Assigned	Truck 34	4	4	0
O5 to D3	Not Assigned	Truck 35	1.5	1.5	0
O6 to D3	Not Assigned	Truck 36	3	3	0
O1 to D4	Not Assigned	Truck 41	1	1	0
O2 to D4	Not Assigned	Truck 43	3	3	0
O3 to D4	Lane 4	Truck 43	2	3	1
O4 to D4	Not Assigned	Truck 44	4	4	0
O5 to D4	Not Assigned	Truck 45	1.5	1.5	0
O6 to D4	Not Assigned	Truck 46	3	3	0

Notations: ***O1: Origin 1***
D1: Destination 1
Truck 11: The #1 truck to Destination 1

Table 5.16 presents the test results of a 10-door problem with level 1 in Flow profile, level 2 in Arrival time and level 2 in Available time (*122* trial). As explained above, the decrease in profit in *121* trial is caused by the shorter Available time. Trial *122* obtained an objective function value of 4246.38 that is 95.99% of the profit upper bound, which can also be explained by the changing of the Available time. Compared with trial *121*, trial *122* has an average Available time of 3.55 rather than 1.825, therefore, more cargo can be consolidated and shipped out in a single outgoing trailer which increases the trailer utilization.

The solution for a 10-door problem with level 2 in Flow profile, level 1 in Arrival time and level 1 in Available time (trial *211*) is shown in Table 5.17. The profit in this solution is 7298.66 is 90.75% of the upper bound and revenue reaches 96.24% of the revenue upper bound.

The solution of the 10-problem with the same level of Flow profile and Arrival time but with level 2 in Available time (trial *212*) is listed in Table 5.18. We notice that trial *212* gives the same solution as the trial *211*, which indicates that level 1 of Available time is long enough for a good consolidation process.

The next trial is for a problem with level 2 in both Flow profile and Arrival time, and with level 1 (*221* trial) in Available time. The results are shown in Table 5.19. As the standard deviation of Arrival time increases from 0.585 to 1.114, it is more difficult to consolidate cargos from different origins. Furthermore, the decrease in Available time makes the situation even worse for the consolidation process. For these reasons, the objective function value for this problem only reaches 6612.86 which is 82.23% of the profit upper bound.

The last trial is for a 10-door problem with all level 2 in Flow profile, Arrival time, and Available time (trial *222*) and the results are shown in Table 5.20. As the Available time increases, it becomes easier to consolidate cargos and the objective function value is 7397.66 which reaches 91.99% of the profit upper bound.

Table 5.16 Test results of 10-door problem with level 1 in Flow profile, level 2 in Arrival time and level 2 in Available time

General Solution

Initial Solution	Initial Revenue	Initial Traveling Cost	Initial Time Penalty Cost
2635.51	3053.51	418	0
Upper Bound of Profit	Upper Bound of Revenue	Lower Bound of Traveling Cost	Lower Bound of Time Penalty Cost
4423.88	4726.88	303	0
TS Solu.	Revenue	Traveling Cost	Time Penalty Cost
4246.38	4726.88	426	54.5
Proportion of Profit UB	Proportion of Revenue UB		
95.99%	100.00%		

Door assignment

Origin	Assig. Door
O1	Door 2
O2	Door 9
O3	Door 8
O4	Door 3
O5	Door 4
O6	Door 7
Destination	**Assig. Door**
D1	Door 1
D2	Door 6
D3	Door 5
D4	Door 10

Storage Lane Assignment		Outgoing Trailer Assignment			
Cargo between each pair of origin destination	Assig. Storage Lane	Assig. Truck	Arriving Time	Depart. Time	Staging Time
O1 to D1	Not Assigned	Truck 11	1	1	0
O2 to D1	Not Assigned	Truck 12	3	3	0
O3 to D1	Not Assigned	Truck 13	2	2	0
O4 to D1	Not Assigned	Truck 14	4	4	0
O5 to D1	Not Assigned	Truck 15	1.5	1.5	0
O6 to D1	Not Assigned	Truck 16	3	3	0
O1 to D2	Not Assigned	Truck 21	1	1	0
O2 to D2	Not Assigned	Truck 22	3	3	0
O3 to D2	Lane 6	Truck 25	2	3	1
O4 to D2	Not Assigned	Truck 24	4	4	0
O5 to D2	Lane 4	Truck 25	1.5	3	1.5
O6 to D2	Not Assigned	Truck 25	3	3	0
O1 to D3	Lane 2	Truck 31	1	3	2
O2 to D3	Not Assigned	Truck 31	3	3	0
O3 to D3	Lane 5	Truck 33	2	2	0
O4 to D3	Not Assigned	Truck 34	4	4	0
O5 to D3	Lane 4	Truck 34	1.5	4	2.5
O6 to D3	Not Assigned	Truck 36	3	3	0
O1 to D4	Not Assigned	Truck 41	1	1	0
O2 to D4	Not Assigned	Truck 43	3	3	0
O3 to D4	Lane 3	Truck 43	2	3	1
O4 to D4	Not Assigned	Truck 44	4	4	0
O5 to D4	Not Assigned	Truck 45	1.5	1.5	0
O6 to D4	Not Assigned	Truck 46	3	3	0

Notations:

O1: Origin 1

D1: Destination 1

Truck 11: The #1 truck to Destination 1

Table 5.17 Test results of 10-door problem with level 2 in Flow profile, level 1 in Arrival time and level 1 in Available time

General Solution

Initial Solution	Initial Revenue	Initial Traveling Cost	Initial Time Penalty Cost
3817.59	4466.59	649	0
Upper Bound of Profit	Upper Bound of Revenue	Lower Bound of Traveling Cost	Lower Bound of Time Penalty Cost
8042.17	8534.17	492	0
TS Solution	Revenue	Traveling Cost	Time Penalty Cost
7298.66	8213.66	874	41
Proportion of Profit UB	Proportion of Revenue UB		
90.75%	96.24%		

Storage Lane Assignment / **Outgoing Trailer Assignment**

Cargo between each pair of origin destination	Assig. Storage Lane	Assig. Truck	Arriving Time	Depart. Time	Staging Time
O1 to D1	Not Assigned	Truck 11	1	1	0
O2 to D1	Lane 4	Truck 12	1.5	2	0.5
O3 to D1	Not Assigned	Truck 13	1	1	0
O4 to D1	Not Assigned	Truck 12	2	2	0
O5 to D1	Lane 3	Truck 15	1.5	2.5	1
O6 to D1	Not Assigned	Truck 15	2.5	2.5	0
O1 to D2	Lane 2	Truck 22	1	1.5	0.5
O2 to D2	Not Assigned	Truck 22	1.5	1.5	0
O3 to D2	Not Assigned	Truck 23	1	1	0
O4 to D2	Not Assigned	Truck 24	2	2	0
O5 to D2	Lane 5	Truck 22	1.5	1.5	0
O6 to D2	Not Assigned	Truck 26	2.5	2.5	0
O1 to D3	Lane 2	Truck 31	1	1.5	0.5
O2 to D3	Not Assigned	Truck 31	1.5	1.5	0
O3 to D3	Lane 2	Truck 35	1	1.5	0.5
O4 to D3	Lane 3	Truck 34	2	2.5	0.5
O5 to D3	Not Assigned	Truck 35	1.5	1.5	0
O6 to D3	Not Assigned	Truck 34	2.5	2.5	0
O1 to D4	Not Assigned	Truck 41	1	1	0
O2 to D4	Lane 4	Truck 42	1.5	2	0.5
O3 to D4	Lane 2	Truck 42	1	2	1
O4 to D4	Not Assigned	Truck 42	2	2	0
O5 to D4	Lane 3	Truck 45	1.5	2.5	1
O6 to D4	Lane 4	Truck 45	2.5	2.5	0

Door assignment

Origin	Assig. Door
O1	Door 2
O2	Door 9
O3	Door 7
O4	Door 3
O5	Door 8
O6	Door 4
Destination	Assig. Door
D1	Door 1
D2	Door 6
D3	Door 5
D4	Door 10

Notations: ***O1: Origin 1***
D1: Destination 1
Truck 11: The #1 truck to Destination 1

Table 5.18 Test results of 10-door problem with level 2 in Flow profile, level 1 in Arrival time and level 2 in Available time

General Solution

Initial Solution	Initial Revenue	Initial Traveling Cost	Initial Time Penalty Cost
3817.59	4466.59	649	0
Upper Bound of Profit	Upper Bound of Revenue	Lower Bound of Traveling Cost	Lower Bound of Time Penalty Cost
8042.17	8534.17	492	0
TS Solu.	Revenue	Traveling Cost	Time Penalty Cost
7298.66	8213.66	874	41
Proportion of Profit UB	Proportion of Revenue UB		
90.75%	96.24%		

Door assignment

Origin	Assig. Door
O1	Door 2
O2	Door 9
O3	Door 7
O4	Door 3
O5	Door 8
O6	Door 4
Destination	**Assig. Door**
D1	Door 1
D2	Door 6
D3	Door 5
D4	Door 10

Storage Lane Assignment		Outgoing Trailer Assignment			
Cargo between each pair of origin destination	Assig. Storage Lane	Assig. Truck	Arriving Time	Depart. Time	Staging Time
O1 to D1	Not Assigned	Truck 11	1	1	0
O2 to D1	Lane 4	Truck 12	1.5	2	0.5
O3 to D1	Not Assigned	Truck 13	1	1	0
O4 to D1	Not Assigned	Truck 12	2	2	0
O5 to D1	Lane 3	Truck 15	1.5	2.5	1
O6 to D1	Not Assigned	Truck 15	2.5	2.5	0
O1 to D2	Lane 2	Truck 22	1	1.5	0.5
O2 to D2	Not Assigned	Truck 22	1.5	1.5	0
O3 to D2	Not Assigned	Truck 23	1	1	0
O4 to D2	Not Assigned	Truck 24	2	2	0
O5 to D2	Lane 5	Truck 22	1.5	1.5	0
O6 to D2	Not Assigned	Truck 26	2.5	2.5	0
O1 to D3	Lane 2	Truck 31	1	1.5	0.5
O2 to D3	Not Assigned	Truck 31	1.5	1.5	0
O3 to D3	Lane 2	Truck 35	1	1.5	0.5
O4 to D3	Lane 3	Truck 34	2	2.5	0.5
O5 to D3	Not Assigned	Truck 35	1.5	1.5	0
O6 to D3	Not Assigned	Truck 34	2.5	2.5	0
O1 to D4	Not Assigned	Truck 41	1	1	0
O2 to D4	Lane 4	Truck 42	1.5	2	0.5
O3 to D4	Lane 2	Truck 42	1	2	1
O4 to D4	Not Assigned	Truck 42	2	2	0
O5 to D4	Lane 3	Truck 45	1.5	2.5	1
O6 to D4	Lane 4	Truck 45	2.5	2.5	0

Notations: ***O1: Origin 1***
D1: Destination 1
Truck 11: The #1 truck to Destination 1

Table 5.19 Test results of 10-door problem with level 2 in Flow profile, level 2 in Arrival time and level 1 in Available time

General Solution

Initial Solution	Initial Revenue	Initial Traveling Cost	Initial Time Penalty Cost
3817.59	4466.59	649	0
Upper Bound of Profit	Upper Bound of Revenue	Lower Bound of Traveling Cost	Lower Bound of Time Penalty Cost
8042.17	8534.17	492	0
TS Solu.	Revenue	Traveling Cost	Time Penalty Cost
6612.86	7428.86	750	66
Proportion of Profit UB	Proportion of Revenue UB		
82.23%	87.05%		

Door assignment

Origin	Assig. Door
O1	Door 4
O2	Door 3
O3	Door 9
O4	Door 2
O5	Door 8
O6	Door 7
Destination	Assig. Door
D1	Door 5
D2	Door 10
D3	Door 1
D4	Door 6

Storage Lane Assignment		Outgoing Trailer Assignment			
Cargo between each pair of origin	Assig. Storage Lane	Assig. Truck	Arriving Time	Depart. Time	Staging Time
O1 to D1	Not Assigned	Truck 11	1	1	0
O2 to D1	Lane 3	Truck 12	3	4	1
O3 to D1	Not Assigned	Truck 13	2	2	0
O4 to D1	Not Assigned	Truck 12	4	4	0
O5 to D1	Lane 3	Truck 16	1.5	3	1.5
O6 to D1	Not Assigned	Truck 16	3	3	0
O1 to D2	Lane 4	Truck 21	1	2	1
O2 to D2	Lane 4	Truck 23	3	3	0
O3 to D2	Not Assigned	Truck 21	2	2	0
O4 to D2	Not Assigned	Truck 24	4	4	0
O5 to D2	Lane 3	Truck 26	1.5	3	1.5
O6 to D2	Not Assigned	Truck 26	3	3	0
O1 to D3	Lane 4	Truck 31	1	2	1
O2 to D3	Not Assigned	Truck 33	3	3	0
O3 to D3	Not Assigned	Truck 31	2	2	0
O4 to D3	Not Assigned	Truck 36	4	4	0
O5 to D3	Lane 3	Truck 31	1.5	2	0.5
O6 to D3	Lane 2	Truck 36	3	4	1
O1 to D4	Not Assigned	Truck 41	1	1	0
O2 to D4	Lane 3	Truck 42	3	4	1
O3 to D4	Not Assigned	Truck 43	2	2	0
O4 to D4	Not Assigned	Truck 42	4	4	0
O5 to D4	Not Assigned	Truck 45	1.5	1.5	0
O6 to D4	Not Assigned	Truck 46	3	3	0

Notations: ***O1: Origin 1***
D1: Destination 1
Truck 11: The #1 truck to Destination 1

Table 5.20 Test results of 10-door problem with level 2 in Flow profile, level 2 in Arrival time and level 2 in Available time

General Solution

Initial Solution	Initial Revenue	Initial Traveling Cost	Initial Time Penalty Cost
3817.59	4466.59	649	0
Upper Bound of Profit	Upper Bound of Revenue	Lower Bound of Traveling Cost	Lower Bound of Time Penalty Cost
8042.17	8534.17	492	0
TS Solu.	Revenue	Traveling Cost	Time Penalty Cost
7397.66	8213.66	750	66
Proportion of Profit UB	Proportion of Revenue UB		
91.99%	96.24%		

Door assignment

Origin	Assig. Door
O1	Door 4
O2	Door 2
O3	Door 9
O4	Door 3
O5	Door 7
O6	Door 8
Destination	**Assig. Door**
D1	Door 5
D2	Door 10
D3	Door 1
D4	Door 6

Storage Lane Assignment		Outgoing Trailer Assignment			
Cargo between each pair of origin destination	Assig. Storage Lane	Assig. Truck	Arriving Time	Depart. Time	Staging Time
O1 to D1	Not Assigned	Truck 11	1	1	0
O2 to D1	Lane 2	Truck 12	3	4	1
O3 to D1	Lane 1	Truck 14	2	2	0
O4 to D1	Not Assigned	Truck 12	4	4	0
O5 to D1	Lane 2	Truck 15	1.5	3	1.5
O6 to D1	Not Assigned	Truck 15	3	3	0
O1 to D2	Lane 4	Truck 21	1	3	2
O2 to D2	Not Assigned	Truck 21	3	3	0
O3 to D2	Lane 4	Truck 25	2	3	1
O4 to D2	Not Assigned	Truck 24	4	4	0
O5 to D2	Lane 2	Truck 25	1.5	3	1.5
O6 to D2	Not Assigned	Truck 25	3	3	0
O1 to D3	Lane 4	Truck 32	1	3	2
O2 to D3	Not Assigned	Truck 32	3	3	0
O3 to D3	Not Assigned	Truck 35	2	2	0
O4 to D3	Not Assigned	Truck 36	4	4	0
O5 to D3	Lane 2	Truck 35	1.5	2	0.5
O6 to D3	Lane 3	Truck 36	3	4	1
O1 to D4	Not Assigned	Truck 41	1	1	0
O2 to D4	Lane 2	Truck 44	3	4	1
O3 to D4	Lane 4	Truck 44	2	4	2
O4 to D4	Not Assigned	Truck 44	4	4	0
O5 to D4	Lane 2	Truck 44	1.5	4	2.5
O6 to D4	Lane 3	Truck 44	3	4	1

Notations:
O1: Origin 1
D1: Destination 1
Truck 11: The #1 truck to Destination 1

Using the objective function value (profit) of these 8 trials (shown in Table 5.21) as the input, a General Linear Model was generated in *Minitab 14*. The Minitab report is attached in Appendix A.

Table 5.21 Profit solution and percent of upper bound for each trial

Flow Profile Level	Arrival Time Level	Available Time Level	Profit	% Upper Bound
1	1	1	4301.38	97.23%
1	1	2	4301.38	97.23%
1	2	1	2952.97	66.75%
1	2	2	4246.38	95.99%
2	1	1	7298.66	90.75%
2	1	2	7298.66	90.75%
2	2	1	6612.86	82.23%
2	2	2	7718.17	95.97%

From the Minitab report, we have the regression equation:

Profit = 5600 – 1649.48(flow profile) + 200.01(AT) – 308.54(AVT) + 150.84(flow profile)*(AT) – 14.81(flow profile)*(AVT) + 308.54(AT)*(AVT)

*AT stands for ***Arrival Time***

*AVT stands for ***Available Time***

Table 5.22 T value of each factor

	Flow Profile	AT	AVT	Flow Profile *AT	Flow Profile *AVT	AT*AVT
T-value	-111.37	13.5	-20.83	10.18	-1	20.83

Table 5.22 lists the T value of each factor in this experiment:

According to the T-test results, we conclude that:

1. The Flow Profile is a significant factor to the Profit.
2. The significance of other factors, Arrival Time and Available Time, is moderate.

3. The 2-factor interaction of AT and AVT is also moderate significant to the profit. This can be explained by the fact that these two factors together decide how much time cargo can stay in the facility which can significantly affect the time penalty cost.

5.3 Conclusions

This research illustrates that in order to achieve an efficient cross dock operation we should consider not only the cross dock distribution center individually, but also the overall logistics system as a whole. The analysis indicates that the cross dock cargo consolidation operations are affected by many factors such as flow profile, arrival time, and available time. We notice that all these factors are not determined solely within the cross dock distribution center, but are related to other components in the logistics system. The flow profile can be affected by the location of the cross docking center. If the center is located in a location that can serve more suppliers, the consolidation process becomes easier as there are more choices to consolidate when loading the shipping trucks. Also for the arrival time and available time, it is a good strategy that we schedule the transshipping cargo in the way that the variance of arrival time of cargo from different origins is small. With such a schedule, even in the case that the available time for cargo is short, in order to maintain the time efficiency of cross docking operations, it is still possible to consolidate more cargo so that the utilization of the shipping trailer is increased.

In the real case, the flow profile, cargo arrival time and available time are already determined. With these constraints, the Model we developed can be used to optimize the shipping trailer utilization and minimize the material handling equipment traveling distance using a staging process and still maintain the time efficiency with respect to the cargo available time.

Chapter 6 Summary and future research

6.1 Summary

The current literature on cross-docking can be classified into three major areas: layout design or the door assignment problem, staging location assignment, and scheduling. Even though these three areas of research are full of opportunities to be explored separately, there is no literature published that address all three from an integrated perspective.

The objective of the door assignment problem is to minimize the travel distance of material handling equipment. A shortest distance is assigned to each pair of incoming and outgoing doors so the sum of travel distance can be calculated based on the quantity flowing through them. However, in reality, material handling equipment may not always travel through these shortest paths. With respect to the staging process, unit loads unloaded from incoming trucks can be staged for a short period of time in a cross-docking facility, because of the storage capacity, these storage locations may not always be in the shortest path. Also, considering the trailer assignment problem, we know that higher outgoing trailer utilization can increase the efficiency of the logistics system. Whether a cargo is assigned to a specific outgoing truck depends on its transshipment schedule. With the purpose of increasing the trailer utilization, some cargo can be staged for a short period of time waiting for later arriving cargo, so they can be shipped out in one truck. This trailer assignment strategy will affect the staging process, which will also affect the door assignment.

The most significant contribution of this research is the development of a new model that integrates door assignment, staging location assignment and trailer assignment problems, which could provide us a higher point of view of the operations in a cross-docking facility. The more integrated perspective results in a nonlinear mixed integer model. During the model analysis, we found that it is unlikely to obtain optimal solutions to problems with more than 10 doors. A 10-door problem was tested in *Lingo 8.0 Professional* with a Pentium 4 2.4 GHz and 512M RAM PC, after 8 hours, only a feasible solution could be found. In order to tackle larger problems, we develop a Tabu Search heuristic coded in the JAVA language based on an open source Tabu Search framework named *OpenTS*. This heuristic provides us a much more efficient way of solving this model. For some 10-door problems, it takes around 5.5 hours for 18 iterations. Since we are lacking an optimal solution to compare and evaluate the results obtained from Tabu Search heuristic, an upper-bound is calculated. The tabu search heuristic program found solutions within 82% to 97% of the upper-bounds for the different data sets tested in this research, and the TS solution also beat the feasible solution from *Lingo*.

Considering the fact that there exist two transshipment scenarios in cross-docking operations:

Scenario 1: Transshipment cargo has a flexible schedule, without losing the time efficiency of cross-docking; each cargo is assigned a time window. Within this time window, cargo can be staged shortly waiting for later arriving cargo so they can be shipped out in a same outgoing truck. Model 1 in this research is based on this scenario.

Scenario 2: All transshipment cargo has a fixed and strict schedule, their arrival and departure times are determined beforehand within the overall logistics systems. Since the schedule is not flexible, we cannot use the time window of each cargo to help to consolidate cargo as we do in scenario 1. Therefore, in this case, in order to reduce costs, we focus on material handling equipment traveling distance in the facility considering the door assignment and staging location assignment.

For the purpose of comparing these two scenarios, a simplified model based on model 1 is presented. This model minimizes the traveling cost inside the cross-docking facility considering door assignment and staging location assignment, while the time factor is excluded. From the test result for a 10-door problem, we notice that the MH traveling cost of Model 1 is only 80.4% of the traveling cost of Model 2, which can be explained by some of the cargo travels through the shortest distance without any staging process.

In order to get more insight into how different factors affect the profit level, a multi-factor experiment was designed that includes 3 factors, each with 2 levels: flow profile, arrival time, and available time for transshipping cargo. From the experimented results, we can conclude that the flow profile is the most significant factor for profit, the significance of arrival time and available time is moderate, and finally the 2-factor interaction of arrival time and available time is significant.

This research illustrates that in order to achieve an efficient cross dock operation we should consider not only the cross dock distribution center individually, but also the overall logistics system as a whole. The analysis indicates that the cross dock cargo consolidation operations are affected by many factors such as flow profile, arrival time, and available time. We notice that all these factors are not determined solely within the cross dock distribution center, but are related to other components in the logistics system. However, in the real case that the flow profile, cargo arrival time and available time are already determined, the Model we developed can be used to optimize the shipping trailer utilization and minimize the material handling equipment traveling distance using a staging process and still maintain the time efficiency with respect to the cargo available time.

6.2 Future research

Model 1 need to be further examined for bigger cross dock having more number of doors. Cross docks with around 40 – 120 door should be considered to build on this integrated perspective and to study their impact in a more complex environment. However, the tabu search program developed during this research is not efficient enough. We are going to modify the current program in order to handle large scale cross dock problems.

Reference

1. Bartholdi, J.J. and K.R. Gue (2004), The Best Shape for a Crossdock, *Transportation Science*, 38, pp. 235-244
2. Bartholdi, J.J. and K.R. Gue (2000), Reducing labor cost in an LTL crossdocking terminal, *Operation Research*, 48(6), pp. 823-832
3. Bartz-Beielatein, T., A. Chmielewski, M. Janas, B. Naujoks and R. Scheffermann (2006), Optimizing Door Assignment in LTL-Terminals by Evolutionary Multiobjective Algorithms, *2006 IEEE Congress on Evolutionary Computation*, Sheraton Vancouver Wall Centre Hotel, Vancouver, BC, Canada, July 16-21, 2006
4. Bermudez, R. & Cole M.H. (2001), A genetic algorithm approach to door assignments in breakbulk terminals, *Technical Report MBTC-1102*, Mack-Blackwell Transportation Center, University of Arkansas, Fayettevilee, Arkansas, 2001.
5. Connolly, D.T. (1990), An improved annealing scheme for the QAP, *European Journal of Operational Research*, 46 pp. 93-100
6. Gue, K.R. and K. Kang (2001), Staging Queues in Material Handling and

Transportation Systems, *Proceedings of the 2001 Winter Simulation Conference*, Dec. 9-12, Arlington, VA, pp. 1104-1108.

7. Gendreau, M. (2003), An introduction to tabu search. F. Glover, G. A. Kochenberger, eds. *Handbook of Metaheuristics*. Kluwer Academic Publishers, Boston, MA.
8. Hauser, K. and Chung, C. (2003), Comparison of two crossdocking layouts at a JIT manufacturer. *Issues in Information Systems*, 15, pp. 486–492.
9. Hauser, K. and Chen H. Chung (2006), Genetic algorithms for layout optimization in crossdocking operations of a manufacturing plant, *International Journal of Production Research*, Vol. 44, No. 21, 1 November 2006, pp. 4663–4680
10. Iris, F.A. Vis and J.R. Kees (2004), Short term storage of goods in cross-docking operations, *Progress in Material Handling Research*: 2002 , R. Meller et al. (eds.), Material Handling Institute, Charlotte, North Carolina, pp. 441-452.
11. Kondo, T, M Tamai, N Vining - *US Patent 6,698,655*, 2004, Super cross-dock logistics system and method.
12. Li, Y, A Lim and B Rodrigues. (2004), Crossdocking—JIT scheduling with time windows, *Journal of the Operational Research Society 55*, pp. 1342–1351
13. Magableh, G.M., M.D. Rossetti and S. Mason (2005), Modeling and analysis of a generic cross-docking facility, *Proceedings of the 2005 Winter Simulation Conference*, Orlando, Florida, pp. 1613 – 1620
14. OpenTS – Java Tabu Search, [Online], Available from: http://www.coin-

or.org/Ots/index.html

15. Sandal, S. (2005), Staging approaches to reduce overall cost in a crossdock environment. *Thesis (M.S.)*, University of Missouri-Columbia.
16. Scheithauer, G. (1992), *Operations Research Proceeding* 1991, Springer-Verlag Berlin Heidelberg, pp. 445-452
17. Thornburg, K. & A. Hummel, Lingo Tutorial, [Online], Available from http://www.icaen.uiowa.edu/~ie166/Private/Lingo.pdf
18. Ting C-J., and C-H. Chen, W-L Weng Chen, "Coordinate Inbound and Outbound Schedules at a Cross-Docking Terminal" *The Fifth Asia-Pacific Conference on Industrial Engineering and Management Systems*, Gold Coast, Australia, December 12-15, 2004. (NSC -2213-E-155-050 91)
19. Tsui, L. Y. and C. H. Chang, (1992), Optimal Solution to a Dock Door Assignment Problem, *Computers & Industrial Engineering*, 23, pp. 283-286.
20. Taylor, G.D. and J.S. Noble (2004), Determination of Staging Needs in a Crossdock Environment, *Proceedings of 2004 Industrial Engineering Research Conference*, Houston, TX, May 15-18, 2004, 6 pages.
21. Uday, M.A. and S. Viswanathan (2000), Effective cross docking for improving distribution efficiencies, *International Journal of Logistics: Research and Applications*, 33, pp. 291-302.

APPENDIX A

General Linear Model: Profit versus Flow Profile, AT (Arrival Time), AVT (Available Time)

Factor	Type	Levels	Values
Flow Profile	fixed	2	1, 2
AT	fixed	2	1, 2
AVT	fixed	2	1, 2

Analysis of Variance for Profit, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Flow Profile	1	21766307	21766307	21766307	12402.56	0.006
AT	1	320036	320036	320036	182.36	0.047
AVT	1	761582	761582	761582	433.95	0.031
Flow Profile*AT	1	182025	182025	182025	103.72	0.062
Flow Profile*AVT	1	1755	1755	1755	1.00	0.500
AT*AVT	1	761582	761582	761582	433.95	0.031
Error	1	1755	1755	1755		
Total	7	23795041				

S = 41.8925   R-Sq = 99.99%   R-Sq(adj) = 99.95%

Term		Coef	SE Coef	T	P
Constant		5600.01	14.81	378.09	0.002
Flow Profile					
1		-1649.48	14.81	-111.37	0.006
AT					
1		200.01	14.81	13.50	0.047
AVT					
1		-308.54	14.81	-20.83	0.031
Flow Profile*AT					
1	1	150.84	14.81	10.18	0.062
Flow Profile*AVT					
1	1	-14.81	14.81	-1.00	0.500
AT*AVT					
1 1		308.54	14.81	20.83	0.031

Least Squares Means for Profit

Flow Profile	Mean	SE Mean
1	3951	20.95
2	7249	20.95
AT		
1	5800	20.95
2	5400	20.95

AVT

1		5291	20.95
2		5909	20.95

Flow Profile*AT

1	1	4301	29.62
1	2	3600	29.62
2	1	7299	29.62
2	2	7200	29.62

Flow Profile*AVT

1	1	3627	29.62
1	2	4274	29.62
2	1	6956	29.62
2	2	7543	29.62

AT*AVT

1	1	5800	29.62
1	2	5800	29.62
2	1	4783	29.62
2	2	6017	29.62