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Cross-Docking: A Proven LTL Technique to Help Suppliers Minimize Products' Unit Costs Delivered to the Final Customers

Vahid Ghomi
University of Mississippi

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CROSS-DOCKING: A PROVEN LTL TECHNIQUE TO HELP SUPPLIERS MINIMIZE PRODUCTS' UNIT COSTS DELIVERED TO THE FINAL CUSTOMERS

A dissertation presented in partial fulfillment of requirements for the degree of PhD of Business Administration
in the Department of Marketing
The University of Mississippi

by

VAHID GHOMI

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ABSTRACT

This study aims at proposing a decision-support tool to reduce the total supply chain costs (TSCC) consisting of two separate and independent objective functions including total transportation costs (TTC) and total cross-docking operating cost (TCDC). The full-truckload (FT) transportation mode is assumed to handle supplier→customer product transportation; otherwise, a cross-docking terminal as an intermediate transshipment node is hired to handle the less-than-truckload (LTL) product transportation between the suppliers and customers. TTC model helps minimize the total transportation costs by maximization of the number of FT transportation and reduction of the total number of LTL. TCDC model tries to minimize total operating costs within a cross-docking terminal. Both sub-objective functions are formulated as binary mathematical programming models. The first objective function is a binary-linear programming model, and the second one is a binary-quadratic assignment problem (QAP) model. QAP is an NP-hard problem, and therefore, besides a complement enumeration method using ILOG CPLEX software, the Tabu search (TS) algorithm with four diversification methods is employed to solve larger size problems. The efficiency of the model is examined from two perspectives by comparing the output of two scenarios including; i.e., 1) when cross-docking is included in the supply chain and 2) when it is excluded. The first perspective is to compare the two scenarios' outcomes from the total supply chain costs standpoint, and the second perspective is the comparison of the scenarios' outcomes from the total supply chain costs standpoint. By addressing a numerical example, the results confirm that the present of cross-docking within a supply chain can significantly reduce total supply chain costs and total transportation costs.

DEDICATION

This dissertation is dedicated to my parents, who have been a constant source of support and encouragement during the challenges of my education and life. I am truly thankful for having you in my life. This work is also dedicated to my beloved wife, Mina, who has always loved me unconditionally and whose never-ending support and encouragement have helped me to work hard for the things that I aspire to achieve.

ACKNOWLEDGMENTS

I express my deepest appreciation to my advisor, Dr. Bahram Alidaee as I am indebted to him. Since my first contact with him in 2013 till now, Dr Alidaee have believed in me like nobody else and gave me endless support. It all started in Fall 2013 when he encouraged me to apply for the program. On the academic level, Dr Alidaee have taught me fundamentals of conducting scientific research in the mathematical programming models. Under his supervision, I learned how to define a research problem, find a solution to it, and finally publish the results. On a personal level, Dr Alidaee inspired me by his diligence and passion. To summarize, I would give Dr Alidaee most of the credit for becoming the kind of Doctor I am today.

In the meantime, I would like to express my appreciation to my committee members, Dr. Saim Kashmiri, Dr. David M. Gligor, and Sumali Conlon.

The last but not the least, I could not have financed my studies without the assistantship provided by the Department of Marketing in the School of Business Administration.

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CHAPTER 1

INTRODUCTION

1.1 Role of Supply Chain Logistics and Cross-Docking

The world is changing rapidly and continuously, and the impact of all those changes on the transport & logistics (T&L) sector is significant, as a connecting link in the ‘global economy.’

To increase customer satisfaction and deliver superior customer value while pursuing profit [197; 101; 83], not only manufacturers are demanded to produce low cost, high quality and mass customized products [187; 69; 81], but logistics companies need to handle a high volume of items in a short amount of time [248; 141; 139].

One of the most challenging part of a supply chain is how to quickly deliver products from suppliers to customers [235] with high quality, and low cost. These would be almost impossible to achieve without efficient and effective cooperation, coordination and communication at all level that constitute a supply chain logistics [106; 249].

Supply chain logistics is the backbone of global trade and is the task of integrating organizational units along a supply chain and coordinating materials, information and financial flows to fulfill final customer demands with the aim of improving competitiveness of the manufacturing company as a whole [214]. Logistical considerations which encompass physical distribution of goods and lead-time for transportation are generic factors that create considerable challenges across numerous industries and commercial sectors [240; 129]. Although shorter delivery lead-time is a key factor in remaining competitive [121; 199; 129] and may attract greater number of customers and generate more demand, it directly relates to manufacturer inventory and sometimes cause additional holding costs [240; 129].

In order to reduce the pressure created by holding additional inventory on the firms production unit costs [199; 129], an efficient supply chain logistics can streamline the material flow from the point of production of product to the point of sale by reducing material handling, operation cost [27; 22], inventory holding, order picking, transportation costs and delivery time [248; 8; 226], while meeting customers' expectations. In fact, an efficient supply chain logistics can make a tradeoff between service level and inventory [121] by lowering transshipment costs, inventory holding costs, backorder or loss of sale costs [209], turnover time [40; 214], storage space, handling cost, order-cycle time [206; 112; 210]; and increasing inventory turnover, customer responsiveness [248], and on-time deliveries [37; 33].

1.2 Transition from Warehousing to Cross-Docking

As customers are requiring shorter lead times, as suppliers are offering more support in terms of product assortments and order assemblies, as supply chains become more streamlined, and as information technology becomes even more timely and more accurate [213], supply chain logistics which is the task of integrating organizational units along a supply chain and coordinating materials, information and financial flows, raise insignificance [214]. Since the major supply chain functions including purchasing, manufacturing, inventory, and distribution are strongly interrelated by materials and information flows, they cannot be individually managed [58; 230; 68]. In fact, it is impossible to achieve a state of integrated supply chain logistics capabilities without cooperation, coordination and communication at all levels within the firm and among the other components of a supply chain [106; 249; 81] including suppliers, manufacturers, warehouses and customers carrying goods from the upstream to the downstream side of the supply chain [58; 230; 68]. Under the pressure of global competition, companies try to cut costs by reducing inventory at every step of their operation, including distribution centers [12; 248; 128] to rapidly fulfill final customer demands [139] with the aim of improving competitiveness of the manufacturing company [214]. The main purpose of distribution center is its ability to fulfill a variety of orders in a timely manner.

Banyai (2013A) [21] noted that less inventory helps to improve the return of investment. Also, it can also mean less space, equipment, and labor required for handling and storing the products, as well as a reduced risk of product damages and obsolescence [77]. To this end, a well-designed distribution network system is very important [139]. A major component of any distribution network system is a warehouse or distribution center [139]. The operation of a distribution center typically consists of five basic functions: receiving, sorting, storing, retrieving, and shipping [248; 13; 198; 139; 21; 226] as well as inspection, packaging, palletizing, wrapping and labeling as per the instructions of the owner to manage customer demand-driven in a flexible environment [176; 142]. Developing policies to improve the efficiency of distribution center operation is an active research area [139]. The goal in any logistics system is to reduce the costs and increase the productivity; however, the best way to achieve it is not by simply improving a function (i.e., receiving, sorting, storing, retrieving, and shipping), but by eliminating it if feasible [248; 13; 198; 139; 21; 226].

By reducing the costs and increasing the productivity firms like Walmart gains not only competitive advantage but also sustainable competitive advantage among other rivals in the competitive environment. Wal-Mart's sustainable competitive advantage for more than ten years is driven by its low-cost, high volume strategy which targets in increasing profits and customer satisfaction. It retains a low cost of operation, which helps it to produce and sell a variety of goods of competitive or even better quality, at lower costs than other competitive retailers. In fact, Wal-Mart can beat and surpass its competitors such as Kmart and Target Corporation in the 1980s by decreasing prices and therefore implementing its sustainable competitive advantage [203; 27]. Barney (1995a) [25] distinguished between firms' competitive advantages and firms' sustainable competitive advantages. He explained that a firm is said to have a competitive advantage when it is implementing a value creating strategy not simultaneously being implemented by any current or potential competitors. These competitive advantages reflect the firm′s ability to provide a high level of customer service resulting in a competitive performance which cannot be easily copied by other competitors and thus have sustainable value [193; 117]. On the other hand, a firm is said to have a sustained competitive advantage when it is implementing a value creating strategy not only simultaneously being implemented by any current or potential competitors; but other firms are unable to duplicate the benefits of this strategy [25]. According to resource-based view (RBV) theory, a company like Walmart use rare, valuable, inimitable, and non-substitutable resources to ensure sustained competitive advantage [24; 56].

To this end, many companies apply different strategies to control their costs; one of them is streamlining the distribution operations [3]. As far as the concern of carrying inventory, many companies try to avoid keeping unnecessary level of inventory in their system. Kelsch (1996a) [121] addressed that carrying inventory is more expensive than expediting material flow in the supply chain.

The goal of supply chain management is to maximize the efficiency in the supply chain processes by minimizing total supply chain costs and delivering superior end customer value [53; 52; 16]. Thus, companies should embrace lean strategies with an emphasis on cost cutting [36; 133; 81]. Christiansen et al. (2003) [52] noted that manufacturers are becoming leaner by reducing inventory. Therefore, to cut wastes and reduce inventory values, including incoming stock, work-in-progress, finished goods, scrap and waste, and inventory in transit [100; 142], many companies are expecting smaller lots, shipped more frequently to replenish their stock levels [64; 111; 142]. This is supported with Theory of Constraints (TOC) which offers for low inventories, but constantly adjusting to ensure that there are no availability problems [86].

1.3 Cross-docking: Definitions

In a traditional warehouse, the freight moves from receiving to storage and then picking the freight to shipping by orders [232; 3; 183; 39; 118; 125; 229; 4].

Overall, a supplier tends to produce products in big batches, and thus sends FTs of one type of products directly to the customers to remove intermediate people to reduce the final costs of the products. But a retailer hardly ever needs high volumes of a single product. A traditional way to cope with the problem is to make the products transit through a stock. The stock can be in the manufacturer’s plant, near the retailer’s shop, or somewhere in between. The manufacturer can push all the production to storage while retailers pull only the needed quantity. This solution is quite flexible but has a major drawback: stock is expensive. The desire to decrease logistics costs has led organizations to investigate more profitable approaches to supply chain management [99] named cross-docking. Cross-docking system proposes an alternative solution: transferring goods directly from the truck coming from the manufacturer to several outbound trucks going to different retailers. The outbound trucks are loaded with goods coming from different manufacturers, i. e. different inbound trucks. Overall, the goods stay less than 24 hours in the platform, which accelerates the flow of goods and eliminates most of the storage costs – making it a lean approach [8; 30; 59; 60; 119; 126; 180; 233; 239]. The main purpose of the cross-dock in this setting is to enable a just-in-time supply of readily usable materials to the manufacturer. Accordingly, value-added logistics activities, such as packaging, pricing, or labeling are often performed at the cross-dock [27].

For a formal definition of cross-docking, it is a logistics technique that eliminates the storage and order picking functions of a warehouse while still allowing it to serve its receiving and shipping functions. The idea is to transfer shipments directly from inbound to outbound trailers without storage in between. Shipments typically spend less than 24 hours in a cross-docking terminal, sometimes less than an hour [68; 205; 232; 8; 79; 143; 185; 109; 43]. A cross-docking terminal is a facility (Figure 1) in a supply chain that receives goods from suppliers and sorts these goods into alternative groupings based on the downstream delivery point [233]. No reserve storage of the goods occurs, and staging occurs only for the short periods required to assemble a consolidated, economical load for immediate onward carriage via the same mode as the receipt or a different mode [233].

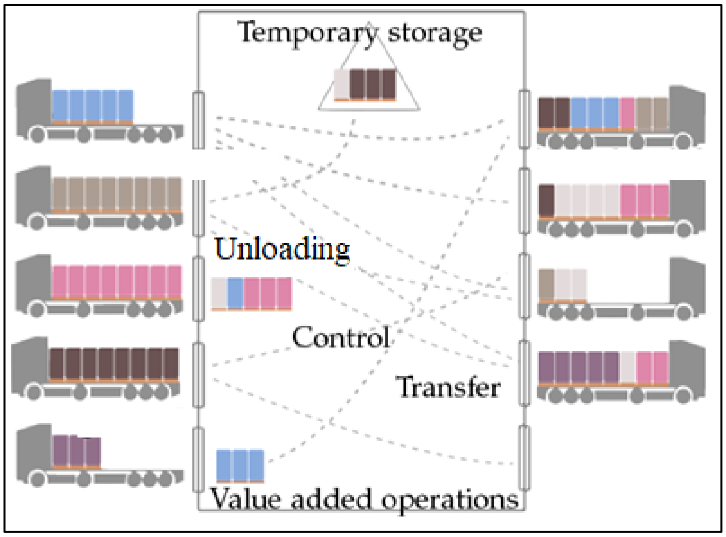


Figure 1: Cross-docking terminal

The products consolidation is the common function among all cross-docking terminals. Freight (or shipment) consolidation combines small orders to enable dispatch of larger loads resulting in lower transportation cost per unit weight, but delay before releasing the aggregate shipment may impact customer service [99; 43]. At the same time, the rapid transshipment of products at the cross-dock should enhance distribution responsiveness [43].

1.4 Cross-Docking a system to achieve Supply Chain Flexibility, Agility and Lean

Supply chain managers used to believe that buffering of inventory or excessing capacity help to increase supply chain flexibility to achieve competitive advantage, especially in more competitive and uncertain markets [100; 94; 178]. However, business communities have realized that being flexible toward customers' volatile demands in a production system only is insufficient [174]. Thus, in addition of flexibility in terms of increasing buffering of inventory, firms demand to integrate, synchronize and converge intrafirm and interfirm operational and strategic capabilities [153; 204; 71; 72; 83] throughout the supply chain from the suppliers to the end customers to eliminate redundant or wasted effort.

Supply Chain Performance is defined as the extended supply chain's activities in meeting end-customer requirements, including product availability, on-time delivery, and all necessary inventory [123; 55] and capacity in the supply chain to deliver that performance in a responsive manner [42].

Scholars listed dimensions of supply chain performance as; flexibility [207; 44], growth in market shares, growth in sales, customer satisfaction, new customer projects [28; 56], overall customer value [142], supply chain competence [95; 178], supply chain integration and information sharing among supply chain members [186; 82], Efficient Consumer Response, Vendor Managed Inventory, Continuous Replenishment Programs [53; 52], supplier satisfaction [32], and finally, efficient consolidation of goods from different suppliers to a specific set of customers to reduce total logistics costs [109].

To monitor the performance of a supply chain, Beamon (1999) [28] and Christiansen et al. (2003a) [52] suggested three types of measures including: 1) efficiency-oriented measures which relate to the usage of resources, 2) effectiveness-oriented measures that are related to outputs, and, 3) response-oriented measures that are related to the flexibility of the supply chain.

Mentzer and Konrad (1991a) [151] defined effectiveness as the extent to which customer-related objectives have been met by providing superior service to the common end customer. In order to maximize supply chain effectiveness firms should be agile to create a responsive supply chain to the volatile customers' demands [54; 142; 81]. Secondly, to maximize the efficiency - the ratio of resources utilized against the results derived [151; 84] - in the supply chain processes, all members in a chain should try to minimize total supply chain costs [87] i.e., Nine Areas of Waste consisting of motion, inventory, waiting time, transportation, information, quality, overproduction, processing, and creativity. This can be achieved by performing lean strategy across supply chain by reducing delivery times, reducing distortion of demand, reducing double buffering, reducing administrative costs, and improved capacity planning [52]. Thirdly, supply chain flexibility which is the capabilities of promptness and the degree to which a firm can adjust its speed is applied to increase the level of supply chain responsiveness [142]. Supply chain flexibility which is a reaction to dynamic environments [222; 80; 56] enables supply chain to adjust its speed, destinations, and volume in line with changes in customer demand [172]. Lummus et al. (2003) [169] extended that increased supply chain flexibility results in improved performance in customer service, time-to-market, cycle time, and supply chain inventory [142]. In fact, within lean, cost efficiency is considered a market winner, while within agility and flexibility it is only considered a market qualifier.

False trade-offs between cost and quality occur when there is redundant or wasted effort, poor control or accuracy, or weak coordination. Gligor (2014) [87] implied that firms can achieve superior operational efficiencies, effectiveness, and responsiveness by integrating their operations with those of their supply chain members. They extended that this integration can facilitate the identification of redundant aspects; i.e., extra inventory, redundant and extra efforts, of their operations not only within their firms but across their supply chain. This integration helps firms to focus on optimizing core activities to maximize the speed of response to changes in customer expectations [47; 55], cycle time, throughput, work-in-process (WIP) and shipped containers as performance measures [216] within stable material flows [83].

For the sake of increasing supply chain effectiveness, efficiency and responsiveness [52] and reducing costs and risks associated with buffering of inventory in any level of supply chain (i.e., work-in-progress, finished goods, scrap and waste, and inventory in transit) [213; 165] as well as unnecessary activities (i.e., Handling, Storage, Operations administration, General administrative expenses) [202], many firms switch-over from traditional warehouse to cross-docking [3].

Traditional warehousing and shipping procedures demand distribution centers with stocks of product on hand to deliver to customers. On the other hand, cross-docking is the unloading of product directly from incoming transport onto outbound transport with little and short-term storage in between. Generally, cross-docking is assumed to be a logistics technique which tries to eliminate all non-value adding activities [165], damage, cost and time and increase inventory turnover, customer responsiveness, better control of the distribution operation [248], on-time deliveries [37], and shortens total transfer time and transportation lead-time [198].

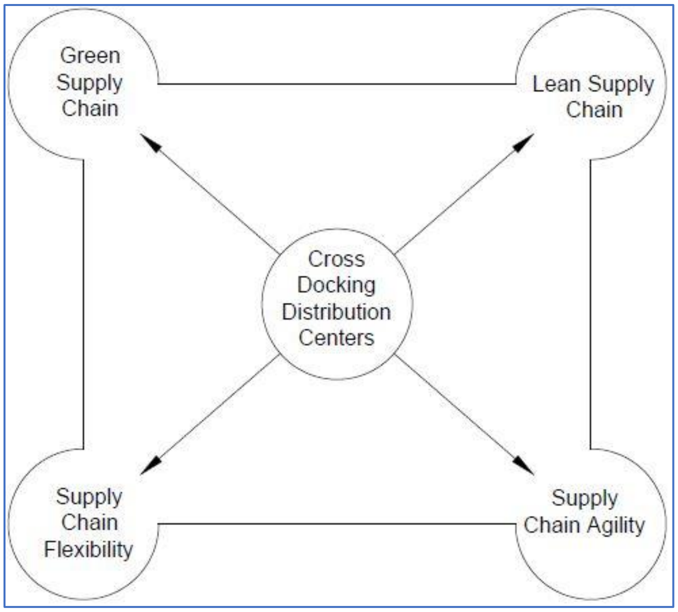


Figure 2: The role of cross-docking in supply chain management

By removing non-value adding activities and increasing the responsive level of supply chain, cross-docking is a technique that simultaneously can facilitate 1) supply chain flexibility which is the ability of supply chain to adapt or respond to change [44] effectively, 2) supply chain agility which is defined as the capacity to rapidly respond to changing customer needs [81], and

3) lean processes by eliminating wastes and unnecessary efforts [147; 69]. Figure 2 illustrates a holistic conceptual perspective of the effect of cross-docking technique on supply change flexibility, supply chain agility, and lean process.

1.5 Shapes of Cross-docking terminals

Although the material handling workload is one of the most common performance measures used in cross-docking studies, other criteria such as congestion, the relationship between travel distances and labor/equipment costs (which depend on the cross-docking shape and/or type of material handling systems used for different types of freight moved through the cross-docking), storage space for equipment and for load staging ahead of OTs, potential wait time in the yard for ITs, among others, may also play a role in cross-docking operation and design [41]. In fact, cross-docking appears to be more sensitive to shape when flows are more uniform.

Bartholdi and Gue (2004a) [27] have done a comprehensive research over the shape of cross-docking terminals. The explained that with respect to labor costs, the best shape for small to mid-sized cross-docking is a narrow rectangle or I-shape, which gets maximum use of its most central doors. They discuss that docks in the shape of an I, L, or T are most common, but unusual ones may be found, including those in the shape of a U, H, or E [27]. Usually scholars divide cross-docking terminals into I, L (Yellow Transportation, Chicago Ridge, IL), T (American Freightways, Atlanta, GA), U (Consolidated Freightways, Portland, OR), H (Central Freight, Dallas, TX), E (unknown owner, Chicago) and X shapes [27; 243; 135] which are shown in Figure 3. The developed countries (such as America and Canada) have already built more than CDCs, and I-shaped CDC among them are the most widespread [27; 243; 135].

But what is the best shape of a cross-dock? At first glance, it seems that an I-dock would always be better than an L-dock of the same number of doors because the L-shaped dock has two additional corners but no greater centrality. Yet there are instances in which the L-shape was slightly preferable to the I. This arose because the L-shape changes the distances between doors, and some pairs of doors are closer than they otherwise would be. Occasionally, just the right patterns of freight flow matched this altered distribution of distances so that the total labor cost was slightly less than that for an I-shape. Such events were extreme cases and rare in our testing. Consequently, as a practical matter, an I-shaped dock is always preferable to an L-shaped dock of the same number of usable doors. Similarly, the H-shaped dock performed slightly better than an X in a few extreme cases even though, as a practical matter, the X is superior to the H. [27; 103]. Finally, Bartholdi and Gue (2004) [27] concluded that the best shape depends on the distribution of flows and the fraction of doors devoted to receiving; and when size of the cross-dock increase the most labor-efficient shapes for a cross-docking are I, T, and X, successively.

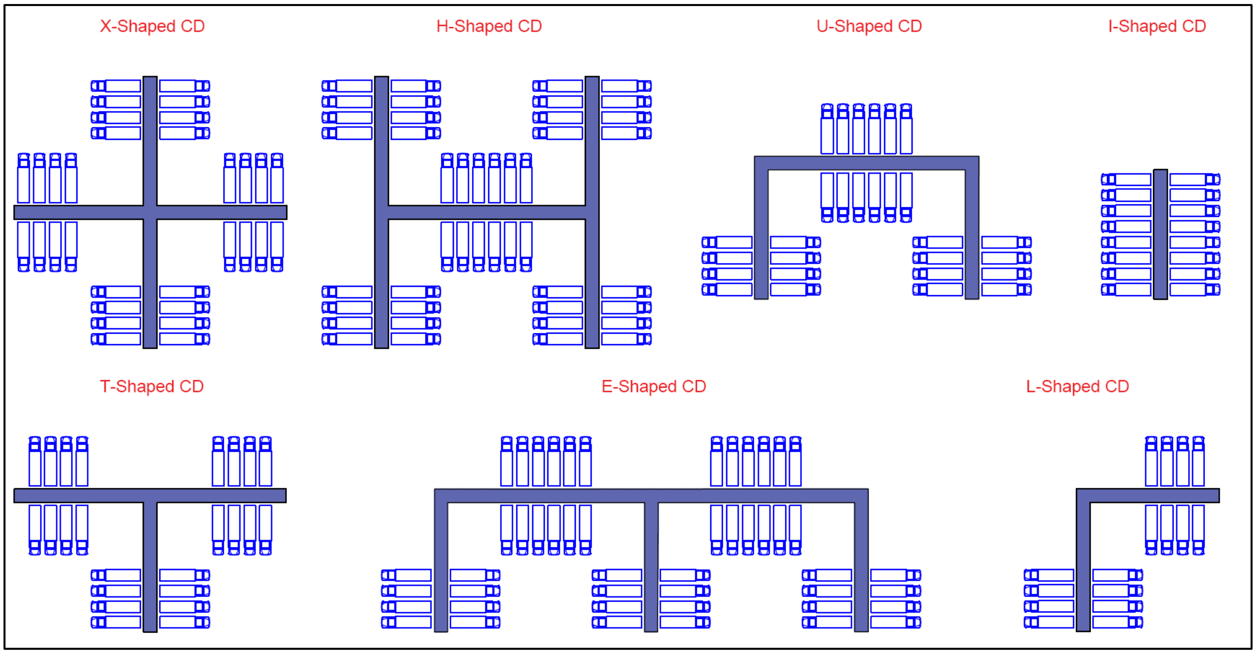


Figure 3: Conceptual frameworks of cross-docking terminals

1.6 Products Suitable for Cross-docking

Cross-Docking is highly relevant in practice to the zero-inventory policy companies which is to avoid obstacles for material handling devices inside a terminal and can be applied in refrigerated foods but for any kind of good, i.e., flowers, cosmetics or medicine, which require special treatment provided only by trailers [38]. This leads to reduce the inventory holding costs, order picking costs, transportation costs and delivery time [131]. Therefore, one of the industries that this technique can mainly serve are the industries of perishable products [131]. In the following, there are a list of materials that are better suited to cross-docking than others.

1. The first and foremost important material are perishable items that require immediate shipment. The peculiarity of frozen foods and other refrigerated products, e.g., pharmaceuticals, vegetables, flowers, cosmetics or medicine, frozen foods, and dairy products, which typically require special arrangements as it is to be made sure that the cooling chain is not broken [38; 68]. Such cross-docking terminals require a special kind of transshipment policy: Perishable goods are not allowed to be intermediately stored inside the terminal. Once a frozen good is unloaded from its refrigerated inbound trailer it must be directly moved and loaded onto its designated refrigerated outbound trailer. Otherwise a defrost and decay of comestible goods threatens [12; 200; 181; 68; 214; 169; 229; 4].
2. High-quality items that do not require quality inspections during goods receipt
3. Promotional items and items that are being launched
4. Products with a constant demand or low demand variance
5. Pre-picked, pre-packaged customer orders from another production plant or warehouse
6. Products that are pre-tagged (barcoded, RFID), pre-ticketed, and ready for sale at the customer.

1.7 Research Objective

In this research, a supply chain of multiple suppliers and retailers and a single cross-docking terminal is considered. The aim of this study is to minimize total costs of supply chain including total transportation costs, i.e., transportation between supplier and customers, between suppliers and cross-docking terminal and between cross-docking terminal and customers; and total transshipment costs inside the cross-docking terminal. The cross-dock facility that is just to consolidate goods and products received from suppliers and transfer directly to the customers.

In this research we seek to achieve the following objectives as;

1. To minimize total supply chain transportation costs by
    a. Maximizing number of FT product transportation directly from suppliers to customers, from suppliers to CD terminal, and from CD terminal to customers' sites.
    b. Minimizing number of LTL transportations from the suppliers' sites to CD terminal and then from CD terminal to the customers' sites.
2. To minimize total operations costs of products' transshipment within CD terminal by minimization of total products' travel distance costs using best truck-door assignments.
3. Achieving these objectives helps us minimize the overall products' unit costs comparing the time that CD terminal is excluded from the supply chain and products are directly transported from suppliers to customers.

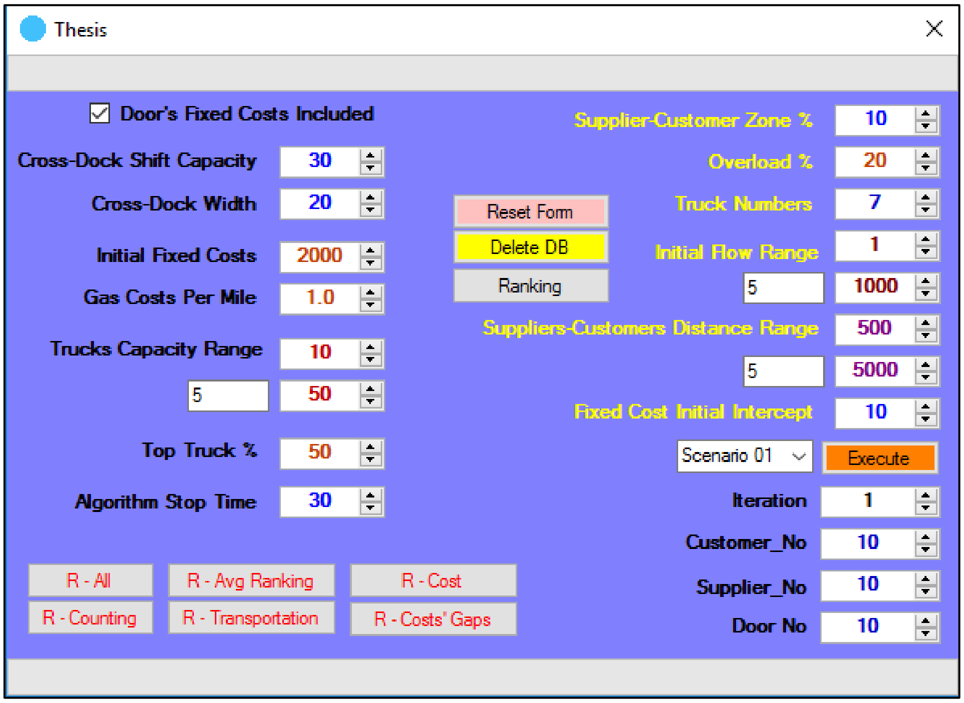
1.8 Contribution to Research

In addition, to contribute to existing literature, the present study also contribute to practical implications as are listed in the following.

1. Consideration of a dynamic fleet with different capacities in which their fixed and variable costs vary based on their associated capacities.
2. A novel binary-linear programming algorithm is developed that maximizes total number of FT product transportation and minimizes the total number of LTL transportation. This ultimately helps managers reduce overall products' unit costs and miles transported from

suppliers to customers. Further, this algorithm helps increase the overall transportation quality by reducing total number of LTL transportation. In fact, the higher transportation quality, the more transportation networks tend to green supply chain management.

3. Concerning the minimization of the total operations costs within the cross-docking terminal, local neighborhood search and Tabu-search are employed. Some practical interest in the Tabu search algorithm comes from its potential use in heuristic, in which the search neighborhood is defined in terms of trucks-doors assignment.
4. In addition of the conventional format of quadratic assignment problems of cross-docking related problems, we assume different fixed costs for the cross-dock doors on both. The assumed fixed cost is a function of door location and door shift-capacity. Dynamic fixed costs force model to arrange truck-door assignment is such way to avoid congesting in the middle of terminal.
5. Practical parameter setting for tabu search algorithm is another contribution of this research to the literature. Here, we assume that the type of initial solution to start algorithm, type of diversification method, type of tabu-tenure structure; i.e., pairwise or point, and finally type of loop searching within the solutions influence the quality of the tabu-search output. Therefore, initially we experiment different combinatorial setting, and after the best combination is determined, the larger size problems are examined.



☑ Door's Fixed Costs Included

Cross-Dock Shift Capacity	30
Cross-Dock Width	20
Initial Fixed Costs	2000
Gas Costs Per Mile	1.0
Trucks Capacity Range	10
	5 50
Top Truck %	50
Algorithm Stop Time	30
Supplier-Customer Zone %	10
Overload %	20
Truck Numbers	7
Initial Flow Range	1
	5 1000
Suppliers-Customers Distance Range	500
	5 5000
Fixed Cost Initial Intercept	10
	Scenario 01
Iteration	1
Customer_No	10
Supplier_No	10
Door No	10

Figure 4: Interface of the Simulated Software Developed in Visual Studio C-Sharp

1.9 Research Methodology

The following steps will be followed to solve the problem discussed in this research:

1. Review the literature related to distribution centers and cross-docking terminals from the mathematical programming perspective.
2. Categorize the assumptions and objective functions of those mathematical programming models related to cross-docking researches.
3. Perform sensitivity analysis and Taguchi method to test the effect of the key parameters on the formulated model's outputs.
4. Code the formulated model using Visual Studio C#, SQL Server 2014, and Matlab. An interface of the developed software is shown in Figure 4.

1.10 Organization of the Dissertation

Chapter 1 introduced the research problem, the objective, its significance, and the methodology. Chapter 2 gives presents a comprehensive literature review on cross-docking from th mathematical programming perspective. As the objective of this study is to minimize the total supply chain costs (TSCC) including the total transportation costs (TTC) and total cross-docking's operations costs (TCDC), chapter 3 is assigned to just formulate the binary-linear mathematical programming models that helps minimize TTC. Chapter 4 concentrates on just cross-docking operations' costs using a binary-quadratic mathematical programming model to minimize TCDC. Chapter 5 concentrates on product transportation from the suppliers' sites to the customers' sites while cross-docking is included within the supply chain. This chapter is a combination of chapter 3 and 4 which seeks to minimize TSCC. In all chapter 3, 4, and 5, parameters settings are discussed to show the best factors' combinations that help achieve the minimum corresponding objective functions. Chapter 6 presents the conclusion and direction for the future research.

Before beginning chapter 3, there is a prelude section on page 74 that shows the direction of the mathematical formulation in detail.

CHAPTER 2

CROSS-DOCKING: STATE OF THE ART

Abstract

A less-than-truckload (LTL) transportation company manages shipments that individually do not justify a dedicated trailer. Cross-docking is a practice in LTL logistics that is designed to deliver LTL products from suppliers to a wide variety of customers from wholesalers, to large retailers, to small stores with limited demands. Cross-docking is a practice when customers are geographically dispersed, and a direct supplier→customer shipment or milk-run strategy results in partially empty trucks and longer transportation lead times as products are stored further away from their demand points. Consolidation of differently sized shipment with the same destination to full-truck loads is the pivotal character of a cross-docking terminal that helps achieve the economies in transportation costs. Therefore, many companies now consider it equally valuable for increasing speed to market, especially if their supply chain is global. Despite the existence of many types of research on cross-docking from the mathematical programming perspective, there is still lacking a comprehensive literature review that offers valuable insight to researchers. So, to build scientific progress, this paper presents an overview of the cross-docking studies. This study tries to categorize all assumptions and objective functions that are the interests of many analytic-oriented scholars in the context of cross-docking. In the meantime, a long list of advantages and challenges associated with cross-docking services are presented. To develop a comprehensive

literature review,198 journal articles and doctoral dissertation are reviewed. With the help of this study, the existing literature is discussed, and future research needs are identified.

2.1Introduction

In contrast to the traditional warehousing that is considered as a "high-cost function associated with dark and dusty sheds" [217], with a cross-docking operation, warehousing is perceived as a vital value-adding link between suppliers and retailers. Cross-docking helps eliminate storage (inventory holding cost) and order picking (labor intensive) activities from the five significant warehousing functions including receiving, storage, order picking, packing and shipping [190; 27; 217; 241].

The cross-docking process consists of three main stages including, unloading, value-adding activities and consolidation, and loading with a minimum dwell time of products in between. Once an inbound truck arrives at the terminal's inbound yard for several end destinations, it is assigned to an appropriate inbound/receiving door to be unloaded. During the first stage, products (packages, boxes, cartons) are scanned, verified, and assigned to specific destinations. The second stage is accomplished during products transshipment between receiving and shipping door. The process of material handling is accomplished either manually by forklift or placing carts on dragline or automatically using slider belt conveyor, roller bed conveyor, horizontal belt conveyor, incline and decline conveyor, brake and meter conveyor, wire mesh conveyor; or portable conveyor. During the material handling process value-adding services like weighting, sizing, sorting, labeling, packaging, and consolidation are executed until the consolidated products are loaded into the outbound trucks on shipping docks to the same destinations/customers. Once an outbound truck has been loaded completely, the truck will move away from the terminal to allow another truck to dock for loading [51; 141; 205; 214; 89; 229; 67; 155].

Although Silk Road traders seem to be the pioneered that operated cross-docking [70; 130], cross-docking practice started by the US trucking industry in the 1930s using LTL operations. Then the practice spread to the US military in the 1950s and followed by Wal-Mart as the first retailer to implement it in the late 1980's. Since then it has attracted attention from academia and mostly in the recent years.

In the best of our knowledge, only three articles published in the OMEGA, present a review on cross-docking studies. Boysen and Fliedner (2010) [37] take a general approach about the truck scheduling problem and provide a classification of the considered problems. Agustina et al. (2010) [2] provide an overall perspective of the mathematical model used in the cross-docking context and classify models based on their decision levels (strategic, tactical, or operational) and then subdivided by problem type. However, neither of these papers considered vehicle routing and temporary storage. Van Belle (2012) [228] try to fill the gap of literature from different stands point and classify cross-docking studies based on the location of cross-dock terminal, layout design, cross-docking networks, vehicle routing problem, truck door assignment, truck scheduling, and temporary storage. Another type of classification is presented in this researches that has not been viewed in other three articles. The objective of this study is to categorize all assumptions and objective functions discussed in the mathematical modeling problems that are of the interests of most analytic-oriented scholars in the context of cross-docking regardless of their decision horizon's level. This categorization helps not only scholars understand the current trend of research in cross-docking but also, cross-docking practitioners to find the right literature to start or improve their cross-docking operations. Moreover, we will present a list of the advantages and challenges associated with the cross-docking practice within supply chain management.

This paper is organized as follow. The next section discusses the scope and limitation of the review. Further, the types of products suitable for cross-docking is discussed in section 3. Advantages and challenges of cross-docking practice are elaborated in section 4. Section 5 presents the literature's categorization based on the models' common assumptions and models' objective functions. Potential future researches to improve and extend the current study are discussed in section 6. The conclusion will be the final section.

2.2Scope and limitation of the review

Scholars in the field of mathematical programming are profoundly interested in researching at three levels including long-term strategic decision level, medium-term tactical decision level, and short-term operational decision level [196; 2; 68; 4].

Mathematical models in the *strategic decision level* tried to determine solutions that affect long-term horizon. This level determines decision such as number and location of cross-docking [146; 41; 2], shape (layout) of cross-docking terminal [96; 27], number of vehicles in a distribution network [2], and network design problems [2; 105]. Researches in the *tactical decision level* concern medium-term planning which cost much less compared to the strategical level. Tactical level addresses some solutions to find an optimal number of trucks at each arc in distribution network [99], assignment of inbound-trucks and outbound-trucks to cross-docking terminal's doors [220; 221; 41], and planning of deliveries in a network of cross-docking terminals [49]. The short-term plan is addressed in the *operational decision level* to determine the optimality in scheduling problem, transshipment problem, dock door assignment problem, vehicle routing problem, and product allocation problem [2; 67].

The scope of this review encompasses all cross-docking studies, in the context of linear, quadratic, and non-linear mathematical programming models. 250 mathematical programming articles with different decision horizons (operational, tactical, and strategic) are studied to address an overall aspect of the cross-docking trends in academia. Due to the diversity in mathematical programming models' formulation, the review is limited to the main assumptions and objective functions that are of interest of the most researchers.

2.3Products suitable for cross-docking

Cross-Docking is highly relevant to the zero-inventory policy and is appropriate for those industries that are dealing with valuable/perishable goods like flowers, cosmetics or medicine [38]. In the following, a list of products that need to transfer through the cross-docking systems is presented.

1. Perishable items that require immediate shipment: The peculiarity of frozen foods and other refrigerated products, e.g., pharmaceuticals, vegetables, flowers, cosmetics or medicine, frozen foods, and dairy products, which typically require special arrangements as it is to be sure that the cooling chain is not broken [38; 68]. Such cross-docking terminals require a special kind of transshipment policy: Perishable goods are not allowed to be intermediately stored inside the terminal. Once a frozen product is unloaded from its refrigerated inbound trailer it must be directly moved and loaded onto its designated refrigerated outbound trailer. Otherwise; a defrost and decay of comestible goods threatens [12; 200; 181; 68; 214; 169; 229; 4].
2. High-quality items which do not require quality inspections during goods receipt
3. Promotional items and items that are being launched
4. Products with a constant demand or low demand variance
5. Pre-packaged customer orders from another production plant or warehouse

6. Products that are pre-tagged (barcoded, RFID), pre-ticketed, and ready for sale at the customers’ sites

2.4Advantages and challenges of cross-docking systems

The cross-docking advantages make it an essential logistics practice which has received increased attention in today’s globalized market [203; 203; 76; 238; 96; 38]. Nonetheless, amidst its popularity, there are some challenges related with cross-docking [241; 232; 3; 21; 169] which could affect the performance of a firm/supply chain. In the following, you can find a list of 35 advantages and 11 challenges addressed by practitioners and scholars on cross-docking practice.

2.4.1Advantages

1. Easier for bulk orders: If a company tries to sell items in lots, it would be easier to have them labeled, packaged, and ready to ship at the cross-docking terminal than to pick up, assemble, and package them before shipment.
2. Improved Efficiency: Freight integration is handled faster in the presence of cross-docking. [228; 137; 169].
3. Improved product quality and reduced damages: Since screen product quality is handled during the unloading and staging process, labors can easily inspect inventory for defects incurred during transit [2].
4. Minimal handling equals less damage: In conjunction with the reduction in storage costs, the number of touches on each inventory item is reduced. [12; 27; 60; 60; 214; 22; 137; 128; 169].
5. Reduced storage space or warehouse footprint: Cross-docking makes sense for retailers with a limited warehouse footprint by helping them to hold their inventory at a minimum level [12; 27; 60; 22; 228; 128; 169; 179].

6. Reduced warehousing time: cross-docking help retailers store products in +a warehouse reduced to less than 24 hours [99; 234; 169].
7. Reduced labor costs: The reduction of material handling due to inventory reduction leads directly to the labor cost savings by eliminating the processes of put-away, order picking, order location, and replenishing activities. [77; 21; 179; 228; 169].
8. Centralized processing: Cross-docking retains the advantages of a centralized inventory at the manufacturing site and the consolidation of shipments at cross-docking facilities [217; 60; 231; 8; 68; 214; 139].
9. Increased turnover: High and fast inventory turnover help products move quickly through the cross-docking terminal [248; 139; 228; 140; 169].
10. Reduced safety stock: By increasing the turnover, cross-docking help reduce safety stocks at retailers' sites [21].
11. Reduced overstock: Frequent deliveries allow customers to continuously replenish inventory, ensuring that their inventories are always full of limited or no overstock [241; 209; 228; 169].
12. Improved retailers' flexibility: Fast inventory turnover increase the retailers' flexibility to respond to unpredicted demands of the customers. [12; 169; 35].
13. Reduce order cycle time: Due to the inventory reduction using cross-docking, retailers order cycle time decreases [12; 60; 60; 68; 128; 169].
14. Reduced response time to customers' order or help increase firm agility: Cross-docking helps shorten the time between a customers' order and the actual delivery of the ordered goods. [12; 232; 139; 140; 169].

15. Reduced delivery lead time and delivery: Cross-docking helps handling a high volume of items in a short amount of time and expediting the customer order [217; 228; 105; 75; 140; 169; 179].
16. Easily can simulate the system: A pilot program can demonstrate how all the chosen components inside cross-docking work [77].
17. Reduced freight costs: When the dock is in the final destinations of product, and those final destinations are a fair distance from the point of origin, cross-docking can result in significant savings in freight costs [77].
18. Low Transportation costs: The utilization of cross-docking can help reduce transportation costs. Products destined for a similar endpoint can be transported as a full load, reducing overall distribution cost [8; 228; 75; 105; 169; 214; 228].
19. Accelerate cash flow: Cross-docking can accelerate cash flow through reduced inventory level and reduced operating expenses [12; 60; 60; 68; 128].
20. Improving relationship among all chains: Miscommunication can fail the process flow and reduce total systems efficiency [231].
21. Reduced pilferage added: Savings can be gained through reduced pilferage (i.e., reduction in inventory caused by shoplifting, or petty thievery by the employees) and shrinkage (i.e., an allowance made for a reduction in the earnings of business due to wastage or theft) through faster turnarounds. [77].
22. More environmentally friendly: Transportation has fuller loads for each trip, therefore, a saving in transportation costs.
23. Reduced order picking costs: Due to inventory reduction, cross-docking can help of elimination of ‘order picking’ process [75].

24. Better control of distribution operation: Inventory reduction leads to increase inventory turnover and better control of the distribution operation [248; 139; 140].
25. Reduced bullwhip: As retailers are not carrying inventory in the distribution center using cross-docking, the retailer benefits from the bullwhip effect [99; 234; 169].
26. Increased stores availability: Cross-docking can help increase the numbers of stores that an organization has due to the LTL product delivery [169; 21].
27. Increased retailers' market share: Cross-docking helps retain current customers and capture additional market share [2] by creating less inventory, more accurate delivery times, and overall better service to customers.
28. Improved utilization resources: Cross-docking helps improve utilization of resources, i.e., to maximize productivity and valuable space utilization. Also, it increases the truck utilization by FT policy [228; 169].
29. Reduced fixed asset costs: Cross-docking provides fixed asset cost savings as it requires less facility square footage. Thus, smaller facilities need less cash expenditure to operate.
30. Reduced throughput time from suppliers to the customers: Accelerated products flow through the warehouse instead of sitting in it as storage results in faster-moving products arrive in the hands of consumers quicker [77; 12; 60; 128].
31. Increased just-in-time: Cross-docking programs support customers' just-in-time strategies [77] by harmonizing incoming flows of products with outbound flows [164; 33b; 99; 180; 40].
32. Customer Satisfaction: Cross-docking programs support customers' just-in-time strategies [77], which results in improving customer service and responsiveness [60; 231; 128].
33. Prevent to drop products' value: Cross-docking system with inventory reduction approach helps prevent products from losing their actual values.

2.4.2Challenges and drawbacks

Implementing cross-docking is not easy and needs a lot of consideration and preparation. In the following, a list of some challenges that practitioners usually face during the implementation of cross-docking is presented.

1. Project management: Implementation of cross-docking needs much management attention and takes technology, time, effort.
2. Supplier trust factor: Success of cross-docking terminals in more dependent on the operation of its suppliers that provide the right product on time and in perfect condition
3. More capital investment to set up: Setting up the terminal's structures is time-consuming and need more capital investment to make the products' transshipment run smoothly.
4. Time-consuming: The management team involved in the terminal are needed to dedicate more time to plan and follow up to ensure the process is working efficiently.
5. Expensive technology: The technology which is being used may be quite expensive [12; 169].
6. Sophisticated information technology (IT): Cross-docking must be programmed and monitored carefully and needs operations of advanced IT systems and up to date information and telecommunication system to realize the efficiencies [177; 3; 21].
7. Need close relationship: Inadequate cooperation among all components of production and distribution networks can increase the cost and minimize the benefits for all [246].
8. Risk of Shrinkage: Since products are not packed away in accordance with the specific method or style of the company, the risk of lost inventory or damaged merchandise is increased in the long term.

9. Material handling challenges: According to Bartholdi and Gue (2004) [27] material handling in cross-docking is a labor-intensive since cargo is often oddly shaped (particularly in the LTL industry), so automation is difficult.

2.5Literature review on mathematical programming models

Cross-docking mathematical programming researchers must deal with many decision factors, i.e., assumptions and constraints, during the process of short-term (operational), medium-term (tactical), and long-term (strategic) decision-making. Many applications in the cross-docking studies lead to mathematical models that can be written as mixed integer programming (MIP), non-linear programming (NLP), binary-integer programming (BIP), linear programming (LP), quadratic programming (QP), and mixed integer non-linear programming (MINLP). Apparently, there are some overlaps among some them, for instance, QP is a case of NLP or MIP. Also, QP is a specific format of BIP and vice versa. Table 1 represents a list of all publications in the field of cross-docking from different mathematical programming models' studies. It is observed that MIP has drawn attention from most scholars in recent years while MINLP has attracted the least. In those type of problems that scholars deal with integer (including binary) variables, two approaches including exact and heuristic/meta-heuristic ones are employed to find the optimal solution or at least some solutions near the optimal points (local optimum point). Exact methods like branch-and-bound, branch-and-cut, brand-and-price tree, complete enumeration method, and dynamic programming are suitable for non-NP hard and small size problems and guarantee to find the optimal solutions using the commercial solvers presented in Table 2. It is seen that the popularity of the CPLEX solver comparing to the other solvers causes it to be of interests of many researchers in cross-docking studies. Regarding the NP-hard problems that are suitable for medium-size or large-size problems, scholars employ heuristic and metaheuristic methods to find a trade-off between solution quality and computation time as well as a compromise between implementation effort and yields. Heuristic methods like hill climbing are such algorithms that try to find the optimal solutions by examining all neighborhood before deciding to move to that neighbor or to explore another, however, when they trap into the local optimum points, they stop and return solutions. In fact, the quality of their output directly links to the goodness of the initial random solution. On the other hand, metaheuristic methods like Tabu search and Genetic algorithm try to diversify the solution pool once they trap into the locality by the heuristic techniques. Table 3 and Table 4 present list of publications that implement exact, heuristic, and meta-heuristic methods in the field of cross-docking.

To reduce the sensitivity of parameters during the implementation of heuristic and meta-heuristic methods, researchers employ some statistical techniques, i.e., ANOVA, response surface method (RSM), and Taguchi method, to handle their models' parameters settings. Table 5 presents a list of all publications that apply these statistical techniques to figure the best parameters settings. Employing statistical methods like experimental design can help find useful parameter setting for the meta-heuristic as well as the heuristic methods.

Table 1: Overview of different types of mathematical programming model (MPM) in cross-docking researches

MPM	Publication
MIP	[200; 77; 248; 50; 59; 141; 180; 40; 162; 198; 215; 225; 3; 68; 188; 214; 105; 118; 128; 189; 4; 6; 66; 108; 114; 127; 145; 160; 194; 223; 35; 67; 7; 10; 17; 18; 34; 74; 78; 122; 124; 166; 191; 218; 237; 245; 247; 19]
NLP	[26; 99; 217; 48; 182; 241; 13; 38; 184; 209; 8; 46; 131; 239; 15; 22; 29; 65; 104; 140; 173; 138]
BIP	[152; 88; 33; 90; 143; 185; 79; 73; 92; 109; 126; 211; 57; 110; 155; 246; 61; 242]
LP	[146; 41; 219; 79; 183; 63; 91; 89; 11]
QP	[220; 250; 98; 212]
MINLP	[154; 161; 5]

Table 2: Overview of the usage of solvers in cross-docking researches

Software	Publication
CPLEX	[185; 219; 41; 180; 152; 225; 99; 200; 48; 50; 88; 126; 4; 108; 145; 158; 194; 17; 18; 74; 78; 122; 166; 191; 218; 242; 247]
GAMS	[105; 88; 6; 66; 114; 154; 160; 161; 5; 17; 19; 93; 124]
GRASP	[79; 79; 108]
Lingo	[3; 143; 237]
Matlab	[7]

Table 3: Overview of deterministic methods in cross-docking researches

Deterministic Method	Publications
Branch-and-bound	[217; 48; 144; 188; 33; 29; 189]
Branch-and-cut	[67; 78]
Branch-and-price tree	[57]
Complete enumeration method	[248; 185; 250]
Dynamic programming	[221; 183; 9; 23; 144; 182; 40; 38; 184; 209; 232; 104; 191]

Table 4: Overview of heuristic and meta-heuristic methods in cross-docking researches

Meta-heuristic methods	**Publications**
Ant Colony	[162; 140; 14; 138; 154]
Bee colony	[245]
Biogeography-based optimization	[93]
Differential evolution	[140; 13; 15; 139; 10; 18]
Electromagnetism-like algorithm	[198; 122]
Fuzzy Logic	[75; 161; 223]
Genetic Algorithm	[221; 198; 63; 143; 146; 152; 13; 88; 14; 239]
Harmony Search	[108]
Hybrid differential evolution	[140; 139]
Particle swarm optimization	[13; 14; 15; 163; 155; 93; 122; 237; 247]
Petri Net Model	[219]
Problem Decomposition	[246]
Pseudo-polynomial	[182]
Simulated Annealing	[198; 41; 140; 26; 38; 46; 39; 128; 189; 11; 108; 127; 138; 154; 160; 35; 7; 10; 17; 18; 19; 34; 122; 191; 242]
Simulation	[141; 109]
Strength Pareto Evolutionary	[163]
Sweeping algorithm	[66]
Tabu Search	[23; 152; 198; 225; 139; 65; 73; 140; 210; 138; 194; 211; 110; 166; 245]
Scatter Search	[211; 212]
Variable neighborhood search	[73; 128; 226; 35; 198]
Hill climbing	[163; 220; 226; 158; 57; 248; 59; 79; 250; 68; 98; 180; 99; 200; 8; 131; 29; 39; 92; 118; 114; 145; 158; 61; 218]

Table 5: Overview of result evaluators in cross-docking researches

Evaluation Method	**Publication**
ANOVA	[77; 143; 41; 198; 225; 13; 15; 139; 138; 154; 163; 10; 122]
Response Surface Methodology	[10]
Taguchi Method	[198; 225; 13; 15; 139; 226; 154; 156; 19; 122]

Regardless of the type of the solution technique which can be either exact, heuristic, or meta-heuristic, the efficiency of any mathematical programming model directly depends on the assumptions that scholars assume during the modeling process. In any mathematical programming model, there are assumptions that create boundaries or constraints of a problem. Employing assumptions, modelers make a distinction between the real work problems and the abstract models. In addition, the goal of any mathematical programming model is to find an optimal solution based on the developed objective function(s) by the researchers. The objective function is an equation to be optimized when the models' constraints match appropriately with the models' assumptions. Depending on the type of a problem, a researcher employs either a single objective function (for short-term horizon) or multi-objective functions model (for tactical or strategic time horizon).

Due to the significance of the assumptions and objective functions, in this study, we try to categorize all assumptions and objective functions that are the interests of most analytic-oriented scholars in the context of cross-docking. Here, we classify entire assumptions in the cross-docking problems into six distinct groups including 1) costs and penalties-related assumptions, 2) facility-related assumptions, 3) freight-related assumption, 4) layout-related assumptions, 5) truck-related assumptions, and finally, 6) other assumptions. The categorization of the objective functions is into three groups including utilization-based objective functions, cost-based objective functions, and time-based objective function. In the meantime, we break down each group into other sub-groups for better understanding.

2.5.1Common assumptions

2.5.1.1 Costs and penalties related assumptions

2.5.1.1.1 Facilities' fixed costs

Fixed facility expenses reflect investments in land, labor, and equipment [99]. These costs are considered when scholars examine the possibility of opening a new cross-docking terminal [115; 146]. The size and location of a cross-docking facility become the main factors [103] when the ratio of truck costs/facility costs is used as a decision-making measure to choose either have direct shipments from suppliers to customers or indirect shipments via a cross-docking facility [99]. The smaller the ratio, the lower the number of indirect shipments using the cross-docking facility and higher the number of direct transfers.

2.5.1.1.2 Transshipment (operating) costs

Transshipment (operational or throughput) costs are function of; 1) the cost per mile of forklift operation and maintenance [180] 2) the distance between the receiving door where it is unloaded and the shipping door where it is loaded [140] 3) the unit quantity of products transferred inside cross-docks per pallet [99] 4) the amount of products transported inside cross-docks per each incoming and outgoing truck [126] for material-handling activities. 5) the distance between two cross-docking facilities [209] 6) the operational cost per unit time between two cross-docks [152] 7) fixed setup cost associated with coordinating a shipment on a per-track basis [77] 8) product types transshipped inside the cross-docks [99] 9) hourly pay rate per team member [180].

2.5.1.1.3 Demand satisfaction' costs and penalties

All demands are assumed to be satisfied during the planning horizon. Yu et al. (2015) [247] assume penalty cost as a proportional to the unsatisfied demands because of products' shortage in the retail stores [241] and the unfulfilled cargo shipments by trucks [152].

2.5.1.1.4 Holding additional inventories at suppliers and customers' locations

Gumus and Bookbinder (2004) [99] ignored inventory-holding cost at manufacturers and retailers and assumed that these costs would not affect decisions on the sites of consolidation facilities. However, trucks' early arrivals at customers' location incur extra costs due to holding extra inventory at customers' warehouses [14; 131; 104; 4; 6; 161; 78; 247]. Conversely, trucks' late departures from the suppliers' location incur extra costs due to holding extra inventory at suppliers' storage.

2.5.1.1.5 Product types related costs and penalties

Mokhtarinejad et al. (2015) [156] assumed penalty costs for those perishable products which depart later than their time scheduling from the cross-docking terminals.

2.5.1.1.6 Penalties on earliness and tardiness in arrival and departure time of vehicles

Just-in-time philosophy is to fulfill a task on time and not to complete before or after that time [13], and therefore, any earliness or tardiness concerning the trucks arrival to or departure from cross-docks considers as a time violation and are discouraged [88]. Bodnar et al. (2015) [35] assumed that all tardiness costs are equal and known. Some researchers like Fakhrzada and Esfahanib (2013) [73] considered different unit penalty costs for the earliness and lateness. Yang et al. (2015) [242] assumed that penalty cost is incurred when a truck is delayed or rescheduled to another dock to complete the task due to a limited number of doors. Liao et al. (2013) [140] assumed that an outbound truck departs at a predetermined point in time. They assign a penalty for any product unit that failed to arrive at the needed outbound truck in time, and the unit penalty is product dependent.

2.5.1.1.7 Vehicle waiting times penalties

Konur and Golias (2013) [126] translated trucks' waiting time to temporary storage and the driver labor costs during the waiting time. Mokhtarinejad et al. (2015) [156] addressed a penalty cost for trucks' waiting time during unloading/loading at the docks. Boysen and Fliedner (2010) [37] assumed trucks rejection policy (lost shipment) for those trucks that their service windows are missed even if only by a few seconds. Similarly, Boysen et al. (2013) [39] defined a prespecified contract penalty when a shipment misses its outbound truck.

2.5.1.1.8 Overtime penalties

Rosales et al. (2009) [180] penalized overtime with 5 percent additional cost, but no prohibit it if it implies an economic benefit to the operating process. This cost is an agreement with a specified indemnity or an estimated loss in value for the customer [35].

2.5.1.2 Facility-related assumptions

2.5.1.2.1 Facility' breakdown

Facilities' breakdown is of those that barely researchers assume in their models. Liao et al. (2014) [138] assumed that cross-docks' doors never break down and are available throughout the scheduling period. Conversely, Adewunmi and Aickelin (2012) [1] assumed the possibility of failure for automated order picking machines within the cross-docking distribution centers. Soltani and Sadjadi (2010) [198] assumed downtime due to conveyor' breakdown which affects the flow time of products in the cross-dock.

2.5.1.2.2 Workforce

Workforces in a cross-docking researches divide into the unloading/loading labors and forklift drivers. Almost in all studies, it is assumed that all workers and forklifts' drivers are available at the beginning of the night, and when the last load is moved, the forklift driver is assigned to another inbound truck [8; 9; 17; 27; 33; 41; 140; 180; 198].

2.5.1.2.3 Temporary storage

A group of researchers allowed products to be temporarily (intermediate or staging) stored in the cross-docking shop-floor or in front of shipping dock to wait for the consolidation process [146; 37; 215; 224; 9; 118; 11; 194; 10; 17; 191; 247]. This help them have more flexibility on cross-docking process and decrease transportation costs [5]. They assumed unlimited or infinite temporary storage or intermediate buffer facilities to hold the moving products until the appropriate outbound truck comes into the shipping dock [11; 194; 35; 18; 218; 237]. The second group prohibited any intermediate storage for the sake of model simplification [198; 139; 73; 7]; and therefore, they assumed all products be shipped directly via the shortest path from their origin door to destination door [248; 143].

2.5.1.2.4 Yard space and parking

Yard space for the inbound/outbound trucks is assumed to be unlimited and available in many cross-docking studies [238; 4; 103].

2.5.1.2.5 Transferring products

Some scholars assume that products move from the receiving dock to the shipping dock on a system of conveyors at the minimum delay [145; 148; 149; 150; 167; 169; 198; 202; 205; 248]. In addition, forklifts and pallet jacks are assumed to transfer products from inbound truck to outbound truck [26; 99; 168; 41].

2.5.1.3 Freight modifications-related assumptions

2.5.1.3.1 Value-adding activities

Distribution centers like cross-docking support the orderly staging of pallets and value-added processing like packaging, pricing, labeling, material handling, sorting and repackaging [176; 142; 27; 200]. Some suppose sorting and consolidation time in the cross-docking modeling assuming different product from different suppliers [99; 73; 93]. However, to avoid the complexity of the mathematical models many others consider no consolidation for a FT shipment (nor is it possible) as well as no other value-adding processes like sorting, labeling, packing, and unpacking [220; 221; 99; 23; 224; 194; 17; 237].

2.5.1.3.2 Splitting freights

Splitting loads in the delivery process mean the demand of a customer can be delivered by more than one vehicle [154]. However, for the sake of simplicity, many researchers avoid splitting loads and assume a time window for all suppliers and customers [134; 236; 210]. Tootkaleh et al. (2015) [218] assume that splitting of the truckloads is not allowed, and all inbound trucks loads are unloaded simultaneously.

2.5.1.3.3 Preemption

Preemption is an activity in which a truck can leave the dock (node) before completely loading or unloading its freight. Boysen and Fliedner (2010) [37] define preemption when loading or unloading a truck is interrupted, the half-full trailer is removed from the dock and replaced by another one, and consequently, the unfinished trailer must revisit the terminal to finish processing. Many researchers don’t allow any types of interruption in terms of preemption during loading or unloading a truck; and assume that a docked truck must be completely processed before it leaves the dock. They believe that once trucks docked, an inbound or outbound truck cannot remove and leave the dock before it is completely unloaded or loaded [37; 214; 183; 140; 11; 138; 67; 17; 18; 19].

2.5.1.4 Layout-related assumptions

2.5.1.4.1 Doors related assumptions

Most researchers assumed the number of doors is known, fixed and limited in advance [3; 138; 191; 245; 67]. Dondo and Cerda (2013) [79] explain that the cross-docking facility should have a sufficiently large number of doors so that every truck can immediately start unloading/loading operations after it arrives at the terminal or it becomes ready for delivery duties. It is usually assumed that the number of dock doors are multiple and is greater than the number of vehicles to avoid trucks scheduling at both sides of the dock [220; 167; 41; 144; 9; 118; 140; 138; 18; 245; 19].

2.5.1.4.2 Travel distance related assumptions

Assuming the transfer velocities are all similar across the cross-dock, the time needed to transship goods from inbound to outbound trucks can be either directly proportional to rectilinear distances between the doors [167; 152; 127; 17] or just the distance between inbound and outbound doors irrespective of the type of material handling movement inside the cross-docking [220; 221; 167; 23].

2.5.1.5 Trucks-related Assumptions

2.5.1.5.1 Trucks' availability

A system is assumed to reach stability very fast because of enough transportation capacity [239]. Therefore, many researchers addressed that all inbound/outbound trucks are available, and enough at the beginning of the planning and scheduling horizon as well as anytime they are needed [41; 248; 40; 162; 46; 183; 118; 140; 4; 108; 74; 218; 191; 19].

2.5.1.5.2 Trucks' breakdown

Except for Amini and Tavakkoli-Moghaddam (2015) [10] that assume that the number of breakdowns of each truck in the unit of time follows a poison distribution function, none the scholars assumed truck's breakdown in the cross-docking studies.

2.5.1.5.3 Trucks' overload

Truck overload is prohibited in all studies, and each vehicle has a specific size which can transport lots of different products, but its weight/volume capacity must never be exceeded the truck limit [162; 198; 68; 67; 7; 18; 245].

2.5.1.5.4 Trucks’ types

The shipped parts can occupy various spaces of the vehicle [93]. While some people assume that each truck can be different (heterogeneous) in capacity and handles multiple product types [105; 67; 19], there are many researches that assume that the vehicle fleet is homogeneous, and all vehicles have the same capacity for the pickups and deliveries [99; 146; 77; 162; 46; 65; 73; 4; 108; 93]; and therefore, all vehicles have the same operational costs [73].

2.5.1.5.5 Trucks’ changeover

Trucks’ setup times are truck changing times or changeover [138], and Shiguemoto et al. (2014) [194] assumed that the duration of exchanging of vehicles on the dock (receiving or shipping) is known. Many people allowed truck changeover and believed it to be constant and the same for all vehicles [248; 63; 11; 17; 122; 237]. Dondo et al. (2011) [68] assume that the length of a vehicle stop has a fixed and a variable component. The fixed-contribution may depend on the site, while the variable part is proportional to the number of products to pick-up or delivery by the vehicle.

2.5.1.5.6 Trucks arrival and departure time’s related assumptions

In contrast with Konur and Golias (2013) [126] that assume unknown trucks arrival time window in their model, many researchers think that the arrival sequence of inbound trucks, as well as their contents and the position of the merchandise in the truck, are known as a priori to the cross-docking operators at the beginning of the planning horizon [63; 139; 183; 191]. They assume that all trucks are ready at their arrival time and their arrival time windows and pattern are known in advance [11; 126; 220; 221].

2.5.1.6 Cross-docking policy-related assumptions

2.5.1.6.1 Freight' information

Inbound truck contents assume to be known, and the containing products are supposed not to be dedicated. The shipped loads are supposed to have the same cross-sections that can utilize the whole frontal cross-section of the truck [108; 162]. Even though the cross-docking system can work more effectively and productively providing that similar product items are consolidated [157; 248; 14], there are some other researches that assume nonhomogeneous freight as freight mix on arriving vehicles in their studies [27].

2.5.1.6.2 Congestion's related assumptions

Congestion occurs when many forklifts travels are assigned to the same area as the cross dock [26; 41; 89; 229], and/or unloading/loading activity starts late which results in increasing the number of trucks and congestion at the yard [185; 183]. To avoid congestion Gelareh et al. (2015) [78] assume a priori congested cross-dock. Bozer and Carlo (2008) [41] recommended preventing congestion at the outbound doors by not assigning three or more adjacent outbound trucks. Boysen and Fliedner (2010) [37] recommend minimizing the maximum inventory level during the planning horizon, e.g., to avoid exceeding the available stock space to reduce extraordinary congestions.

2.5.1.6.3 Cross-docking's performance measures

While all customers and products have the same priority [247], on-time shipments, accuracy in order fulfillment [121; 7] and no significant operational changes during the planning horizon [41] are considered as the metrics of a cross-docking system to monitor its performance. In cross-docking, all trucks are supposed to leave docks as soon as they finish unloading all commodities, so the earlier the inbound trucks depart, the less waiting and handling time they must serve the customers [185].

2.5.1.6.4 Deadlines' policies

Each cross-docking has its own deadline and release time policy. Some scholar assumes deadlines for the trucks departure time to leave the docks corresponds to the final period of the horizon [191; 19]. They defined deadline as the truck's latest allowed departure time [33]. Boysen and Fliedner (2010) [37] explained that deadlines for the departure of outbound trucks need to be regarded to meet due dates negotiated with the customers. On the contrary, some other researchers don't consider timeframe to simplify their models as they assumed no due date as they suppose that inbound trailers do not affect the total lateness of outbound trailers [37; 15].

2.5.1.6.5 Door assignment and truck scheduling

In practice, to help managers facilitate material flows, the shipping doors are usually assigned to the destinations and receiving doors all are designated to the predefined origins [231; 143; 17; 18; 19]. However, some researchers like Wisittipanich and Hengmeechai (2015) [237], Boysen et al. (2010) [40] and Yu and Thapa (2015) [246] assume no predefined restriction (e.g., release or due dates) on trucks' assignments to existing doors, and therefore, the arriving products are transferred to any shipping dock by-products needed for each outbound truck [17].

2.5.1.6.6 Direct and indirect shipment

Supplier-customer shipping products can be routed either directly or indirectly via the distribution centers like cross-docks centers [77; 93]. If the quantity shipped equals (a multiple of) truck capacity, direct shipment is the most cost-efficient means of transportation [99; 22; 6; 156].

Otherwise, the cross-docking facilities are the best solutions and more economical to make fully truckload shipments [93].

2.5.1.6.7 Trucks' routing

It is usually assumed that vehicles route length is bounded by a given distance [93]. Researchers typically consider the long-distance from the supplier to the customer through CD [99; 146]. Yan and Tang (2009) [241] assume that the long-distance between the suppliers and the region of customers. Yin and Chuang (2015) [245] believe that the cross-docking location is constant; and, does not affect the vehicle routing decision.

Concerning the services offered by each vehicle, Hu et al. (2013) [109] assume that in the planning horizon, each truck can only serve one route at a time; and all scheduled routes are close, beginning, and ending at the cross-docking terminal [105; 160; 67]. Gonzalez-Feliu (2012) [90] assigned vehicles to each node and not used the same vehicle on more than one route.

2.5.1.6.8 Supplier-customer's orders

Each store is supposed to be innocent and will not fabricate the order quantity. In each specific period t, each retailer observes the demand of customers, meets the requirement with on-hand inventory, and replenish its stock by placing an order to the distribution center. Also, back ordering is allowable when out-of-stock occurs, while lost sales could be more appropriate in other cases [241]. The demand of the customers and suppliers' capacity assume to be positive [146; 105]. Gumus and Bookbinder (2004) [99] assume that the system is in steady state, so regardless of transportation and location decisions, the mean stock and retailer demand rates are constant.

Yan and Tang (2009) [241] and Hanchuan et al. (2013) [104] assume that each retail store's demand is correlated between two adjacent periods (simple autoregressive process), while the requests between two stores are independent and with the same parameters of the process.

2.5.1.6.9 Negligible parameters

Agustina et al. (2014) [4] assume that all vehicles' speeds are constant in all routes. Since the products arriving a cross-docking should leave it in 24 hours, the products for rare destinations are not cross-docked in practice. Gumus and Bookbinder (2004) [99] assume that transportation-time fluctuations are negligible and retailer demand rates are constant. Oh et al. (2006) [167] believe that the moving distance of incoming wheeled pallets from the receiving door to the pickup area is negligible. Boysen and Fliedner (2010) [37] suppose that the influence of packing times is insignificant and already included in the transportation time lag.

2.5.2Popular objective functions

2.5.2.1 Utilizations-based objective functions

2.5.2.1.1 To maximize throughput inside the terminal

Throughput - a surrogate to estimate buffer inventory at facilities - [120] can be considered as a cross-docking performance measure [216]. The best truck docking sequence for both inbound and outbound trucks can maximize the throughput or products turnover of the cross-docking system [23; 248; 141; 198; 37; 88; 137; 139]. A cross-docking center with maximum throughput [141; 88] accelerate the turnover of goods within the cross-docking center and reduces 1) the likelihood of late shipments, 2) the total process operational time or makespan; and 3) the inventory level at the temporary storage area. It that, cross-docking terminals can handle the zero-inventory policy demanded perishable products and refrigerated foods, i.e., flowers, cosmetics or medicine, which require special treatments [12; 200; 200; 181; 38; 68; 131; 214; 229; 65; 4].

2.5.2.1.2 To maximize trucks' synchronization inside the terminal

An optimum door assignment and truck scheduling can help synchronize better all inbound and outbound shipments [214]. Compared to traditional warehousing which incurs intensive storage and retrieval of goods costs [12; 40], an efficient transshipment process happens where inbound and outbound truckloads are synchronized, so that intermediate storage inside the terminal is kept low and on-time deliveries are ensured [38; 37; 205; 183; 39; 109].

2.5.2.1.3 To maximize routes and truck utilization

Efficient vehicle routing strategy can help reduce total operational and the transportation cost [108] by optimizing the total number of products that are transferred directly [145]. On the basis of the suppliers' locations, cross-docking facilities and customers' locations [239], some researchers try to minimize the total transportation costs by determining 1) the best transportation routes quality [99; 146; 188; 105; 65; 73], 2) the optimal number of the utilized vehicles [105; 73; 108], and 3) the minimum number of routes [105; 21] the optimum trucks' revenue [105; 143; 21; 11; 108; 145] while still satisfying the time's constraints within a cross-docking facility [143].

2.5.2.1.4 To maximize trucks utilizations to carry different products' types

It is usually interesting to determine the best products assignment to trailers when there are products of different sizes, forms, and shapes. In a real-life application some products like flowers, food products, cosmetics, medicine, and pharmaceuticals which are of course of limited shelf life, require special treatment provided only by trailers, e.g., temperature and watering [170; 38; 8; 68;

19]. Any time violation is prohibited for these types of products. For instance, once a frozen good is unloaded from its refrigerated inbound trailer it must be directly moved and loaded onto its designated refrigerated outbound trailer; otherwise, they defrost and consequently decay of comestible goods threatens [38].

2.5.2.2 Costs-based objective functions

2.5.2.2.1 To minimize transshipment (Operational) costs

Transshipment is the shipment of products or containers through an intermediate destination, then to yet another destination to change the means of transport. The best doors assignment and trucks scheduling on the cross-docks centers facilitate the transshipment process of products by 1) cutting down the level of inventories stored in the temporary storage area, and 2) acceleration of products flow from the inbound trucks to the outbound trucks. Many researchers' interests are to assign the best door assignment and trucks scheduling to minimize the transshipment (operational) costs of the cargo shipments and the total number of unfulfilled shipments at the same time [99; 146; 167; 41; 50; 152; 250; 209; 219; 9; 105; 35; 78; 93; 191; 245]. However, transshipment costs are a general term and depending on the model that is established, it can be either sum or just a few numbers of the costs including 1) holding inventories costs, 2) loading and unloading costs, 3) workload costs, 4) manpower costs, 5) cross-docking fixed costs (overhead), 6) facilities maintenance costs and 7) additional handling costs.

2.5.2.2.2 To minimize additional material handling costs due to the temporary storage

In addition to the costs associated with the storing inventories inside the temporary storage zone, there are additional movements of the products from inbound door to the storage area and from the storage area to the outbound door. Also, extra movement not only occupy the transshipment facilities which do not enhance transshipment efficiency [23; 41; 131; 183] but also lead to some unexpected product damages (lead to some errors like 1) unexpected product damages, 2) risk of loss of products, and 3) shipping errors [202; 21]. Having assumed a temporary storage facility inside the terminal, the best doors assignment and trucks scheduling as well as the best temporary storage location lead to minimize the operations costs within the terminal [220; 221; 231; 50; 59; 211; 166; 212].

2.5.2.2.3 To minimize manpower and personnel costs at cross-docks

Within a cross-docking facility, there are 7 group of people involved in the operations process including 1) inbound truck placement team, 2) unloading team 3) product movement teams like forklift drivers and dragline controllers 4) orders modification teams including unpacking, labeling, sorting, consolidation and packing 5) additional handling to/from storage area 6) loading team, and 7) outbound truck placement. Thus, the best doors assignment and trucks scheduling can translate into lower manpower (operational) costs and higher workload balancing efficiency which leads to creating a good working environment [180; 141; 131; 11; 179]. In case of using a network of conveyor belts, a conveyor belt runs through the order picking spots, and its route and speed are fixed [202; 1; 39; 43; 67]. Therefore, all costs associated with the manual product movement change to the automatic material handling expenses.

2.5.2.2.4 To minimize trucks placement costs at both sides of the terminal

Although it is supposed that truck placements along the perimeter of the depot are known [65], the best door assignment and truck scheduling can create efficient trucks placement with minimum charges [37; 8; 131; 9] as the traveling distances between inbound and outbound trucks are minimized.

2.5.2.2.5 To minimize loading and unloading service costs

Trucks service time is affected by the earliness and tardiness in truck scheduling and door assignments. In that, best truck scheduling not only can help lower the loading and unloading expenses by minimizing total service time for all trucks [73; 126; 127; 78; 93], but also, minimize total cost from tardy and early departures for all trucks in terms of deviation from the requested departure time windows [88; 89].

2.5.2.2.6 To minimize purchase costs due to sorting and consolidation process

Cross-docking also can help the retailers to purchase their products at a minimum price as the consolidation process inside the cross-docking centers facilitates LTL deliveries. As different suppliers may supply the same products at different rates, the purchasing costs can be reduced by an appropriate assignment of products demanded by retailers to suppliers during the sorting and consolidation process [5] .

2.5.2.2.7 To minimize temporary storage buffer costs at cross-docking location

Inventory reduction includes the decreasing of lots, reduction of disposition levels, increasing of quality of prognosis and disposition, reliable supply of spare parts, reduction of storage and production levels [20; 214; 208; 22]. Cross-docking is an efficient technique to lessen or even eliminate the holding of additional inventories by reducing warehouses to purely transshipment centers where receiving, and shipping are its only functions and goods are directly transferred from receiving dock to shipping docks [97; 136; 241; 162].

The best way to reduce inventory storage and the costs associated with is to optimize dock doors assignment and trucks scheduling at cross-docks centers [9; 22; 63; 143; 104; 159; 4; 6; 114; 161; 5; 191; 218; 247].

2.5.2.2.8 To minimize transportation costs

Concerning the transportation costs, researchers usually have a similar interpretation of fixed and variable costs. Freight transportation costs typically include a variable cost per item per mile (vehicle operation plus driver wages), and a fixed vehicle cost proportional to the number of trucks employed [62; 99]. Clearly, a high fixed truck-cost implies economies of scale in the network, since, by means of consolidation and careful selection of transshipment points, a third-party logistics [3PL) tries to minimize the number of trucks and increase the average shipment load in return [99]. Even though fixed costs cannot vary during the transportation planning horizon, variable costs are subjected to the traveled distance between the nodes, and therefore can be reduced by minimizing total traveled distance by vehicles [146; 143; 210; 154; 246; 7]. So, the less traveled distance reflects, the less time spent by the vehicles which help minimize the entire operations time in the supply chain. This equals to the sum of the time periods which are allocated to transport products from suppliers to customers, products' shipment from suppliers and cross-docking into the trucks [154; 155].

In the cross-docking analysis routes are divided into four categories including 1) from suppliers → terminals, 2) from terminals → destinations (retailers), 3) directly from suppliers → customers, and finally, 4) among the cross-docking terminal when more than a single terminal is assumed in the problem. However, for the sake of simplicity, some researchers just assume variable costs and exclude transportation fixed charges from their models. A list of a recent literature review on the transportation costs is presented in Table 6 in which transportation cost between every two nodes is broken down into variable costs and fixed costs.

Table 6: A brief literature review on transportation costs in cross-docking modeling

Publications	Variable Costs				Fixed Costs		
	S → CD	CD → C	S → C	CD → CD	S → CD	CD → C	S → C
Bányai (2013) [21]	√	√	---	√	---	---	---
Birim (2016) [34]	√	√	---	---	---	---	---
Charkhgard and Tabar (2011) [46]	√	√	√	---	---	---	---
Cóccola et al. (2015) [57]	√	√	√	---	---	---	---
Dondo et al. (2011) [68]	√	√	√	---	√	√	√
Galbreth et al. (2008) [77]	√	√	√	---	√	√	√
Gonzalez-Feliu (2012) [138]	√	√	---	---	---	---	---
Gümüş and Bookbinder (2004) [19]	√	√	√	√	√	√	√
Hosseini et al. (2014) [108]	√	√	√	---	---	---	---
Huang and Liu (2015) [110]	√	√	√	---	√	√	√
Mohtashami et al. (2015) [155]	√	√	---	---	---	---	---
Mousavi et al. (2013) [88]	√	√	---	---	√	√	---
Mousavi et al. (2014) [161]	√	√	---	---	√	√	---
Serrano et al. (2016) [191]	---	√	---	---	---	---	---
Vahdani et al. (2014) [90]	√	√	---	---	√	√	---
Yang et al. (2016) [242]	√	√	---	---	---	---	---
Yin and Chuang (2016) [245]	√	√	---	---	√	√	---
Yu et al. (2016) [247]	---	---	---	√	---	---	---

2.5.2.2.9 To minimize cross-docks fixed expenses

An abandoned or less used terminal is subjected to many facilities expenses which reflect investments in land to construct a new facility, fire codes, drainage, location, square-footage costs, and site access. To minimize total cross-docking fixed expenses, some researchers try to increase centers' activities by assigning more trucks to them to improve their products turnover [99; 91; 124; 93].

2.5.2.2.10 To minimize floor congestion inside the terminal

The best doors assignment and truck scheduling can reduce floor congestion within a cross-docking terminal. Many scholars try to reduce floor congestion in a cross-docking terminal as it causes 1) excessive labor cost, 2) shipments missing service commitments, 3) slow down the speed of the forklifts, 4) workers waiting time due to interference among forklifts and draglines congestions, 5) impede the (un)loading and storage operations, 6) create bottlenecks in front of stack doors with high levels of flow, 7) halt operations entirely, 8) poor product flow and throughput, and 9) long processing times or makespan [26; 27; 41; 2; 105; 143; 21; 11; 108; 145].

2.5.2.2.11 To minimize total traveled distance inside the cross-docking terminal

The movements of freights inside the terminals are usually made by fork-lift trucks, conveyors and draglines. Therefore, the entire traveling costs are determined by the distance between inbound and outbound doors; and thus, a proper door assignment and truck scheduling can minimize the extra material movement costs within the terminal [168]. Researchers always assume that the optimum door assignment and truck scheduling, a good layout, and a good temporary storage location for incoming unit loads can help reduce total weighted travel distance of the forklift trucks inside the cross-docking terminal without increasing floor congestion [143; 210; 154].

2.5.2.2.12 To minimize backorder penalty costs

Cross-docking help achieve the minimum level of inventories inside the customers storage area [209; 239; 195; 229]. This helps avoid/minimize the back ordering which happens when a customer order is not fulfilled, and the customer is prepared to wait for some time [209; 239; 126]. In this condition, retailers as the recipients of the goods enjoy reduced inventory, and improved customer service levels as their stock can be replenished more frequently, and stock-outs or shortages are averted with higher velocity [137; 39; 104; 21; 104].

2.5.2.2.13 To minimize lost profit costs

Lost profit is manifested as late satisfied orders which are the costs of the customers. These costs are realized in the form of a penalty to be paid by the suppliers or cross-docking facility depending on the framework contract of supply [21]. Lost profit at cross-docking facilities can occur either when the shipment is ready, but the number of trucks exceeds the number of available facilities [219; 73], or outbound trucks leave the cross-docking as inbound trucks arrive late or are not unloaded yet [152].

Boysen et al. (2013) [39] recommended three methods to avoid occurring the delays in a system as; first to add more additional doors inside the cross-docking terminals over a mid-term horizon, second to postpone the departure time and last to reduce the transshipment time inside the cross-docking centers. Among the three, the last one seems to be more sounds as it can be achieved via the best door's assignments and trucks scheduling.

2.5.2.2.14 To minimize customers' costs

Customers become dissatisfied either when they have additional inventory in their storage, or they lack inventory on their shelves. Early delivery increases product unit costs as it incurs the extra inventory costs at customers' location. In the meantime, any late delivery causes customer dissatisfaction as either customer of the retailers to switch to another store or back order happens. Earliness happen when all activities inside the cross-docking terminal finish their jobs earlier than their timetable, and outbound trucks leave terminal earlier than their scheduled time. This ultimately leads to the early delivery of the products to the customers which are sometimes unreasonable due to delivering of extra inventory to the customers [14; 131; 104; 4; 6; 161; 78; 247].

2.5.2.3 Time-Based Objective Functions

2.5.2.3.1 To minimize makespan or operating time inside the terminal

The best truck sequencing can help 1) reduce operations time 2) accelerate the turnover of goods, 3) reduce the probability of late shipments, 4) rapidly empty the terminal, 5) reduce the total waiting time (i.e., difference between the start time and arrival time of trucks), and 6) the entire handling time for all inbound trucks. All these objectives can be achieved by minimizing the makespan or maximizing the throughput of the products inside the cross-docking terminals. In general, researchers have different approaches to define makespan, but all try to increase material flow inside the cross-docking terminals [66; 154; 163; 194; 67; 155; 246; 17; 61; 74; 122].

2.5.2.3.2 To minimize time window violation

Time window violation is a big concern in a cross-docking system as it in cures extra costs within cross-docking terminal and outside for the customers. Thus, the majority of scholars try to minimize time window violation by figuring the best door assignment and truck scheduling so as to have a reliable cross-docking system with minimal total weighted tardiness and earliness simultaneously [163; 161; 35; 10; 18; 78; 237; 247; 19].

In contrast with some researchers that relax the arrival and departure time of the trucks on both sides of the cross-docks to minimize the total costs [141; 88; 73; 15; 38; 163], some other assume a fixed outbound departure schedule to prevent against customers' profit lost [37; 29; 73; 89; 140; 35].

One way to reduce delays on customers' products deliveries is to choose the optimal time window and schedule the transportation of the product from the suppliers through the supply chain with more cross-docking level [21]. This helps minimize the waiting time of the outbound trucks for the inbound trucks [109].

2.6Future Research

Here two new approaches are addressed that seem to have potential avenues for the future researches which are worthy of considerations.

2.6.1A new research direction to increase the cross-docking performance

As it was discussed in the popular objective function section (see section 2.5.2), the performance of a supply chain with an involved cross-docking terminal was viewed from 3 different angles by defining utilization-based objective functions, costs-based objective functions, and time-based objective function. Each tried to increase the system's performance by reducing activities' time violation and expenses while increasing the utilization of the resources involved in the supply chain. There is almost a unanimous agreement that the best door assignment and truck scheduling help reduce transshipment costs, minimize makespan, and increase material flow throughout the cross-docking terminal [220; 221; 59; 250; 40; 214; 118; 246]. However, best door assignment and truck scheduling cannot solely guarantee to increase cross-docking performance, unless the reliability of the transshipment facilities inside the cross-docking terminal and the reliability of the logistics companies from the earliness and tardiness perspectives are ensured.

Earliness and tardiness of unloading, transshipment, and loading activities within a cross-docking terminal can directly influence the overall performance of a supply chain including suppliers, cross-docking terminal, and a series of customers. The unreliability of transshipment facilities within a cross-docking terminal can manifest into earliness or tardiness of each activity within the terminal. If activities are done earlier than their scheduling, customers should expect to have their orders earlier than their expectation, and consequently, they will face additional inventory in their storage which is totally discouraged from the lean and just-in-time approaches. Conversely, due to the delay of all activities within a cross-docking terminal, the products deliveries to customers' sites are done later than the scheduling which leads to the shortage of products in the customers' storage, and consequently customers' dissatisfaction. The same scenario holds true for the third-party logistics companies. In fact, a supply chain cannot be reliable unless it has a reliable logistics system that delivers products on time to the customers at each stage of the chains. Any earliness or tardiness in the delivery of products by trucks can manifest into surplus or shortage of inventory at the customer' warehouse. This customer can be either a cross-docking terminal which is the customer of suppliers or a retailer which is the customer or a cross-docking terminal. Therefore, there are three essential factors presented in Figure 5 that influence the performance of a cross-docking terminal including;

1. The best doors assignment and truck scheduling
2. Reliability of transshipment facilities inside cross-docking-terminal
   2.1 The reliability of unloading team and facilities resided on inbound doors
   2.2 The reliability of material handling, consolidation, and value-adding (e.g., labeling, sorting, and packaging) team
   2.3 The reliability of the loading team and facilities resided on outbound doors

3. Reliability of third-party logistics/trucks' service providers.

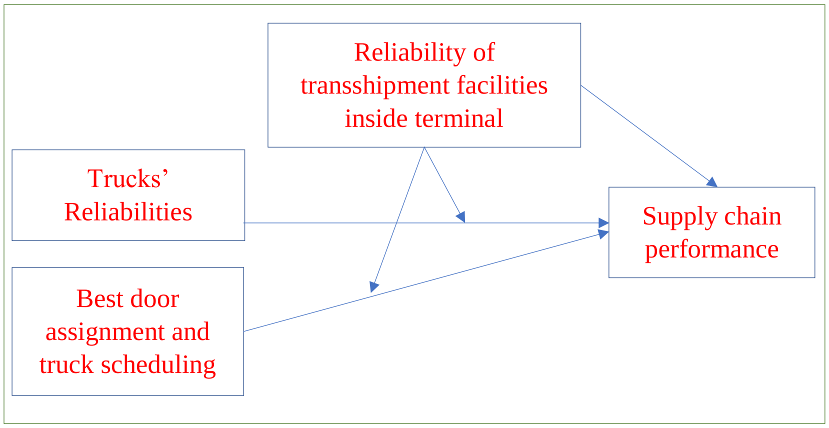


Figure 5: Conceptual framework of the factors influencing the cross-docking's performance

Based on the discussion above, five intuitive propositions are developed as follows;

Proposition 1) The best door assignment and truck scheduling can directly help increase cross-docking performance by reducing overall transshipments costs which ultimately help improve supply chain performance.

Proposition 2) A reliable logistics company can increase the supply chain performance by delivering products on time with no time window violation in terms of earliness or tardiness.

Proposition 3) A cross-docking terminal with reliable transshipment facilities and workforces can establish a dependable supply chain system that facilitates unloading and loading of products to be done on time which can help products delivered on time to the customers with no time windows violation.

Proposition 4) There is a strong relationship between "best door assignment and truck scheduling" with supply chain performance when cross-docking facilities' work reliable and deliver their job on time with no time window violation. Otherwise, a weak relationship exists.

Proposition 5) There is a strong relationship between “Trucks’ reliability” with supply chain performance when cross-docking facilities’ work reliable and deliver their job on time with no time window violation. Otherwise, a weak relationship exists.

2.6.2Time window violation: A measure of system reliability

Having assumed the best door assignment and truck scheduling, a supply chain is still unreliable with high cost unless it has a reliable trucks’ service provider and reliable cross-docking facilities and material handling team. A reliable truck company can ensure to have a reliable on-time delivery at the right place to the right person by preventing delays in delivery to customers. In addition, a reliable cross-docking system can ensure on time, reliable and steady products’ transshipment within the terminal to reduce temporary storage time and increase products’ flow within a narrow area.

Assuming a good communication, cooperation, and coordination among the suppliers, truck companies’ managers, cross-docking’s managers, and customers, the source of unreliability within a supply chain can be at least one of the following reasons;

1. The unreliability of trucks in terms of earliness, tardiness, or breakdown
2. The unreliability of the resources inside terminal including unloading, transshipment, loading team and facilities

Since in a cross-docking terminal all products should flow smoothly with no delay in the intermediate steps, any idle time or delay (tardiness) can translate to the extra penalty costs that affect the cross-docking total costs and ultimately total supply chain cost. Also, it is possible that activity inside the terminal starts and finishes its job earlier than its scheduled time. This earliness (i.e., like the slowness and delay) incurs additional extra costs since any earliness can affect the following activities time, e.g., early departure of outbound trucks leads to the early delivery of the products to the customers which are sometimes unreasonable due to the holding of extra inventory to the customers.

To ensure that products arrive and depart on time with minimum costs and delay, cross-dock centers should firstly try to minimize any type of earliness and tardiness in the course of product transshipment inside the terminal, and secondly, transport companies should be reliable to prevent delays in delivery of products from the suppliers to cross-docks and from cross-dock centers to customers [157; 190; 231].

Here we break down all costs associated with `the time violation (i.e., earliness and tardiness) into 10 different cost centers. These costs can happen either in the first stage of product delivery from suppliers → terminal, in the second stage during products transshipment inside the terminal, or at the last step which is the product delivery from terminal → customers.

The first group includes the costs related to the early arrival of the trucks once the cross-dock unloading and inbound doors facilities are not ready to serve. Therefore, inbound trucks stay idle until they are docked for unloading. Here, trucks idle fixed costs (C1) and inventory holding costs on the incoming trucks (C2) are the costs that affect the total system costs. Also, if a delay occurs and inbound trailers arrive late, the unloading team and inbound doors' facilities should stay idle until they start their services which is the inbound doors facilities idle costs (C3) that affects the total system costs as well.

The second group includes transshipment facilities idle costs (C4), temporary storage costs (C5 and C6), outbound doors facilities idle costs (C7), and finally outbound truck idle costs (C8). Here, it is assumed that the unloading team and inbound door facility team (the predecessor activity of the transshipment) can start and finish their jobs either on time, early or late. Any earliness or tardiness can lead to product stored inside the cross-dock. Two types of warehouses are assumed inside the terminal. The first storage designated to the unloaded bulk products which have not been consolidated yet. The second storage belongs to those processed products which either have no available transshipment facility ready to load them into the trailers or have no truck available at the outbound doors.

The third group elaborates those costs related to the customers and their contract with the suppliers and cross-dock terminals. All the earliness and tardiness of activities within the supply chain logistics not just can affect the variable costs of the products, but the level of customer (dis)satisfaction. Customers need to receive their order on time as getting the product earlier can incur extra inventory costs at customers' sites (C9). Also, getting their orders late causes lost profit and their customer dissatisfaction (C10).

Overall, the time change in each step (unloading → transshipment → loading → product delivery) can affect the starting time of the following/successor activity. Time violation can happen once operation of an activity starts earlier or later than the time scheduled for that; i.e., on time finishing based on the planned timetable. Any time violation on beginning the predecessor activity affect the starting time of the successor activity (A→B; A is the predecessor of B and B is the successor of A), i.e., successor B cannot start earlier than the time predecessor A is finished. Figure 6 presents 6 different relational dependencies between predecessor A and successor B. While we assume that the duration of each activity constant, the starting time of each activity varies and can be either on time, earlier, or later than the scheduled planned. Having assumed that task A should be finished before task B can start, the successor B cannot begin earlier than the finish time of the A.

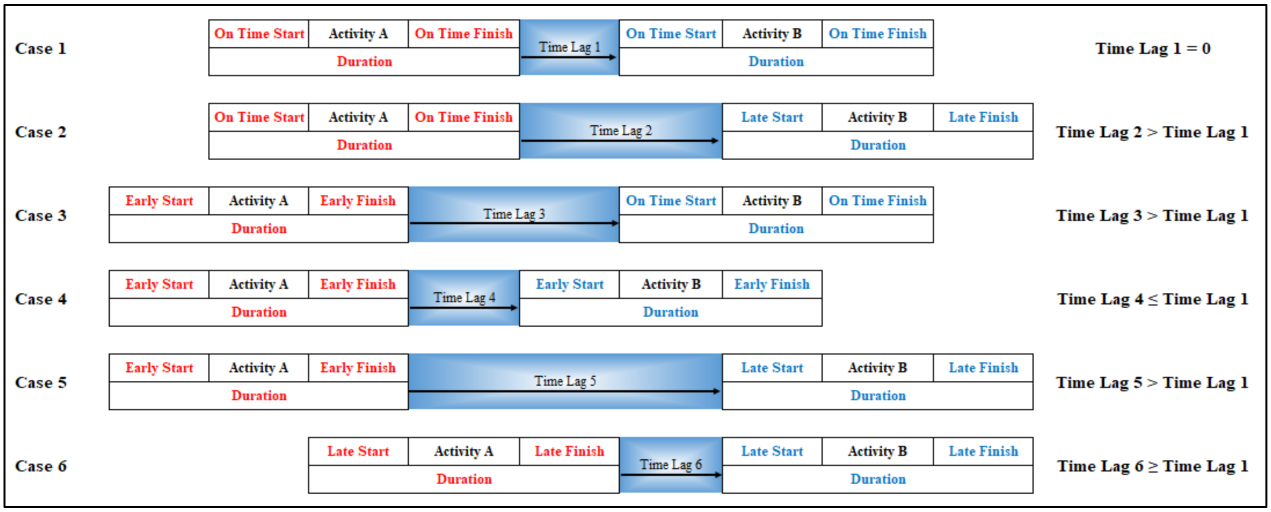


Figure 6: The conceptual illustration of the activities' time violation within the SCL

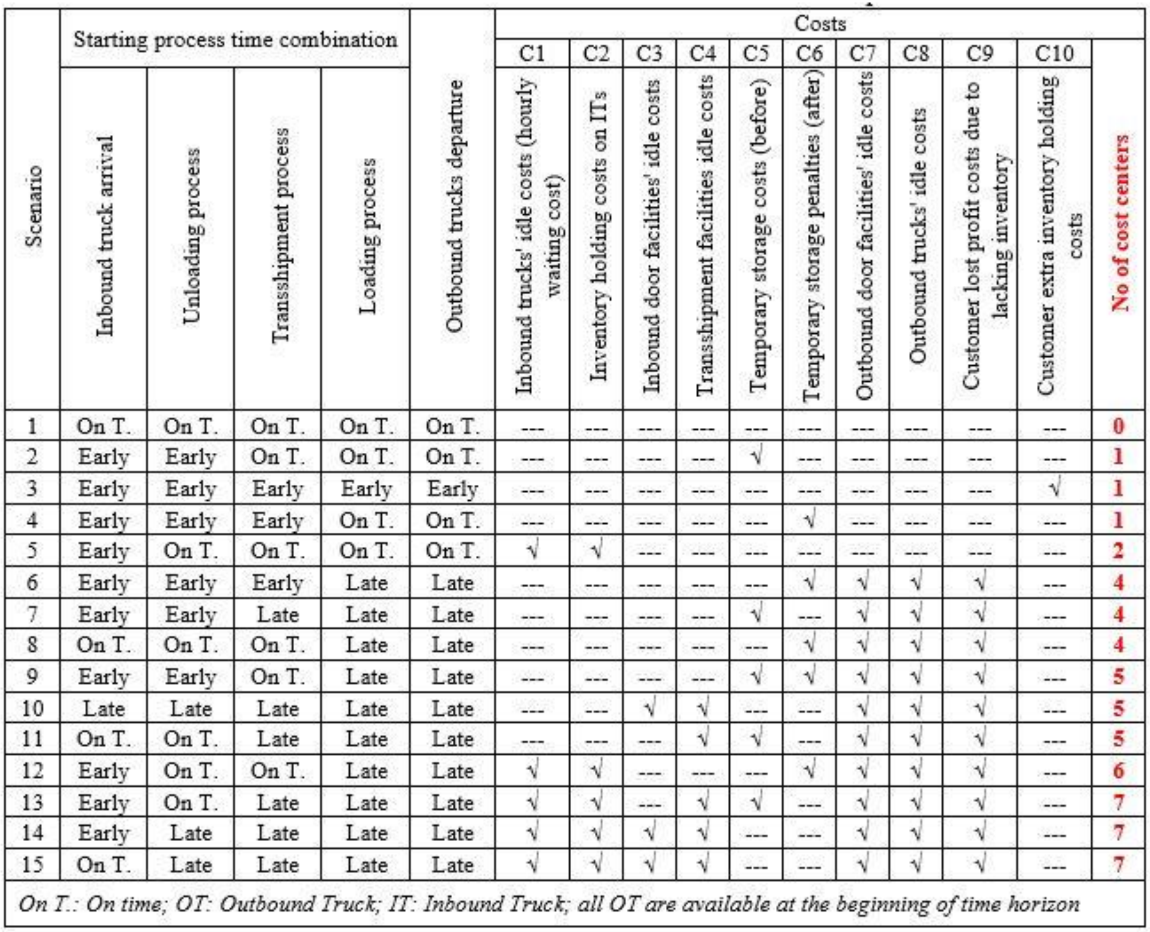
Having assumed the availability of the outbound trucks during the planning horizon, time violation can happen either on 1) inbound trucks arrival, 2) unloading process, 3) transshipment process, and finally 4) loading process. Any time violation upon these four activities can result in the earlier/later departure of outbound trucks which lead to the customer dissatisfaction due to the extra/lacking inventory in their sites.

Each of these activities can start either on time, earlier, or later than their scheduled plan, and therefore, has 3 levels. Thus, there are 3^4=81 beginning time combinations that represent processes within a cross-docking terminal. Out of 81, there are just 15 of them presenting the right sequence, and the rests are impossible sequences as they cannot meet the earliness/tardiness procedure shown in Table 7. For instance, activity B cannot start early when activity A as its predecessor is finished later than its scheduled plan, and it must start later than its scheduled plan (case 6). As a general rule, if an activity begins on time, all its successors can start either on time or later than their scheduled plan (case 1 and case 2). If an activity begins earlier than its scheduled plan, then its successors can either start on time, prior, or later than their scheduled plan (case 3, 4, and 5).

Finally, if an activity starts later than its scheduled plan, then its successors can just start later than their scheduled plan (case 6).

As it is shown in Table 7, a supply chain is in a stable condition with no additional cost if all activities are done on time with no time violation (scenario 1). Apparently, any single time violation from the scheduled plan can incur additional cost to the supply chain. Some time this cost manifest just in a single cost center like the ones listed for the 2nd, 3rd, and 4th scenarios. There, although some activities are started earlier than their scheduled plan, there are still some disadvantages as supply chain faces additional costs like holding additional inventory of bulk material (C6) in the 2nd scenario, or holding additional stock in the customers' site as a result of earliness in the products' deliveries to the customers' site shown in the 3rd scenario. The worst case scenarios happened when scenario 13, scenario 14, and scenario 15 occurred. There, despite the fact that inbound trucks arrive either early or on time, but, as transshipment process starts late then all its successors start later than their scheduled time, and this would result in to incur additional costs and used almost all cost centers. Surprisingly, if all activities begin late from the beginning (scenario 5), the total supply chain cost will be much lower than the time that inbound trucks arrive on time or earlier and transshipment process starts late (see 13th, 14th, and 15th scenarios).

Table 7: Different scenarios that create time violations-related penalties



Scenario	Starting process time combination				Outbound trucks departure	Costs										
						C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	
	Inbound truck arrival	Unloading process	Transshipment process	Loading process		Inbound trucks' idle costs (hourly waiting cost)	Inventory holding costs on ITs	Inbound door facilities' idle costs	Transshipment facilities idle costs	Temporary storage costs (before)	Temporary storage penalties (after)	Outbound door facilities' idle costs	Outbound trucks' idle costs	Customer lost profit costs due to lacking inventory	Customer extra inventory holding costs	**No of cost centers**
1	On T.	On T.	On T.	On T.	On T.	---	---	---	---	---	---	---	---	---	---	**0**
2	Early	Early	On T.	On T.	On T.	---	---	---	---	√	---	---	---	---	---	**1**
3	Early	Early	Early	Early	Early	---	---	---	---	---	---	---	---	---	√	**1**
4	Early	Early	Early	On T.	On T.	---	---	---	---	---	√	---	---	---	---	**1**
5	Early	On T.	On T.	On T.	On T.	√	√	---	---	---	---	---	---	---	---	**2**
6	Early	Early	Early	Late	Late	---	---	---	---	---	√	√	√	√	---	**4**
7	Early	Early	Late	Late	Late	---	---	---	---	√	---	√	√	√	---	**4**
8	On T.	On T.	On T.	Late	Late	---	---	---	---	---	√	√	√	√	---	**4**
9	Early	Early	On T.	Late	Late	---	---	---	---	√	√	√	√	√	---	**5**
10	Late	Late	Late	Late	Late	---	---	√	√	---	---	√	√	√	---	**5**
11	On T.	On T.	Late	Late	Late	---	---	---	√	√	---	√	√	√	---	**5**
12	Early	On T.	On T.	Late	Late	√	√	---	---	---	√	√	√	√	---	**6**
13	Early	On T.	Late	Late	Late	√	√	---	√	√	---	√	√	√	---	**7**
14	Early	Late	Late	Late	Late	√	√	√	√	---	---	√	√	√	---	**7**
15	On T.	Late	Late	Late	Late	√	√	√	√	---	---	√	√	√	---	**7**

On T.: On time; OT: Outbound Truck; IT: Inbound Truck; all OT are available at the beginning of time horizon

2.6.3Cross-docking and supply chain Performance

Cross-docking provides smaller volumes of more visible inventories that are delivered faster and more frequently [60; 228]. By removing non-value adding activities and increasing the responsive level of supply chain, cross-docking helps simultaneously satisfy 1) *supply chain flexibility* which is the ability of supply chain to effectively adapt or respond to change, i.e., help stock's volume be adjusted easily at customer's storage based on the customers' unpredicted demands [82], 2) *supply chain agility* which is the supply chain capacity to respond to changing customer needs rapidly by replenishing products at customer's storage frequently [82], and 3) *lean* process which is the eliminating of wastes and unnecessary efforts like storage and order picking within the terminal [147; 69]. In the meantime, shipment consolidation enables companies to cut transportation costs [175; 99]. This reduction manifests a reduction in the number of LTL trucks and increase in the total number of FT trucks which ultimately help maximize the usage of the roads [146]. In fact, by increasing the potential of FT product transportation, cross-docking enables the supply chain to drive *green* by consuming less fuel. Figure 7 illustrates a holistic conceptual perspective of the effect of cross-docking practice on different dimensions of supply chain management which ultimately helps increase supply chain performance which is finally manifested in supply chain satisfaction.

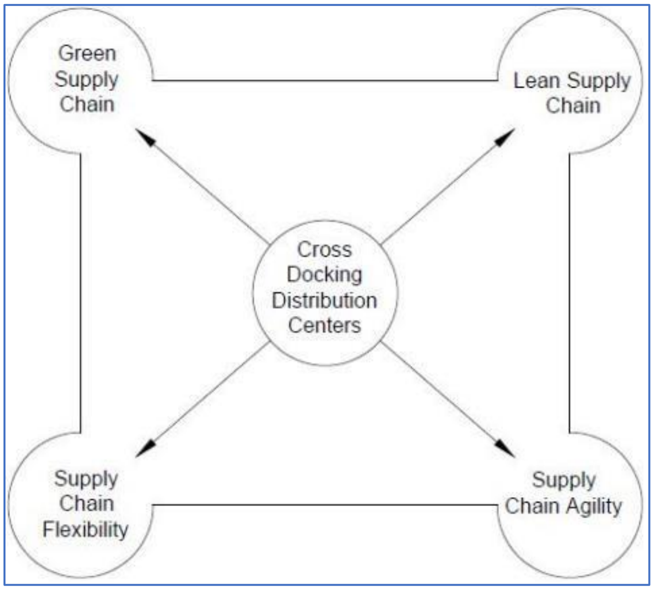


Figure 7: The effect of cross-docking in supply chain management

2.7Conclusion

This article introduces a new classification in the field of cross-docking’s mathematical programming studies. With the help of this classification, existing literature is briefly categorized based on their objective functions and the assumptions that are of interests of many scholars. Here, the assumption on the current literature are classified into six categories including 1) costs and penalties related assumptions, 2) facilities-related assumptions, 3) freight modifications-related assumptions, 4) layout-related assumptions, 5) trucks-related assumptions, and 6) cross-docking policy-related assumptions. Scholars use these assumptions to make a boundary for their problems and then establish their constraints to find the optimum solution for their models' objective functions. Objective functions are classified into three categories including 1) utilization-based objective functions which seek to maximize throughput and truck utilization within the supply chain and cross-docking, 2 and 3) time-based and cost-based objective functions. In the 2nd and 3rd groups, existing literature tried to find solutions that help minimize the overall supply chain costs while avoiding time window violation. In addition, all advantages and challenges related to cross-docking practice are presented in this research. This list is a collection of all the pros and cons on cross-docking analyses addressed by the scholars and practitioners. Finally, by offering future research, three potential avenues are established which can develop new problems in the field of supply chain management.

PRELUDE TO CHAPTER 3, 4, AND 5

The proposed mathematical model tries to minimize total supply chain cost (TSCC) which consists of two separate and independent parts including total transportation costs (TTC) and total cross-docking's operations costs (TCDC) shown in Eq. 1. The former helps minimize the total transportation costs while maximizing the number of FT transportation (FT) and decreasing the total number of LTL transportation (LTT). The latter tries to minimize total operations costs within a cross-docking terminal by solving a quadratic assignment problem which is an NP-hard problem.

Both sub-objective functions are formulated as binary mathematical programming models. While the first objective function is a binary-linear programming model, the second one is a binary-quadratic programming model.

$$TSCC = TTC + TCDC \qquad \text{Eq. 1}$$

In chapter 3 the concentration is just on transportation costs, and we don't address the transshipment costs within the cross-docking terminal. In chapter 4, the focus is on the transshipment costs within a cross-docking terminal. There are two approaches concerning the chapter 4 and supplier-customer product flow in the second part of the objective function. In that, if we want to consider total supply chain costs (TSCC), the output flow of chapter 3 is assumed to be the input of product flow for chapter 4 (the final LTL matrix shown in Table 14); otherwise, if the total operations costs within cross-docking terminal (TCDC) is desired, we can assume a matrix with random integer numbers.

And finally, chapter 5 that concentrates on the total supply chain costs and consider the TTC and TCDC and compare the outputs when cross-docking is involved with time that is excluded from the supply chain. There, we describe a multi-echelon supply chain in which both direct shipments and cross-docking are available to move products from the suppliers to multiple customers’ locations either directly using FT trucks or indirectly through a single cross-docking terminal using LTL trucks. Our model is motivated by an actual supply chain environment in which cross-docking supports the effort to meet demands at customer locations at a minimal cost.

CHAPTER 3

MINIMIZING TOTAL TRANSPORTATION COSTS

Abstract

This study aims at proposing a decision-support tool to reduce the total transportation costs while cross-docking is involved in the supply chain. The FT transportation mode is assumed to handle suppliers→customers product transportation; otherwise, a cross-docking terminal as an intermediate transshipment node is hired to handle the transportation of the LTL products between the suppliers and customers.

In the following, the boundary of the problem is defined by a list of general and specific assumptions. Next, binary-linear mathematical programming formulations are presented. The efficiency of the model is examined from two perspectives by comparing the output of two scenarios; i.e., 1) when cross-docking is included in the supply chain and 2) when it is excluded. The first perspective is to compare the two scenarios' outcomes from the total supply chain transportation costs standpoint, and the second perspective is the comparison of the scenarios' outcomes from the total supply chain transportation miles standpoint. By addressing a numerical example, the results confirm that the present of cross-docking within a supply chain can significantly reduce total transportation costs and total transportation miles. In order to figure the best parameter setting that lead to a minimal transportation costs and miles, the Taguchi method using Minitab software are employed to implement $L2_{16}^{5}$ orthogonal array on multiple factors

including trucks' initial fixed costs ($1000 vs $2000), trucks' initial variable costs ($0.2 vs $1.0), trucks' capacities (10-50 vs 10-166), percentage of trucks for long transportation (20% vs 50%), and problem size (small vs medium). According to the experimental data, the optimal combination of design parameters with different levels of transportation's factors is obtained. The results confirm the literature findings concerning the combination of parameters. Finally, this chapter will be ended by a brief conclusion of the findings.

3.1Overall assumptions

In analyzing this problem, we make several assumptions as follows.

1. Unlimited products are available from a single supplier and that demands for those products are known but varying - reflecting a common situation in practice and one that has been assumed by previous work in this area [77].
2. The demand must satisfy in each period.
3. There is no space and labor limitation at the customer site, and an unlimited number of shipment trucks handle unloading activities.
4. Due to geographic dispersion, each shipment can only serve a single customer site (i.e., no milk run deliveries are possible).
5. The customer can choose the shipping mode and is responsible for all transportation costs.
6. The analysis is done from the customer's perspective: the manager of multiple customer locations must determine the quantity, timing, and route for shipments to meet demands over the planning horizon.
7. All suppliers produce and ship only one product type (or products of similar size and weight).

3.2Specific assumptions

In addition to the general assumptions, there are two unique assumptions that are developed in this research. In fact, one of the contributions of this study is the development of these assumptions which ultimately helps minimize the total supply chain's transportation costs.

1. For each truck, a dynamic fixed cost and a variable cost are assumed which are varied relative to the truck's capacity [31; 102; 77]. To determine the fixed cost and variable cost of each truck, a basic initial fixed cost and variable cost for the truck with largest capacity are assumed. Here C_t, F_t and, V_t represent truck's capacity, truck's fixed cost and truck's variable cost respectively. Also, F_{max}, V_{max} and C_{max} denote the fixed cost, variable cost, and truck capacity of the largest truck with maximum capacity. Therefore F_t and V_t are functions of C_t, F_{max}, V_{max} and C_{max} respectively using Eq. 2 and Eq. 3.

$$F_t=F_{max}\left[\frac{C_t}{C_{max}}\right] \qquad \text{Eq. 2} \qquad\qquad V_t=V_{max}\left[\frac{C_t}{C_{max}}\right] \qquad \text{Eq. 3}$$

2. Short-distance and long-distance product transportation are concerns of this study. To maximize the efficiency of the product transportation, an imaginary zone is considered, and any type of product transportation within the zone is considered as short-distance product transportation; otherwise, long-distance product transportation. The cross-docking terminal is located within the zone as well. Regarding the product transportation on each route shown in Figure 8, two policies are assumed, and at the same time, either of them is applied. The first is to use entire fleet with all capacities for short-distance product transportation, and the second is to just use a partial number of them with larger capacities for long-distance product transportation. As it is listed in Table 8, if two nodes are inside the zone, the transportation between these nodes is implemented using entire fleet;

otherwise, top X% of trucks with larger capacities are employed to carry the long-distance product transportation. For instance, if the maximum truck capacity in a fleet is 90 product-unit and we select “top 35%” of the trucks for long-distance transportation, those trucks with capacities greater than or equal 58.50 product-unit (90×0.65=58.50) are selected. In Figure 8, m, n, and CD represent supplier, customer, and cross-docking terminal respectively. In all instances, we assume that the supplier-customer original distances are random integer numbers between 500 to 5000 miles.

Table 8: Truck assignment scenarios to different zone conditions

Condition	Supplier Location	Customer Location	Fleet selection for each route		
			S→CD	CD→Cu	S→Cu
1	Inside Zone	Inside Zone	Entire fleet	Entire fleet	Entire fleet
2	Inside Zone	Outside Zone	Entire fleet	Partial Fleet	Partial Fleet
3	Outside Zone	Inside Zone	Partial Fleet	Entire fleet	Partial Fleet
4	Outside Zone	Outside Zone	Partial Fleet	Partial Fleet	Partial Fleet

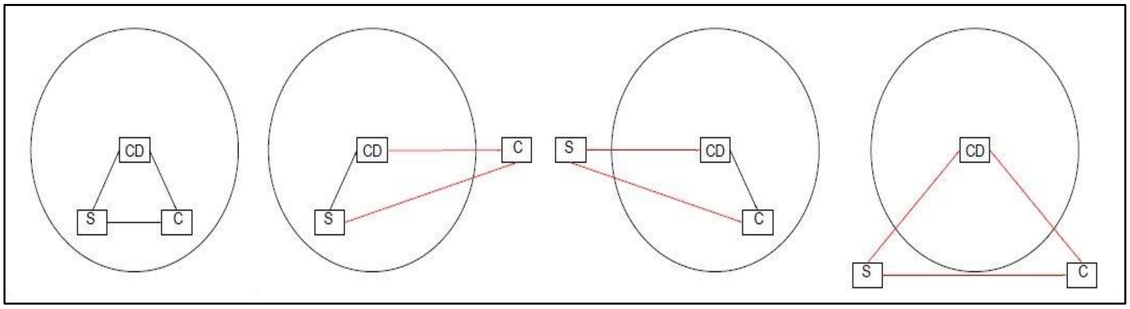


Figure 8: Suppliers-customers location with respect to CD's zone

3.3Problem Description and Formulation

To show the significance of cross-docking in a supply chain, two scenarios are addressed as follows. The first is a binary-linear programming model that assumes cross-docking within the zone, and second is a binary-linear programming model that excludes cross-docking from the supply chain.

3.3.1Scenario 1: Total transportation costs when Cross-Docking is Included

Three significant functional players including suppliers, customers, and a single cross-dock (CD) are assumed. By minimizing total transportation costs on each route shown in Figure 8; i.e., supplier→customer, supplier→CD, and CD→customer, the total supply chain transportation costs is minimized when the transportation costs on each route is minimized.

Concerning the process of selection of appropriate trucks for product transportation between each two nodes, two scenarios are implemented. If two nodes are within the zone (see Figure 8), then short distance product transportation is assumed, and therefore, entire fleet are selected to handle the product transportation; otherwise, the long-distance product transportation policy is implemented using the top X% percentage of the trucks with larger capacities.

Regarding supplier→customer routes' product transportation, FT product transportation is done in multiple runs until there will be no further possibility for FT direct shipment. The process is continuously implemented until the remaining flow for each customer at the suppliers' site become less than the minimum truck capacity on the respected fleet shown in Table 8.

The second stage is the supplier→cross-docking product transportation which is done by the transportation of the remaining LTL products at suppliers' sites. However, before transportation is started, all LTL customers' demands at each suppliers' site are consolidated at suppliers' sites to create a larger batch of products. This process helps increase the number of FT product transportation from each supplier' site to the cross-docking terminal and in the meantime minimize the number of LTL transportation on the same routes. Again, truck selection is a function of the supplier' location. Depending on the location of supplier that can be either inside or outside of the CD's zone, appropriate trucks that maximize the number of FT product transportation and minimize the number of LTL transportation are selected. After the supplier→cross-docking FT product transportation is implemented, appropriate trucks that minimize total LTL supplier→cross-docking product transportation costs are selected.

Once supplier→cross-docking product transportation is implemented and the consolidation of the products at the CD terminal is finished, then the cross-docking→customer routes are activated to distribute products from the cross-docking terminal and deliver them to the customers. Like the process of supplier→cross-docking product transportation, here, initially product transportation is implemented using FT product transportation, and for the remaining LTL products, the best trucks are selected. Still, the location of customer, i.e., either inside or outside of zone, indicates type of fleet to handle cross-docking→customer's product transportation.

On the basis of the addressed procedures above, the first sub-objective function shown in Eq. 1; i.e., total transportation costs (TTC), is partitioned into five sub-sections including 1) supplier→customer' FT product transportation cost ($TC_{FT}^{S\to C}$) 2) supplier→CD's FT product transportation cost ($TC_{FT}^{S\to CD}$) 3) supplier→CD's LTL transportation costs ($TC_{LTT}^{S\to CD}$) 4) CD→customer' FT product transportation cost ($TC_{FT}^{CD\to C}$), and finally, 5) CD→customer' LTL transportation costs ($TC_{LTT}^{CD\to C}$). The minimization of the cost on each section will ultimately help minimize the total supply chain transportation cost.

$$\text{Total transportation costs} = TTC = TC_{FT}^{S\to C} + TC_{FT}^{S\to CD} + TC_{LTT}^{S\to CD} + TC_{FT}^{CD\to C} + TC_{LTT}^{CD\to C}$$

It is noteworthy to mention that an additional penalty is taken into consideration for the LTL transportations. In doing so, in the objective functions of the models that handle LTL product transportation, in addition of variable cost, a multiplier ($\alpha_t = \left[\frac{C_t}{load}\right]$) is assumed which acts as a penalty that magnifies the impact of amount of the number of products that are carried by a truck.

In fact, the more products each truck carries, the lower the variables costs are expected for it. Here, the variable costs in the LTL's mathematical programming models are function of truck's variable cost×distance between two nodes×amount of product each truck carries. This leads algorithm to manage the best truck to carry the LTL products from suppliers to cross-docking terminal and from cross-docking terminal to the customers' sites. In fact, concerning the LTL transportation, $1 \leq \left[\frac{C_t}{load}\right]$ is a penalty that magnifies the impact of variable cost, given $1 \leq load \leq C_t$. The assumption of this penalty helps us make intuitive sense given that economies of scale are leveraged when a truck with a high fixed cost and variable cost is loaded nearly full [99; 77]. On the other hand, the shorter distance each truck travel, the lower the variable cost is expected.

In this section, we present a binary-linear programming formulation of multiple suppliers and multiple customers to find the best truck assignment for each route shown in Figure 8. Also, the formulation employs different fixed and variable cost function for each truck.

Notation

m: Index of Suppliers
n: Index of Customers
f: Index of Flow
t: Index of Truck
d: Index of Distance between supplier and customers
r: Index of Run for each algorithm
$\lfloor a \rfloor$: Round down to the nearest integer number
f_{mn}^{0} = the initial flow between m^{th} supplier to n^{th} customer n before transportation
FT: FT Transportation
LTL: LTL Transportation

The notions relate to the fleet are listed as follows, and Table 9 conceptually represent the fleet employed for long-distance versus short-distance product transportation

e: Entire truck (ET) fleet’s index for short-distance transportation	*p:* Partial truck (PT) fleet’s index for long-distance transportation
ET_C^e: et^{th} truck capacity ET_F^e: et^{th} truck fixed cost (Eq. 2 on page 78) ET_V^e: et^{th} truck variable cost (Eq. 3 on page 78)	PT_C^p: pt^{th} truck capacity PT_F^p: pt^{th} truck fixed cost PT_V^p: pt^{th} truck variable cost

Table 9: Fleet characteristics for short and long-distance transportation (The notations)

Fleet for short-distance transportation (E: Entire)				Fleet for long-distance trans. (P = Partial)			
T. index	Capacity	Fixed Costs	Variable Costs	T. index	Capacity	Fixed Costs	Variable Costs
ET^1	ET_C^1	ET_F^1	ET_V^1	PT^1	1	Big number	Big number
ET^2	ET_C^2	ET_F^2	ET_V^2	PT^2	1	Big number	Big number
ET^3	ET_C^3	ET_F^3	ET_V^3	PT^3	1	Big number	Big number
ET^4	ET_C^4	ET_F^4	ET_V^4	PT^4	PT_C^4	PT_F^4	PT_V^4
ET^5	$\mathrm{ET}_\mathrm{C}^5 = C_{max}$	$\mathrm{ET}_\mathrm{F}^5 = F_{max}$	$\mathrm{ET}_\mathrm{V}^5 = V_{max}$	PT^5	PT_C^5	PT_F^5	PT_V^5

Binary Variables

$ET_{a\rightarrow b}^t$: To assign et^{th} truck for a → b’s short-distance product transportation when *a* and *b* are inside the zone.

$PT_{a\rightarrow b}^t$: To assign pt^{th} truck for a → b’s long-distance product transportation when either *a* and *b* are outside the zone.

Using these variables and notations, we express the objective functions as the sum of FT (FTL) and LTL (LTL) shipping costs. In the following, section 1 addresses the supplier→customer’s FT product transportation, section 2 and section 3 account for the supplier→cross-docking and cross-docking→customer indirect routes’ product transportation using FT and LTL transportation mode.

Section 1: Suppliers-customers FTL Transportation (optimization model 1)

$$U_r^{FT:\,m\to n} = min\left(\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{t=1}^{T} ET_{m\to n}^{t}\left\lfloor\frac{f_{m\to n}^{r-1}}{ET_C^t}\right\rfloor(ET_F^t + ET_V^t \times d_{m\to n}) + \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{t=1}^{T} PT_{m\to n}^{t}\left\lfloor\frac{f_{m\to n}^{r-1}}{PT_C^t}\right\rfloor(PT_F^t + PT_V^t \times d_{m\to n})\right) \qquad \text{Eq. 4}$$

$$\text{Subject to: } \sum_{t=1}^{T}(ET_{m\to n}^{t} + PT_{m\to n}^{t}) = \sum_{t=1}^{T} ET_{m\to n}^{t} + \sum_{t=1}^{T} PT_{m\to n}^{t} = 1: \forall m, \forall n \qquad \text{Eq. 5}$$

In section 1, the objective function (Eq. 4) is to minimize total supplier-customer FT product transportation (FT) transportation cost at rth run by minimizing total transportation's fixed costs and variable costs. It consists of two independent parts and depending on the location of the suppliers and customers - either inside or outside of the CD's zone - either gets value and the other one equals zero. Eq. 5 is a linear-binary equation that ensures to select just one truck out of the two fleets shown in Table 9.

$$f_{m\to n}^{r} = f_{m\to n}^{r-1} - \left(\sum_{t=1}^{T} ET_{m\to n}^{t}\left\lfloor\frac{f_{m\to n}^{r-1}}{ET_C^t}\right\rfloor ET_C^t + \sum_{t=1}^{T} PT_{m\to n}^{t}\left\lfloor\frac{f_{m\to n}^{r-1}}{PT_C^t}\right\rfloor PT_C^t\right): \forall m, \forall n, \forall r \qquad \text{Eq. 6}$$

Eq. 6 is not a part of the optimization model and is an equation that updates supplier-customer flow matrix after rth run. After each update, the optimization model is run until all supplier-customer flow become less than the minimum truck capacity at both fleet's groups shown in Table 9.

Once further FT supplier-customer transportation becomes impossible, the remaining flow at each supplier site are consolidated using Eq. 7 and next stage which is the product transportation from suppliers' sites to the CD is began. Likewise, Eq. 8 takes care of transportation of consolidated items inside CD to the customers' sites. Eq. 9 is the summation of all supplier-customer FT product transportation cost after p runs.

$$f_{m\to CD}^{0}=\sum_{n=1}^{N} f_{m\to n}^{p}:\forall m \qquad \text{Eq. 7}$$

$$f_{CD\to n}^{0}=\sum_{m=1}^{M} f_{m\to n}^{p}:\forall n \qquad \text{Eq. 8}$$

$$TC_{FT}^{S\to C}=\sum_{p=1}^{P} U_{p}^{FT-mn} \qquad \text{Eq. 9}$$

Section 2-1: FT product transportation from Suppliers to CD (Model Optimization 2-1)

$$U_{p}^{FT:\,m\to CD}=min\left(\sum_{m=1}^{M}\sum_{t=1}^{T} ET_{m\to CD}^{t}\left\lfloor\frac{f_{m\to CD}^{r-1}}{ET_{C}^{t}}\right\rfloor\left(ET_{F}^{t}+ET_{V}^{t}\times d_{m\to CD}\right)+\sum_{m=1}^{M}\sum_{t=1}^{T} PT_{m\to CD}^{t}\left\lfloor\frac{f_{m\to CD}^{r-1}}{PT_{C}^{t}}\right\rfloor\left(PT_{F}^{t}+PT_{V}^{t}\times d_{m\to CD}\right)\right) \qquad \text{Eq. 10}$$

$$\text{Subject to: }\sum_{t=1}^{T}\left(ET_{m\to CD}^{t}+PT_{m\to CD}^{t}\right)=1:\forall m \qquad \text{Eq. 11}$$

Subsection 2-1 accounts for the optimization of FT product transportation from suppliers' sites to the CD terminal. Objective function (Eq. 10) ensures to minimize supplier→CD FT product transportation cost at rth run. Depending on the location of mth supplier which can be either inside or outside of the CD's zone, constraint (Eq. 11) ensures to select appropriate trucks unless the amount of remaining flows at suppliers' sites become less than the smallest truck capacity at rth run.

$$f_{m\to CD}^{r}=f_{m\to CD}^{r-1}-\left(\sum_{t=1}^{T} ET_{m\to CD}^{t}\left\lfloor\frac{f_{m\to CD}^{r-1}}{ET_{C}^{t}}\right\rfloor ET_{C}^{t}+\sum_{t=1}^{T} PT_{m\to CD}^{t}\left\lfloor\frac{f_{m\to CD}^{r-1}}{PT_{C}^{t}}\right\rfloor PT_{C}^{t}\right):\forall m,\forall r \qquad \text{Eq. 12}$$

Like Eq. 6, Eq. 12 is not part of the optimization model. However, this is an equation that updates supplier→CD flow matrix after rth run. After each update, the optimization model 2-1 is run until all the supplier→CD flow become less than the minimum truck capacity in their fleet group.

$$TC_{FT}^{S\rightarrow CD} = \sum_{r=1}^{r} U_r^{FT:\, m\rightarrow CD} \qquad \text{Eq. 13}$$

Eq. 13 is the summation of all supplier→CD FT product transportation costs after rth run.

Section 2-2: Suppliers-CD LTL Transportation (model optimization 2-1)

$$\begin{aligned} TC_{LTL}^{S\rightarrow CD} = min\Bigg(&\sum_{m=1}^{M}\sum_{t=1}^{T} ET_{m\rightarrow CD}^{t}.\left[ET_F^t + \left(\frac{ET_C^t}{f_m^r}\right).ET_V^t \times\ d_{m\rightarrow CD}\right] \\ &+ \sum_{m=1}^{M}\sum_{t=1}^{T} PT_{m\rightarrow CD}^{t}.\left[PT_F^t + \left(\frac{PT_C^t}{f_m^r}\right).PT_V^t \times\ d_{m\rightarrow CD}\right]\Bigg) \end{aligned} \qquad \text{Eq. 14}$$

$$\text{Subject to: } \sum_{t=1}^{T}\left(ET_{m\rightarrow CD}^{t} + PT_{m\rightarrow CD}^{t}\right) = 1 : \forall m \qquad \text{Eq. 15}$$

Section 2-2 ensures the best truck assignment to each supplier→CD route that minimizes total LTL product transportation shown in objective function (Eq. 14). Constraint/Eq. 15 assigns the best truck to each supplier→CD route to transfer the LTL remaining products at each supplier's site. The total transportation costs at this stage is computed in just 1 run as all flows at all suppliers' sites are less than the minimum trucks' capacity. According to Eq. 17, in addition of the normal variables' costs (PT_V and ET_V) that were assumed in the FT product transportation, a multiplier of $\left(\frac{truck\ capacity}{less-than-truckload}\right)$ is assumed which is multiplied by the variable costs to increase the magnitude of variable costs. This way we force algorithm to select the best truck that minimizes the total LTL product transportation.

Section 3-1: CD→customers FTL transportation (model optimization 3-1)

$$\begin{aligned} U_p^{FT:\, CD\rightarrow n} = min\Bigg(&\sum_{n=1}^{N}\sum_{t=1}^{T} ET_{CD\rightarrow n}^{t}\left\lfloor\frac{f_{CD\rightarrow n}^{r-1}}{ET_C^t}\right\rfloor\left(ET_F^t + ET_V^t \times\ d_{CD\rightarrow n}\right) \\ &+ \sum_{n=1}^{N}\sum_{t=1}^{T} PT_{CD\rightarrow n}^{t}\left\lfloor\frac{f_{CD\rightarrow n}^{r-1}}{PT_C^t}\right\rfloor\left(PT_F^t + PT_V^t \times\ d_{CD\rightarrow n}\right)\Bigg) \end{aligned} \qquad \text{Eq. 16}$$

$$\text{Subject to: } \sum_{t=1}^{T}\left(ET_{CD\rightarrow n}^{t} + PT_{CD\rightarrow n}^{t}\right) = 1 : \forall n \qquad \text{Eq. 17}$$

The same procedure explained in 1st, and 2nd section is applied for the transportation of consolidated products at cross-docking to the customers' sites. Objective function (Eq. 16) minimizes the total FT product transportation from CD→customers' sites at rth run. Constraint Eq. 17 takes care of the best truck assignment that helps minimize the objective function at rth run. Again, the location of each customer indicates the type of fleet that is chosen for the transportation.

$$f_{CD\rightarrow n}^{r} = f_{CD\rightarrow n}^{r-1} - \left(\sum_{t=1}^{T} ET_{CD\rightarrow n}^{t} \left\lfloor \frac{f_{CD\rightarrow n}^{r-1}}{ET_{C}^{t}} \right\rfloor ET_{C}^{t} + \sum_{t=1}^{T} PT_{CD\rightarrow n}^{t} \left\lfloor \frac{f_{CD\rightarrow n}^{r-1}}{PT_{C}^{t}} \right\rfloor PT_{C}^{t} \right) : \forall n, \forall r \qquad \text{Eq. 18}$$

After each run, the CD-customer flow matrix is updated using Eq. 18.

$$TC_{FT}^{CD\rightarrow n} = \sum\nolimits_{\mathrm{r}=1}^{\mathrm{r}} U_{r}^{FT-CD\rightarrow n} \qquad \text{Eq. 19}$$

Eq. 19 is the summation of all r runs FT product transportation costs from CD terminal to customers' sites.

Section 3-2: CD-customers LTL transportation (model optimization 3-2)

$$\begin{aligned} TC_{LTL}^{CD\rightarrow C} = min \Bigg(& \sum_{n=1}^{N} \sum_{t=1}^{T} ET_{CD\rightarrow n}^{t} . \left[ET_{F}^{t} + \left(\frac{ET_{C}^{t}}{f_{n}^{r}} \right) . ET_{V}^{t} \times d_{CD\rightarrow n} \right] \\ & + \sum_{n=1}^{N} \sum_{t=1}^{T} PT_{CD\rightarrow n}^{t} . \left[PT_{F}^{t} + \left(\frac{PT_{C}^{t}}{f_{n}^{r}} \right) . PT_{V}^{t} \times d_{CD\rightarrow n} \right] \Bigg) \end{aligned} \qquad \text{Eq. 20}$$

$$Subject\ to: \sum_{t=1}^{T} \left(ET_{CD\rightarrow n}^{t} + PT_{CD\rightarrow n}^{t} \right) = 1 : \forall n \qquad \text{Eq. 21}$$

Section 3-2 ensures the optimization of the best truck selection to transfer LTL products from the CD terminal to the customers' sites. Objective function (Eq. 20) minimizes the LTL transportation and constraint (Eq. 21) helps achieve this goal (The same procedure explained in section 2-2 is applied for this section).

$$\mathrm{TTC}_{\mathrm{CD\ Included}} = \mathrm{TC}_{\mathrm{FT}}^{\mathrm{S\rightarrow C}} + \mathrm{TC}_{\mathrm{FT}}^{\mathrm{S\rightarrow CD}} + \mathrm{TC}_{\mathrm{LTL}}^{\mathrm{S\rightarrow CD}} + \mathrm{TC}_{\mathrm{FT}}^{\mathrm{CD\rightarrow C}} + \mathrm{TC}_{\mathrm{LTL}}^{\mathrm{CD\rightarrow C}} \qquad \text{Eq. 22}$$

Eq. 22 turns out the total transportation costs ($\mathrm{TTC}_{\mathrm{CD\ Included}}$) for both direct supplier→customer product transportation as well as the indirect type via the CD terminal.

3.3.2Scenario 2: Total transportation costs when Cross-Docking is Excluded

To check the efficiency of our binary-linear programming model to minimize the total transportation costs presented in Eq. 22, two scenarios are developed, and the outcome of them are compared. The first which is addressed in section 3.3.1 is assumed cross-docking as an intermediary facility to handle LTL product transportation from supplier to customers. While all assumptions concerning the short-distances and long-distances product transportation are held, the second scenario exclude cross-docking from the supply chain and supports direct product transportation from suppliers to customers using FT and LTL product transportation modes. Therefore, in case both supplier and customer happen to be inside the zone, we will use entire fleet; otherwise, we will use top X% of the trucks with larger capacities.

Concerning the mathematical programming formulation, the FT product transportation follows the section 1's procedure addressed in the previous section. Next, the LTL direct product transportation are done like the FT using the bests trucks that minimizes the LTL product transportation costs.

$$\mathrm{TTC}_{\mathrm{CD\ Excluded}} = \mathrm{TC}_{\mathrm{FT}}^{\mathrm{S \to C}} + \mathrm{TC}_{\mathrm{LTL}}^{\mathrm{S \to C}} \qquad \text{Eq. 23}$$

3.4Total Transportation Mile

In addition to the total transportation costs that is the main objective function of this study, quality usage of the roads is the second objective function that indicates the effectiveness of present of cross-docking within a supply chain. In fact, the more FT and less LTL product transportation indicate the higher quality usage of the road that indirectly leads to achieve the goal of economies of scale and product-unit cost reduction. Although the quality usage of the roads is not the objective function of this research, determining that the higher quality usage of the roads is equivalent to the decrease in the number of LTL and the increase in the number of FT product transportation. Total product-unit transportation mile (TTM) is an indicator that shows the quality usage of the roads and like total product-unit transportation cost (TTC) consists of 5 different sub-sections. In fact, after computing each section of mathematical programming formulation explained in section 3.3, the corresponding product-unit transportation mile is computed. TTM helps check the productivity of a transportation system, and the smaller will be the better; i.e., like the total supply chain transportations costs. For each route presented in Table 8, transportation mile (Eq. 26) consists of two parts including TM_{FT} (Eq. 24) and TM_{LTL} (Eq. 25). TM_{FT} returns FT product-unit transportation mile between 1^{st} and 2^{nd} nodes and is the multiplication of the 1^{st} node → 2^{nd} flow ($\text{flow}_{FT} = \text{ w}^{th}\text{ truck capacity}$) by the integer number of trucks ($\left\lfloor\frac{\text{flow}_{FT}}{\text{w}^{th}\text{ truck capacity}}\right\rfloor$) by the distance between 1^{st} node and 2^{nd} node ($distance_{1^{st}\text{ node}\rightarrow 2^{nd}\text{ node}}$). And TM_{LTL} takes care of the 2^{nd} part of the transportation that handles LTL. To put more value to those trucks that carry more products near to the truck's capacity, we assume an additional penalty that increases the TM_{LTL} in case W^{th} truck carries LTL product-units $\left(\frac{w^{th}\text{ truck capacity}}{\text{flow}_{LTL}}\right)$. In fact, the closer the number of carried product-units to the capacity of the selected W^{th} truck, the less penalty incurred to the TM_{LTL}. Again, to check the efficiency of the proposed linear model, TTM is computed once CD is included in the supply chain versus when CD is excluded from the supply chain shown in Eq. 27 and Eq. 28 respectively.

$$TM_{FT}=\text{flow}_{FT}\times\left\lfloor\frac{\text{flow}_{FT}}{\text{w}^{th}\text{ truck capacity}}\right\rfloor\times\text{distance}_{1^{st}\text{ node}\rightarrow 2^{nd}\text{ node}} \qquad \text{Eq. 24}$$

$$\mathrm{TM_{LTT}}=\mathrm{flow_{LTL}}\times\left(\frac{\mathrm{w^{th}\ truck\ capacity}}{\mathrm{flow_{LTL}}}\right)\times\mathrm{distance}_{1^{\mathrm{st}}\ \mathrm{node}\rightarrow 2^{\mathrm{nd}}\ \mathrm{node}} \qquad \text{Eq. 25}$$

$$\mathrm{TM}^{1^{\mathrm{st}}\ \mathrm{node}\rightarrow 2^{\mathrm{nd}}\ \mathrm{node}}=\mathrm{TM}_{\mathrm{FT}}^{1^{\mathrm{st}}\ \mathrm{node}\rightarrow 2^{\mathrm{nd}}\ \mathrm{node}}+\mathrm{TM}_{\mathrm{LTL}}^{1^{\mathrm{st}}\ \mathrm{node}\rightarrow 2^{\mathrm{nd}}\ \mathrm{node}} \qquad \text{Eq. 26}$$

$$\mathrm{TTM_{CD\ Included}} = \mathrm{TM_{FT}^{S\rightarrow C}} + \mathrm{TM_{FT}^{S\rightarrow CD}} + \mathrm{TM_{LTL}^{S\rightarrow CD}} + \mathrm{TM_{FT}^{CD\rightarrow C}} + \mathrm{TM_{LTL}^{CD\rightarrow C}} \qquad \text{Eq. 27}$$

$$\mathrm{TTM_{CD\ Excluded}} = \mathrm{TM_{FT}^{S\rightarrow C}} + \mathrm{TM_{LTL}^{S\rightarrow C}} \qquad \text{Eq. 28}$$

3.5Checking model efficiency

To demonstrate the effectiveness of the mathematical model and the efficiency of the solution algorithm proposed in this research, we check the total product transportation costs/miles efficiency shown in Eq. 29 and Eq. 30 by examining the ratio of TTC (TTM) when CD is included (see Eq. 22 and Eq. 27) in the supply chain against the TTC (TTM) when CD is excluded (see Eq. 23 and Eq. 28) from the supply chain using the following formula. As a matter of fact, the smaller these ratios, the larger the differences between to scenarios' outcome.

$$\text{Transportation cost ratio (TCR)} = \frac{\mathrm{TTC_{CD\ included}}}{\mathrm{TTC_{CD\ Excluded}}}\times 100 \qquad \text{Eq. 29}$$

$$\text{Transportation mile ratio (TMR)} = \frac{\mathrm{TTM_{CD\ included}}}{\mathrm{TTM_{CD\ Excluded}}}\times 100 \qquad \text{Eq. 30}$$

3.6Numerical Example

A single I-shaped cross-dock distribution [10 doors on each side) model with a small case including 6 suppliers and 8 customers is illustrated in Figure 9 to demonstrate effectiveness of the mathematical model and the efficiency of the solution algorithm proposed in this research. Initially, 3 matrices of supplier-customer flow, supplier-customer distance, and fleet groups are generated and present in Table 10, Table 11, and Table 12 respectively.

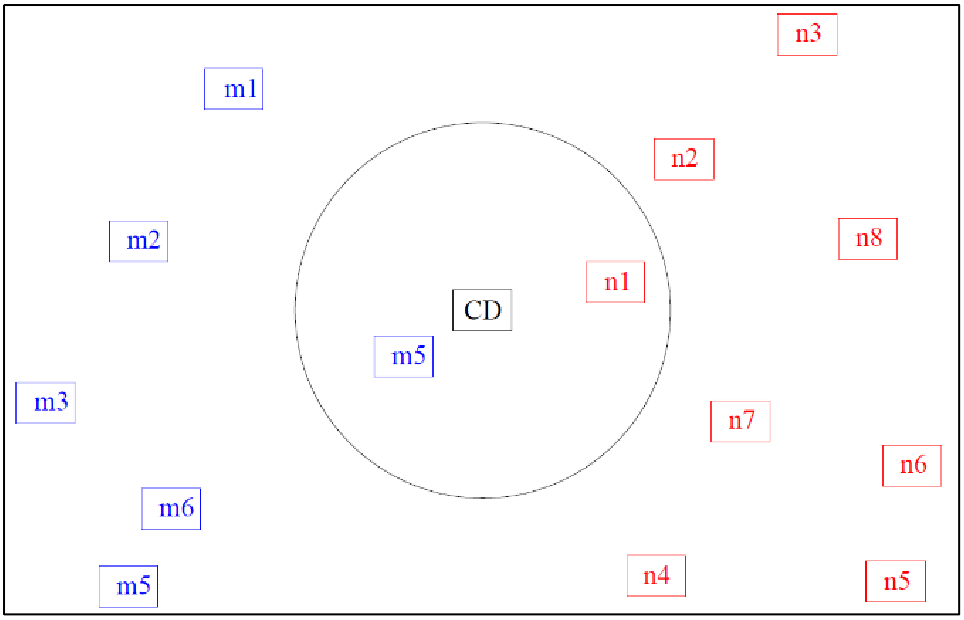


Figure 9: Graphical depiction of a single CD including 6 suppliers, and 8 customers

A set of 7 different trucks with different capacities, fixed costs, and variable costs is presented in Table 12 representing the transportation fleet for short-distance and long-distance product transportation. The basic fixed and variable costs are \$2000 and \$1 and are assigned for the 7th truck with the largest capacities. Also, truck capacities are assumed to be random numbers between 10 and 100. For instance, the second top truck's capacity equal to 80, and therefore, following Eq. 2 and Eq. 3, 6th truck's associated fixed and variable costs are $\$2000\times\frac{45}{50}=\$1800$ and $\$1\times\frac{45}{50}=\$0.9$ respectively.

The right sub-table in Table 12 lists 7 truck types and their associated fixed and variable costs which are hired for long-distance transportation. In this instance, it is assumed that the top 50% of the trucks are assigned for the long-distance transportation while 100% of the fleet is hired for the short-distance product transportation between the nodes within CD's zone.

Table 10: Supplier-customer initial flow

---		Customers' Indices							
		N1	N2	N3	N4	N5	N6	N7	N8
Suppliers' Indices	M1	20	0	630	30	25	640	375	40
	M2	0	5	45	35	5	5	15	425
	M3	560	30	45	850	20	15	20	45
	M4	40	40	40	40	30	20	40	5
	M5	35	160	25	20	5	520	35	10
	M6	15	25	370	10	50	5	10	15

Table 11: Supplier-customer original distances

---		Customers' Indices								CD
		N1	N2	N3	N4	N5	N6	N7	N8	
Suppliers' Indices	M1	1957	3135	2419	2364	5329	3841	6343	3451	1620
	M2	1522	3070	2427	2414	6292	4678	6174	2547	1395
	M3	3918	4282	5112	4752	8223	7279	8330	5279	3835
	M4	2936	4643	3537	3090	6311	6216	7272	4000	2765
	M5	1003	2120	1714	1454	5232	3858	5020	2155	410
	M6	3834	4561	4569	3863	5908	4904	7862	4574	3265
CD		605	1880	1305	1045	4900	3470	4795	1835	---

Table 12: Fleet characteristics for short and long-distance transportation

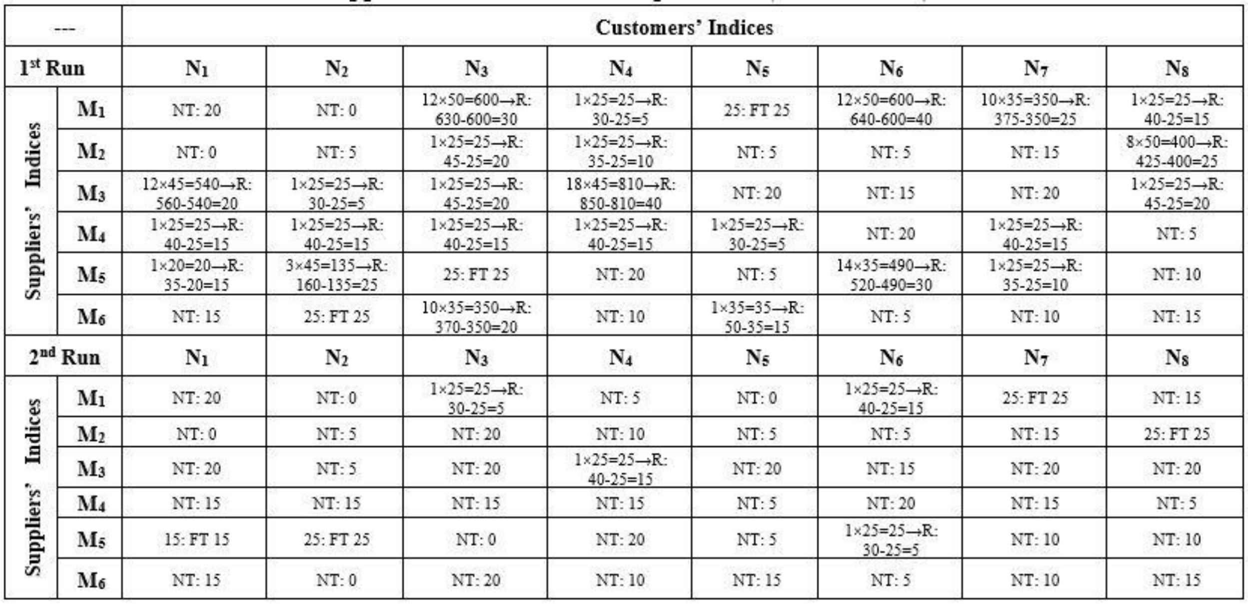
Fleet for short-distance transportation					Fleet for long-distance-transportation			
T. No.	Capacity	Fixed Costs	Var. Costs		T. No	Capacity	Fixed Costs	Var. Costs
T1	15	600	0.3		T1	15	Infinity	Infinity
T2	20	800	0.4		T2	20	Infinity	Infinity
T3	25	1000	0.5		T3	25	1000	0.5
T4	35	1400	0.7		T4	35	1400	0.7
T5	40	1600	0.8		T5	40	1600	0.8
T6	45	1800	0.9		T6	45	1800	0.9
T7	50	2000	1		T7	50	2000	1

3.6.1Numerical example of the 1st scenario: Cross-docking is included

Concerning FT product transportation policy, initially the FT product transportation is implemented using the largest truck (truck selection is performed using the truck selection policy based on the truck assignment scenarios listed in Table 9 for long versus short distance product transportation) until the number of remaining products becomes greater than the capacity of the second largest truck. Next, we start product transportation using the 2nd largest truck and repeat transportation until the number of remaining products becomes greater than the capacity of the second largest trucks. We repeat the algorithm until when the remaining of the products at suppliers' sites become less than the smallest truck capacity. Then, we consider the 2nd policy which is to transfer the remaining LTL products with any truck that costs us least. Table 13 shows the procedure of direct supplier→customer product transportation once CD is included in the supply chain. For example, in the 1st run of direct FT product transportation, the direct FT product transportation from 1st supplier to the 1st customer ($M_1 \rightarrow N_{1)}$ is not implemented as the corresponding flow between these two nodes is 20 product-unit which is less than the smallest truck capacity in the fleet of vehicles. However, the algorithm lets us have FT product transportation on $M_1 \rightarrow N_3$ route. According to the distance matrix shown in Table 11, M_1 locates inside the CD's zone while N_3 is outside of it. Thus, the 2nd fleet of trucks assigned to handle the long-distance product transportation from $M_1 \rightarrow N_3$ (see Table 12). As the initial $M_1 \rightarrow N_3$ flow is 630, the algorithm automatically selects 12 number of 7th truck with 50 product-unit capacity. By transferring 600 = 12×50 product-unit of 635 in the 1st run, in the 2nd run, the algorithm examines the possibility of direct 35 product-unit $M_1 \rightarrow N_3$ FT product transportation. In the 2nd run, the algorithm selects the 3rd truck with 25 product-unit capacity, and hence, allows to transfer another 25 product-unit directly from $M_1 \rightarrow N_3$ employing 1 unit of 3rd trucks assigned for long-distance product transportation. Finally, the direct $M_1 \rightarrow N_3$ FT product transportation stops at 2nd run as the remaining 5 product-unit becomes less than the smallest truck capacity.

The algorithm of direct transportation stops at 2nd run as all supplier-customer flows becomes less than the smaller truck capacity on their corresponding fleet shown in Table 12. Total FT product transportation cost at 1st and 2nd run is $564,317.00 and $20,840.90 respectively presented in Table 18. Table 13 illustrates the direct FT product transportation from the suppliers to the customers in 2 runs. In the first run, most products are transferred, and in the second run, just a few numbers of products are directly transferred, and the rest stay in the suppliers' sites until become consolidated at each supplier's site and then transferred to the cross-docking terminals. There are three coded acronyms including NT, R, and FT which are used in all the product transportation Table 13, Table 15, and Table 16. *NT* stands for "*No Transportation*" and it happens when no product transportation occurs between two nodes either due to zero number of products or impossibility of LTL product transportation. For instance, there is a long-distance product transportation from M1→N1, and their corresponding flows equals 20 product-unit which is lower than the smallest truck with capacity equals 25 (see Table 12). Therefore, there is no possibility for the FT product transportation from $M_1 \rightarrow N_1$. The second acronym is *R* which stands for "Remaining products for the next run." For instance, in the first run, 12 number of 7th truck is selected to transfer 600 product-unit from $M_1 \rightarrow N_3$. The remaining product for the next run of the FT product transportation equals $R = 630 - 600 = 30$. However, in the second run we check the possibility of another FT product transportation and then employ 3rd truck [25 product-unit capacity) and transfer another 25 units; thus, the remaining product for next FT product transportation would be equal $R = 30 - 25 = 5$ product-unit. The third acronym *FT* stands for FT product transportation, and it occurs in the X^{th} run when the all remaining products are transferred using FT product transportation and no other products remain at the supplier's site to be transferred in the next run.

Table 13: Supplier-customer FTL transportation (CD Included)



---		Customers' Indices							
1st Run		N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8
Suppliers' Indices	M_1	NT: 20	NT: 0	12×50=600→R: 630-600=30	1×25=25→R: 30-25=5	25: FT 25	12×50=600→R: 640-600=40	10×35=350→R: 375-350=25	1×25=25→R: 40-25=15
	M_2	NT: 0	NT: 5	1×25=25→R: 45-25=20	1×25=25→R: 35-25=10	NT: 5	NT: 5	NT: 15	8×50=400→R: 425-400=25
	M_3	12×45=540→R: 560-540=20	1×25=25→R: 30-25=5	1×25=25→R: 45-25=20	18×45=810→R: 850-810=40	NT: 20	NT: 15	NT: 20	1×25=25→R: 45-25=20
	M_4	1×25=25→R: 40-25=15	1×25=25→R: 40-25=15	1×25=25→R: 40-25=15	1×25=25→R: 40-25=15	1×25=25→R: 30-25=5	NT: 20	1×25=25→R: 40-25=15	NT: 5
	M_5	1×20=20→R: 35-20=15	3×45=135→R: 160-135=25	25: FT 25	NT: 20	NT: 5	14×35=490→R: 520-490=30	1×25=25→R: 35-25=10	NT: 10
	M_6	NT: 15	25: FT 25	10×35=350→R: 370-350=20	NT: 10	1×35=35→R: 50-35=15	NT: 5	NT: 10	NT: 15
2nd Run		N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8
Suppliers' Indices	M_1	NT: 20	NT: 0	1×25=25→R: 30-25=5	NT: 5	NT: 0	1×25=25→R: 40-25=15	25: FT 25	NT: 15
	M_2	NT: 0	NT: 5	NT: 20	NT: 10	NT: 5	NT: 5	NT: 15	25: FT 25
	M_3	NT: 20	NT: 5	NT: 20	1×25=25→R: 40-25=15	NT: 20	NT: 15	NT: 20	NT: 20
	M_4	NT: 15	NT: 15	NT: 15	NT: 15	NT: 5	NT: 20	NT: 15	NT: 5
	M_5	15: FT 15	25: FT 25	NT: 0	NT: 20	NT: 5	1×25=25→R: 30-25=5	NT: 10	NT: 10
	M_6	NT: 15	NT: 0	NT: 20	NT: 10	NT: 15	NT: 5	NT: 10	NT: 15

Table 14 is matrix of supplier-customer LTL flows (all flows are less than the capacity of the smallest truck for both fleet shown Table 12) which are not worth being transferred directly from suppliers' sites to the customers' site.

Table 14: Supplier-customer LTLs' flows transferred via CD terminal

---		Customers' Indices								CD
		N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	
Suppliers' Indices	M_1	20	0	5	5	0	15	0	15	60
	M_2	0	5	20	10	5	5	15	0	60
	M_3	20	5	20	15	20	15	20	20	135
	M_4	15	15	15	15	5	20	15	5	105
	M_5	0	0	0	20	5	5	10	10	50
	M_6	15	0	20	10	15	5	10	15	90
CD		70	25	80	75	50	65	70	65	---

In order to transfer the remaining supplier→customer LTL products presented in Table 14, initially, all products at each supplier's site are consolidated (CD column in Table 14), and then transferred to the single CD. The consolidation of products at suppliers' sites helps increase the number of FT product transportation and decrease the number of LTL product transportation from suppliers' sites to the cross-docking terminal. After consolidation of products, the products initially are transferred from suppliers' sites to the cross-docking terminal using FT transportation (see the FT product transportation in Table 15). Afterward, the remaining LTL products at suppliers' sites are transferred to the terminal by appropriate trucks that minimize total LTL product transportation cost (see the LTL product transportation in Table 15).

On the other side of the terminal, the same policy is employed, and initially, the consolidated products at cross-docking terminal (CD row in Table 14) are transferred to the customers' sites using FT policy (see the FT product transportation in Table 16). The similar process of the transportation of the remaining LTL products from supplier→cross-docking terminal is applied for the LTL product transportation from the cross-docking terminal to each customer's site (see the LTL product transportation in Table 16). In the LTL sections of Table 15 and Table 16, the amount of each LTL flow is computed, and the amount of the products that a truck carries vacant is addressed as *empty*.

For instance, as it is illustrated in Table 14, the consolidated products at M_3's site equals 135 product-units. In the 1st run of FT product transportation shown in Table 15, two T_7 trucks with 50 product-unit capacity are selected to carry M_3→CD FT product transportation. However, in the 2nd run of the FT product transportation from M_3→CD, the remaining 35 products at M_3's site is transferred to the CD by a T_3 truck with 25 product-unit capacity. Concerning the remaining 10 product-unit at M_3 supplier, an LTL truck with 25 product-unit capacity is hired; and thus, "*10 with 25 →empty: 15*" is reported. Similar procedure is carried out on product transportation from other suppliers to CD and from CD to all customers, and all results are presented in Table 15 and Table 16.

Table 15: Supplier→CD FTL and LTL product transportation

Supplier→CD FTL transportation				Supplier→CD LTL transportation	
1st Run	CD	2nd Run	CD	Last	CD
M1	1×35=35→R: 60-35=25	M1	25: FT 25	M1	NT
M2	1×35=35→R: 60-35=25	M2	25: FT 25	M2	NT
M3	2×50=100→R: 135-100=35	M3	1×25=25→R: 35-25=10	M3	10 with 25 →empty: 15
M4	2×40=80→R: 105-80=25	M4	25: FT 25	M4	NT
M5	1×35=35→R: 50-35=15	M5	15: FT 15	M5	NT
M6	1×50=50→R: 90-50=40	M6	1×25=25→R: 40-25=15	M6	15 with 25 →empty: 10
NT: No/zero Transfer to next run, R: Remaining for the next run; FT: FT with Truck X that has zero remaining for the next run					

Table 16: CD→customer FTL and LTL product transportation

CD→customer FTL transportation				CD→customer LTL transportation	
1st Run	CD	2nd Run	CD	Last	CD
N1	1×40=40→R: 70-40=30	N1	1×20=20→R: 30-20=10	N1	10 with 25 →Empty: 15
N2	25: FT 25	N2	NT: 0	N2	NT: 0+
N3	1×45=45→R: 80-45=35	N3	1×25=25→R: 35-25=10	N3	10 with 25 →Empty: 15
N4	1×40=40→R: 75-40=35	N4	1×25=25→R: 35-25=10	N4	10 with 25 → Empty: 15
N5	1×35=35→R: 50-35=15	N5	No Transfer: 15	N5	15 with 25 → Empty: 10
N6	1×35=35→R: 65-35=30	N6	1×25=25→R: 30-25=5	N6	5 with 25 → Empty: 20
N7	1×40=40→R: 70-40=30	N7	1×25=25→R: 30-25=5	N7	5 with 25 → Empty: 20
N8	1×35=35→R: 65-35=30	N8	1×25=25→R: 30-25=5	N8	5 with 25 → Empty: 20
NT: No/zero Transfer to next run, R: Remaining for the next run; FT: FT with Truck X that has zero remaining for the next run					

3.6.2Numerical example of the 2nd scenario: Cross-docking is Excluded

Having all assumptions held, the supplier→customer FT product transportation (see Table 13 on page 95) is exactly similar to what we have done in section 3.6.1; when cross-docking is included in the supply chain. However, concerning the LTL product transportation (see Table 14) the best truck is selected for each route that help minimize the total LTL product transportation costs. Table 17 illustrates all direct LTL product transportation among suppliers and customers once cross-docking is excluded from the supply chain. There, *E* represents amount of empty product-unit on each truck.

Table 17: Supplier-customer LTL product transportation

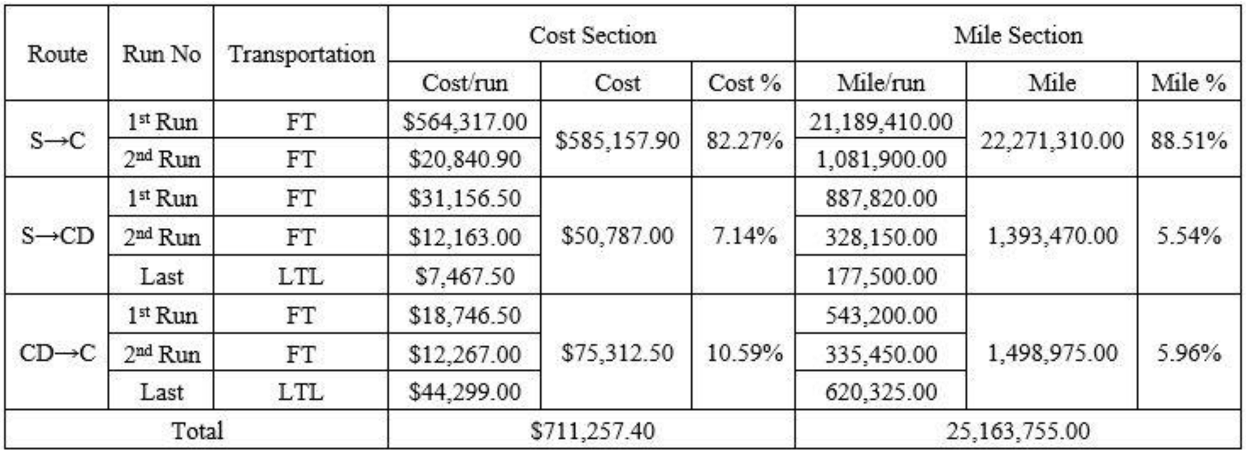
Last		Customers' Indices							
		N1	N2	N3	N4	N5	N6	N7	N8
Suppliers' Indices	M1	20 with 25 (E=5)	NT	5 with 25 (E=20)	5 with 25 (E=20)	NT	15 with 25 (E=10)	NT	15 with 25 (E=10)
	M2	NT	5 with 25 (E=20)	20 with 25 (E=5)	10 with 25 (E=15)	5 with 25 (E=20)	5 with 25 (E=20)	15 with 25 (E=10)	NT
	M3	20 with 25 (E=5)	5 with 25 (E=20)	20 with 25 (E=5)	15 with 25 (E=10)	20 with 25 (E=5)	15 with 25 (E=10)	20 with 25 (E=5)	20 with 25 (E=5)
	M4	15 with 25 (E=10)	15 with 25 (E=10)	15 with 25 (E=10)	15 with 25 (E=10)	5 with 25 (E=20)	20 with 25 (E=5)	15 with 25 (E=10)	5 with 25 (E=20)
	M5	NT	NT	NT	20 with 25 (E=5)	5 with 25 (E=20)	5 with 25 (E=20)	10 with 25 (E=15)	10 with 25 (E=15)
	M6	15 with 25 (E=10)	NT	20 with 25 (E=5)	10 with 25 (E=15)	15 with 25 (E=10)	5 with 25 (E=20)	10 with 25 (E=15)	15 with 25 (E=10)

3.6.3Model Efficiency

Table 18 and Table 19 list the total supply chain transportation costs (miles) calculated for each scenario.

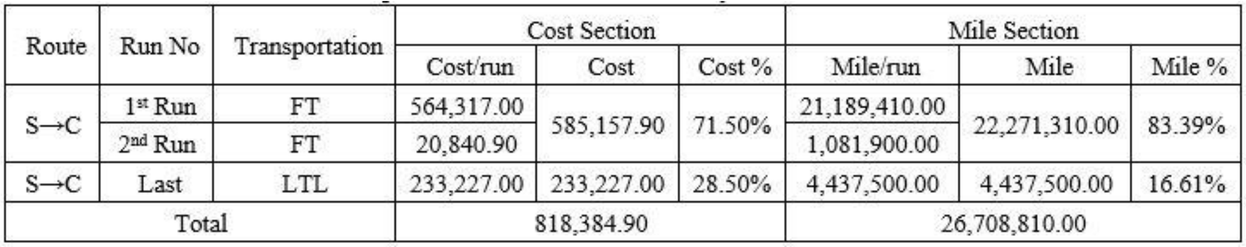
Each table dichotomized the costs (miles) analysis into FT versus LTL analysis to deliver better insights. As it is presented in Table 18, 82.27% and 88.51% of total transportation costs and miles relative to the FT product transportation when cross-docking is included within the supply chain. The portion of FT product transportation costs and miles reduce considerably to 71.50% and 83.39% in the second scenario shown in Table 19. As it is shown in Table 20, transportation cost ratio (TCR) and transportation mile ratio (TMR) for this instance with 6 suppliers and 8 customers equal 86.91% and 94.22% respectively. This result shows the significant advantage of practicing cross-docking to reduce not only the product-unit cost but also the product-unit mile. These notable reductions are due to more FT product transportation (less LTL product transportation) in the first scenario and manifest themselves in the decrease on the proportion FT product transportation costs and miles when cross-docking is excluded from the supply chain.

Table 18: Transportation cost and mile analysis when CD included



Route	Run No	Transportation	Cost Section			Mile Section		
			Cost/run	Cost	Cost %	Mile/run	Mile	Mile %
S→C	1st Run	FT	$564,317.00	$585,157.90	82.27%	21,189,410.00	22,271,310.00	88.51%
	2nd Run	FT	$20,840.90			1,081,900.00		
S→CD	1st Run	FT	$31,156.50	$50,787.00	7.14%	887,820.00	1,393,470.00	5.54%
	2nd Run	FT	$12,163.00			328,150.00		
	Last	LTL	$7,467.50			177,500.00		
CD→C	1st Run	FT	$18,746.50	$75,312.50	10.59%	543,200.00	1,498,975.00	5.96%
	2nd Run	FT	$12,267.00			335,450.00		
	Last	LTL	$44,299.00			620,325.00		
Total			$711,257.40			25,163,755.00		

Table 19: Transportation cost and mile analysis when CD excluded



Route	Run No	Transportation	Cost Section			Mile Section		
			Cost/run	Cost	Cost %	Mile/run	Mile	Mile %
S→C	1st Run	FT	564,317.00	585,157.90	71.50%	21,189,410.00	22,271,310.00	83.39%
	2nd Run	FT	20,840.90			1,081,900.00		
S→C	Last	LTL	233,227.00	233,227.00	28.50%	4,437,500.00	4,437,500.00	16.61%
Total			818,384.90			26,708,810.00		

Table 20: Cost and mile product unit ratio

Scenario	Total Transportation Cost	Total Transportation Mile
CD Included	711,257.40	25,163,755.00
CD Excluded	818,384.90	26,708,810.00
TCR & TMR: $\frac{\text{CD Included}}{\text{CD Excluded}}$	86.91%	94.22%

Aggregation of all FT and LTL product transportation costs presented in Table 18 and Table 19 are shown in Table 21. The comparison between two scenarios shows us that the total transportation costs (miles) in the 1st scenario (a supply chain with a CD) is must less than the total transportation costs (miles) for the 2nd scenario (a supply chain without a CD), and therefore, Both TCR and TMR ratios are less than 1 shown in Table 20. However, by looking at the portion of FT versus LTL for each scenario presented in Table 21, it is noted that the portion of FT product transportation is 92.72% and 96.83 on total transportation costs and total transportation miles respectively and are much further than their correspondent values in the second scenario. In contrast, the portion of LTL product transportation cost and mile [7.28% and 3.17%) are much less than their counterparts in the 2nd scenario. Therefore, it turns out that by assuming cross-docking as an intermediate transshipment node within the supply chain, we have FT product transportation and less LTL which are the key factors to achieve economies of scale, less product unit costs, and higher quality usage of the roads.

Table 21: transportation cost (TTC) and mile (TTM) when CD included vs. excluded

Scenario	Transportation	Cost Section		Mile Section	
		Cost	Cost %	Mile	Mile %
CD Included	FT	659,490.90	92.72%	24,365,930.00	96.83%
	LTL	51,766.50	7.28%	797,825.00	3.17%
CD Excluded	FT	585,157.90	71.50%	22,271,310.00	83.39%
	LTL	233,227.00	28.50%	4,437,500.00	16.61%

Another indicator that shows the efficiency and effectiveness of the proposed binary-linear programming model and results is the number of trucks that are used for FT product transportation against the LTL product transportation. According to the data shown in Table 22, in the 1st scenario, 153 trucks are hired for the FT product transportation and 125 FT product transportation in the 2nd scenario. Conversely, in the 1st scenario, we just hire 8 trucks for LTL product transportation and 39 trucks in the 2nd scenario. The number of LTL trucks is an indicator that shows the level of economies of scale within a supply chain. In fact, the higher (fewer) the number of FT (LTL) trucks, the higher (fewer) economies of scale is expected which results in less (higher) product-unit cost and higher (less) quality usage of the roads. By looking at the total number of trucks hired in each scenario; i.e.,161 trucks when cross-docking included and 164 trucks when cross-docking excluded, we showed that the proposed model is an efficient practice that not only helps minimize the total transportation costs and miles, but also the increase the efficiency of the transportation network by reducing number of trucks from the network which results in reduction of pollution produced by the additional trucks in the networks. Also, Table 22 shows that the model emphasizes more on the trucks with larger capacities to handle product transportation between each two nodes.

Table 22: Number of truck assignment in each route between each two nodes

Truck	Cross-docking terminal Included							Cross-Dock Excluded	
	FT				LTL			FT	LTL
	S→C	S→CD	CD→C	Sum	S→CD	CD→C	Sum	S→C	S→C
50	32	3	---	35	---	---	---	32	---
45	33	---	1	34	---	---	---	33	---
40	---	2	3	5	---	---	---	---	---
35	35	3	3	41	---	---	---	35	---
25	23	5	6	34	2	6	8	23	39
20	1	---	1	2	---	---	---	1	---
15	1	1	---	2	---	---	---	1	---
Total				153	---		8	125	39

In the current example, the transportation cost ratio (TCR) and the transportation mile ratio (TMR) are 86.91% and 94.22% respectively. This indicates that, regardless of the operational costs of a cross-docking terminal, transportation costs and miles are much lower when we involve CD terminal to take care of supplier→customer LTL batch sizes. Nonetheless, depending on the size of the problem and the way we set up other parameters like initial fixed costs, initial variable costs, range of truck capacities, and percentage of trucks assigned for long-distance product transportation, these ratios can vary. The contribution of this study is to figure the best parameter settings to minimize these ratios. In the following section, we will elaborate more about the parameters setting employing Taguchi orthogonal array technique.

3.7Robust Parameter Design

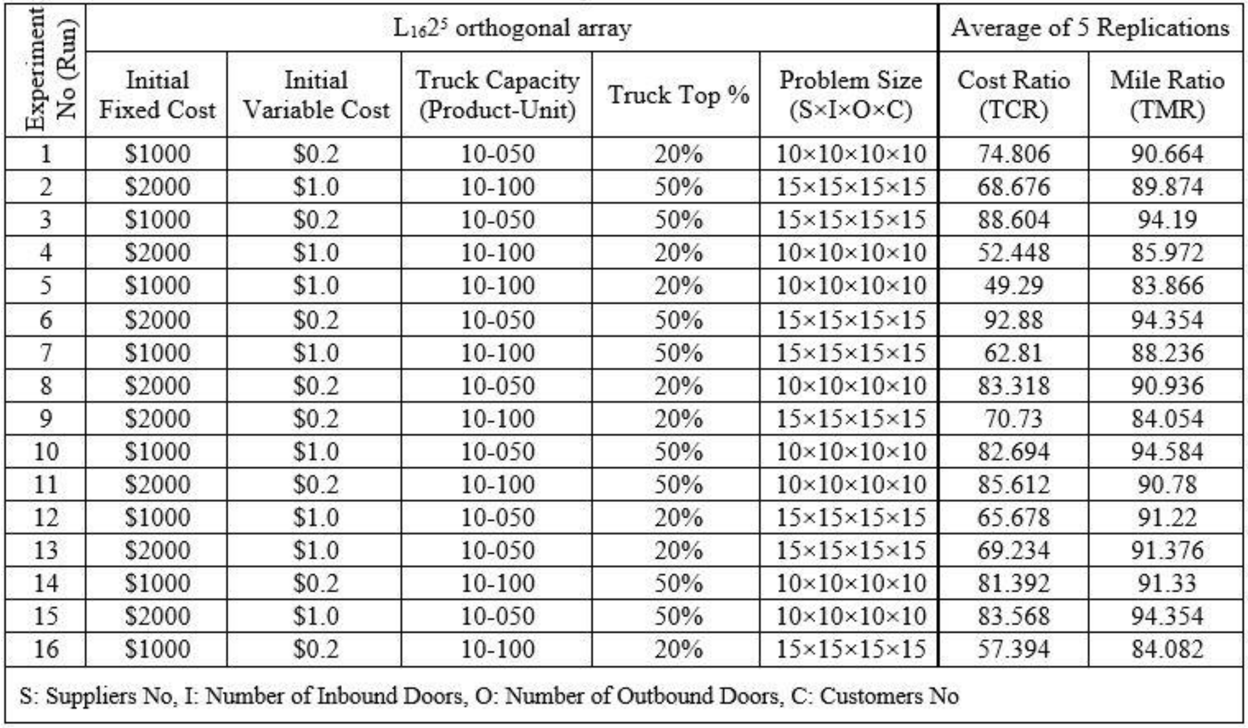
Since full factorial design is the most expensive method to perform the experiments to achieve the best parameters setting to yield the optimum output, we propose a procedure based on statistical design of experiments and Taguchi method that finds effective settings for tuning parameters used in heuristics. Taguchi’s robust parameter design seeks to identify controllable factors (signals) that minimize the effect of the noise factors. Taguchi method offers a cost-effective and labor-saving means to investigate several factors simultaneously and identifies those that have primary impacts on the target value [244; 192; 198]. It is statistically proven that a small fraction of setting factors; i.e., the orthogonal array in Taguchi method, produces most information from all the possible combinations [116].

In Taguchi method, there are two measures that should be considered simultaneously; Target value and Signal-to-Noise ratio. While the former is simply measuring the mean value of the output, the signal to noise ratio measures the sensitivity of the quality investigated to those uncontrollable factors in the experiment [132]. The term signal stands for the desired target for good products, and the term noise represents the undesirable value. In fact, the Taguchi method goal is not only to optimize an arbitrary objective function, but also to reduce the sensitivity of engineering designs to uncontrollable factors or noise [107]. It is to determine the controllable process parameter settings for which noise or variation has a minimal effect on the product's or process's functional characteristics Taguchi proposes to maximize the function S/N ratio because greater S/N ratio results in smaller product variance around the target value, or the least standard deviation from the target value.

In order to minimize TCR and TMR, five parameters/factors are assumed including 1) initial fixed costs ($1000 vs. $2000), 2) initial variable costs ($0.2 vs. $1.0), 3) range of truck capacities (10-50 vs. 10-166), 4) percentage of trucks assigned for long-distance product transportation manipulate (20% vs. 50%), and 5) problem size (10×10×10×10 vs. 15×15×15×15). These factors are manipulated using $L_{16}2^5$ orthogonal array design shown in Table 23. For each experiment, five replications are implemented and averaged results for both TCR and TMR are presented in the last two columns. The objective of these experiments is to find the best factors' combination that helps minimize TCR and TMR. Therefore, smaller-is-better signal-to-noise (S/N) ratio shown in Eq. 31 is calculated for each factor level combination.

$$S/N = -10\log_{10}\left[\frac{\sum_{i=1}^{i=n} {y_i}^2}{n}\right] \qquad \text{Eq. 31}$$

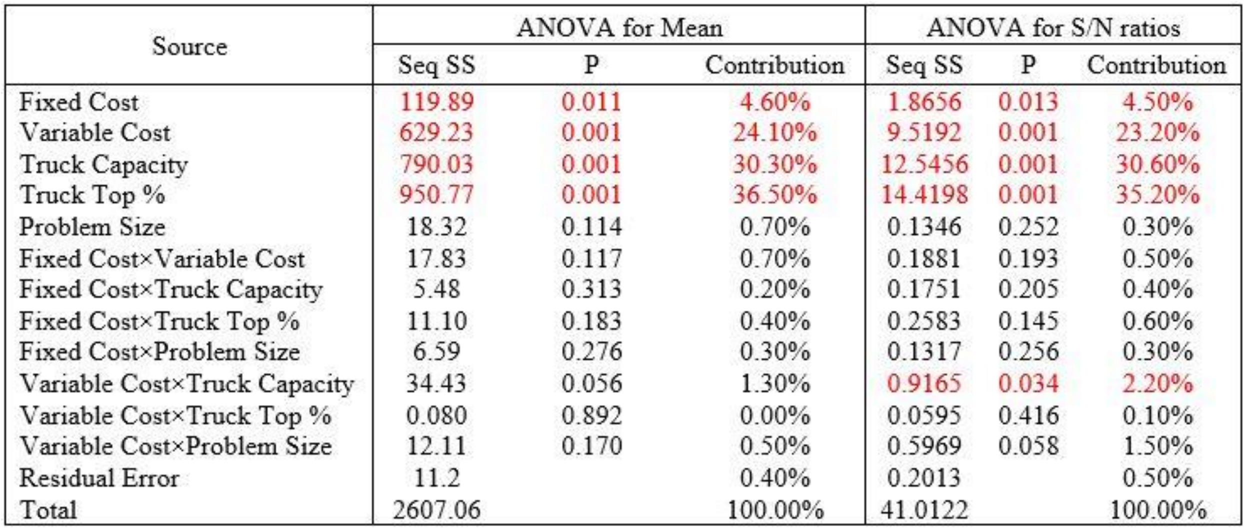
Table 23: $L_{16}2^5$ orthogonal array and average of cost-ratio and mile-ratio for 5 experimental replications



Experiment No (Run)	$L_{16}2^5$ orthogonal array					Average of 5 Replications	
	Initial Fixed Cost	Initial Variable Cost	Truck Capacity (Product-Unit)	Truck Top %	Problem Size (S×I×O×C)	Cost Ratio (TCR)	Mile Ratio (TMR)
1	$1000	$0.2	10-050	20%	10×10×10×10	74.806	90.664
2	$2000	$1.0	10-100	50%	15×15×15×15	68.676	89.874
3	$1000	$0.2	10-050	50%	15×15×15×15	88.604	94.19
4	$2000	$1.0	10-100	20%	10×10×10×10	52.448	85.972
5	$1000	$1.0	10-100	20%	10×10×10×10	49.29	83.866
6	$2000	$0.2	10-050	50%	15×15×15×15	92.88	94.354
7	$1000	$1.0	10-100	50%	15×15×15×15	62.81	88.236
8	$2000	$0.2	10-050	20%	10×10×10×10	83.318	90.936
9	$2000	$0.2	10-100	20%	15×15×15×15	70.73	84.054
10	$1000	$1.0	10-050	50%	10×10×10×10	82.694	94.584
11	$2000	$0.2	10-100	50%	10×10×10×10	85.612	90.78
12	$1000	$1.0	10-050	20%	15×15×15×15	65.678	91.22
13	$2000	$1.0	10-050	20%	15×15×15×15	69.234	91.376
14	$1000	$0.2	10-100	50%	10×10×10×10	81.392	91.33
15	$2000	$1.0	10-050	50%	10×10×10×10	83.568	94.354
16	$1000	$0.2	10-100	20%	15×15×15×15	57.394	84.082
S: Suppliers No, I: Number of Inbound Doors, O: Number of Outbound Doors, C: Customers No							

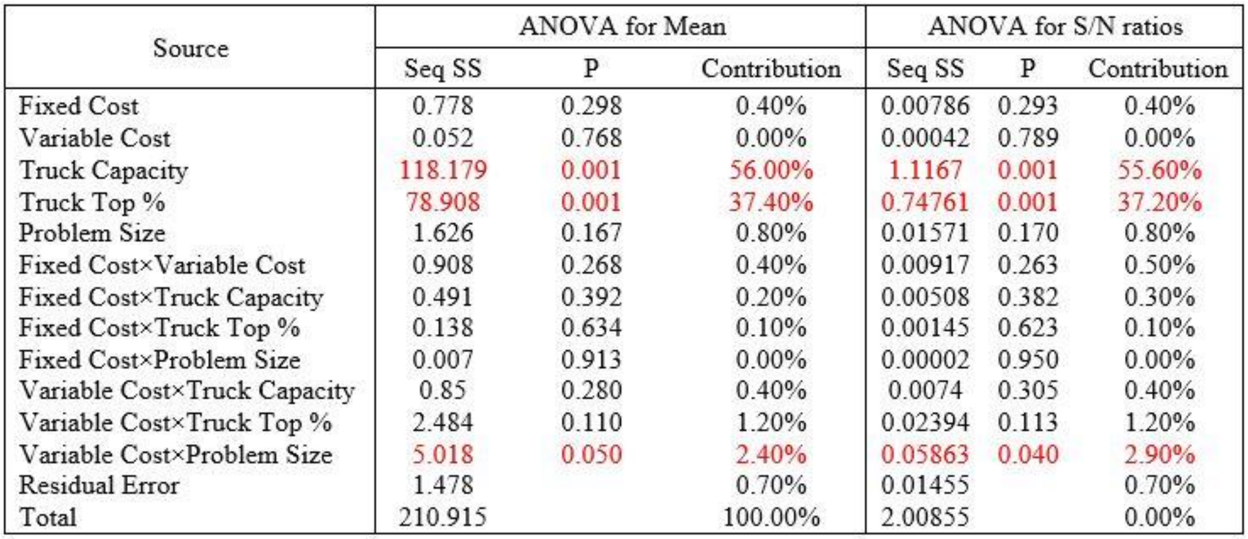
Analysis of Variance (ANOVA) shown in Table 24 and Table 25 present the analysis for mean and S/N ratio and explained the differences among factors listed in Table 23 on TCR and TMR. Concerning the ANOVA on mean and S/N ratio for TCR presented in Table 24, all factors except problem size significantly influence the outputs. On each table, sequential sums of square (Seq SS) are measures of variation for different factors of the model, and their corresponding values on contribution column displays the percentage that each source in the ANOVA table contributes to the total sequential sums of squares (Seq SS). Here, the contribution of the first four factors on the variation of mean and S/N ratio for TCR analysis are 95.5% and 93.5% respectively. In fact, by controlling these four factors, we can control the variation of mean and S/N ratio by 95.5% and 93.5% respectively. In the meantime, interaction effects of the factors on both outputs are negligible as none of them (except Variable Cost×Truck Capacity) are significant in the ANOVA analysis shown in Table 24. Concerning the TMR's analysis of variance shown in Table 25, the analysis shows that except Truck Capacity, Truck Top %, and Variable Cost×Problem Size other factors and interactions have insignificant effect on mean and S/N ratio. The TMR analysis shows that the contribution of Truck Capacity and Truck Top % on mean and S/N ratio's variations are 93.4% and 92.8%. In fact, just by controlling these variables, we can control the variation of mean and S/N ratio by 93.4% and 92.8% respectively.

Table 24: Analysis of Variance for Means (Cost Ratio or TCR)



Source	ANOVA for Mean			ANOVA for S/N ratios		
	Seq SS	P	Contribution	Seq SS	P	Contribution
Fixed Cost	119.89	0.011	4.60%	1.8656	0.013	4.50%
Variable Cost	629.23	0.001	24.10%	9.5192	0.001	23.20%
Truck Capacity	790.03	0.001	30.30%	12.5456	0.001	30.60%
Truck Top %	950.77	0.001	36.50%	14.4198	0.001	35.20%
Problem Size	18.32	0.114	0.70%	0.1346	0.252	0.30%
Fixed Cost×Variable Cost	17.83	0.117	0.70%	0.1881	0.193	0.50%
Fixed Cost×Truck Capacity	5.48	0.313	0.20%	0.1751	0.205	0.40%
Fixed Cost×Truck Top %	11.10	0.183	0.40%	0.2583	0.145	0.60%
Fixed Cost×Problem Size	6.59	0.276	0.30%	0.1317	0.256	0.30%
Variable Cost×Truck Capacity	34.43	0.056	1.30%	0.9165	0.034	2.20%
Variable Cost×Truck Top %	0.080	0.892	0.00%	0.0595	0.416	0.10%
Variable Cost×Problem Size	12.11	0.170	0.50%	0.5969	0.058	1.50%
Residual Error	11.2		0.40%	0.2013		0.50%
Total	2607.06		100.00%	41.0122		100.00%

Table 25: Analysis of Variance for Means (Mile Ratio or TMR)



Source	ANOVA for Mean			ANOVA for S/N ratios		
	Seq SS	P	Contribution	Seq SS	P	Contribution
Fixed Cost	0.778	0.298	0.40%	0.00786	0.293	0.40%
Variable Cost	0.052	0.768	0.00%	0.00042	0.789	0.00%
Truck Capacity	118.179	0.001	56.00%	1.1167	0.001	55.60%
Truck Top %	78.908	0.001	37.40%	0.74761	0.001	37.20%
Problem Size	1.626	0.167	0.80%	0.01571	0.170	0.80%
Fixed Cost×Variable Cost	0.908	0.268	0.40%	0.00917	0.263	0.50%
Fixed Cost×Truck Capacity	0.491	0.392	0.20%	0.00508	0.382	0.30%
Fixed Cost×Truck Top %	0.138	0.634	0.10%	0.00145	0.623	0.10%
Fixed Cost×Problem Size	0.007	0.913	0.00%	0.00002	0.950	0.00%
Variable Cost×Truck Capacity	0.85	0.280	0.40%	0.0074	0.305	0.40%
Variable Cost×Truck Top %	2.484	0.110	1.20%	0.02394	0.113	1.20%
Variable Cost×Problem Size	5.018	0.050	2.40%	0.05863	0.040	2.90%
Residual Error	1.478		0.70%	0.01455		0.70%
Total	210.915		100.00%	2.00855		0.00%

Figure 10 displays differences between the level means for all factors that affect the TCR and TMR responses for both mean and S/N ratio analysis. In all main effect analysis, the larger differences between the means' levels, the more significant its corresponding factor. In all four main effect analysis, there is a significant difference between the levels of *truck capacity* and *top truck %* factors. Also, there are consistency between the main effect analysis for mean and main effect analysis for S/N ratio in main effect analysis. In all graphs, the larger S/N ratio[1] on a specific level for one factor mirrors to the smaller mean value on its corresponding mean's graph and vice versa. The interaction of factors displays in Figure 10 indicate how the relationship between one categorical factor and a continuous response (TCR or TMR) depends on the value of the second categorical factor. It is noticed that the more non-parallel the lines are in the interaction analysis, the greater the strength of the interaction. Overall, most of the interaction presented in Figure 11 and Figure 10 seem to be parallel, and therefore, we consider the effect of them negligible for our analysis.

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[1] The larger S/N ratio is always desirable.

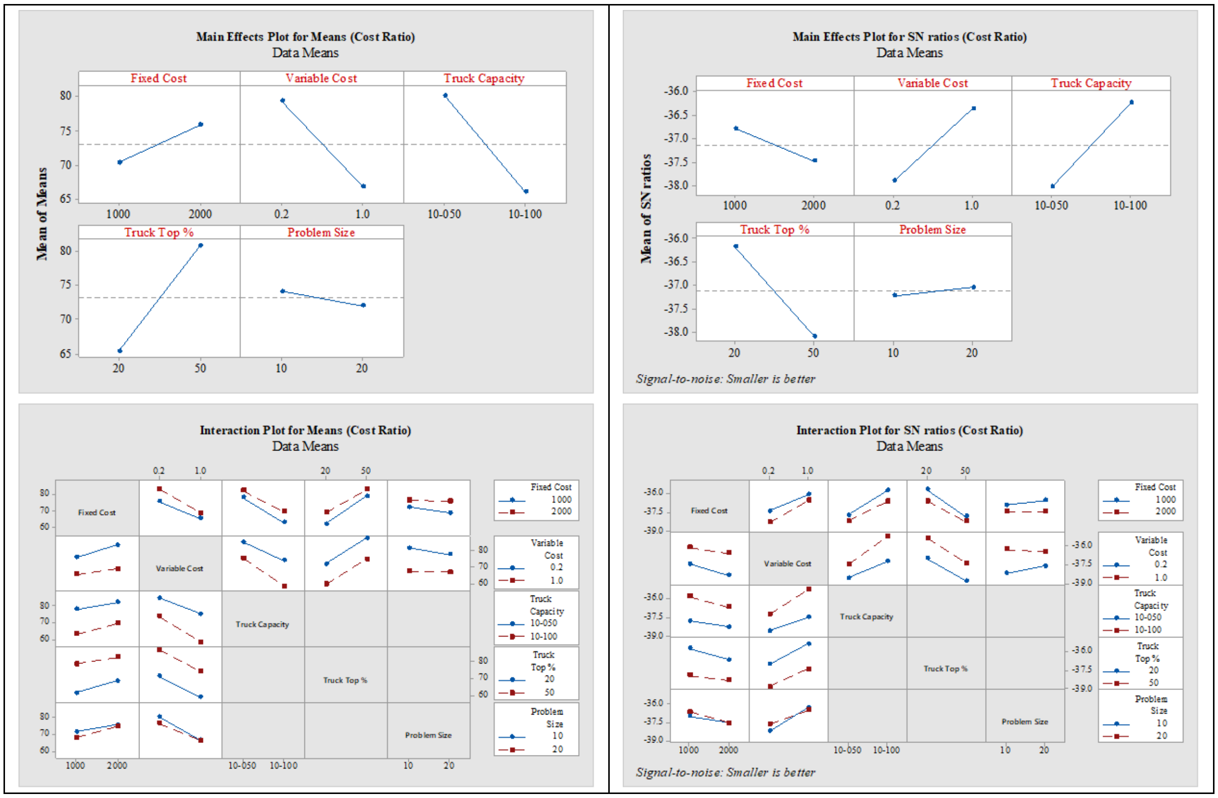


Figure 10: Main effect and interaction effect plots for mile ratio

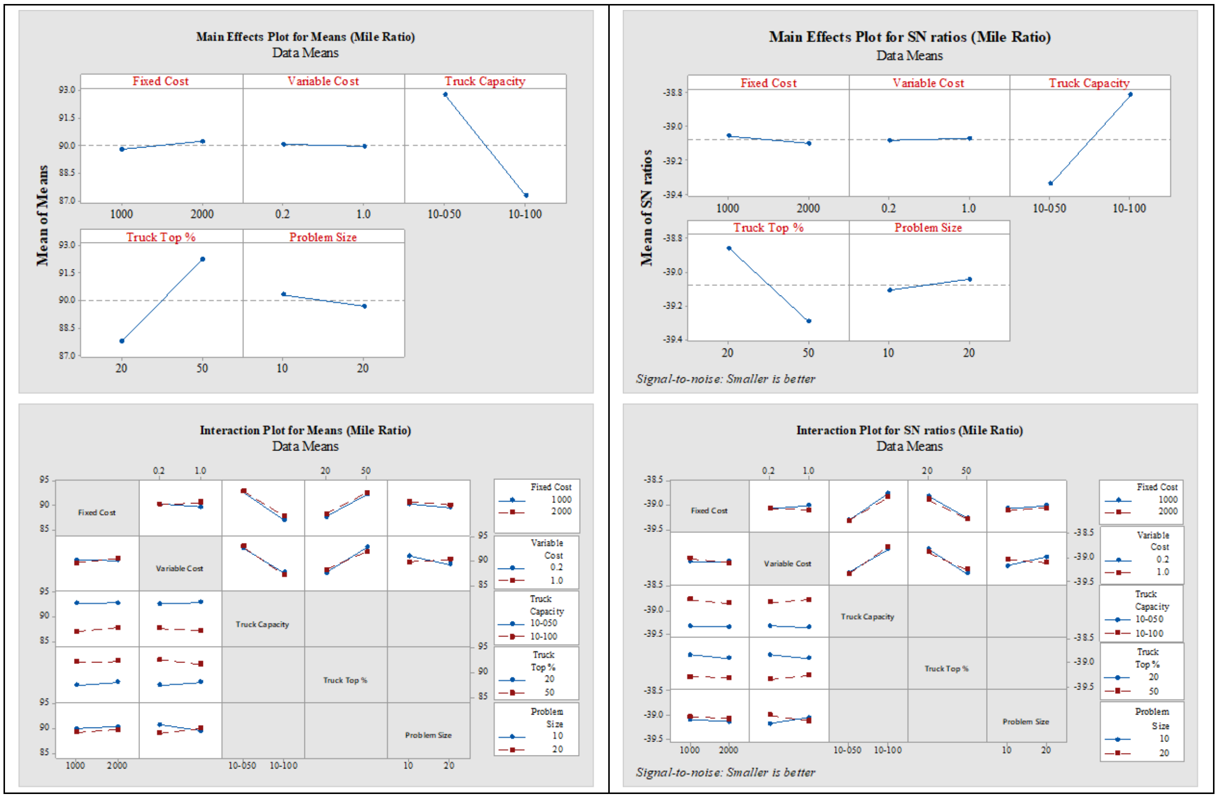


Figure 11: Main effect and interaction effect plots for cost ratio analysis

Table 26 and Table 27 are presenting model' summary. R^2 is just one measure of how well the model fits the data and shows the percentage of variation in the response that is explained by the model. Overall, the model consisting of the listed five factors can explain over 99% of the responses variation on means and S/N ratios for both TCR and TMR. On the other hand, adjusted R^2 is a modified version of R^2 that has been adjusted for the number of predictors and is the percentage of the variation in the response that is explained by the model. Overall, all adjusted R^2 are larger than 96%.

In the second half of the Table 26 and Table 27, all response tables on mean and S/N ratio for both TCR and TMR are presented. In the mean section of the table, a separate mean for each combination of control factor levels is presented, and we select the ones that have the minimum value. Also, in the S/N ratio section of the table, a separate S/N ratio for each combination of control factor levels in the design is calculated, and in all cases, we select the maximum value. In both tables, delta measures the size of the effect by taking the difference between the highest and lowest characteristic average for a factor. And finally, the rank that helps quickly identify which factor has the largest effect. All ranks in both tables link directly to the contribution of the corresponding factor.

Based on the final analysis shown in Table 26 and Table 27, we can conclude that the top truck % and truck capacity are the 2 important factors that have pivotal contribution to control TCR and TMR variation. Finally, we can predict that a large size model with the small initial fixed cost, large initial variable cost, larger trucks' capacities, and assignment of a small portion of larger trucks for long-distance transportation can yield smaller transportation cost ratio (TCR) and transportation mile ratio (TMR).

Table 26: Response Table for Means and S/N ratio (Cost Ratio - TCR)

---	Model Summary		Level Selection	Level	Fixed Cost	Variable Cost	Truck Capacity	Top Truck %	Problem Size
	R^2	R^2 (Adj.)							
Mean	99.57%	97.85%		1	70.33	79.34	80.1	65.36	74.14
				2	75.81	66.8	66.04	80.78	72
				Delta	5.47	12.54	14.05	15.42	2.14
				Rank	4	3	2	1	5
S/N Ratio	99.51%	97.55%		1	-36.79	-37.9	-38.02	-36.18	-37.22
				2	-37.47	-36.36	-36.25	-38.08	-37.04
				Delta	0.68	1.54	1.77	1.9	0.18
				Rank	4	3	2	1	5
Selected Level					1 [1000)	2 [1.0)	2 [10-166]	1 [20%)	2 [82]

Table 27: Response Table for Means and S/N ratio (Mile Ratio - TMR)

---	Model Summary		Model Summary	Level	Fixed Cost	Variable Cost	Truck Capacity	Top Truck %	Problem Size
	R^2	R^2 (Adj.)							
Mean	99.30%	99.28%		1	89.77	90.05	92.71	87.77	90.31
				2	90.21	89.94	87.27	92.21	89.67
				Delta	0.44	0.11	5.44	4.44	0.64
				Rank	4	5	1	2	3
S/N Ratio	96.50%	96.38%		1	-39.05	-39.08	-39.34	-38.86	-39.11
				2	-39.1	-39.07	-38.81	-39.29	-39.05
				Delta	0.04	0.01	0.53	0.43	0.06
				Rank	4	5	1	2	3
Selected Level					1 [1000)	2 [1.0)	2 [10-166]	1 [20%)	2 [82]

3.8Conclusion

This work considers the problem of satisfying transportation requests from a set of suppliers to a set of customers. Instead of commonly approach of direct-shipping of products, an intermediate transshipment point – cross-docking terminal – is hired to handle the LTL product transportation. For this purpose, a multi-stage binary-linear programming is proposed to minimize total supply chain transportation costs and transportation miles. In that, initially, the FT product transportation policy is implemented to handle FT product transportation from the suppliers to the customers. After the FT transportation becomes impossible at each suppliers' sites, then the remaining products are consolidated and the second stage of the transportation network which is the transportation of products from suppliers to cross-docking terminal is activated. Again, initially products are transferred to the terminal using FT trucks, and for the rest LTL products at each supplier’s site, an appropriate truck is hired that minimize the total LTL transportation costs. The contribution of this study is listed as follows;

1. By establishing an imaginary zone, we facilitate short-distance and long-distance product transportation.
2. This study not only focuses on transportation product-unit costs but also on the transportation product-unit miles.
3. Practicing cross-docking helps reduce transportation mile and transportation costs.
4. The assumption of dynamic fixed costs and variable costs is another contribution of this study. The trucks’ variable costs vary by the capacity of the trucks. However, the variable cost of transportation in the proposed objective functions are functions of the distances that each truck travel plus the number of products that they carry. In fact, the more they carry, the less is paid for the variable costs. Also, they shorter they travel the less is paid for the variable costs. This helps achieve the economy of scale of choosing the best and appropriate truck that minimizes transportations variable costs. Although, the fixed costs for the larger trucks are higher than the smaller ones, the more the bigger trucks carry, the fewer variable costs are supposed to be paid.
5. The transportation cost and mile ratios (TCR and TMR) are the indicators that are developed to show the significance of cross-docking within a transportation network when cross-docking is practiced comparing the time that it is excluded from the network.
6. To figure the best parameters settings that minimize the TCR and TMR, Taguchi method with a set of $L2_{16}^{5}$ orthogonal array is employed to examine different combination of multiple factors including trucks’ initial fixed costs ($1000 vs $2000b), trucks’ initial variable costs ($0.2 vs

$1.0b), trucks' capacities (10-50 vs 10-166), percentage of trucks for long transportation (20% vs 50%), and problem size (small vs medium). According to the experimental data, the optimal combination of design parameters with different levels of transportation's factors is obtained. The results confirm the literature findings concerning the combination of parameters and suggest that the combination of a very wide range fleet's capacity with lower fixed cost and higher variable cost results in better TCR and TMR while using small percentage of the trucks with larger capacities for long distance transportation. The last factor is the size of the problem. By increasing number of suppliers and customers within a transportation network, lower TCR and TMR are expected to observe.

CHAPTER 4

MINIMIZING TOTAL CROSS-DOCKING OPERATION COSTS

Abstract

The main purpose of this study is to create an appropriate coordination between inbound and outbound flow in the cross-docking. This coordination helps minimize: the floor congestion in the middle of terminal, the inventory storage within cross-docking terminal, and the early and tardy product delivery to the customers. This paper provides a comprehensive literature review on mathematical programming approaches in dock door assignment problems in cross docking planning. The Problem is formulated as a bilinear-quadratic assignment problem. The findings indicate that as the problem size grows, the bilinear-quadratic assignment problem model size expands quickly to the extent that the ILOG CPLEX Solver can hardly manage. Therefore, a new approach on Tabu search (TS) algorithm is employed in which TS is integrated with the hill-climbing method to solve the 9 sets of problems. To diversify the TS solution, four diversification methods are developed to avoid TS's being trapped in local optimal points. The computational experiments conducted indicate that meta-heuristics TS dominates the CPLEX Solver in nearly all test cases adapted from industrial applications.

Taguchi robust parameters settings is employed to propose the best combination of the signal factors. The result suggests that the best way to improve TS output quality is to start it from the best initial solution.

4.1Introduction

Cross-docking is a logistics practice that eliminates the storage and order picking functions of a warehouse while still allowing it to serve its receiving and shipping functions. The idea is to transfer LTL (LTL) shipments directly from inbound to outbound trailers without storage in between (as shown in Figure 12). Shipments typically spend less than 24 hours in a cross-docking terminal, sometimes less than an hour [205; 232; 8; 79; 143; 185; 109; 43]. While it is typical to handle sorting, labeling, and packaging inside terminal, the products consolidation is the main characteristics of a cross-docking terminal. Freight consolidation helps reduce product transportation cost through combining small orders (LTL) to enable dispatch of larger loads (Truck Load or TL). However, any types of violation during transshipment process would result in delays in product shipment, which impacts customer satisfaction at the end of the chain [99; 43].

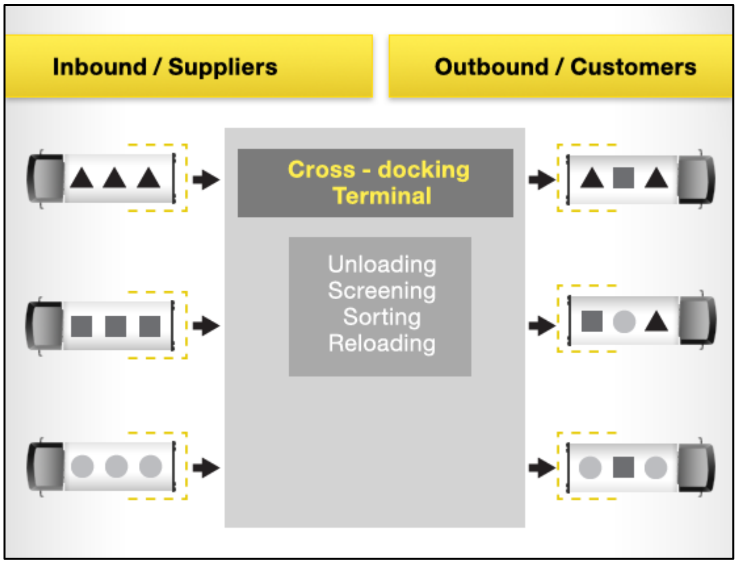


Figure 12: Cross-docking terminal

In 1990, Tsui and Chang [221] systematically introduced a bilinear-quadratic assignment problem (QAP) in the context of the cross-docking practice. Since then, a plethora of studies have investigated the significance of cross-docking formulation from different perspectives such as: 1) maximizing the utilization of resources [23; 248; 141; 198; 37; 88; 137; 139], 2) minimizing operations costs within cross-docking terminal [93; 191; 245], and 3) minimizing time-windows violation within cross-docking operations time [219; 3; 14; 68; 15; 143]. Some researchers view cross-docking from decision-making perspectives i.e. 1) long-term strategic decision level 2) medium-term tactical decision level, and 3) short-term operational decision level [196; 2; 68; 4]. The studies focusing on the long-term strategic decision level sought to determine solutions such as the number and location of cross-docking facilities [146; 41,2], the shape or layout of cross-docking terminal [28,3), the number of vehicles in a distribution network [2], and network design problems [24,29]. Studies on the tactical decision level explored: medium-term planning and addresses solutions regarding the optimal number of trucks at each arc in distribution network [19], assigning inbound-trucks and outbound-trucks to cross-docking terminal's doors [30,31,27), and planning deliveries in a network of cross-docking terminals [49]. Short-term plan studies addressed issues at the operational decision level to determine the optimum solution in scheduling problem, transshipment problem, dock door assignment problem, vehicle routing problem, and product allocation problem [24,11).

Except the strategic decision level in which researchers study the number and location of terminals, the other studies mainly focused on products transshipment operations from the inbound trucks to the outbound trucks within the terminal. The majority of those studies concluded that the best truck scheduling and door assignment are the best solutions to increase cross-docking efficiency. In fact, the core of their cross-docking studies is the truck-door assignment model developed by Tsui and Chen (1990) [221]. In almost all studies, the model developed by Tsui and Chen (1990) [221] is either the main focus of the study [41; 59; 250; 98; 195; 212] or a part of the research in which the truck-door assignment is used to solve a more complex problem [37; 8; 131; 9].

The contribution of this paper is to first provide a systematic solution to solve the bilinear-quadratic assignment problem developed by Tsui and Chen (1990) [221] using the Tabu-search algorithm. Second, in addition to the objective function developed in Tsui and Chen (1990) [221] model, which minimizes total travelled distance within the cross-docking terminal, a dynamic fixed cost is assumed for each door. This cost is varied by the quantity of the products assigned to each door. Hence, the algorithm is set to avoid concentrating trucks with high load in the center of terminal which leads to floor congestion for forklifts in the middle of the terminal. The third contribution is to determine the most optimal and make parameter settings robust using Taguchi method to expedite the meta-heuristics process and achieve high quality output with minimal processing time.

The reminder of this article is organized as follows. A list of products appropriate for cross-docking is presented in section 0. In section 4.3, a brief literature review on cross-docking is presented. Section 0 and 4.5 present general and specific assumptions for the current problem. Section 4.6 and 4.7 discuss mathematical programming model and the problem-solving process. Section 0 discusses the model efficiency formula. Section 4.9 describes the process of robust parameter design using Taguchi method. In section 4.10, nine different sets of problem are numerically tested, and their results are compared. Finally, section 0 and 4.12 present limitations, conclusion and future researches.

4.2Products Suitable for Cross-docking

The following is a list of materials that are better suited to cross-docking than others.

1. The most important materials are perishable items that require immediate shipment; in particular, frozen foods and other refrigerated products, e.g., pharmaceuticals, vegetables, flowers, cosmetics or medicine, and dairy products, which typically require special arrangements to ensure that the cooling chain is not broken [38; 68]. Such cross-docking terminals require a special kind of transshipment policy; for instance, perishable goods are not allowed to be intermediately stored inside the terminal. Once a frozen good is unloaded from its refrigerated inbound trailer, it must be moved and loaded directly onto its designated refrigerated outbound trailer. Otherwise a defrost and decay of comestible goods threatens [12; 200; 181; 68; 214; 169; 229; 4].
2. High-quality items that do not require quality inspections during goods receipt
3. Promotional items, and items that are being launched
4. Products with a constant demand or low demand variance
5. Pre-picked, pre-packaged customer orders from another production plant or warehouse

4.3Literature Review

Reviewing the mathematical programming literature on cross-docking, the following three objective functions were found around which the research interests have revolved: 1) maximizing utilization-based objective functions 2) minimizing cost-based objective functions, 3) minimizing time-based objective functions.

In the first category, scholars have sought methods to maximize resources/process utilization by;

1) maximizing throughput inside the terminal to accelerate the turnover inside the terminal and reduce a) the likelihood of late shipments,) the total process operational time or make-span; and c) the inventory level at the temporary storage area [229; 65; 4]

2) maximizing truck synchronization inside the terminal [183; 39; 109]
3) maximizing trucks utilizations [99; 146; 188; 105; 65; 73]

Cost-based objective functions are the second category that is of interest for most mathematical programming scholars. Each researcher has explored cost minimization from a different perspective like:

1) Minimizing transshipment (Operational) costs within terminal, i.e., the shipment of products or containers through an intermediate destination, then to yet another destination to change the means of transport [219; 9; 105; 35; 78; 93; 191; 245].
2) Minimizing additional material handling costs due to temporary storage [23; 41; 131; 183]
3) Minimizing manpower and personnel costs at cross-docks [180; 141; 131; 11; 179]
4) Minimizing trucks placement costs at both sides of the terminal [37; 8; 131; 9]
5) Minimizing loading and unloading service costs [73; 126; 127; 78; 93]
6) Minimizing purchase costs due to sorting and consolidation processes [5]
7) Minimizing temporary storage buffer costs at cross-docking location [20; 214; 208; 22]
8) Minimizing transportation costs in the cross-docking analysis routes are divided into four categories including routes 1) from suppliers (S) → terminals (CD), 2) from terminals (CD) → destinations (retailers) (C), 3) directly from suppliers (S) → customers (C), and finally, 4) among the cross-docking terminal when more than a single terminal is assumed in the problem. A list of recent literature on the transportation costs is presented in Table 28 in which the transportation cost between each two nodes is broken down into variable costs and fixed costs.

Table 28: A brief literature review on transportation costs in cross-docking modeling

Publications	Variable Costs				Fixed Costs		
	S → CD	CD → C	S → C	CD → CD	S → CD	CD → C	S → C
Bányai (2013) [21]	√	√	---	√	---	---	---
Birim (2016) [34]	√	√	---	---	---	---	---
Charkhgard and Tabar (2011) [46]	√	√	√	---	---	---	---
Cóccola et al. (2015) [57]	√	√	√	---	---	---	---
Dondo et al. (2011) [68]	√	√	√	---	√	√	√
Galbreth et al. (2008) [77]	√	√	√	---	√	√	√
Gonzalez-Feliu (2012) [138]	√	√	---	---	---	---	---
Gümüş and Bookbinder (2004) [19]	√	√	√	√	√	√	√
Hosseini et al. (2014) [108]	√	√	√	---	---	---	---
Huang and Liu (2015) [110]	√	√	√	---	√	√	√
Mohtashami et al. (2015) [155]	√	√	---	---	---	---	---
Mousavi et al. (2013) [88]	√	√	---	---	√	√	---
Mousavi et al. (2014) [161]	√	√	---	---	√	√	---
Serrano et al. (2016) [191]	---	√	---	---	---	---	---
Vahdani et al. (2014) [90]	√	√	---	---	√	√	---
Yang et al. (2016) [242]	√	√	---	---	---	---	---
Yin and Chuang (2016) [245]	√	√	---	---	√	√	---
Yu et al. (2016) [247]	---	---	---	√	---	---	---

9) Minimizing floor congestion inside the terminal: many scholars have tried to reduce floor congestion in a cross-docking terminal as it 1) causes excessive labor cost, 2) fails shipments service commitments, 3) slows down the speed of the forklifts, 4) increases workers' waiting time due to interference among forklifts and draglines congestions, 5) impedes the (un)loading and storage operations, 6) creates bottlenecks before stack doors with high flow levels , 7) halts operations entirely, 8) causes poor product flow and throughput, and 9) creates long processing times or make-span [26; 27; 41; 2; 105; 143; 21; 11; 108; 145].

10) Minimizing total traveled distance inside the cross-docking terminal using quadratic assignment problem (QAP) and its derivatives [50; 59; 45; 33; 143; 210; 154].

11) Minimizing backorder penalty costs: cross-docking helps achieve the minimum level of inventories inside the customers storage area [209; 239; 195; 229].

12) Minimizing lost profit costs: lost profit is manifested as late satisfied orders which are the costs of the customers [219; 73].
13) Minimizing customers' extra inventory costs due to early product delivery [3; 14; 131; 104; 4; 6; 161; 78; 247].

The third category is the time-based objective functions which proceeds as follows;

1) Minimizing make-span or operating time inside the terminal: the make-span reduction helps to increase material flow inside the cross-docking terminal [246; 17; 61; 74; 122].
2) Minimizing time window violation: time window violation is a big concern in a cross-docking system as it incurs extra costs both within and outside cross-docking terminal for the customers. Thus, most scholars try to minimize time window violation by figuring the best door assignment and truck scheduling so as to have a reliable cross-docking system with minimal total weighted tardiness and earliness simultaneously [161; 35; 10; 18; 78; 237; 247; 19].

Mathematical programming researchers in the field of cross-docking also deal with many decision factors, i.e., assumptions and constraints, during the process of short-term (operational), medium-term (tactical), and long-term (strategic) decision-planning. Many applications in the cross-docking studies lead to mathematical models that can be formulated as mixed integer programming (MIP), non-linear programming (NLP), binary-integer programming (BIP), linear programming (LP), quadratic programming (QP), and mixed integer non-linear programming (MINLP). There are some overlaps among some of them; for instance, QP is a case of NLP or MIP. Also, QP is a specific format of BIP and vice versa. Table *29* represents a list of the most recent publications in the field of cross-docking.

In integer programming (including binary), two approaches, i.e., exact and heuristic/meta-heuristic are employed to find the optimal solution or at least some solutions near the optimal point (local optimum point). Exact methods like branch-and-bound, branch-and-cut, brand-and-price tree, complete enumeration method, and dynamic programming are suitable for small size-NP hard problems and guarantee to find the optimal solutions using the commercial solvers presented in Table 30. It is seen that comparing to the other solvers, the popularity of the CPLEX solver makes it to be of interest for many researchers in cross-docking studies.

Table 29: An overview on different types of mathematical programming models (MPM) in cross-docking studies

MPM	Publication
MIP	[17; 18; 34; 74; 78; 122; 124; 166; 191; 218; 237; 245; 247; 19];
NLP	[26; 99; 217; 48; 182; 241; 13; 38; 184; 209; 8; 46; 131; 239]
BIP	[152; 88; 33; 90; 143; 185; 79; 73; 92; 109; 126; 211; 57];
LP	[146; 41; 219; 79; 183; 63; 91; 89; 11]
QP	[220; 250; 98; 212]
MINLP	[154; 161; 5];

Table 30: An overview on the usage of solvers in cross-docking studies

Software	Publication
CPLEX	[158; 194; 17; 18; 74; 78; 122; 166; 191; 218; 242; 247]
GAMS	[105; 88; 6; 66; 114; 154; 160; 161; 5; 17; 19; 93; 124]
GRASP	[79; 79; 108]
Lingo	[3; 143; 237]
Matlab	[7]

Regarding the NP-hard problems like QAP, scholars employ heuristic and metaheuristic methods to find a trade-off between solution quality and computation time as well as a compromise between implementation effort and yields. Heuristic methods like hill climbing are algorithms that try to find the optimal solutions by examining all neighborhood before deciding to move to that neighbor or to explore another; however, when they get trapped into the local optimum points, they stop and return solutions. In fact, their output quality is directly linked to the quality of the initial random solution. On the other hand, metaheuristic methods like Tabu search and Genetic algorithm try to diversify the solution pool once they get trapped into the locality by the heuristic techniques. Table 31 and Table 32 present a list of publications that implement exact, heuristic, and meta-heuristic methods in the field of cross-docking.

Table 31: An overview on deterministic methods in cross-docking studies

Deterministic Method	Publications
Branch-and-bound	[217; 48; 144; 188; 33; 29; 189]
Branch-and-cut	[67; 78]
Branch-and-price tree	[57]
Complete enumeration method	[248; 185; 250]
Dynamic programming	[183; 9; 23; 144; 182; 40; 38; 184; 209; 232]

Table 32: An overview on heuristic and meta-heuristic methods in cross-docking studies

Meta-heuristic methods	Publications
Ant Colony	[162; 140; 14; 138; 154]
Bee colony	[245]
Biogeography-based optimization	[93]
Differential evolution	[140; 13; 15; 139; 10; 18]
Electromagnetism-like algorithm	[198; 122]
Fuzzy Logic	[75; 161; 223]
Genetic Algorithm	[198; 63; 143; 146; 152; 13; 88; 14; 239]
Harmony Search	[108]
Hybrid differential evolution	[140; 139]
Particle swarm optimization	[13; 14; 15; 163; 155; 93; 122; 237; 247]
Petri Net Model	[219]
Problem Decomposition	[246]
Pseudo-polynomial	[182]
Simulated Annealing	[198; 41; 140; 26; 38; 46; 39; 128; 189]
Simulation	[141; 109]
Strength Pareto Evolutionary	[163]
Sweeping algorithm	[66]
Tabu Search	[210; 138; 194; 211; 110; 166; 245]
Scatter Search	[211; 212]
Variable neighborhood search	[73; 128; 226; 35; 198]
Hill climbing	[29; 39; 92; 118; 114; 145; 158; 61; 218]

To reduce the sensitivity of parameters during the implementation of heuristic and meta-heuristic methods, researchers employ some statistical techniques, i.e., ANOVA, response surface method (RSM), and Taguchi method, to handle their models' parameter settings. Table 33 presents a list of all publications that have applied these statistical techniques to figure out the best parameter settings. Employing statistical methods like experimental design can help to find useful parameter setting for the meta-heuristic as well as the heuristic methods.

Table 33: An overview on result evaluators in cross-docking studies

Evaluation Method	Publication
ANOVA	[15; 139; 138; 154; 163; 10; 122]
Response Surface Methodology	[10]
Taguchi Method	[198; 225; 13; 15; 139; 226; 154; 156; 19; 122]

4.4Common assumptions

The problem is formulated as a binary quadratic programming problem, and its basic assumptions are listed as follows;

1. The product transshipment cost between each pair of inbound-outbound doors is assumed to be $1.00 per product-unit.
2. Unlimited products are available from a single supplier, and the demands for those products are known but varying - reflecting a common situation in practice [77].
3. An I-shaped cross-docking terminal is assumed with an equal number of docks at each side in which one receiving door faces to one shipping door [65; 135; 27].
4. Other cross-docking operations such as sorting, labeling, packing, and unpacking are not taken into consideration in the model.
5. The entire fleet are available at time zero.
6. All received products must be shipped.
7. We don't assume temporary storage cost within terminal because long-term storage is not allowed.
8. The total number of receiving products for each type of product is the same as the total number of shipping products for each type of product.
9. Truck changeover time is fixed and the same for all inbound and outbound trucks.
10. Cross-dock facilities and labors are unlimited.

11. Only one unit of a product can be loaded into the shipping truck at a time. Therefore, simultaneously loading products from a receiving truck and the temporary storage into a shipping truck is prohibited.
12. The sequence of unloading products from the truck or loading products to the truck is not considered.
13. The demand must be met in each period.
14. The moving time for products from the receiving dock to the shipping dock is the same for all products.
15. The delay time for truck changes is the same for all receiving and shipping trucks.
16. Packaging size of products is set as the same, and thus, the time for loading and unloading a single product unit is constant.
17. Backlogging is not allowed.
18. We assume that the distance between each pair of doors on each side of the terminal equals to 5 distance-units. Therefore, the distances between ith ID and jth OD are computed based on rectilinear travel distances using Manhattan distance formula shown in Eq. 32.

$$distance_{i\to j} = cross\ dock\ width + 5 \times |i - j| \qquad \text{Eq. 32}$$

19. The number of inbound-doors is equal to the number of outbound-doors, and each ID has a corresponding OD right across the CD terminal.
20. The number of suppliers ≤ the number of Customer ≤ the number of IDs=ODs

4.5Specific assumption

In addition to common assumptions that the majority of scholars assumed in their models, in this study, a dynamic fixed cost is assumed for each door which varies depending on the product load assigned to it. This load can either be on the inbound-door side or on the outbound-door side.

As illustrated in Figure 13, non-equal variable costs are spread and assigned on inbound (outbound) doors from the center of the terminal in descending (ascending) order toward the end on both sides of the inbound (outbound) yards. This helps to assign those trucks with the higher load to doors with lower variable costs. The second factor influencing doors' fixed costs is the cross-docking shift capacity, i.e., the increase in one leads to the decrease in the other one and vice versa. The third factor is the amount of the flow assigned to each door. In that respect, the more flow we assign to each door, the more fixed cost we expect to be incurred to the operations costs. The formulas shown in Eq. 33, indicate that the doors' fixed costs are a non-linear function of the flow assigned to each door (f_m or f_n), the cross-dock shift capacity, and the door's variable cost (C_i or C_j).

$$V_{im} = f(f_m, shift^{-1}, C_i) = \frac{f_m C_i}{shift}$$

$$V_{jn} = f(f_n, shift^{-1}, C_j) = \frac{f_n C_j}{shift} \qquad \text{Eq. 33}$$

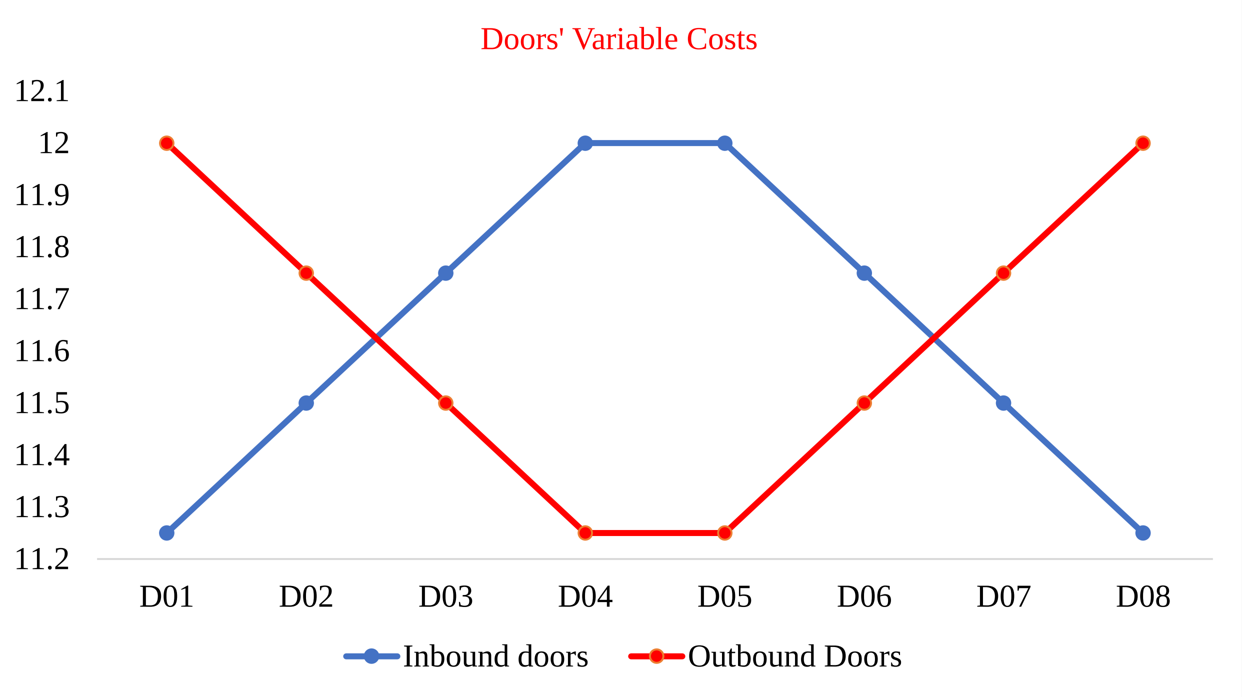


Figure 13: Doors' variable costs on both sides of a CD with 10 doors on each side

According to the dynamic fixed cost assigned to each door on both sides of the terminal, intuitively, the cost function encourages suppliers with high flows to be assigned to doors far away from the center of the terminal. Conversely, the model tries to assign customers with high demand in the center. Assigning suppliers with low demand for unloading and customers with high flow for freight loading helps to minimize the level of floor congestion in the center of the terminal. 2nd and 3rd parts of the objective function shown in Eq. 34 attempt to minimize the total fixed cost of assigning the supplier-inbound door and outbound door-customer.

4.6Problem Description

This study is an attempt to modify the quadratic assignment problem proposed by Tsui and Chang (1990A) [221] to solve truck assignment problems in a single cross-docking terminal. The proposed model by Tsui and Chang (1990A) [221] optimized the truck assignment through minimizing the total traveled-distance operations cost within the terminal. In addition to their assumption, the dynamic fixed costs is assumed for each door at both sides of the terminal.

Notation

m: The number of suppliers
n: The number of customers
i: The number of inbound doors
j: The number of outbound doors
f_{mn}: LTL flow between mth supplier and nth customer
f_m: The amount of flow transferring from mth supplier to cross-docking (CD)
f_n: The amount of flow transferring to nth customer from CD
d_{ij}: The distance between inbound and outbound doors
C_i: ith inbound door's fixed cost in US Dollar (USD)
C_j: jth outbound door's fixed cost in USD
shift: CD's doors shift capacity
V_{mi}: The fixed cost of assigning mth supplier to ith inbound-door which equals to $\frac{f_m C_i}{\text{shift}}$
V_{jn}: The fixed cost of assigning jth outbound-door to nth customer which equals to $\frac{f_n C_j}{\text{shift}}$

Decision Variables:

$X_{mi} = 1$ if mth supplier is assigned to ith inbound door, else $X_{mi} = 0$
$Y_{jn} = 1$ if nth customer is assigned to jth outbound door, else $Y_{mi} = 0$
X_{mi} and Y_{jn} are permutation matrices and are characterized by the following constraints.

The mathematical model of the problem is formulated as follows:

$$min\, Z = \sum_{m=1}^{m}\sum_{i=1}^{i}\sum_{j=1}^{j}\sum_{n=1}^{n} X_{mi} f_{mn} d_{ij} Y_{jn} + \sum_{m=1}^{m}\sum_{i=1}^{i} X_{mi} V_{mi} + \sum_{j=1}^{j}\sum_{n=1}^{n} Y_{jn} V_{jn} \qquad \text{Eq. 34}$$

Constraints		Description
$\sum_{i=1}^{I} X_{mi} \le 1, m = 1,2,3\,, \cdots, m$	Eq. 35	To ensure that each inbound truck (supplier/origin) is assigned to at most one inbound door
$\sum_{m=1}^{M} X_{mi} = 1, i = 1,2,3\,, \cdots, i$	Eq. 36	To ensure that each inbound door is assigned to one inbound truck (supplier/origin).
$\sum_{n=1}^{N} Y_{=jn} = 1, j = 1,2,3\,, \cdots, j$	Eq. 37	To ensure that each outbound door is assigned to one outbound truck (customer/destination)
$\sum_{j=1}^{J} Y_{jn} \le 1, n = 1,2,3\,, \cdots, n$	Eq. 38	To ensure that each outbound truck (customer/destination) is assigned to at most one outbound door

This research focuses on attempting to optimize the simultaneously assigning supplier-ID and OD-customer (ID = inbound door, OD = outbound door) to minimize the total operation costs within cross-docking terminal as shown in Eq. 34. The first part of the objective function attempts to minimize the total workload cost which is the sum of the flows × rectilinear distances over the planning horizon, and the second and third part of the objective function account for the total fixed cost of truck-door assignment.

4.7Problem solving process

After, developing a binary-quadratic programing model, three methods are employed to solve the proposed model. The first method is a complete enumeration method that is employed to find an optimum solution testing all possible sequences using ILOG CPLEX solver version 12.6.0.0. As the problem size grows from medium to large, solvers like ILOG CPLEX, Gurobi, Minto, and CBC, can hardly manage to converge the optimum solution due to the computational time required to solve the problem. For the current study, CPLEX solver is developed for just small size problems. However, for the medium to large size problems- the second method- a hill-climbing algorithm is developed as a heuristic. Tabu-search –the third method– is employed to a meta-heuristic algorithm. The second and third methods are developed to solve problems of practical sizes, i.e., larger than the small size problems.

The hill-climbing heuristic algorithm finds solutions quite fast; however, the solution found may not necessarily be optimal. The output of the second approach is used as the initial solution of the Tabu-search technique in the third approach. To check the performance of the study, the hill-climbing and meta-heuristic Tabu-search results are compared with the results of the CPLEX solver for the small-size problems and presented in Table 41, Table 42, and Table 43.

4.7.1 Complete Enumeration Method

The number of decision variables for the binary-quadratic assignment problem is m×i+n×j which are all binary variables. The number of constraints is m+i+j+n including m+n inequality constraints and of i+j equality ones. For the sake of consistency, in all instances developed in this study (Table 41, Table 42, and Table 43), it is assumed that m=i=j=n and is called instances of m-dimension. For example, a 7-dimension instance consists of 7 suppliers, 7 inbound-doors, 7 outbound-doors, and 7 customers. Thus, there is a problem with 28 constraints and 98 binary decision variables.

In the present study, a receiving truck is assigned to a receiving inbound door and stays in there until it finishes its unloading operation. Therefore, each receiving truck must appear once in the receiving truck sequence. To assign m suppliers (receiving trucks) to i inbound doors ($m \leq i$), there are $\frac{i!}{(i-m)!}$ possibilities. Likewise, each shipping truck appear only once in the shipping truck sequence because a shipping truck stays in the shipping dock until all its needed products are loaded. Therefore, to assign n customers (shipping trucks) to j outbound doors ($n \leq j$), there are $\frac{j!}{(j-n)!}$ possibilities. The total number of possible sequences to minimize total operation cost within cross-docking terminal shown in Eq. 34 is $\frac{i!}{(i-m)!} \cdot \frac{j!}{(j-n)!}$. For example, in a problem with m=i=j=n=7, the total number of possible sequences is 7! × 7! = 25,401,600. By increasing the size of the problem to m=i=j=n=10, for example, the total number of possible sequences will be 10! × 10! = 1.3×10^{13}. In this case, it is not practical to solve this problem by enumerating all possible sequences. Therefore, it is required to employ a method which finds the solutions within a reasonable amount of time.

In this study, we implement a complete enumeration approach using ILOG CPLEX for small-size problems to provide a basis for benchmarking the performance of the heuristic and metaheuristic algorithm. As a general rule, the problems having similar characteristics of QAP in the context of a cross-docking analysis are divided into small size and large size problems.

For problems like $m \leq n \leq i=j < 10$ that are small or tractable enough to allow "finitely convergent" algorithms to obtain and verify optimal solutions, CPLEX reaches to optimal solutions with no ILOG CPLEX's setting manipulation and "out of memory" error message. The second subset comprises of those problems with $10 \leq m \leq n \leq i=j$ that terminate after a few runs and return "MIP starts not constructed because of out-of-memory status" error message. With regard to the larger size problems, complete enumeration approaches are inefficient to get optimal solutions, and solvers like ILOG CPLEX give up finding the optimum solution due to lack of memory on a personal laptop like the one with a processor "Intel(R) Core (TM) i7-6500U CPU @ 2.50 GHz 2.60 GHz" and a memory of 12.00 GB installed.

4.7.2 Hill-climbing heuristic method

The proposed mathematical programming shown in Eq. 34 is a highly complex bilinear model. If either the receiving door from supplier (X_{mi}) or the shipping door to customers (Y_{jn}) are known, the remaining problem becomes a standard assignment problem and can be solved inexpensively within a desirable time. However, in the current study both X_{mi} and Y_{jn} are not given, and thus, the above formulation is a bilinear problem, and like all QAP problems, this bilinear problem is a highly complex NP complete [227; 50]. To discover a good local optimum point, the hill-climbing algorithm developed by Tsui and Chang (1990A) [221] is practiced based on the following description.

To find the best local optimum point out of a set of local optimum points, multi-start hill climbing heuristic is employed. Heuristics provide a way to obtain good but not-guaranteed optimal solutions to hard problems within reasonable computational times. since the quality of the local solution in the hill-climbing algorithm depends directly on the quality of the initial solution, to find the best local optimum solution, maximum 100 random unique assignments X_{mi} of supplier are initially generated to inbound door, and 100 random unique assignment Y_{jn} of outbound door to the customer. Then the one with the minimum cost is selected.

A characteristic feature of this model is that the solution points are equal with their inverse setting. In that respect, a permutation string of assignments of supplier to inbound door, i.e., X_{mi}, results in an optimal string N^1 which minimizes $Z1 = f(M^1,N)$. On the other hand, the inverse of the string (X_{mi}) of supplier to inbound door results in an optimal inverse string N^1 which minimizes $Z2 = f(M^1,N)$ while $Z1 = Z2$. For example, in an instance with 8 suppliers, 8 customers, 8 inbound and 8 outbound doors, the truck-door assignment $X_{mi} = [6,4,1,7,0,2,5,3)$ results in an optimal truck-door assignment of $Y_{jn} = [3,6,1,0,5,2,4,7)$ which yields the minimum cost $Z1 = 72625.42$. On the other hand, the inverse of X_{mi}, i.e., $X^{-1}_{mi} = [3,5,2,0,7,1,4,6)$ results in an optimal truck-door assignment of $Y^{-1}_{jn} = [7,4,2,5,0,1,6,3)$ which is the inverse of Y_{jn} and yields the minimum cost $Z2 = Z1=72625.42$.

Therefore, in order to increase the efficiency, the algorithm is set to avoid searching the inverse of the stored Xs or Ys and ignore symmetry. In the meantime, since the goal is to achieve 200 distinct local optimum solutions, after each run, the database is checked to ensure whether X* and Y* or inverse of X* and Y* are available. However, the number of solutions that can be eliminated due to symmetry condition depends on the size of the I-shaped terminal.

Table 34 presents the steps in the proposed hill-climbing algorithm. For instance, 43 unique local optimum solutions created by hill-climbing approach (Figure 14) are achieved after removing duplicate values.

```
Timer = 0b;
Counter0 = 0b;
For m = 1 to 200
    1. Counter1 = 0b;
    2. Generate an initial assignment $M^1$
    3. Counter2 = 0b;
    4. while (string $M^1$ or its inverse are in the database A and Counter2 $\leq$ 10)
       {
       Generate an initial assignment $M^{1;}$
       Counter2 = Counter2 + 1;

       }
    5. Save string $M^1$ and its inverse in database A;
    6. Find the optimal solution $N^1$ which minimizes $f(M^1,N)$;
    7. Find the optimal solution $M^2$ which minimizes $f(M,N^{1)}$;
    8. Let $M^1$equal $M^2$, repeat steps 4 and 5 until the procedure converges to point L*(M*,N*)
    9. If (string M* or its inverse is in the database A OR string N* or its inverse strings is in the database )
       {
       Counter1 = Counter1 + 1;
       if (Counter1 $\leq$ 10)
           {
           Go to step 2;
           }
           else
           {
               Counter0 = Counter0 + 1;
            Break this condition;
           }
       }
    10. Save string M* and its inverse in the database A
    11. Save string N* and its inverse in the database B
    12. Save L* point in database C;
    13. If (Counter0>20)
       {

           Break for loop;
       }

Next
14. Remove all duplicate points from the database C;
15. Sort all points in database C
16. Timer = save CPU time
17. Report Timer and the minimum cost's point in the database C;
```

Note: the timer is checked to evaluate the total time to generate maximum 200 solutions.

Table 34: The hill-climbing heuristic pseudocode to generate at most 200 local optimum solutions

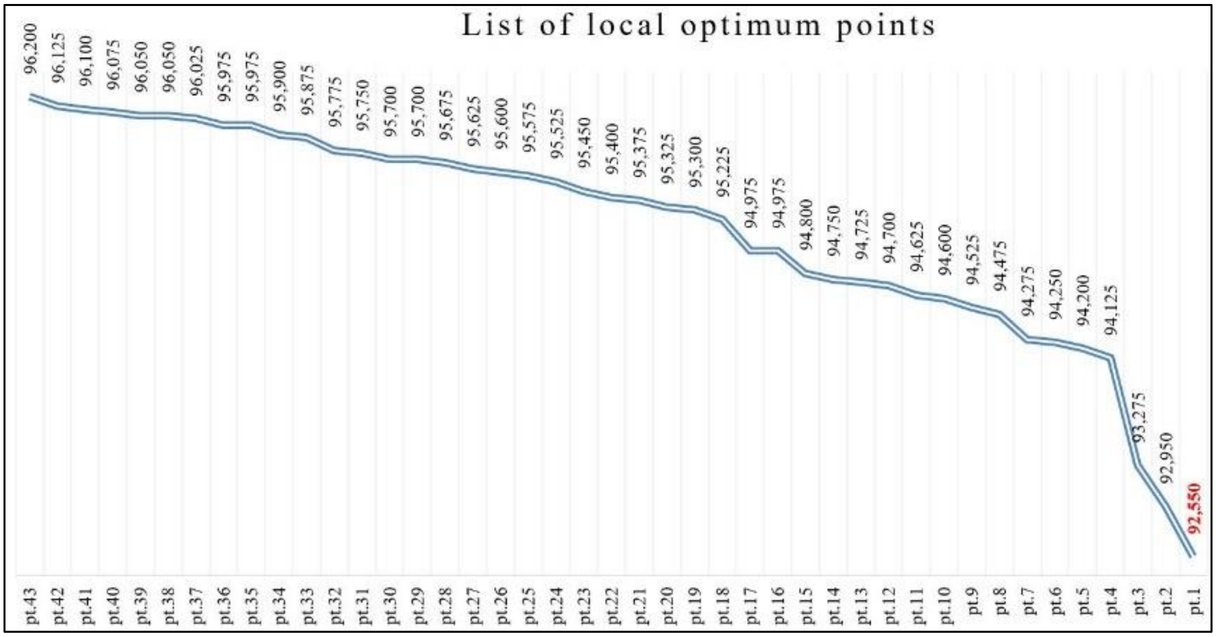


Figure 14: 43 unique local optimum solutions achieved by hill-climbing approach

4.7.3 Tabu Search Characteristics and Framework

Fred Glover introduced the idea of Tabu Search (TS) in 1986 and formalized it in 1987. TS is a metaheuristic search method and consists of neighborhood search and the use of short-term memory. TS employs local search methods used for mathematical optimization. Local search methods like hill-climbing tend to get stuck in suboptimal regions or on plateaus where many solutions are equally fit. TS guides a local heuristic search procedure to explore the solution space beyond local optimality. The local procedure is a search that uses an operation called *move* to define the neighborhood of any given solution. A main component of the tabu search is its use of adaptive memory, which creates a more flexible search behavior. Memory-based strategies are, therefore, the hallmark of tabu search approaches.

Permutation problems are an important class of combinatorial optimization problems that can be applied in: classical traveling salesman problems, quadratic assignment problems (QAP), production sequencing problems, and a variety of design problems. For problems that are small or tractable enough to allow ”finitely convergent” algorithms to obtain and verify optimal solutions, evolutionary algorithms like Tabu search and Genetic algorithm produce solutions that are optimal or within a fraction of a certain percent of optimality, while requiring much less effort (in some cases, on the order of minutes versus days of computer time). However, for larger and more difficult problems, those customarily encountered in practical settings, evolutionary algorithms obtain solutions that rival and often surpass the best solutions previously found through other approaches.

In the following, seven features of a Tabu search algorithm are discussed and in the last section, the proposed TS framework is presented.

4.3.3.1 Short-term memory

Based on the idea of the tabu search, the best possible move is always simply made using diversification, even if this makes the objective value somewhat worse. However, if the *move* gets out of the local optimum on the very next move, the objective can possibly decrease the most by moving right back to the same local optimum. Therefore, the search must be forced to continue diversifying for a few moves. The approach employed in tabu search to prevent returning to the same local optimum is to keep a list of the last *m* moves and not to allow moves in the list to be repeated while they still remain on the list (they are currently "tabu"). Overall, many researchers suggested that the number of moves (m) in the list must typically be set equal to 7 (i.e., m = 7). Hence, before reaching the local optimum, the neighborhood procedure will improve at each step, so that the likelihood of repetition declines, and the current m moves, which are "tabu" would never be chosen by any means unless if it provides better solution. After leaving the local optimum and attempting to diversify into a different region of solutions, the tabu list hopefully forces diversification until the old solution area is left behind.

4.3.3.2 Tabu status

In short-term memory, there is a list of tabu moves that are forbidden to be considered during the searching process unless aspiration criteria let them be removed from the tabu list (tabu-tenure).

4.3.3.3 Initial solution

The initial solution is represented by a sequence of truck assignments to the doors at each side. Even though the type of QAP is a zero-one problem, a permutation technique is employed to apply truck-door assignment. Through a permutation technique, the algorithm is set to stay within the feasibility region and not trespass the infeasible solution space. There are two approaches concerning the initial solution for the TS algorithm. The first approach is to select the best local optimum point generated in section 4.7.2 (hill-climbing heuristic method) to start the TS algorithm, and the second approach is to randomly assign suppliers to the inbound-doors and customers to the outbound-doors using permutation technique. In case there is inequality between truck numbers (suppliers or customers) and door numbers, all trucks are assigned to the available doors. For those vacant doors, the value of (-1) is assigned to the corresponding door.

4.3.3.4 Neighborhood or move structure

Pairwise exchanges (or swaps) are used to define neighborhoods in permutation problems, which identifies moves that lead from one solution to the next.

4.3.3.5 Aspiration criteria

An aspiration criterion is a rule that allows the tabu status to be overridden in cases where the forbidden exchange exhibits desirable properties. Following Glover procedure, a tabu move passes through a series of three levels of criteria to finally become a permissible exchange if:

1. the forbidden move results in a global best solution;
2. the tabu exchange under consideration is the first forbidden move examined in the current iteration of the algorithm;
3. the cost of the forbidden exchange is better than all previous exchanges examined on the current working solution, and the move becomes permissible.

4.3.3.6 Diversification

Diversification helps create a new vector based on a procedure that operates through mapping a given collection of vectors into one or more new collections that differ from the original collection in a manner consistent with the concept of previously-employed diversity [85].

To diversify the solution space, after the algorithm reaches a local optimum solution, four diversification methods (M1, M2, M3, and M4) are employed to restart the search process from a new point. All methods are based on the permutation technique and don't permit solutions violate the feasibility condition.

M1 and M2 are the most recent diversification methods developed by Glover in 2017 [85], and the third (M3) was developed by James et. al. (2009) [113]. M1, M2, and M3 are adapted from the literature. The forth diversification method, M4, was developed for this study. In all algorithms presented in the following, n represents doors numbers, and the output of these algorithms is the assigning suppliers or customers to the inbound or outbound doors, respectively. Therefore, if it happens that the number of suppliers and customers turn out to be fewer than door numbers, first, the algorithms are run, and then the value of those assignment greater than supplier/customer numbers will be changed to zero; zero means unassigned doors. Finally, the -current working solution is replaced with the global best solution, and at each subsequent restart, a diversified version of the global best solution is utilized. In the following, detailed pseudocode and numerical illustrations are provided to show the operation of methods and the collections of solutions they create.

➢ Permutation Mapping Algorithm (M1)

Table 35 presents the pseudocode of permutation mapping algorithm.

Table 35: the pseudocode of permutation mapping algorithm (M1)

```
Initialize g ← (integer part of (n/2)) – 1;
K ← declare a null string array with g member
for i = 0 to g
        declare L ← null;
        for j = 0 to g
                p = (i+1)+g×j;
                if (p<=door_no)
                {
         L = L + "," + p;
                }
                K[i] = L;
        next j
next i
return reverse K
```

Ex: door_no = n = 14 and g = 6. Therefore, P_{14} (g: 1) = [1 7 13), P_{14} (g: 2) = [2 8 14), P_{14} (g: 3) = [3 9), P_{14} (g: 4) = [4 10), P_{14} (g: 5) = [5 11), and P_{14} (g: 6) = [6 12).

Assembling these sub-permutations in reverse order yields:
P_{14} (g) = [6,12,5,11,4,10,3,9,2,8,14,1,7,13)

➢ Recursive Permutation Mapping (M2)

M2 creates a recursive vector of the vector created by M1. Unlike Glover 2017 [85] that started by mapping procedure, an easier procedure is assumed in this study to produce the recursive vector of the vector created by M1. At first, the permutation vector is converted to a zero-one matrix, and then its transpose is determined. Matrix transpose is the shorter and quicker version of recursive mapping proposed by Glover 2017 [85]. After matrix transpose is done, the new zero-one matrix is converted into a vector of permutation numbers. In the following, M2 is the recursive mapping of M1. Therefore, the pseudocode of this algorithm is as follows: 1) receive permutation P, 2) convert permutation P to zero-one matrix, 3) transpose the zero-one matrix and call it Q and 4) convert the Q matrix to permutation format. For instance, the recursive form of vector [2,4,5,1,3] is [4,1,5,2,3].

- DivTS Restart Approach (M3)

The DivTS restart approach shown in Table 36 forcefully diversifies the search but in a more tactical manner than a random restart.

Table 36: the pseudocode of permutation mapping algorithm (M3)

```
Initialize step ← if door No. is less than 10 then step = 3, otherwise, step = door No/10 + 2;
K ← declare a null string array with step member
for (int start = step - 1; start >= 0; start--)
{
        string L= "";
        for (int j = start; j < door_no; j = j + step)
        {
                L=L + "," + input[j];
        }
        K[t] = L;
        t++;
}
Return K
```

For instance, the given solution is S = [8, 1, 5, 10, 9, 3, 7, 2, 12, 11, 6, 4). If step = 3, then through the first pass of the inner loop, start = 3, which results in the partial solution SS = [5, 3, 12, 4). The starting position is then readjusted to start = 2, generating in the next pass of the inner loop SS = [5, 3, 12, 4, 1, 9, 2, 6). This process is continued until start = 1, in the case which a full starting solution is generated SS = [5, 3, 12, 4, 1, 9, 2, 6, 8, 10, 7, 11).

- Recursive DivTS Restart Approach (M4)

The same procedure explained for the “Recursive Permutation Mapping (M2)” is implemented for M4 in that firstly the permutation vector developed by M3 is determined and then converted to a zero-one matrix. Afterward, the zero-one matrix is transposed. The permutation vector of the new zero-one matrix is the output of M4 which is supposed to differ from the original collection in a manner consistent with the concept of diversity previously employed.

1.7.3.1 Termination criteria

The algorithm stops under the following conditions: 1) when total computation time exceeds 180 minutes, 2) when the search process within the loops leads to no improvement on the objective function, 3) when no feasible solution in the neighborhood of solution is found, 4) when the number of iterations since the last improvement is larger than half of the door numbers, and 5) when evidence can be given that an optimum solution has been obtained

1.7.3.2 Tabu Search Framework

In the framework presented in Table 37, a Tabu search framework is elaborated which consists of diversification step, aspiration criteria, and termination condition. Instead of having termination condition at the end of algorithm, they are set in the middle of the search process to break the search process as soon as at least one of the termination conditions is met.

Table 37: Tabu search framework

```
1. Use the initial solution
   $X_{current} = X_{initial}$
   $Y_{current} = Y_{initial}$
   $Cost_{current} = Cost_{initial}$
2. Generate a set of neighborhood solutions $N(X_{current}, Y_{current})$
3. If an improvement happens in the neighborhood cost, then
   3.1 check aspiration criterial and see if tabu status can be removed from the tabu tenure list.
   3.2 $X_{current} = X_{new}$
       $Y_{current} = Y_{new}$
       $Cost_{current} = Cost_{new}$
   3.3 Update tabu tenure
   3.4 Check the termination condition
   3.5 Go to step 2;
4. Check the termination condition
5. If there is no improvement in the neighborhood cost
   5.1 Apply one of the diversification methods on $(X_{current}, Y_{current})$ and generate $X_{diversification}$ and
       $Y_{diversification}$
   5.2 $X_{current} = X_{diversification}$
       $Y_{current} = Y_{diversification}$
       $Cost_{current} = Cost_{Diversification}$
   5.3 Go to step 2;
```

4.8Checking Model Efficiency

To evaluate the performance of the developed algorithm and check the efficiency of the meta-heuristic, a relative percentage deviation (cost gap %) is used as follows:

$$\text{Cost Gap \%}=\frac{\text{Cost - Global Cost at R}^{\text{th}}\text{Run}}{\text{Cost}}\times 100 \qquad \text{Eq. 39}$$

4.9Robust Parameter Design

Since full factorial design is the most expensive method to achieve the best parameter setting to yield the optimum output, a procedure is proposed in this study based on statistical method of design of the experiments and Taguchi method that finds effective settings for tuning parameters used in heuristics. Taguchi's robust parameter design identified controllable factors (signals) that minimize the effect of the noise factors. Taguchi method offers a cost-effective and labor-saving means to investigate several factors simultaneously and identify those that have primary impacts on the target value [244; 192; 198]. It is statistically proven that a small fraction of setting factors, i.e., the orthogonal array in Taguchi method, produces most information from all the possible combinations [116].

In Taguchi method, there are two measures that should be considered simultaneously: Target value and Signal-to-Noise ratio. While the former is simply measuring the mean value of the output, the signal-to-noise ratio measures the sensitivity of the quality investigated for those uncontrollable factors in the experiment [132]. The term signal stands for the desired target for good products, and the term noise represents the undesirable value. In fact, the goal of Taguchi method is not only to optimize an arbitrary objective function, but also to reduce the sensitivity of engineering designs for uncontrollable factors or noise [107]. To determine the controllable process parameter-settings for which noise or variation has a minimal effect on the product or process' functional characteristics, Taguchi proposes to maximize the function S/N ratio. Because, the greater S/N ratio results in smaller product variance around the target value, or the least standard deviation from the target value.

4.9.1 Signal Factors

There are many factors in Tabu-search process that directly impact the quality of the outputs. Here, the metaheuristic output quality is defined as the smaller cost gap percentage shown by Eq. 39. In the following, a list of Seven important factors that are applied in this study is presented.

4.10.1.1Initial Solution

The quality of initial solution can affect the output quality in the metaheuristic techniques. Most scholars like Sousa et. Al (2016) [201] concluded that the proper initial solutions can provide solutions near the optimal one with a low execution time, solving some of the drawbacks of the metaheuristics. Having assumed that, the variability of the metaheuristic output is tested by having experiences in two levels; the best initial solution versus a random initial solution.

4.10.1.2 Search Order

This study hypothesizes that comparing a random search within the loops, a systematic search order; i.e., like natural-number search order from left to right, to find the best neighbor solution results in higher output quality.

4.10.1.3 Tabu Status

Tabu type is the third factor that might influence the quality of the metaheuristic algorithm output.

In this study, two approaches for the tabu moves are assumed. The first is the pairwise tabu in which two trucks on two separate doors are exchanged and remained tabu until they are removed from the tabu tenure list. The second is the single tabu in which the assigned truck to a door remains tabu and, after m iterations, gets removed from the tabu list. In the pairwise tabu status, tabu tenure stores all tabus in the $a,b|c$ format where a and b are door numbers and represent the pairwise tabu status; i.e., *(a,)*, and c represents the number of moves that *(a,)* remains tabu unless aspiration criteria allow it be removed from the list. The condition for the single tabu status is quite different, and the tabu tenure stores all tabus in $a|c$ format when a represents the door number which is tabu and *c* represents the number of moves that door *a* remains tabu unless aspiration criteria let it be removed from the list. In both formats, by tabuing door numbers, exchanging the content of each door is avoided for a certain number of moves; i.e., *c*. For example, in the 7,0|1; 4,7|2; 2,3|3; 6,1|4; 5,3|5, the pair [5,3) remains tabu for 5 iterations unless the aspiration criteria help it be removed from the tabu tenure list. However, in the 4|3; 7|5; 0|2; 1|5; 7|5, the 4th and 7th doors remain tabu for 3 and 5 next moves, respectively. In the former, if the outer loop reaches the 5th door and the inner loop reaches the 3rd door or vice versa, the algorithm skips this pair as they are Tabu. In the latter , if the outer loop reaches the 4th door and the inner loop reaches the 2nd door, the exchange between the contents of the 2nd and the 4th door never occur as the 4th door is tabu for the other 3 moves. Both scenarios force tabus to be tabu unless aspiration criteria help them be removed from the list.

4.10.1.4 The Problem Size

By the increase in problem size, the metaheuristic algorithms spend more time to find a high-quality neighborhood solution. In other words, the small size problems reach/approach the optimum solution faster than the larger size problems. Therefore, it is hypothesized that the metaheuristic output quality is higher in the small size problems than the larger ones.

4.10.1.5 Cross-docking Terminal Shift Capacity

As cross-docking terminal shift directly influences the dynamic fixed costs on both sides of the terminal (see the 2nd and 3rd part of the objective function developed in Eq. 34), it is hypothesized that there is a significant difference between lower shift capacity and higher shift capacity on the quality of the developed metaheuristic algorithm output.

4.10.1.6 Cross-docking Terminal Width

Cross-docking terminal width directly affects the travelling distance between inbound and outbound doors. Therefore, it is hypothesized that there is a significant difference between metaheuristic output quality when there is a narrower terminal versus a wider one.

4.9.2 Noise Factors – Diversification Methods

Diversification is the major component of any metaheuristic algorithm that helps generate diverse solutions so as to explore the search space on a global scale and aims to force the search through unvisited areas in the solution space [171]. Therefore, the type of diversification can directly affect the metaheuristics output qualities. As there is no unique diversification method, in this study, it is decided to consider diversification techniques as a noise factor. This decision helps removing the effect of diversification techniques and focusing on the signal factors. This consideration would not ignore the importance of diversification; however, it makes the decision-making process more robust with respect to diversification methods.

4.9.3 Parameters Settings

In order to minimize cost gap percentage shown in Eq. 39, six signal factors are assumed: 1) initial solution (best vs. random), 2) search order (L2R vs. random), 3) tabu status (pair vs. single), 4) problem size (10×10×10×10 vs. 14×14×14×14), 5) cross-docking terminal' shift capacity (20 vs 30), and finally 6) cross-docking terminal width (20 yards vs. 30 yards). Concerning the problem size, 10×10×10×10 means the problem include 10 suppliers, 10 customers, 10 inbound doors and 10 outbound doors.

These signal factors are manipulated using a $L_{16}2^5$ orthogonal array design shown in Table 38. In each combination shown in Table 38, five experiments are run for each diversification method (M1 through M4), and then the average of each diversification result in the corresponding column is reported. The objective of these experiments is to find the best factors' combination that helps to minimize the cost gap percentage. Therefore, the smaller-is-better signal-to-noise (S/N) ratio shown in Table 38 is calculated for each factor level combination.

$$S/N = -10\log_{10}\left[\frac{\sum_{i=1}^{i=n} {y_i}^2}{n}\right] \qquad \text{Eq. 40}$$

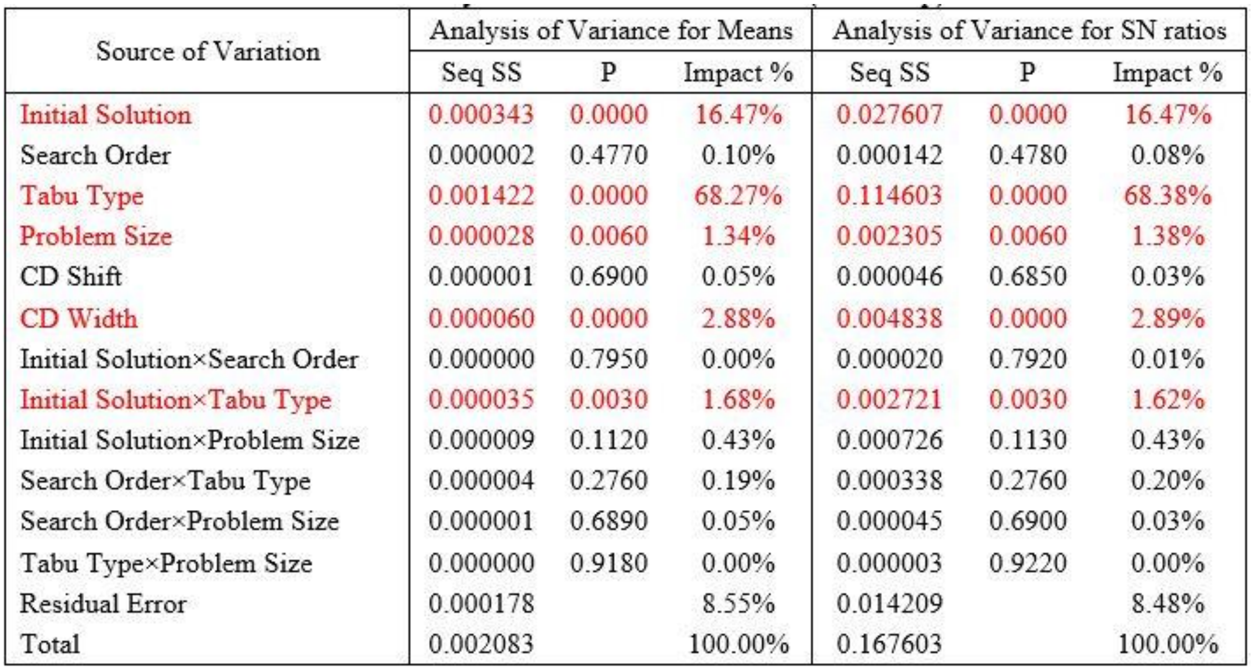
Table 38: $L_{16}4^12^6$ orthogonal array to determine the best parameter setting in Tabu-search method

Experiment	Orthogonal array (Signal Factors)						Diversifications (Noises)			
	Initial Solution	Search Order	Tabu Status	Problem Size	CD Shift	CD Width	M1	M2	M3	M4
1	Best	L2R	Pair	10	20	20	---	---	---	---
2	Best	L2R	Single	14	20	20	---	---	---	---
3	Random	Random	Pair	10	30	30	---	---	---	---
4	Random	Random	Single	14	30	30	---	---	---	---
5	Random	Random	Pair	10	20	20	---	---	---	---
6	Random	Random	Single	14	20	20	---	---	---	---
7	Best	L2R	Pair	10	30	30	---	---	---	---
8	Best	L2R	Single	14	30	30	---	---	---	---
9	Best	Random	Pair	14	20	30	---	---	---	---
10	Best	Random	Single	10	20	30	---	---	---	---
11	Random	L2R	Pair	14	30	20	---	---	---	---
12	Random	L2R	Single	10	30	20	---	---	---	---
13	Random	L2R	Pair	14	20	30	---	---	---	---
14	Random	L2R	Single	10	20	30	---	---	---	---
15	Best	Random	Pair	14	30	20	---	---	---	---
16	Best	Random	Single	10	30	20	---	---	---	---

Analysis of Variance (ANOVA) shown in Table 39 presents the analysis for mean and S/N ratio and explains the differences among signal factors listed in Table 40 on cost gap percentage analysis. According to the ANOVA analyses on mean and S/N ratio, all signal factors, except search order and cross-docking terminal shift, significantly influence the cost gap percentage outputs. Meanwhile, the interaction between Initial Solution and Tabu Type is significant and explains less than 2% of the output variation from the mean and signal to noise ration.

On each table, sequential sums of square (Seq SS) are measures of variation for different factors of the model, and their corresponding values on contribution column display the percentage that each source in the ANOVA table contributes to the total sequential sums of squares (Seq SS). Here, the contribution of significant factors on the variation of mean and S/N ratio cost gap percentage analysis are 90.64% and 90.74%, respectively. In fact, by controlling these factors, the variation of mean and S/N ratio can be controlled by 90.64% and 90.74% respectively.

Table 39: Analysis of Variance for Means (Cost-Gap)



Source of Variation	Analysis of Variance for Means			Analysis of Variance for SN ratios		
	Seq SS	P	Impact %	Seq SS	P	Impact %
Initial Solution	0.000343	0.0000	16.47%	0.027607	0.0000	16.47%
Search Order	0.000002	0.4770	0.10%	0.000142	0.4780	0.08%
Tabu Type	0.001422	0.0000	68.27%	0.114603	0.0000	68.38%
Problem Size	0.000028	0.0060	1.34%	0.002305	0.0060	1.38%
CD Shift	0.000001	0.6900	0.05%	0.000046	0.6850	0.03%
CD Width	0.000060	0.0000	2.88%	0.004838	0.0000	2.89%
Initial Solution×Search Order	0.000000	0.7950	0.00%	0.000020	0.7920	0.01%
Initial Solution×Tabu Type	0.000035	0.0030	1.68%	0.002721	0.0030	1.62%
Initial Solution×Problem Size	0.000009	0.1120	0.43%	0.000726	0.1130	0.43%
Search Order×Tabu Type	0.000004	0.2760	0.19%	0.000338	0.2760	0.20%
Search Order×Problem Size	0.000001	0.6890	0.05%	0.000045	0.6900	0.03%
Tabu Type×Problem Size	0.000000	0.9180	0.00%	0.000003	0.9220	0.00%
Residual Error	0.000178		8.55%	0.014209		8.48%
Total	0.002083		100.00%	0.167603		100.00%

The differences between the level means for all factors that affect the cost gap percentage responses for both mean and S/N ratio analysis is displayed in Table 40. In all main effect analyses, the larger the differences between the means levels, the more significant its corresponding factor.

In all graphs, the larger S/N ratio[2] on a specific level for each factor mirrors to the smaller mean value on its corresponding mean's graph and vice versa.

Table 40 presents the model summary. R^2 is just one measure of how well the model fits the data and shows the percentage of variation in the response that is explained by the model. Overall, the model consisting of the listed six factors can explain over 91% of the response variations on means and S/N ratios for cost gap percentage analysis. On the other hand, adjusted R^2 is a modified version of R^2 that has been adjusted for the number of predictors and is the percentage of the variation in the response that is explained by the model. Overall, all adjusted R^2 are larger than 89%.

In the second half of Table 40, all response tables on mean and S/N ratio for cost gap percentage are presented. In the mean section of the table, a separate mean for each combination of control factor levels is presented, and the ones that have the minimum value are selected. Also, in the S/N ratio section of the table, a separate S/N ratio for each combination of control factor levels in the design is calculated, and in all cases, the maximum value is selected. In both tables, delta measures the effect size through taking the difference between the highest and lowest characteristic average for a factor. And finally, the rank helps to quickly identify which factor has the largest effect. All ranks in both tables link directly to the contribution of the corresponding factor.

Based on the final analysis shown in Table 40, it is concluded that the combination of best initial solution, left to right search order within loops, pair tabu status, small size problem, lower shift capacity, and longer cross-docking terminal width result in better control over the cost gap

---

[2] The larger S/N ratio is always desirable.

percentage both from mean and S/N ratio analyses. All these levels help maximize the S/N ratio which result in minimum variance from the target value.

Table 40: Response table for Means and S/N ratio (Cost-Gap)

---	R^2	R^2 (Adj.)	Level	Initial Solution	Search Order	Tabu Type	Problem Size	CD Shift	CD Width
Mean	91.47%	89.47%	1	0.9646	0.9667	0.9622	0.9662	0.9668	0.9679
			2	0.9692	0.9671	0.9716	0.9676	0.967	0.9659
			Delta	0.0046	0.0003	0.0094	0.0013	0.0002	0.0019
			Rank	2	5	1	4	6	3
S/N Ratio	91.52%	89.53%	1	0.3133	0.294	0.3349	0.2985	0.2934	0.2838
			2	0.2718	0.2911	0.2502	0.2865	0.2917	0.3012
			Delta	0.0415	0.003	0.0846	0.012	0.0017	0.0174
			Rank	2	5	1	4	6	3
Level Selection				1 (Best)	1 (L2R)	1 (Pair)	1 (small)	2 (small)	2 (wider)

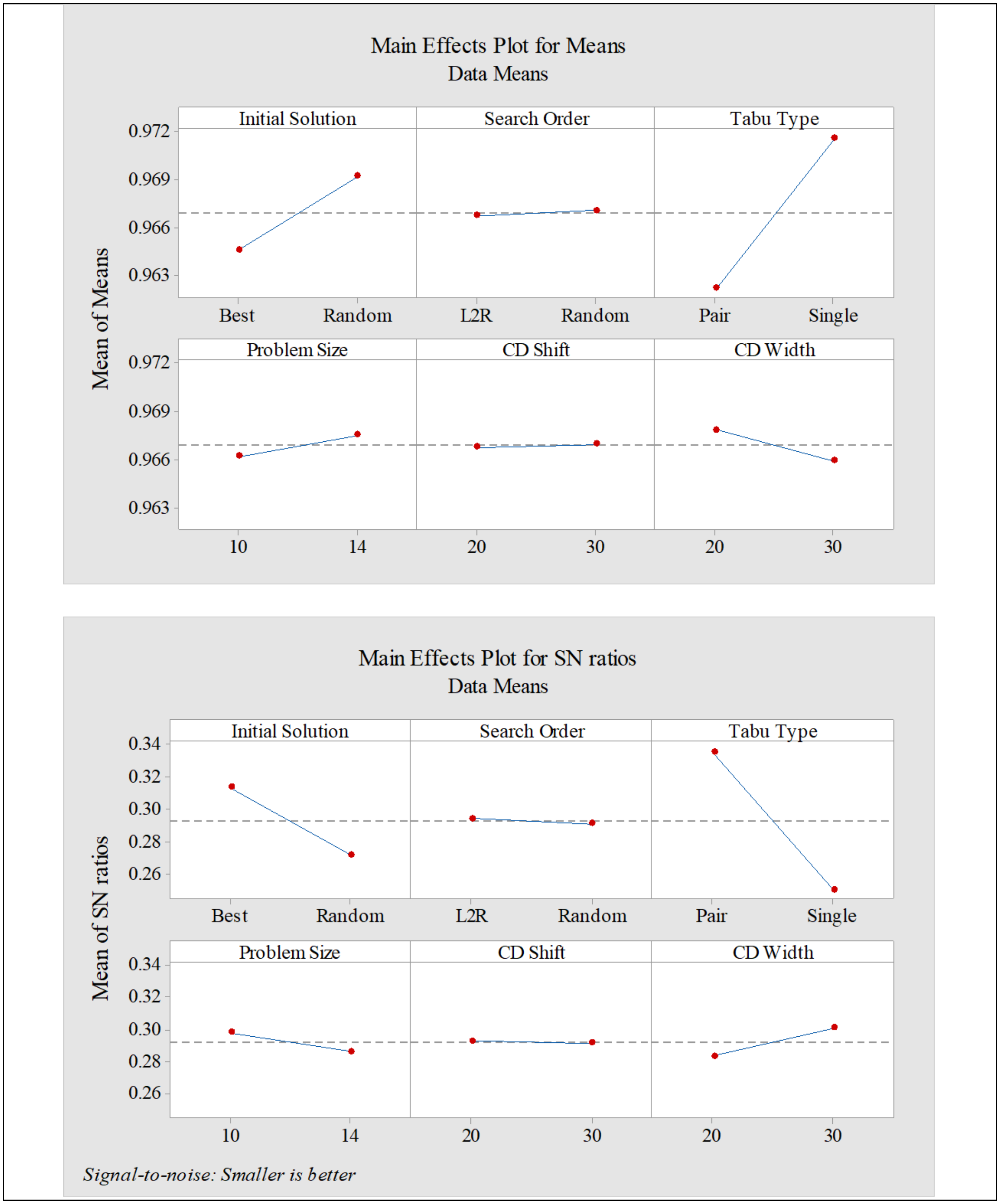


Figure 15: Main effect and interaction effect plots for cost-gap

4.10Numerical Examples

In order to evaluate the efficiency of the Tabu search framework shown in Table 41, nine sets of problems including 7×7×7×7, 10×10×10×10, 15×15×15×15, 20×20×20×20, 25×25×25×25, 30×30×30×30, 35×35×35×35, 40×40×40×40, and 45×45×45×45 are randomly generated. For simplicity, equal number of suppliers, customers, inbound and outbound doors are assumed, and each set is replicated for five times. Each experience is run using different methods for the problem-solving including enumeration method (CPLEX), hill-climbing technique, and Tabu search metaheuristic technique. Tabu search metaheuristic is implemented five times for each diversification method. The corresponding cost gap percentage and time-to-best (CPU time measured in seconds) are reported for each technique which are shown in Table 41. In the CPLEX section, the relative MIP gap tolerance (Gap %) which is a distance between upper and lower bound of the MIP solution is also reported. The desired value is the one that is closer to zero. As it is shown in Table 41, by the increase in the problem size, the relative MIP gap increases. Only for small cases, CPLEX converges and reaches the optimality; the relative MIP gap is lower than 20%. However, for larger size problems, CPLEX does not converge and does not reach optimality, and it reports “MIP starts not constructed because of out-of-memory status.” And we see the relative MIP gap is observed to be greater than 60%, and for the largest problem size, it is almost 100% which indicates that the CPLEX stops right after it starts searching to find the first feasible points.

Following the hill-climbing algorithm described previously, in the initial solution section, a maximum of 200 local optimum solutions are generated, and the best one is selected as the best initial solution. In addition, the time reported in the initial solution section is the time that is spent to generate maximum 200 local optimum points. It is noteworthy to consider that the total time to generate maximum 200 local optimum points is well below the time CPLEX reports to reach the solution; i.e., either the optimal or non-optimal one.

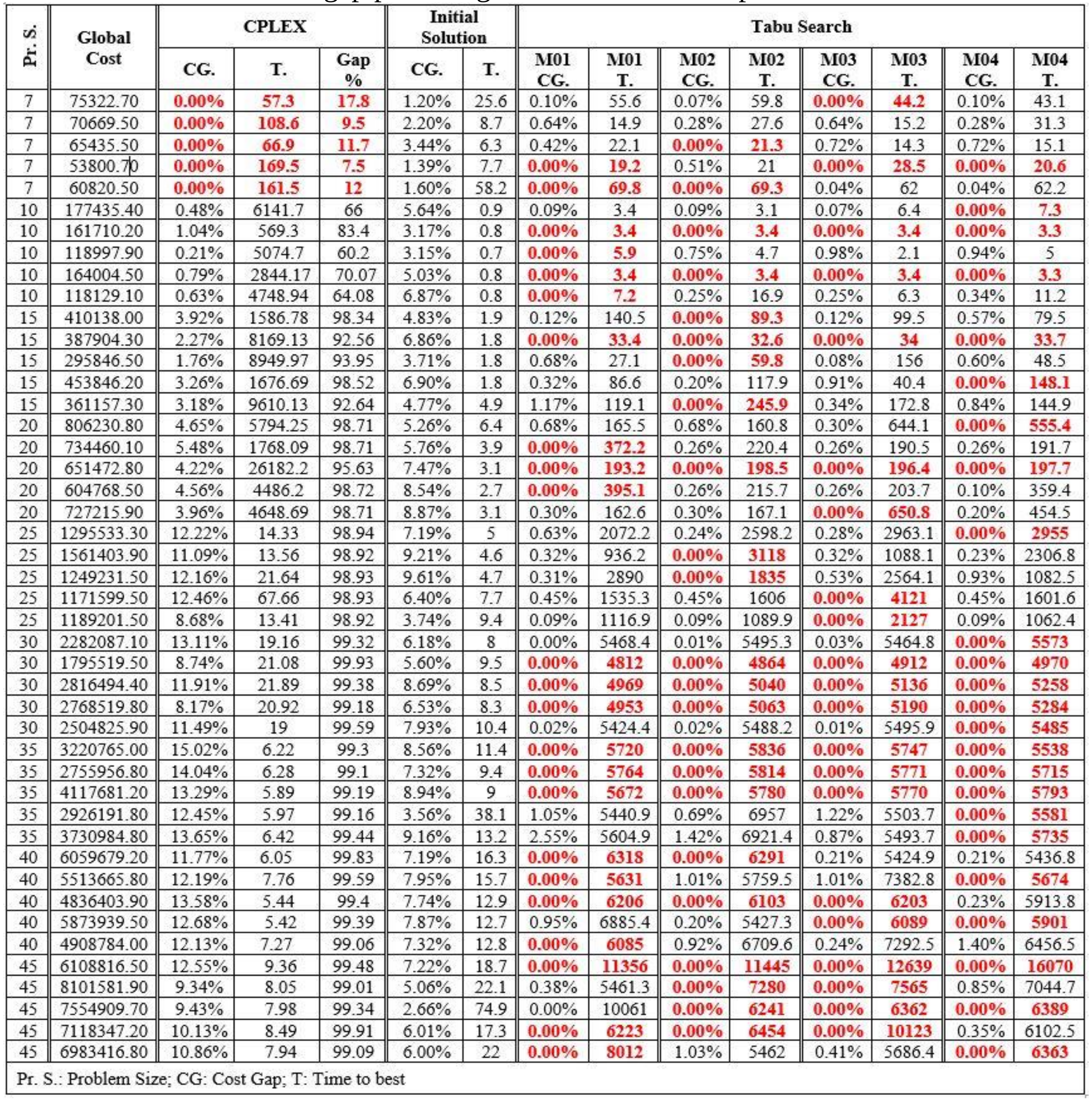
As the initial solution to start TS is the best local optimum solution, time-to-best is added to generate the best initial solution to the TS time. For instance, when TS uses M1 diversification method for the first instance, TS's time-to-best (shown in Table 41) equals 55.60 seconds. So, 25.6 of 55.60 is spent to achieve maximum 200 solutions and 30 seconds for the TS process. However, if we choose a random point as initial solution, the TS process takes much less time to achieve a better solution.

Excepting the 7×7×7×7 instances that reach optimality by CPLEX technique, in other instances, the red and bolded values indicate the global lowest solution which are not necessarily the optimum values. In all instances, none of the best initial solutions are the global points with the lowest costs. Moreover, looking at all TSs' columns, it can be observed that in all instances, except the 7×7×7×7, TS has superiority over the CPLEX not only from the cost perspective but also from the time-to-best standpoint.

Table 42 shows the average of the data presented in Table 41. For each problem set presented in Table 41, the methods are sorted and ranked in ascending order based on their cost gap percentage and time. The corresponding ranks for all methods are reported in Table 43. Overall, all tabu search techniques have remarkably significant advantages over the other two techniques; i.e., hill-climbing approach to achieve the best local optimal solutions and the enumeration technique using ILOG CPLEX.

When the Tabu search technique is broken down to the diversification methods in Table 43, it was noticeable that the Tabu search with Permutation Mapping Diversification Method (M1) achieve the highest number of optimal solutions. The Recursive Permutation Mapping (M2) is the second-best alternative to solve the proposed model. The third lowest ranking corresponding to Recursive DivTS Restart Approach (M4) indicates the importance of M4 in problem solving with respect to M1 and M2. M3, the DivTS Restart Approach, receives the forth position of importance with respect the other 3 diversification methods. Therefore, the ranking from the best to the worst can be arranged as follows; Tabu search (M1, M2, M4, and M3), CPLEX, and then Best Initial Solution.

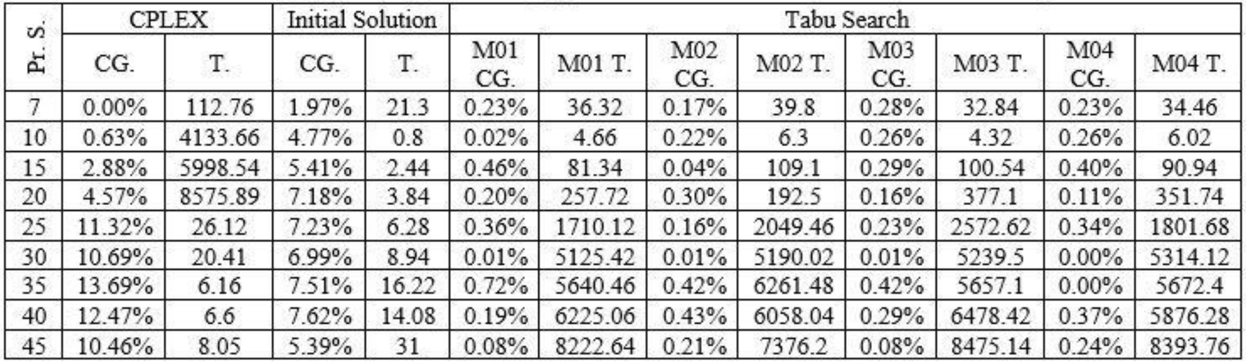
Table 41:Cost gap percentage and time-to-best report for 45 instances



Pr. S.	Global Cost	CPLEX			Initial Solution		Tabu Search							
		CG.	T.	Gap %	CG.	T.	M01 CG.	M01 T.	M02 CG.	M02 T.	M03 CG.	M03 T.	M04 CG.	M04 T.
7	75322.70	**0.00%**	**57.3**	**17.8**	1.20%	25.6	0.10%	55.6	0.07%	59.8	**0.00%**	**44.2**	0.10%	43.1
7	70669.50	**0.00%**	**108.6**	**9.5**	2.20%	8.7	0.64%	14.9	0.28%	27.6	0.64%	15.2	0.28%	31.3
7	65435.50	**0.00%**	**66.9**	**11.7**	3.44%	6.3	0.42%	22.1	**0.00%**	**21.3**	0.72%	14.3	0.72%	15.1
7	53800.70	**0.00%**	**169.5**	**7.5**	1.39%	7.7	**0.00%**	**19.2**	0.51%	21	**0.00%**	**28.5**	**0.00%**	**20.6**
7	60820.50	**0.00%**	**161.5**	**12**	1.60%	58.2	**0.00%**	**69.8**	**0.00%**	**69.3**	0.04%	62	0.04%	62.2
10	177435.40	0.48%	6141.7	66	5.64%	0.9	0.09%	3.4	0.09%	3.1	0.07%	6.4	**0.00%**	**7.3**
10	161710.20	1.04%	569.3	83.4	3.17%	0.8	**0.00%**	**3.4**	**0.00%**	**3.4**	**0.00%**	**3.4**	**0.00%**	**3.3**
10	118997.90	0.21%	5074.7	60.2	3.15%	0.7	**0.00%**	**5.9**	0.75%	4.7	0.98%	2.1	0.94%	5
10	164004.50	0.79%	2844.17	70.07	5.03%	0.8	**0.00%**	**3.4**	**0.00%**	**3.4**	**0.00%**	**3.4**	**0.00%**	**3.3**
10	118129.10	0.63%	4748.94	64.08	6.87%	0.8	**0.00%**	**7.2**	0.25%	16.9	0.25%	6.3	0.34%	11.2
15	410138.00	3.92%	1586.78	98.34	4.83%	1.9	0.12%	140.5	**0.00%**	**89.3**	0.12%	99.5	0.57%	79.5
15	387904.30	2.27%	8169.13	92.56	6.86%	1.8	**0.00%**	**33.4**	**0.00%**	**32.6**	**0.00%**	**34**	**0.00%**	**33.7**
15	295846.50	1.76%	8949.97	93.95	3.71%	1.8	0.68%	27.1	**0.00%**	**59.8**	0.08%	156	0.60%	48.5
15	453846.20	3.26%	1676.69	98.52	6.90%	1.8	0.32%	86.6	0.20%	117.9	0.91%	40.4	**0.00%**	**148.1**
15	361157.30	3.18%	9610.13	92.64	4.77%	4.9	1.17%	119.1	**0.00%**	**245.9**	0.34%	172.8	0.84%	144.9
20	806230.80	4.65%	5794.25	98.71	5.26%	6.4	0.68%	165.5	0.68%	160.8	0.30%	644.1	**0.00%**	**555.4**
20	734460.10	5.48%	1768.09	98.71	5.76%	3.9	**0.00%**	**372.2**	0.26%	220.4	0.26%	190.5	0.26%	191.7
20	651472.80	4.22%	26182.2	95.63	7.47%	3.1	**0.00%**	**193.2**	**0.00%**	**198.5**	**0.00%**	**196.4**	**0.00%**	**197.7**
20	604768.50	4.56%	4486.2	98.72	8.54%	2.7	**0.00%**	**395.1**	0.26%	215.7	0.26%	203.7	0.10%	359.4
20	727215.90	3.96%	4648.69	98.71	8.87%	3.1	0.30%	162.6	0.30%	167.1	**0.00%**	**650.8**	0.20%	454.5
25	1295533.30	12.22%	14.33	98.94	7.19%	5	0.63%	2072.2	0.24%	2598.2	0.28%	2963.1	**0.00%**	**2955**
25	1561403.90	11.09%	13.56	98.92	9.21%	4.6	0.32%	936.2	**0.00%**	**3118**	0.32%	1088.1	0.23%	2306.8
25	1249231.50	12.16%	21.64	98.93	9.61%	4.7	0.31%	2890	**0.00%**	**1835**	0.53%	2564.1	0.93%	1082.5
25	1171599.50	12.46%	67.66	98.93	6.40%	7.7	0.45%	1535.3	0.45%	1606	**0.00%**	**4121**	0.45%	1601.6
25	1189201.50	8.68%	13.41	98.92	3.74%	9.4	0.09%	1116.9	0.09%	1089.9	**0.00%**	**2127**	0.09%	1062.4
30	2282087.10	13.11%	19.16	99.32	6.18%	8	0.00%	5468.4	0.01%	5495.3	0.03%	5464.8	**0.00%**	**5573**
30	1795519.50	8.74%	21.08	99.93	5.60%	9.5	**0.00%**	**4812**	**0.00%**	**4864**	**0.00%**	**4912**	**0.00%**	**4970**
30	2816494.40	11.91%	21.89	99.38	8.69%	8.5	**0.00%**	**4969**	**0.00%**	**5040**	**0.00%**	**5136**	**0.00%**	**5258**
30	2768519.80	8.17%	20.92	99.18	6.53%	8.3	**0.00%**	**4953**	**0.00%**	**5063**	**0.00%**	**5190**	**0.00%**	**5284**
30	2504825.90	11.49%	19	99.59	7.93%	10.4	0.02%	5424.4	0.02%	5488.2	0.01%	5495.9	**0.00%**	**5485**
35	3220765.00	15.02%	6.22	99.3	8.56%	11.4	**0.00%**	**5720**	**0.00%**	**5836**	**0.00%**	**5747**	**0.00%**	**5538**
35	2755956.80	14.04%	6.28	99.1	7.32%	9.4	**0.00%**	**5764**	**0.00%**	**5814**	**0.00%**	**5771**	**0.00%**	**5715**
35	4117681.20	13.29%	5.89	99.19	8.94%	9	**0.00%**	**5672**	**0.00%**	**5780**	**0.00%**	**5770**	**0.00%**	**5793**
35	2926191.80	12.45%	5.97	99.16	3.56%	38.1	1.05%	5440.9	0.69%	6957	1.22%	5503.7	**0.00%**	**5581**
35	3730984.80	13.65%	6.42	99.44	9.16%	13.2	2.55%	5604.9	1.42%	6921.4	0.87%	5493.7	**0.00%**	**5735**
40	6059679.20	11.77%	6.05	99.83	7.19%	16.3	**0.00%**	**6318**	**0.00%**	**6291**	0.21%	5424.9	0.21%	5436.8
40	5513665.80	12.19%	7.76	99.59	7.95%	15.7	**0.00%**	**5631**	1.01%	5759.5	1.01%	7382.8	**0.00%**	**5674**
40	4836403.90	13.58%	5.44	99.4	7.74%	12.9	**0.00%**	**6206**	**0.00%**	**6103**	**0.00%**	**6203**	0.23%	5913.8
40	5873939.50	12.68%	5.42	99.39	7.87%	12.7	0.95%	6885.4	0.20%	5427.3	**0.00%**	**6089**	**0.00%**	**5901**
40	4908784.00	12.13%	7.27	99.06	7.32%	12.8	**0.00%**	**6085**	0.92%	6709.6	0.24%	7292.5	1.40%	6456.5
45	6108816.50	12.55%	9.36	99.48	7.22%	18.7	**0.00%**	**11356**	**0.00%**	**11445**	**0.00%**	**12639**	**0.00%**	**16070**
45	8101581.90	9.34%	8.05	99.01	5.06%	22.1	0.38%	5461.3	**0.00%**	**7280**	**0.00%**	**7565**	0.85%	7044.7
45	7554909.70	9.43%	7.98	99.34	2.66%	74.9	0.00%	10061	**0.00%**	**6241**	**0.00%**	**6362**	**0.00%**	**6389**
45	7118347.20	10.13%	8.49	99.91	6.01%	17.3	**0.00%**	**6223**	**0.00%**	**6454**	**0.00%**	**10123**	0.35%	6102.5
45	6983416.80	10.86%	7.94	99.09	6.00%	22	**0.00%**	**8012**	1.03%	5462	0.41%	5686.4	**0.00%**	**6363**

Pr. S.: Problem Size; CG: Cost Gap; T: Time to best

Table 42:The average summary of cost gap and time for 45 instances for nine categories



Pr. S.	CPLEX		Initial Solution		Tabu Search							
	CG.	T.	CG.	T.	M01 CG.	M01 T.	M02 CG.	M02 T.	M03 CG.	M03 T.	M04 CG.	M04 T.
7	0.00%	112.76	1.97%	21.3	0.23%	36.32	0.17%	39.8	0.28%	32.84	0.23%	34.46
10	0.63%	4133.66	4.77%	0.8	0.02%	4.66	0.22%	6.3	0.26%	4.32	0.26%	6.02
15	2.88%	5998.54	5.41%	2.44	0.46%	81.34	0.04%	109.1	0.29%	100.54	0.40%	90.94
20	4.57%	8575.89	7.18%	3.84	0.20%	257.72	0.30%	192.5	0.16%	377.1	0.11%	351.74
25	11.32%	26.12	7.23%	6.28	0.36%	1710.12	0.16%	2049.46	0.23%	2572.62	0.34%	1801.68
30	10.69%	20.41	6.99%	8.94	0.01%	5125.42	0.01%	5190.02	0.01%	5239.5	0.00%	5314.12
35	13.69%	6.16	7.51%	16.22	0.72%	5640.46	0.42%	6261.48	0.42%	5657.1	0.00%	5672.4
40	12.47%	6.6	7.62%	14.08	0.19%	6225.06	0.43%	6058.04	0.29%	6478.42	0.37%	5876.28
45	10.46%	8.05	5.39%	31	0.08%	8222.64	0.21%	7376.2	0.08%	8475.14	0.24%	8393.76

Table 43: Methods' comparison based on their ranking for each instance

Problem Size	CPLEX	Initial Solution	Tabu Search			
			M1	M2	M3	M4
7	1	6	4	2	5	3
10	5	6	1	2	3	4
15	5	6	4	1	2	3
20	5	6	3	4	2	1
25	6	5	1	1	2	3
30	6	5	2	3	4	1
35	6	5	4	3	2	1
40	6	5	1	4	2	3
45	6	5	1	2	3	4
Average	5.11	5.44	2.33	2.44	2.78	2.56
Overall Rank	5	6	1	2	4	3

4.11Limitations of the study

The limitations encountered during the study are as follows;

1) The bilinear-quadratic assignment problem developed in this study; i.e., XQY, is the general format of the common quadratic assignment problem of XQX. Based on our research, there is no available sample on the internet to check the efficiency of the algorithm with their results. And all other studies have just reported their final output results, as well.
2) The proposed heuristic and meta-heuristic algorithms are coded in the Visual Studio C# 2017, and in this study, parallel programing method was implemented in which many calculations or the execution of processes are carried out simultaneously. Also, in order to increase the efficiency of memory usage , SQL Server 2014 is employed to store the output

data in each run of the algorithms. In addition, some parts of the coding for this study was developed in the Matlab and used the Matlab dll files in the main program developed in VS C#. Due to complexity of the main software, there was no chance to install it on a super computer to test problems sizes larger than 45×45×45×45.

3) Concerning complete enumeration approaches, solvers like ILOG CPLEX give up finding the optimum solution due to lack of memory on a personal laptop; like one with a processor "Intel(R) Core (TM) i7-6500U CPU @ 2.50 GHz 2.60 GHz" and an installed memory of 12.00 GB. It is noteworthy that we didn't change the CPLEX default setting and the results are generated using the settings offer by the CPLEX

4.12Conclusion and Future Study

Cross docking as a way to optimize the supply is an important way to build a sustainable competitive advantage in competitive market as it allows retail chains to maximize the availability and turnover of products for customers while reducing the company's additional inventory cost. The findings corroborate the anecdotal evidence that, given the appropriate conditions, cross-docking can provide significant value to organizations. This study mainly focused on the most important part of cross-docking which is the transshipment of products from inbound doors to the outbound doors with minimal travelled distances. Unlike other studies, in this study, a dynamic fixed cost was assumed for each door which is varied by the quantity of the load assigned to that door.

The results showed that the advantages of using heuristic (hill-climbing) and meta-heuristic (Tabu search) methods outweighed their disadvantages (getting trapped in the local optimum solution) in contrast with the enumeration techniques that seek optimality.

Tabu search technique is employed to solve the proposed problem. In order to increase the efficiency of the algorithm to get higher quality results in a minimum processing time, Taguchi robust parameters settings has been done to find the best combination of signal factors including 1) initial solution, 2) search order, 3) tabu status, 4) problem size, 5) cross-docking shift capacity, and 6) cross-docking width. Also, the parameters settings are made robust against the variation effect of diversification methods. The result showed that the impact of initial solution and tabu type was more that 84% on the output variations. Also, the results confirm that the best initial solution leads to better output in the Tabu-search meta-heuristic algorithm.

By setting the parameters to their best levels presented in Table 40, the findings shown in Table 41, Table 42, and Table 43 confirmed that Tabu search outperforms the hill-climbing technique and CPLEX from both cost and time perspectives. The efficiency of the developed algorithm manifests itself when the time-to-best of TS was compared with the time-to-best reported by the hill-climbing and CPLEX. Even, the TS time-to-best was significantly lower than CPLEX time-to-best when CPLEX returned optimality in the small size problems; i.e., 7×7×7×7. For instance, CPLEX reached optimality of the last 7×7×7×7 instance at 161st second while Tabu search reached that in around 70th second.

In the future, the researcher plans to consider meta-heuristic methods or evolutionary optimization approaches to solve even larger size problems (few hundred doors and thousands of orders) in a fast and efficient way. Thus, same coding must be developed in the Python platform in order to run the coding on a supercomputer.

CHAPTER 5

MINIMIZING TOTAL SUPPLY CHAIN COSTS

Abstract

This study aims at proposing a decision-support tool to reduce the total supply chain costs (TSCC) consisting of two separate and independent objective functions including total transportation costs (TTC) and total cross-docking operating cost (TCDC). The full-truckload (FT) transportation mode is assumed to handle supplier→customer product transportation; otherwise, a cross-docking terminal as an intermediate transshipment node is hired to handle the less-than-truckload (LTL) product transportation between the suppliers and customers. TTC model helps minimize the total transportation costs by maximization of the number of FT transportation and reduction of the total number of LTL. TCDC model tries to minimize total operating costs within a cross-docking terminal. Both sub-objective functions are formulated as binary mathematical programming models. The first objective function is a binary-linear programming model, and the second one is a binary-quadratic assignment problem (QAP) model. QAP is an NP-hard problem, and therefore, besides a complement enumeration method using ILOG CPLEX software, the Tabu search (TS) algorithm with four diversification methods is employed to solve larger size problems. The efficiency of the model is examined from two perspectives by comparing the output of two scenarios including; i.e., 1) when cross-docking is included in the supply chain and 2) when it is excluded. The first perspective is to compare the two scenarios' outcomes from the total supply

chain costs standpoint, and the second perspective is the comparison of the scenarios' outcomes from the total supply chain costs standpoint. By addressing a numerical example, the results confirm that the present of cross-docking within a supply chain can significantly reduce total supply chain costs and total transportation costs.

5.1Introduction

Cross-docking is designed to consolidate products from different suppliers for different destinations into transportation vehicles with the same destination. In fact, it is a logistics practice that eliminates the storage and order picking functions of a warehouse while still allowing it to serve its receiving and shipping functions. The idea is to transfer LTL shipments directly from inbound to outbound trailers without storage in between as it is shown in Figure 16. Shipments are supposed to spend less than 24 hours in a cross-docking terminal, sometimes less than an hour [205; 232; 8; 79; 143; 185; 109; 43]. While it is typical to handle sorting, labeling, and packaging inside terminal, the products consolidation is the main characteristics of a cross-docking terminal. Freight consolidation helps reduce product transportation cost by combining small orders of LTL to enable dispatch of larger FT loads. In the meantime, any time violation (earliness or tardiness) during transshipment process results in delay or earliness in product delivery, which ultimately impacts customer satisfaction at the end of the chain [99; 43].

Practicing cross-docking helps manager meet the just-in-time goal to improve the return of investment by reducing inventory without loss the flexibility of the system and the availability of the final products to the customers. In doing that, a supply chain is required to facilitate good cooperation, coordination, and communication among significant actors. Having high level of coordination and communication to share knowledge with other significant actors, production companies try to optimize their supply chain by reducing their logistics costs [21] by simplifying their supply chain by practicing cross-docking. In doing so, there are two points of emphasize that need to be considered; the first is transportation systems that handle FT and LTL product transportation and the second is cross-docking operations process that receives product from different suppliers, and then after consolidation, ships them to the customers. An optimal supply chain tends to increase the cooperation between transportation system and cross-docking facilities so as to 1) increase the FT and decrease the LTL product transportation 2) increase the just-in-time approach by increase the inventory turnover in the retailers' sites and, 3) avoid any type of earliness or tardiness to product delivery to the customers as earliness creates the storage of extra inventory in the retailers' sites and tardiness creates the lacking of inventory at the retailers' warehouses which both create end-customers dissatisfaction.

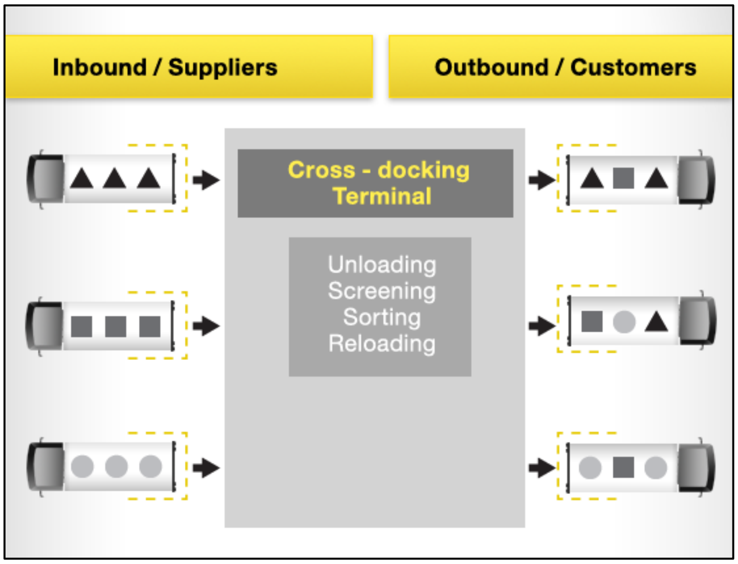


Figure 16: Cross-docking terminal

In 1990, Tsui and Chang [221] systematically introduced an NP-hard bilinear-quadratic assignment problem (QAP) in the context of the cross-docking practice. Since then a relatively large number of studies have investigated the importance of cross-docking formulation from different perspectives such as 1) maximizing the utilization of resources [23, 46, 6, 77, 37, 88, 57, 65), 2) minimizing operations costs within cross-docking terminal [93; 191; 245], and 3) minimizing time windows violation within cross-docking's operations time [152; 141; 13; 38; 37; 88; 219; 3; 14; 68; 15; 143]. Other researchers view cross-docking from decision-making perspectives such as 1) long-term strategic decision level 2) medium-term tactical decision level, and 3) short-term operational decision level [23,24,25,26). Research focused on the long-term strategic decision level seeks to determine solutions such as the number and location of cross-docking facilities [20,27,24), shape (layout) of cross-docking terminal [28,3), number of vehicles in a distribution network [2], and network design problems [24,29]. Research in the tactical decision level explore medium-term planning and addresses solutions regarding the optimal number of trucks at each arc in distribution network [19], assignment of inbound-trucks and outbound-trucks to cross-docking terminal's doors [30,31,27), and planning of deliveries in a network of cross-docking terminals [49]. Short-term plan research addresses issues at the operational decision level to determine the optimality in scheduling problem, transshipment problem, dock door assignment problem, vehicle routing problem, and product allocation problem [24,11).

Of those studies, the majority conclude that the best truck scheduling and door assignment is the best solution to increase cross-docking efficiency. In fact, the core part of the cross-docking studies; i.e., similar to ours, is the truck-door assignment's model that was developed by Tsui and Chen (1990) [221]. In almost all studies, the model developed by Tsui and Chen (1990) [221] is either the main part of the study [41; 59; 250; 98; 195; 212] or part of the research in which the truck-door assignment is used to solve a more complex problem [37; 8; 131; 9].

This research is motivated to provide nine contributions to the existing literature as follows.

1. To develop a systematic binary-linear programing model to implement product transportation from suppliers to customers with minimum total transportation cost. In that, we try to maximize FT and reduce LTL product transportation so as to meet the economies of scale approach.
2. To provide a systematic technique to solve the bilinear-quadratic assignment problem developed by Tsui and Chen (1990) [221] using the Tabu-search algorithm.
3. In addition of the objective function developed in the Tsui and Chen (1990) [221] model, which minimizes the sums up the total distance traveled from all receiving doors to shipping doors, we assume a dynamic fixed cost for each door at cross-docking terminal. This cost is varied by the quantity of the products assigned to each door. Hence, we force the algorithm to avoid concentrating of trucks' with high load in the center of terminal that leads to floor congestion of forklifts in the middle of terminal.
4. To reduce total supply chain costs (TSCC) including total transportation costs (TTC) and total cross-docking operation costs (TCDC) according to Eq. 41.
5. We will show that cross-docking helps increase the number of FT product transportation and reduces the number of LTL product transportation.
6. To show that cross-docking helps reduce the total number of trucks that are hired for product transportation comparing the time that cross-docking is excluded from the chain.
7. By excluding the cross-docking from the supply chain, the cost of FT transportation between suppliers and customers reduces while the cost of LTL transportation increases. However, by including cross-docking in the supply chain otherwise takes place.
8. To check the efficiency of the developed algorithm, we develop two ratios including total transportation ratio (TTCR) and total supply chain cost ratio (TSCCR). The TTCR (Eq. 42) is the comparison of total transportation cost (TTC) when cross-docking is included in the supply

chain with the time that cross-docking is excluded from the supply chain. The TSCCR (Eq. 43) is the comparison of total supply chain cost (TSCC) when cross-docking is included in the supply chain with the time that cross-docking is excluded from the supply chain. However, when cross-docking is excluded from the supply chain total supply chain cost equals total transportation costs.

9. To show that regardless of the size of problem, cross-docking always helps reduce the product-unit cost.

$TSCC = TTC + TCDC$	Eq. 41
$TTCR\%=\frac{TTC_{\text{cross-docking included}}}{TTC_{\text{cross-docking excluded}}}.100$	Eq. 42
$TSCCR\%=\frac{TSCC_{\text{cross-docking included}}}{TSCC_{\text{cross-docking excluded}}}.100=\frac{TTC_{\text{cross-docking included}}+TCDC}{TTC_{\text{cross-docking excluded}}}.100$	Eq. 43

The reminder of this article is organized as follows. A list of products appropriate for cross-docking is presented in section 5.2. In section 5.3 a brief literature review on cross-docking is presented. The proposed model assumptions are presented in section 0. Section 5.5 presents a binary-linear mathematical model to minimize total transportation costs. In section 5.6 we will address an NP-hard binary-quadratic mathematical model that just focuses on cross-docking operating cost and try to minimize the total travelled distance cost by finding the best truck-door assignment. Section 5.7 explains the process of problem solving for the QAP model. A numerical example about the supply chain cost is presented in section 5.8. Section 5.9 present numerically show the implementation of Tabu search algorithm to solve 9 different problem categories. The limitation of study is presented in section 5.10. Finally, section 5.11 addresses the conclusion and future study.

5.2Products Suitable for Cross-docking

The following is a list of materials that are better suited to cross-docking than others.

1. `The most important materials are perishable items that require immediate shipment; in particular, frozen foods and other refrigerated products, e.g., pharmaceuticals, vegetables, flowers, cosmetics or medicine, and dairy products, which typically require special arrangements to ensure that the cooling chain is not broken [38; 68] Otherwise a defrost and decay of comestible goods threatens [12; 200; 181; 68; 214; 169; 229; 4].
2. High-quality items that do not require quality inspections during goods receipt
3. Promotional items, and items that are being launched
4. Products with a constant demand or low demand variance
5. Pre-picked, pre-packaged customer orders from another production plant or warehouse

5.3Literature Review

Reviewing the mathematical programming literature on cross-docking, the following three objective functions were found around which the research interests have revolved: 1) maximizing utilization-based objective functions 2) minimizing cost-based objective functions, 3) minimizing time-based objective functions.

In the first category, scholars have sought methods to maximize resources/process utilization by;

1. maximizing throughput inside the terminal to accelerate the turnover inside the terminal and reduce a) the likelihood of late shipments,) the total process operational time or make-span; and c) the inventory level at the temporary storage area [229; 65; 4]
2. maximizing truck synchronization inside the terminal [183; 39; 109]
3. maximizing trucks utilizations [99; 146; 188; 105; 65; 73]

Cost-based objective functions are the second category that is of interest for most mathematical programming scholars. Each researcher has explored cost minimization from a different perspective like:

1. Minimizing transshipment (Operational) costs within terminal, i.e., the shipment of products or containers through an intermediate destination, then to yet another destination to change the means of transport [219; 9; 105; 35; 78; 93; 191; 245].
2. Minimizing additional material handling costs due to temporary storage [23; 41; 131; 183]
3. Minimizing manpower and personnel costs at cross-docks [180; 141; 131; 11; 179]
4. Minimizing trucks placement costs at both sides of the terminal [37; 8; 131; 9]
5. Minimizing loading and unloading service costs [73; 126; 127; 78; 93]
6. Minimizing purchase costs due to sorting and consolidation processes [5]
7. Minimizing temporary storage buffer costs at cross-docking location [20; 214; 208; 22]
8. Minimizing transportation costs in the cross-docking analysis routes are divided into four categories including routes 1) from suppliers (S) → terminals (CD), 2) from terminals (CD) → destinations (retailers) (C), 3) directly from suppliers (S) → customers (C), and finally, 4) among the cross-docking terminal when more than a single terminal is assumed in the problem. A list of recent literature on the transportation costs is presented in Table 44 in which the transportation cost between each two nodes is broken down into variable costs and fixed costs.

Table 44: A brief literature review on transportation costs in cross-docking modeling

Publications	Variable Costs				Fixed Costs		
	S → CD	CD → C	S → C	CD → CD	S → CD	CD → C	S → C
Bányai (2013) [21]	√	√	---	√	---	---	---
Birim (2016) [34]	√	√	---	---	---	---	---
Charkhgard and Tabar (2011) [46]	√	√	√	---	---	---	---
Cóccola et al. (2015) [57]	√	√	√	---	---	---	---
Dondo et al. (2011) [68]	√	√	√	---	√	√	√
Galbreth et al. (2008) [77]	√	√	√	---	√	√	√
Gonzalez-Feliu (2012) [138]	√	√	---	---	---	---	---
Gümüş and Bookbinder (2004) [19]	√	√	√	√	√	√	√
Hosseini et al. (2014) [108]	√	√	√	---	---	---	---
Huang and Liu (2015) [110]	√	√	√	---	√	√	√
Mohtashami et al. (2015) [155]	√	√	---	---	---	---	---
Mousavi et al. (2013) [88]	√	√	---	---	√	√	---
Mousavi et al. (2014) [161]	√	√	---	---	√	√	---
Serrano et al. (2016) [191]	---	√	---	---	---	---	---
Vahdani et al. (2014) [90]	√	√	---	---	√	√	---
Yang et al. (2016) [242]	√	√	---	---	---	---	---
Yin and Chuang (2016) [245]	√	√	---	---	√	√	---
Yu et al. (2016) [247]	---	---	---	√	---	---	---

9. Minimizing floor congestion inside the terminal: many scholars have tried to reduce floor congestion in a cross-docking terminal as it 1) causes excessive labor cost, 2) fails shipments service commitments, 3) slows down the speed of the forklifts, 4) increases workers' waiting time due to interference among forklifts and draglines congestions, 5) impedes the (un)loading and storage operations, 6) creates bottlenecks before stack doors with high flow levels , 7) halts operations entirely, 8) causes poor product flow and throughput, and 9) creates long processing times or make-span [26; 27; 41; 2; 105; 143; 21; 11; 108; 145].
10. Minimizing total traveled distance inside the cross-docking terminal using quadratic assignment problem (QAP) and its derivatives [50; 59; 45; 33; 143; 210; 154].
11. Minimizing backorder penalty costs: cross-docking helps achieve the minimum level of inventories inside the customers storage area [209; 239; 195; 229].
12. Minimizing lost profit costs: lost profit is manifested as late satisfied orders which are the costs of the customers [219; 73].

13. Minimizing customers' extra inventory costs due to early product delivery [3; 14; 131; 104; 4; 6; 161; 78; 247].

The third category is the time-based objective functions which proceeds as follows;

1. Minimizing make-span or operating time inside the terminal: the make-span reduction helps to increase material flow inside the cross-docking terminal [246; 17; 61; 74; 122].
2. Minimizing time window violation: time window violation is a big concern in a cross-docking system as it incurs extra costs both within and outside cross-docking terminal for the customers. Thus, most scholars try to minimize time window violation by figuring the best door assignment and truck scheduling so as to have a reliable cross-docking system with minimal total weighted tardiness and earliness simultaneously [161; 35; 10; 18; 78; 237; 247; 19].

Mathematical programming researchers in the field of cross-docking also deal with many decision factors, i.e., assumptions and constraints, during the process of short-term (operational), medium-term (tactical), and long-term (strategic) decision-planning. Many applications in the cross-docking studies lead to mathematical models that can be formulated as mixed integer programming (MIP), non-linear programming (NLP), binary-integer programming (BIP), linear programming (LP), quadratic programming (QP), and mixed integer non-linear programming (MINLP). There are some overlaps among some of them; for instance, QP is a case of NLP or MIP. Also, QP is a specific format of BIP and vice versa. Table 45 represents a list of the most recent publications in the field of cross-docking.

In integer programming, two approaches, i.e., exact and heuristic/meta-heuristic are employed to find the optimal solution or at least some solutions near the optimal point (local optimum point). Exact methods like branch-and-bound, branch-and-cut, brand-and-price tree, complete enumeration method, and dynamic programming are suitable for small size-NP hard problems and guarantee to find the optimal solutions using the commercial solvers presented in Table 46. It is seen that comparing to the other solvers, the popularity of the CPLEX solver makes it to be of interest for many researchers in cross-docking studies.

Table 45: An overview on different types of mathematical programming models (MPM) in cross-docking studies

MPM	Publication
MIP	[17; 18; 34; 74; 78; 122; 124; 166; 191; 218; 237; 245; 247; 19];
NLP	[26; 99; 217; 48; 182; 241; 13; 38; 184; 209; 8; 46; 131; 239]
BIP	[152; 88; 33; 90; 143; 185; 79; 73; 92; 109; 126; 211; 57];
LP	[146; 41; 219; 79; 183; 63; 91; 89; 11]
QP	[220; 250; 98; 212]
MINLP	[154; 161; 5];

Table 46: An overview on the usage of solvers in cross-docking studies

Software	Publication
CPLEX	[158; 194; 17; 18; 74; 78; 122; 166; 191; 218; 242; 247]
GAMS	[105; 88; 6; 66; 114; 154; 160; 161; 5; 17; 19; 93; 124]
GRASP	[79; 79; 108]
Lingo	[3; 143; 237]
Matlab	[7]

Regarding the NP-hard problems like QAP, scholars employ heuristic and metaheuristic methods to find a trade-off between solution quality and computation time as well as a compromise between implementation effort and yields. Heuristic methods like hill climbing are algorithms that try to find the optimal solutions by examining all neighborhood before deciding to move to that neighbor or to explore another; however, when they get trapped into the local optimum points, they stop and return solutions. In fact, their output quality is directly linked to the quality of the initial random solution. On the other hand, metaheuristic methods like Tabu search and Genetic algorithm try to diversify the solution pool once they get trapped into the locality by the heuristic techniques. Table 47 and Table 48 present a list of publications that implement exact, heuristic, and meta-heuristic methods in the field of cross-docking.

Table 47: An overview on deterministic methods in cross-docking studies

Deterministic Method	Publications
Branch-and-bound	[217; 48; 144; 188; 33; 29; 189]
Branch-and-cut	[67; 78]
Branch-and-price tree	[57]
Complete enumeration method	[248; 185; 250]
Dynamic programming	[183; 9; 23; 144; 182; 40; 38; 184; 209; 232]

Table 48: An overview on heuristic and meta-heuristic methods in cross-docking studies

Meta-heuristic methods	Publications
Ant Colony	[162; 140; 14; 138; 154]
Bee colony	[245]
Biogeography-based optimization	[93]
Differential evolution	[140; 13; 15; 139; 10; 18]
Electromagnetism-like algorithm	[198; 122]
Fuzzy Logic	[75; 161; 223]
Genetic Algorithm	[198; 63; 143; 146; 152; 13; 88; 14; 239]
Harmony Search	[108]
Hybrid differential evolution	[140; 139]
Particle swarm optimization	[13; 14; 15; 163; 155; 93; 122; 237; 247]
Petri Net Model	[219]
Problem Decomposition	[246]
Pseudo-polynomial	[182]
Simulated Annealing	[198; 41; 140; 26; 38; 46; 39; 128; 189]
Simulation	[141; 109]
Strength Pareto Evolutionary	[163]
Sweeping algorithm	[66]
Tabu Search	[210; 138; 194; 211; 110; 166; 245]
Scatter Search	[211; 212]
Variable neighborhood search	[73; 128; 226; 35; 198]
Hill climbing	[29; 39; 92; 118; 114; 145; 158; 61; 218]

To reduce the sensitivity of parameters during the implementation of heuristic and meta-heuristic methods, researchers employ statistical techniques, i.e., ANOVA, response surface method (RSM), and Taguchi method, to handle their models' parameter settings. Table 49 presents a list of all publications that have applied these statistical techniques to figure out the best parameter settings.

Table 49: An overview on result evaluators in cross-docking studies

Evaluation Method	Publication
ANOVA	[15; 139; 138; 154; 163; 10; 122]
Response Surface Methodology	[10]
Taguchi Method	[198; 225; 13; 15; 139; 226; 154; 156; 19; 122]

5.4Assumption

5.4.1General assumptions

In analyzing this problem, we make several assumptions as follows.

1. Unlimited products are available from a single supplier and that demands for those products are known but varying - reflecting a common situation in practice and one that has been assumed by previous work in this area [77].
2. There is no space and labor limitation at the customer and supplier site, and an unlimited number of shipment trucks handle unloading activities.
3. Due to geographic dispersion, each shipment can only serve a single customer site (i.e., no milk run deliveries are possible).
4. All suppliers produce and ship only one product type (or products of similar size and weight) with packaging size of products set same, and thus, the time for loading and unloading a single product unit is constant.
5. The product transshipment cost between each pair of inbound-outbound doors is assumed to be \$1.00 per product-unit.
6. An I-shaped cross-docking terminal is assumed with an equal number of docks at each side in which one receiving door faces to one shipping door [65; 135; 27].
7. Other cross-docking operations such as sorting, labeling, packing, and unpacking are not taken into consideration in the model.
8. The entire fleet are available at time zero.
9. We don’t assume temporary storage cost within terminal because long-term storage is not allowed.
10. Only one unit of a product can be loaded into the shipping truck at a time.

11. The sequence of unloading products from the truck or loading products to the truck is not considered.
12. The moving time for products from the receiving dock to the shipping dock is the same for all products.
13. Backlogging is not allowed.
14. We assume that the distance between each pair of doors on each side of the terminal equals to 5 distance-units. Therefore, the distances between i^{th} ID and j^{th} OD are computed based on rectilinear travel distances using Manhattan distance formula shown in Eq. 44.

$$distance_{i \to j} = cross\ dock\ width + 5 \times |i - j| \qquad \text{Eq. 44}$$

15. The number of suppliers ≤ the number of customers ≤ the number of IDs=ODs. However, in all instances used for this study, we assume all equal each other.

5.4.2Specific assumptions

1. A dynamic fixed cost and a variable cost are assumed for each truck which are varied relative to the truck's capacity [31; 102; 77]. To determine the fixed cost and variable cost of each truck, a basic initial fixed cost and variable cost for the truck with largest capacity are assumed. Here C_t, F_t and, V_t represent truck's capacity, truck's fixed cost and truck's variable cost respectively. Also, F_{max}, V_{max} and C_{max} denote the fixed cost, variable cost, and truck capacity of the largest truck with maximum capacity. Therefore, F_t and V_t are functions of C_t, F_{max}, V_{max}, and C_{max} respectively using Eq. 45 and Eq. 46.

$$F_t = F_{max}\left[\frac{C_t}{C_{max}}\right] \qquad \text{Eq. 45} \qquad\qquad V_t = V_{max}\left[\frac{C_t}{C_{max}}\right] \qquad \text{Eq. 46}$$

2. Short-distance and long-distance product transportation are concerns of this study. To maximize the efficiency of the product transportation, an imaginary zone is considered, and any type of product transportation within the zone is considered as short-distance product transportation; otherwise, long-distance product transportation. The cross-docking

terminal is located within the zone. Regarding the product transportation on each route shown in Figure 17, two policies are assumed, and at the same time, either of them is applied. The first is to use entire fleet with all capacities for short-distance product transportation, and the second is to just use a partial number of trucks with larger capacities for long-distance product transportation. As they are listed in Table 50, if two nodes are inside the zone, the transportation between them is implemented using entire fleet; otherwise, top X% of trucks with larger capacities are employed to carry the long-distance product transportation. For instance, if the maximum truck capacity in a fleet is 90 product-unit and we select "top 35%" of the trucks for long-distance transportation, those trucks with capacities greater than or equal 58.50 product-unit (90×0.65=58.50) are selected. In Figure 17, m, n, and CD represent supplier, customer, and cross-docking terminal respectively. In all instances, we assume that the supplier-customer original distances are random integer numbers between 500 to 5000 miles.

Table 50: Truck assignment scenarios to different zone conditions

Condition	Supplier Location	Customer Location	Fleet selection for each route		
			S→CD	CD→Cu	S→Cu
1	Inside Zone	Inside Zone	Entire fleet	Entire fleet	Entire fleet
2	Inside Zone	Outside Zone	Entire fleet	Partial Fleet	Partial Fleet
3	Outside Zone	Inside Zone	Partial Fleet	Entire fleet	Partial Fleet
4	Outside Zone	Outside Zone	Partial Fleet	Partial Fleet	Partial Fleet

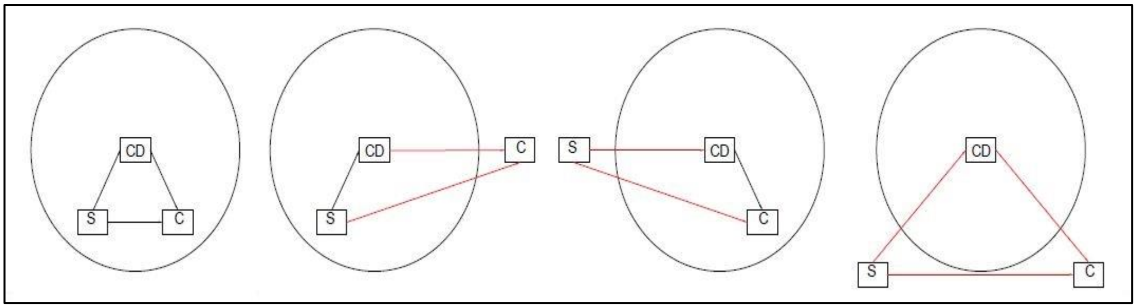


Figure 17: Suppliers-customers location with respect to CD's zone

3. As illustrated in Figure 18, non-equal variable costs are spread and assigned on inbound (outbound) doors from the center of the terminal in descending (ascending) order toward the end on both sides of the inbound (outbound) yards. This helps to assign those trucks with the higher load to doors with lower variable costs. The second factor influencing doors' fixed costs is the cross-docking shift capacity, i.e., the increase in one leads to the decrease in the other one and vice versa. The third factor is the amount of the flow assigned to each door. In that respect, the more flow we assign to each door, the more fixed cost we expect to be incurred to the operations costs. The formulas shown in Eq. 47, indicate that the doors' fixed costs are a non-linear function of the flow assigned to each door (f_m or f_n), the cross-dock shift capacity, and the door's variable cost (C_i or C_j).

$$V_{im} = f(f_m, shift^{-1}, C_i) = \frac{f_m C_i}{shift}$$
$$V_{jn} = f(f_n, shift^{-1}, C_j) = \frac{f_n C_j}{shift} \qquad \text{Eq. 47}$$

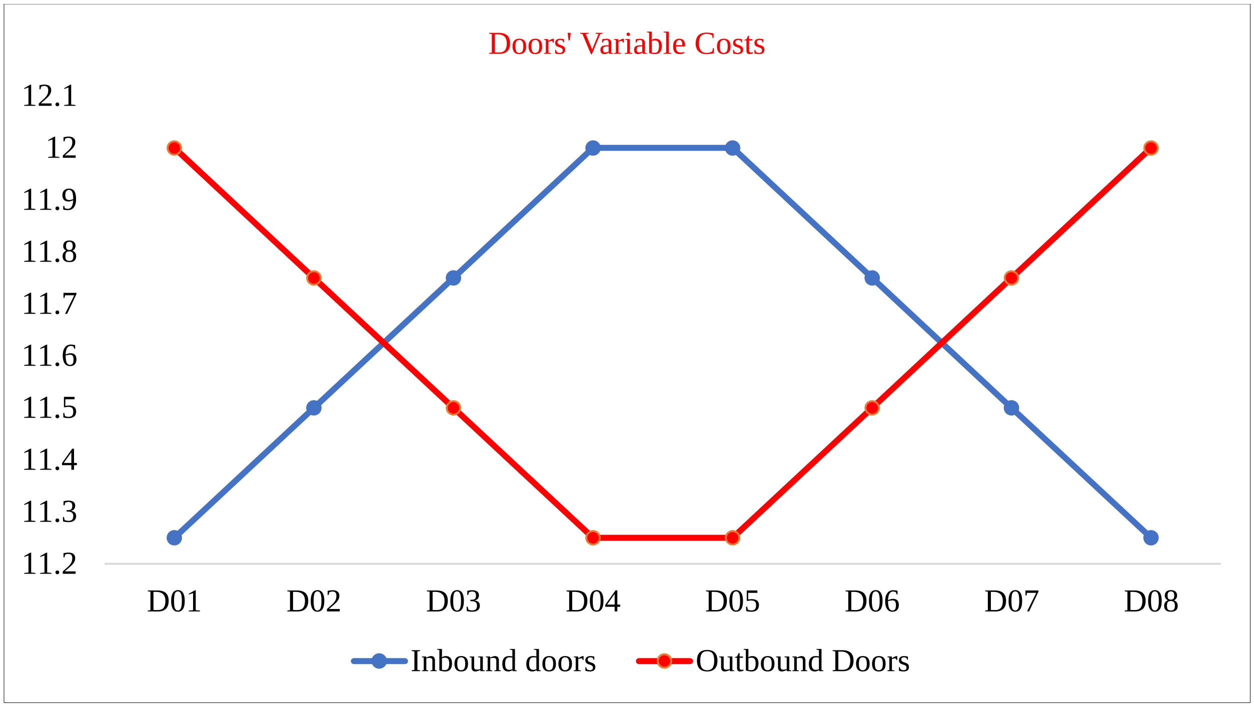


Figure 18: Doors' variable costs on both sides of a CD with 10 doors on each side

5.5Problem Description to Minimize Total Transportation Cost

To show the significance of cross-docking in a supply chain, two scenarios are addressed as follows. The first is a binary-linear programming model that assumes cross-docking within the zone, and second is a binary-linear programming model that excludes cross-docking from the supply chain.

5.5.1Scenario 1: Total transportation costs when Cross-Docking is Included

Three significant functional players including suppliers, customers, and a single cross-dock (CD) are assumed. By minimizing total transportation costs on each route shown in Figure 17; i.e., supplier→customer, supplier→CD, and CD→customer, the total supply chain transportation costs is minimized when the transportation costs on each route is minimized.

Regarding supplier→customer routes' product transportation, FT product transportation is done in multiple runs until there will be no further possibility for FT direct shipment. The process is continuously implemented until the remaining flow for each customer at the suppliers' site become less than the minimum truck capacity on the respected fleet shown in Table 50.

The second stage is the supplier→cross-docking product transportation which is done by the transportation of the remaining LTL products at suppliers' sites. However, before transportation is started, all LTL customers' demands at each suppliers' site are consolidated at suppliers' sites to create a larger batch of products. This process helps increase the number of FT product transportation from each supplier' site to the cross-docking terminal and in the meantime minimize the number of LTL transportation on the same routes. Again, truck selection is a function of the supplier' location. Depending on the location of supplier that can be either inside or outside of the CD's zone, appropriate trucks that maximize the number of FT product transportation and minimize the number of LTL transportation are selected. After the supplier→cross-docking FT product transportation is implemented, appropriate trucks that minimize total LTL supplier→cross-docking product transportation costs are selected.

Once supplier→cross-docking product transportation is done and the consolidation of the products at the CD terminal is finished, then the cross-docking→customer routes are activated. Like the process of supplier→cross-docking product transportation, here, initially product transportation is implemented using FT product transportation, and for the remaining LTL products, the best trucks are selected. Still, the location of customer, i.e., either inside or outside of zone, indicates type of fleet to handle cross-docking→customer's product transportation.

On the basis of the addressed procedures above, the first sub-objective function shown in Eq. 41; i.e., total transportation costs (TTC), is partitioned into five sub-sections including 1) supplier→customer' FT product transportation cost ($TC_{FT}^{S\to C}$) 2) supplier→CD's FT product transportation cost ($TC_{FT}^{S\to CD}$) 3) supplier→CD's LTL transportation costs ($TC_{LTT}^{S\to CD}$) 4) CD→customer' FT product transportation cost ($TC_{FT}^{CD\to C}$), and finally, 5) CD→customer' LTL transportation costs ($TC_{LTT}^{CD\to C}$). The minimization of the cost on each section will ultimately help minimize the total supply chain transportation cost.

$$\textit{Total transportation costs} = TTC = TC_{FT}^{S\to C} + TC_{FT}^{S\to CD} + TC_{LTT}^{S\to CD} + TC_{FT}^{CD\to C} + TC_{LTT}^{CD\to C}$$

It is noteworthy to mention that an additional penalty is taken into consideration for the LTL transportations. In doing so, in the objective functions of the models that handle LTL product transportation, in addition of variable cost, a multiplier ($\alpha_t = \left[\frac{C_t}{load}\right]$) is assumed which acts as a penalty that magnifies the impact of amount of the number of products that are carried by a truck. In fact, the more products each truck carries, the lower the variables costs are expected for it. Here, the variable costs in the LTL's mathematical programming models are function of truck's variable cost×distance between two nodes×amount of product each truck carries. This leads algorithm to manage the best truck to carry the LTL products from suppliers to cross-docking terminal and from cross-docking terminal to the customers' sites. In fact, in the LTL transportation, $1 \le \left[\frac{C_t}{load}\right]$ is a penalty that magnifies the impact of variable cost, given $1 \le load \le C_t$. The assumption of this penalty helps us make intuitive sense given that economies of scale are leveraged when a truck with a high fixed cost and variable cost is loaded nearly full [99; 77]. On the other hand, the shorter distance each truck travel, the lower the variable cost is expected.

In this section, we present a binary-linear programming formulation of multiple suppliers and multiple customers to find the best truck assignment for each route shown in Figure 17. Also; the formulation employs different fixed and variable cost function for each truck.

Notation

m: Index of Suppliers
n: Index of Customers
f: Index of Flow
t: Index of Truck
d: Index of Distance between supplier and customers
r: Index of Run for each algorithm
$\lfloor a \rfloor$: Round down to the nearest integer number
f_{mn}^{0} = the initial flow between m^{th} supplier to n^{th} customer n before transportation
FT: FT Transportation
LTL: LTL Transportation

The notions relate to the fleet are listed as follows, and Table 51 conceptually represent the fleet employed for long-distance versus short-distance product transportation

e: Entire truck (ET) fleet's index for short-distance transportation	*p:* Partial truck (PT) fleet's index for long-distance transportation
ET_C^e: et^{th} truck capacity	PT_C^p: pt^{th} truck capacity
ET_F^e: et^{th} truck fixed cost (Eq. 45 on page 168)	PT_F^p: pt^{th} truck fixed cost
ET_V^e: et^{th} truck variable cost (Eq. 46 on page 168)	PT_V^p: pt^{th} truck variable cost

Table 51: Fleet characteristics for short and long-distance transportation (The notations)

Fleet for short-distance transportation (E: Entire)				Fleet for long-distance trans. (P = Partial)			
T. index	Capacity	Fixed Costs	Variable Costs	T. index	Capacity	Fixed Costs	Variable Costs
ET^1	ET_C^1	ET_F^1	ET_V^1	PT^1	1	Big number	Big number
ET^2	ET_C^2	ET_F^2	ET_V^2	PT^2	1	Big number	Big number
ET^3	ET_C^3	ET_F^3	ET_V^3	PT^3	1	Big number	Big number
ET^4	ET_C^4	ET_F^4	ET_V^4	PT^4	PT_C^4	PT_F^4	PT_V^4
ET^5	$ET_C^5 = C_{max}$	$ET_F^5 = F_{max}$	$ET_V^5 = V_{max}$	PT^5	PT_C^5	PT_F^5	PT_V^5

Binary Variables

$ET_{a \to b}^{t}$: To assign et^{th} truck for a → b's short-distance product transportation when *a* and *b* are inside the zone.

$PT_{a \to b}^{t}$: To assign pt^{th} truck for a → b's long-distance product transportation when either *a* and *b* are outside the zone.

Using these variables and notations, we express the objective functions as the sum of FT and LTL shipping costs. In the following, section 1 addresses the supplier→customer's FT product transportation, section 2 and section 3 account for the supplier→cross-docking and cross-docking→customer indirect routes' product transportation using FT and LTL transportation mode.

Section 1: Suppliers-customers FTL Transportation (optimization model 1)

$$U_r^{FT:\,m\to n} = min\left(\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{t=1}^{T} ET_{m\to n}^{t}\left\lfloor\frac{f_{m\to n}^{r-1}}{ET_C^t}\right\rfloor\left(ET_F^t + ET_V^t\ \times d_{m\to n}\right) + \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{t=1}^{T} PT_{m\to n}^{t}\left\lfloor\frac{f_{m\to n}^{r-1}}{PT_C^t}\right\rfloor\left(PT_F^t + PT_V^t \times d_{m\to n}\right)\right) \qquad \text{Eq. 48}$$

$$\text{Subject to: } \sum_{t=1}^{T}\left(ET_{m\to n}^{t} + PT_{m\to n}^{t}\right) = \sum_{t=1}^{T} ET_{m\to n}^{t} + \sum_{t=1}^{T} PT_{m\to n}^{t} = 1: \forall m, \forall n \qquad \text{Eq. 49}$$

In section 1, the objective function (Eq. 48) is to minimize total supplier-customer FT product transportation (FT) transportation cost at rth run by minimizing total transportation's fixed costs and variable costs. It consists of two independent parts and depending on the location of the suppliers and customers - either inside or outside of the CD's zone - either gets value and the other one equals zero. Eq. 49 is a linear-binary equation that ensures to select just one truck out of the two fleets shown in Table 50.

$$f_{m\to n}^{r} = f_{m\to n}^{r-1} - \left(\sum_{t=1}^{T} ET_{m\to n}^{t}\left\lfloor\frac{f_{m\to n}^{r-1}}{ET_C^t}\right\rfloor ET_C^t + \sum_{t=1}^{T} PT_{m\to n}^{t}\left\lfloor\frac{f_{m\to n}^{r-1}}{PT_C^t}\right\rfloor PT_C^t\right): \forall m, \forall n, \forall r \qquad \text{Eq. 50}$$

Eq. 50 is not a part of the optimization model and is an equation that updates supplier-customer flow matrix after rth run. After each update, the optimization model is run until all supplier-customer flow become less than the minimum truck capacity at both fleet's groups shown in Table 50.

Once further FT supplier-customer transportation becomes impossible, the remaining flow at each supplier site are consolidated using Eq. 51 and next stage which is the product transportation from suppliers' sites to the CD is began. Likewise, Eq. 52 takes care of transportation of consolidated items inside CD to the customers' sites. Eq. 53 is the summation of all supplier-customer FT product transportation cost after p runs.

$$f^{0}_{m\rightarrow CD} = \sum_{n=1}^{N} f^{p}_{m\rightarrow n} : \forall m \qquad \text{Eq. 51}$$

$$f^{0}_{CD\rightarrow n} = \sum_{m=1}^{M} f^{p}_{m\rightarrow n} : \forall n \qquad \text{Eq. 52}$$

$$TC^{S\rightarrow C}_{FT} = \sum_{p=1}^{P} U^{FT-mn}_{p} \qquad \text{Eq. 53}$$

Section 2-1: FT product transportation from Suppliers to CD (Model Optimization 2-1)

$$\begin{aligned} U^{FT:\,m\rightarrow CD}_{p} = min\Bigg(& \sum_{m=1}^{M}\sum_{t=1}^{T} ET^{t}_{m\rightarrow CD} \left\lfloor \frac{f^{r-1}_{m\rightarrow CD}}{ET^{t}_{C}} \right\rfloor \left(ET^{t}_{F} + ET^{t}_{V} \times d_{m\rightarrow CD}\right) \\ & + \sum_{m=1}^{M}\sum_{t=1}^{T} PT^{t}_{m\rightarrow CD} \left\lfloor \frac{f^{r-1}_{m\rightarrow CD}}{PT^{t}_{C}} \right\rfloor \left(PT^{t}_{F} + PT^{t}_{V} \times d_{m\rightarrow CD}\right)\Bigg) \end{aligned} \qquad \text{Eq. 54}$$

Subject to: $\sum_{t=1}^{T} \left(ET^{t}_{m\rightarrow CD} + PT^{t}_{m\rightarrow CD}\right) = 1 : \forall m$ Eq. 55

Subsection 2-1 accounts for the optimization of FT product transportation from suppliers' sites to the CD terminal. Objective function (Eq. 54) ensures to minimize supplier→CD FT product transportation cost at rth run. Depending on the location of mth supplier which can be either inside or outside of the CD's zone, constraint (Eq. 55) ensures to select appropriate trucks unless the amount of remaining flows at suppliers' sites become less than the smallest truck capacity at rth run.

$$f_{m\rightarrow CD}^{r} = f_{m\rightarrow CD}^{r-1} - \left(\sum_{t=1}^{T} ET_{m\rightarrow CD}^{t} \left\lfloor \frac{f_{m\rightarrow CD}^{r-1}}{ET_{C}^{t}} \right\rfloor ET_{C}^{t} + \sum_{t=1}^{T} PT_{m\rightarrow CD}^{t} \left\lfloor \frac{f_{m\rightarrow CD}^{r-1}}{PT_{C}^{t}} \right\rfloor PT_{C}^{t}\right): \forall m, \forall r \qquad \text{Eq. 56}$$

Like Eq. 50, Eq. 56 is not part of the optimization model. However, this is an equation that updates supplier→CD flow matrix after rth run. After each update, the optimization model 2-1 is run until all the supplier→CD flow become less than the minimum truck capacity in their fleet group.

$$TC_{FT}^{S\rightarrow CD} = \sum_{r=1}^{r} U_{r}^{FT:\, m\rightarrow CD} \qquad \text{Eq. 57}$$

Eq. 13 is the summation of all supplier→CD FT product transportation costs after rth run.

Section 2-2: Suppliers-CD LTL Transportation (model optimization 2-1)

$$\begin{aligned} TC_{LTL}^{S\rightarrow CD} = min\Bigg(&\sum_{m=1}^{M}\sum_{t=1}^{T} ET_{m\rightarrow CD}^{t}.\left[ET_{F}^{t} + \left(\frac{ET_{C}^{t}}{f_{m}^{r}}\right).ET_{V}^{t} \times\ d_{m\rightarrow CD}\right] \\ &+ \sum_{m=1}^{M}\sum_{t=1}^{T} PT_{m\rightarrow CD}^{t}.\left[PT_{F}^{t} + \left(\frac{PT_{C}^{t}}{f_{m}^{r}}\right).PT_{V}^{t} \times\ d_{m\rightarrow CD}\right]\Bigg) \end{aligned} \qquad \text{Eq. 58}$$

$$\text{Subject to: } \sum_{t=1}^{T}\left(ET_{m\rightarrow CD}^{t} + PT_{m\rightarrow CD}^{t}\right) = 1: \forall m \qquad \text{Eq. 59}$$

Section 2-2 ensures the best truck assignment to each supplier→CD route that minimizes total LTL product transportation shown in objective function (Eq. 58). Constraint Eq. 59 assigns the best truck to each supplier→CD route to transfer the LTL remaining products at each supplier's site. The total transportation costs at this stage is computed in just 1 run as all flows at all suppliers' sites are less than the minimum trucks' capacity. According to Eq. 58, in addition of the normal variables' costs (PT_V and ET_V) that were assumed in the FT product transportation, a multiplier of $\left(\frac{truck\ capacity}{less-than-truckload}\right)$ is assumed in LTL transportation which is multiplied by the variable costs to increase the magnitude of variable costs. This way we force algorithm to select the best truck that minimizes the total LTL product transportation.

Section 3-1: CD→customers FTL transportation (model optimization 3-1)

$$U_p^{FT:\,CD\rightarrow n} = min\left(\sum_{n=1}^{N}\sum_{t=1}^{T} ET_{CD\rightarrow n}^{t}\left\lfloor\frac{f_{CD\rightarrow n}^{r-1}}{ET_C^t}\right\rfloor\left(ET_F^t + ET_V^t \times\, d_{CD\rightarrow n}\right) + \sum_{n=1}^{N}\sum_{t=1}^{T} PT_{CD\rightarrow n}^{t}\left\lfloor\frac{f_{CD\rightarrow n}^{r-1}}{PT_C^t}\right\rfloor\left(PT_F^t + PT_V^t \times\, d_{CD\rightarrow n}\right)\right) \qquad \text{Eq. 60}$$

$$\text{Subject to: } \sum_{t=1}^{T}\left(ET_{CD\rightarrow n}^{t} + PT_{CD\rightarrow n}^{t}\right) = 1: \forall n \qquad \text{Eq. 61}$$

The same procedure explained in 1st, and 2nd section is applied for the transportation of consolidated products at cross-docking to the customers' sites. Objective function (Eq. 60) minimizes the total FT product transportation from CD→customers' sites at rth run. Constraint Eq. 61 takes care of the best truck assignment that helps minimize the objective function at rth run. Again, the location of each customer indicates the type of fleet that is chosen for the transportation.

$$f_{CD\rightarrow n}^{r} = f_{CD\rightarrow n}^{r-1} - \left(\sum_{t=1}^{T} ET_{CD\rightarrow n}^{t}\left\lfloor\frac{f_{CD\rightarrow n}^{r-1}}{ET_C^t}\right\rfloor ET_C^t + \sum_{t=1}^{T} PT_{CD\rightarrow n}^{t}\left\lfloor\frac{f_{CD\rightarrow n}^{r-1}}{PT_C^t}\right\rfloor PT_C^t\right): \forall n, \forall r \qquad \text{Eq. 62}$$

After each run, the CD-customer flow matrix is updated using Eq. 62.

$$TC_{FT}^{CD\rightarrow n} = \sum_{\mathrm{r}=1}^{\mathrm{r}} U_r^{FT-CD\rightarrow n} \qquad \text{Eq. 63}$$

Eq. 63 is the summation of all r runs FT product transportation costs from CD terminal to customers' sites.

Section 3-2: CD-customers LTL transportation (model optimization 3-2)

$$TC_{LTL}^{CD\to C} = min\left(\sum_{n=1}^{N}\sum_{t=1}^{T} ET_{CD\to n}^{t}.\left[ET_{F}^{t} + \left(\frac{ET_{C}^{t}}{f_{n}^{r}}\right).ET_{V}^{t} \times d_{CD\to n}\right] + \sum_{n=1}^{N}\sum_{t=1}^{T} PT_{CD\to n}^{t}.\left[PT_{F}^{t} + \left(\frac{PT_{C}^{t}}{f_{n}^{r}}\right).PT_{V}^{t} \times d_{CD\to n}\right]\right) \qquad \text{Eq. 64}$$

$$Subject\ to: \sum_{t=1}^{T}\left(ET_{CD\to n}^{t} + PT_{CD\to n}^{t}\right) = 1: \forall n \qquad \text{Eq. 65}$$

Section 3-2 ensures the optimization of the best truck selection to transfer LTL products from the CD terminal to the customers' sites. Objective function (Eq. 64) minimizes the LTL transportation and constraint (Eq. 65) helps achieve this goal (The same procedure explained in section 2-2 is applied for this section).

$$\mathrm{TTC}_{\mathrm{CD\ Included}} = \mathrm{TC}_{\mathrm{FT}}^{\mathrm{S}\to\mathrm{C}} + \mathrm{TC}_{\mathrm{FT}}^{\mathrm{S}\to\mathrm{CD}} + \mathrm{TC}_{\mathrm{LTL}}^{\mathrm{S}\to\mathrm{CD}} + \mathrm{TC}_{\mathrm{FT}}^{\mathrm{CD}\to\mathrm{C}} + \mathrm{TC}_{\mathrm{LTL}}^{\mathrm{CD}\to\mathrm{C}} \qquad \text{Eq. 66}$$

Eq. 66 turns out the total transportation costs ($\mathrm{TTC}_{\mathrm{CD\ Included}}$) for both direct supplier→customer product transportation as well as the indirect type via the CD terminal.

5.5.2Scenario 2: Total transportation costs when Cross-Docking is Excluded

While all assumptions concerning the short-distances and long-distances product transportation are held, the second scenario exclude cross-docking from the supply chain and supports direct product transportation from suppliers to customers using FT and LTL product transportation modes. Therefore, in case both supplier and customer are inside the zone, we will use entire fleet; otherwise, we will use top X% of the trucks with larger capacities.

Concerning the mathematical programming formulation, the FT product transportation algorithm follows the procedure explained in the previous section on FT product transportation. Next, the LTL direct product transportation are done like the FT using the bests trucks that minimizes the LTL product transportation costs. Eq. 67 shows the total product transportation when cross-docking is excluded from the supply chain.

$$\mathrm{TTC}_{\mathrm{CD\ Excluded}} = \mathrm{TC}_{\mathrm{FT}}^{\mathrm{S}\rightarrow\mathrm{C}} + \mathrm{TC}_{\mathrm{LTL}}^{\mathrm{S}\rightarrow\mathrm{C}} \qquad \text{Eq. 67}$$

5.6Problem Description to Minimize the Cross-Docking Operating Costs

This study is an attempt to modify the quadratic assignment problem proposed by Tsui and Chang (1990A) [221] to solve truck assignment problems in a single cross-docking terminal. The proposed model by Tsui and Chang (1990A) [221] optimized the truck assignment through minimizing the total traveled-distance operations cost within the terminal. In addition to their assumption, the dynamic fixed costs are assumed for each door at both sides of the terminal. Dynamic fixed costs intuitively encourage suppliers with high flows to be assigned to doors far away from the center of the terminal. Conversely, the model tries to assign customers with high demand in the center. Assigning suppliers with low demand for unloading and customers with high flow for freight loading helps to minimize the level of floor congestion in the center of the terminal. 2nd and 3rd parts of the objective function shown in Eq. 34 attempt to minimize the total fixed cost of assigning the supplier-inbound door and outbound door-customer.

Notation

m: The number of suppliers
n: The number of customers
i: The number of inbound doors
j: The number of outbound doors
f_{mn}: LTL flow between m^{th} supplier and n^{th} customer
f_m: The amount of flow transferring from m^{th} supplier to cross-docking (CD)
f_n: The amount of flow transferring to n^{th} customer from CD
d_{ij}: The distance between inbound and outbound doors
C_i: i^{th} inbound door's fixed cost in US Dollar (USD)
C_j: j^{th} outbound door's fixed cost in USD
shift: CD's doors shift capacity
V_{mi}: The fixed cost of assigning m^{th} supplier to i^{th} inbound-door which equals to $\frac{f_m C_i}{\text{shift}}$

V_{jn}: The fixed cost of assigning j^{th} outbound-door to n^{th} customer which equals to $\frac{f_n C_j}{\text{shift}}$

Decision Variables:

$X_{mi} = 1$ if m^{th} supplier is assigned to i^{th} inbound door, else $X_{mi} = 0$
$Y_{jn} = 1$ if n^{th} customer is assigned to j^{th} outbound door, else $Y_{mi} = 0$
X_{mi} and Y_{jn} are permutation matrices and are characterized by the following constraints.

The mathematical model of the problem is formulated as follows:

$$min\,Z = \sum_{m=1}^{m}\sum_{i=1}^{i}\sum_{j=1}^{j}\sum_{n=1}^{n} X_{mi} f_{mn} d_{ij} Y_{jn} + \sum_{m=1}^{m}\sum_{i=1}^{i} X_{mi} V_{mi} + \sum_{j=1}^{j}\sum_{n=1}^{n} Y_{jn} V_{jn}$$

Eq. 68

Constraints		Description
$\sum_{i=1}^{I} X_{mi} \leq 1, m = 1,2,3, \cdots, m$	Eq. 69	To ensure that each inbound truck (supplier/origin) is assigned to at most one inbound door
$\sum_{m=1}^{M} X_{mi} = 1, i = 1,2,3, \cdots, i$	Eq. 70	To ensure that each inbound door is assigned to one inbound truck (supplier/origin).
$\sum_{n=1}^{N} Y_{=jn} = 1, j = 1,2,3, \cdots, j$	Eq. 71	To ensure that each outbound door is assigned to one outbound truck (customer/destination)
$\sum_{j=1}^{J} Y_{jn} \leq 1, n = 1,2,3, \cdots, n$	Eq. 72	To ensure that each outbound truck (customer/destination) is assigned to at most one outbound door

This research focuses on attempting to optimize the simultaneously assigning supplier-ID and OD-customer (ID = inbound door, OD = outbound door) to minimize the total operation costs within cross-docking terminal as shown in Eq. 68. The first part of the objective function attempts to minimize the total workload cost which is the sum of the flows × rectilinear distances over the planning horizon, and the second and third part of the objective function account for the total fixed cost of truck-door assignment.

5.7Problem solving process

To minimize total transportation costs (TTC), a simulation software is developed in the Visual Studio C#, and all results are stored in the SQL Server 2014 database. However, for the second objective function that relates to the cross-docking operating costs, the following approaches are developed.

After, developing a binary-quadratic programing model to minimize total cross-docking costs (TCDC), three methods are employed to solve the proposed model. The first method is a complete enumeration method that is employed to find an optimum solution testing all possible sequences using ILOG CPLEX solver version 12.6.0.0. As the problem size grows from medium to large, solvers like ILOG CPLEX, Gurobi, Minto, and CBC, can hardly manage to converge the optimum solution due to the computational time required to solve the problem. For the current study, CPLEX solver is developed for just small size problems. However, for the medium to large size problems- the second method- a hill-climbing algorithm is developed as a heuristic. Tabu-search –the third method– is employed to a meta-heuristic algorithm. The second and third methods are developed to solve problems of practical sizes, i.e., larger than the small size problems.

The hill-climbing heuristic algorithm finds solutions quite fast; however, the solution found may not necessarily be optimal. The output of the second approach is used as the initial solution of the Tabu-search technique in the third approach. To check the performance of the study, the hill-climbing and meta-heuristic Tabu-search results are compared with the results of the CPLEX solver for the small-size problems and presented in Table 70, Table 71, and Table 72.

5.7.1Complete Enumeration Method

The number of decision variables for the binary-quadratic assignment problem is m×i+n×j which are all binary variables. The number of constraints is m+i+j+n including m+n inequality constraints and of i+j equality ones. For the sake of consistency, in all instances developed in this study (Table 70, Table 71, and Table 72), it is assumed that m=i=j=n and is called instances of m-dimension. For example, a 7-dimension instance consists of 7 suppliers, 7 inbound-doors, 7 outbound-doors, and 7 customers. Thus, there is a problem with 28 constraints and 98 binary decision variables.

In the present study, a receiving truck is assigned to a receiving inbound door and stays in there until it finishes its unloading operation. Therefore, each receiving truck must appear once in the receiving truck sequence. To assign m suppliers (receiving trucks) to i inbound doors ($m \leq i$), there are $\frac{i!}{(i-m)!}$ possibilities. Likewise, each shipping truck appear only once in the shipping truck sequence because a shipping truck stays in the shipping dock until all its needed products are loaded. Therefore, to assign n customers (shipping trucks) to j outbound doors ($n \leq j$), there are $\frac{j!}{(j-n)!}$ possibilities. The total number of possible sequences to minimize total operation cost within cross-docking terminal shown in Eq. 68 equals $\frac{i!}{(i-m)!} \cdot \frac{j!}{(j-n)!}$. For example, in a problem with m=i=j=n=7, the total number of possible sequences is 7! × 7! = 25,401,600. By increasing the size of the problem to m=i=j=n=10, the total number of possible sequences will be 10! × 10! = 1.3 × 10^{13}. In this case, it is not practical to solve this problem by enumerating all possible sequences. Therefore, it is required to employ a method which finds the solutions within a reasonable amount of time.

For problems like $m \leq n \leq i=j < 10$ that are small or tractable enough to allow "finitely convergent" algorithms to obtain and verify optimal solutions, CPLEX reaches to optimal solutions with no ILOG CPLEX's setting manipulation and "out of memory" error message. The second subset comprises of those problems with $10 \leq m \leq n \leq i=j$ that CPLEX terminates after a few runs and returns "MIP starts not constructed because of out-of-memory status" error message. With regard to the larger size problems, complete enumeration approaches are inefficient to get optimal solutions, and solvers like ILOG CPLEX give up finding the optimum solution due to lack of memory on a personal laptop like the one with a processor "Intel(R) Core (TM) i7-6500U CPU @ 2.50 GHz 2.60 GHz" and a memory of 12.00 GB installed.

5.7.2 Hill-climbing heuristic method

The proposed mathematical programming shown in Eq. 34 is a highly complex bilinear model. If either the receiving door to supplier (X_{mi}) or the shipping door to customers (Y_{jn}) are known, the remaining problem becomes a standard assignment problem and can be solved inexpensively within a desirable time. However, in the current study both X_{mi} and Y_{jn} are not given, and thus, the above formulation is a bilinear problem, and like all QAP problems, this bilinear problem is a highly complex NP complete [227; 50]. To discover a good local optimum point, the hill-climbing algorithm developed by Tsui and Chang (1990A) [221] is practiced for the current research.

A characteristic feature of this model is that the solution points are equal with their inverse setting. In that respect, a permutation string of assignments of supplier-inbound door, i.e., X_{mi}, results in an optimal string N^1 of outbound door-customer assignment, i.e., Y_{jn} which minimizes $Z1 = f(M^1,N)$. On the other hand, the inverse of the string (X_{mi}) of supplier-inbound door results in an optimal inverse string N^2 which minimizes $Z2 = f(M^2,N)$ while $Z1 = Z2$. For example, in an instance with 8 suppliers, 8 customers, 8 inbound and 8 outbound doors, the truck-inbound door assignment X_{mi} = [6,4,1,7,0,2,5,3) results in an optimal outbound door-truck assignment of Y_{jn} = [3,6,1,0,5,2,4,7) which yields the minimum cost Z1 = 72625.42. On the other hand, the inverse of X_{mi}, i.e., X^{-1}_{mi} = [3,5,2,0,7,1,4,6) results in an optimal truck-door assignment of Y^{-1}_{jn} = [7,4,2,5,0,1,6,3) which is the inverse of Y_{jn} and yields the minimum cost Z2 = Z1=72625.42.

Therefore, in order to increase the efficiency of the space exploration, the algorithm is set to avoid searching the inverse of the stored Xs or Ys and ignore symmetry. In the meantime, since the goal is to achieve 200 distinct local optimum solutions, after each run, the database is checked to ensure whether X^* and Y^* or inverse of X^* and Y^* are available. However, the number of solutions that can be eliminated due to symmetry condition depends on the size of the I-shaped terminal. Table 52 presents the pseudocode of the proposed hill-climbing algorithm. For instance, 43 unique local optimum solutions created by hill-climbing approach (Figure 19) are achieved after removing duplicate values.

Table 52: The hill-climbing heuristic pseudocode to generate at most 200 local optimum solutions

```
Timer = 0;
Counter0 = 0;
For m = 1 to 200
    1. Counter1 = 0;
    2. Generate an initial assignment $M^1$
    3. Counter2 = 0;
    4. while (string $M^1$ or its inverse are in the database A and Counter2 $\leq$ 10)
       {
       Generate an initial assignment $M^{1;}$
       Counter2 = Counter2 + 1;

       }
    5. Save string $M^1$ and its inverse in database A;
    6. Find the optimal solution $N^1$ which minimizes $f(M^1,N)$;
    7. Find the optimal solution $M^2$ which minimizes $f(M,N^{1)}$;
    8. Let $M^1$equal $M^2$, repeat steps 4 and 5 until the procedure converges to point L*(M*,N*)
    9. If (string M* or its inverse is in the database A OR string N* or its inverse strings is in the database )
       {
       Counter1 = Counter1 + 1;
       if (Counter1 $\leq$ 10)
           {
           Go to step 2;
           }
           else
           {
               Counter0 = Counter0 + 1;
            Break this condition;
           }
       }
    10. Save string M* and its inverse in the database A
    11. Save string N* and its inverse in the database B
    12. Save L* point in database C;
    13. If (Counter0>20)
       {

           Break for loop;
       }

Next
14. Remove all duplicate points from the database C;
15. Sort all points in database C
16. Timer = save CPU time
17. Report Timer and the minimum cost's point in the database C;
```

Note: the timer is checked to evaluate the total time to generate maximum 200 solutions.

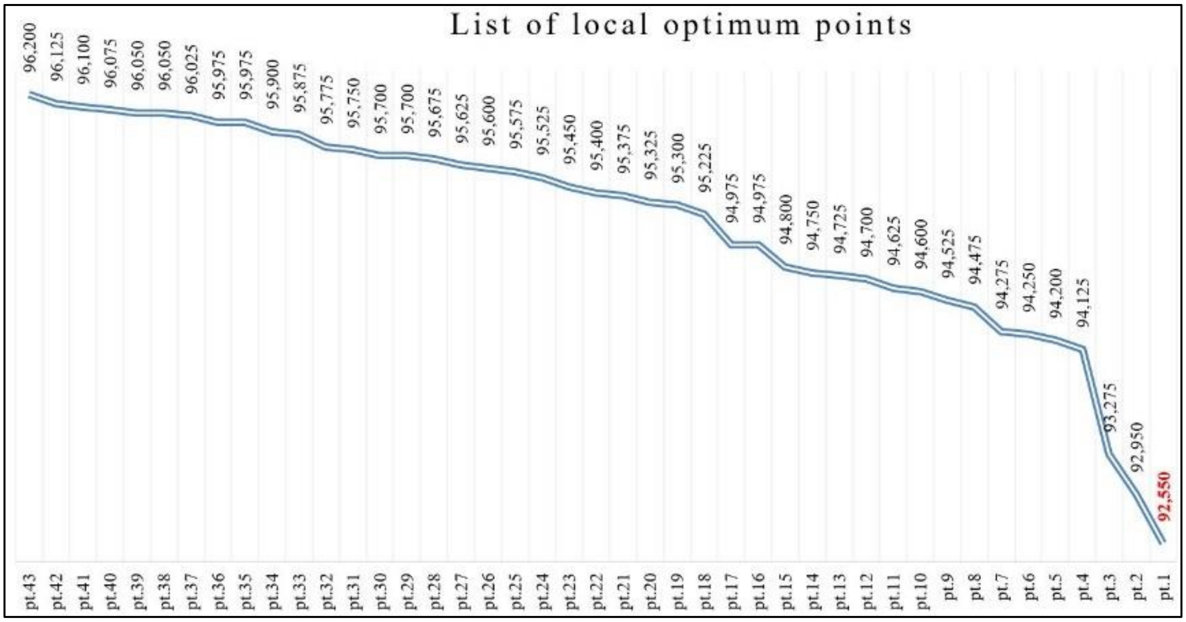


Figure 19: 43 unique local optimum solutions achieved by hill-climbing approach

5.7.3 Tabu Search Characteristics and Framework

Fred Glover introduced the idea of Tabu Search (TS) in 1986 and formalized it in 1987. TS is a metaheuristic search method and consists of neighborhood search and the use of short-term memory. TS employs local search methods used for mathematical optimization. Local search methods like hill-climbing tend to get stuck in suboptimal regions or on plateaus where many solutions are equally fit. TS guides a local heuristic search procedure to explore the solution space beyond local optimality. The local procedure is a search that uses an operation called *move* to define the neighborhood of any given solution. A main component of the tabu search is its use of adaptive memory, which creates a more flexible search behavior. Memory-based strategies are, therefore, the hallmark of tabu search approaches.

Permutation problems are an important class of combinatorial optimization problems that can be applied in: classical traveling salesman problems, quadratic assignment problems (QAP), production sequencing problems, and a variety of design problems. For problems that are small or tractable enough to allow ”finitely convergent” algorithms to obtain and verify optimal solutions, evolutionary algorithms like Tabu search and Genetic algorithm produce solutions that are optimal or within a fraction of a certain percent of optimality, while requiring much less effort (in some cases, on the order of minutes versus days of computer time). However, for larger and more difficult problems, those customarily encountered in practical settings, evolutionary algorithms obtain solutions that rival and often surpass the best solutions previously found through other approaches.

In the following, five features of a Tabu search algorithm are discussed and in the last section, the proposed TS framework is presented.

5.7.3.1 Initial solution

The initial solution is represented by a sequence of truck assignments to the doors at each side. Even though the type of QAP is a zero-one problem, a permutation technique is employed to apply truck-door assignment. Through a permutation technique, the algorithm is set to stay within the feasibility region and not trespass the infeasible solution space. In this research, we use the best local optimum point as the initial solution for the meta-heuristic algorithm.

5.7.3.2 Aspiration criteria

An aspiration criterion is a rule that allows the tabu status to be overridden in cases where the forbidden exchange exhibits desirable properties. Following Glover procedure, a tabu move passes through a series of three levels of criteria to finally become a permissible exchange if:

1. The forbidden move results in a global best solution;
2. The tabu exchange under consideration is the first forbidden move examined in the current iteration of the algorithm;

3. The cost of the forbidden exchange is better than all previous exchanges examined on the current working solution, and the move becomes permissible.

5.7.3.3 Diversification

Diversification helps create a new vector based on a procedure that operates through mapping a given collection of vectors into one or more new collections that differ from the original collection in a manner consistent with the concept of previously-employed diversity [85].

To diversify the solution space, after the algorithm reaches a local optimum solution, four diversification methods (M1, M2, M3, and M4) are employed to restart the search process from a new point. All methods are based on the permutation technique and don't permit solutions violate the feasibility condition.

M1 and M2 are the most recent diversification methods developed by Glover in 2017 [85], and the third (M3) was developed by James et. al. (2009) [113]. M1, M2, and M3 are adapted from the literature. The forth diversification method, M4, was developed for this study. In all algorithms presented in the following, n represents doors numbers, and the output of these algorithms is the assigning suppliers or customers to the inbound or outbound doors, respectively.

- Permutation Mapping Algorithm (M1)

Table 53 presents the pseudocode of permutation mapping algorithm.

Table 53: the pseudocode of permutation mapping algorithm (M1)

```
Initialize g ← (integer part of (n/2)) – 1;
K ← declare a null string array with g member
for i = 0 to g
    declare L ← null;
    for j = 0 to g
        p = (i+1)+g×j;
        if (p<=door_no)
        {
     L = L + "," + p;
        }
        K[i] = L;
    next j
next i
return reverse K
```

Ex: door_no = n = 14 and g = 6. Therefore, P_{14} (g: 1) = (1 7 13), P_{14} (g: 2) = (2 8 14), P_{14} (g: 3) = (3 9), P_{14} (g: 4) = (4 10), P_{14} (g: 5) = (5 11), and P_{14} (g: 6) = (6 12).

Assembling these sub-permutations in reverse order yields:
P_{14} (g) = [6,12,5,11,4,10,3,9,2,8,14,1,7,13]

- Recursive Permutation Mapping (M2)

M2 creates a recursive vector of the vector created by M1. Unlike Glover 2017 [85] that started by mapping procedure, an easier procedure is assumed in this study to produce the recursive vector of the vector created by M1. At first, the permutation vector is converted to a zero-one matrix, and then its transpose matrix is determined. The pseudocode of this algorithm is as follows: 1) receive permutation P, 2) convert permutation P to zero-one matrix, 3) transpose the zero-one matrix and call it Q and 4) convert the Q matrix to permutation format. For instance, the recursive form of vector [2,4,5,1,3] is [4,1,5,2,3].

- DivTS Restart Approach (M3)

The DivTS restart approach shown in Table 54 forcefully diversifies the search but in a more tactical manner than a random restart.

Table 54: the pseudocode of permutation mapping algorithm (M3)

```
Initialize step ← if door No. is less than 10 then step = 3, otherwise, step = door No/10 + 2;
K ← declare a null string array with step member
for (int start = step - 1; start >= 0; start--)
{
        string L= "";
        for (int j = start; j < door_no; j = j + step)
        {
                L=L + "," + input[j];
        }
        K[t] = L;
        t++;
}
Return K
```

For instance, the given solution is S = [8, 1, 5, 10, 9, 3, 7, 2, 12, 11, 6, 4). If step = 3, then through the first pass of the inner loop, start = 3, which results in the partial solution SS = [5, 3, 12, 4). The starting position is then readjusted to start = 2, generating in the next pass of the inner loop SS = [5, 3, 12, 4, 1, 9, 2, 6). This process is continued until start = 1, in the case which a full starting solution is generated SS = [5, 3, 12, 4, 1, 9, 2, 6, 8, 10, 7, 11).

- Recursive DivTS Restart Approach (M4)

The same procedure explained for the "Recursive Permutation Mapping (M2)" is implemented for M4 in that, initially, the permutation vector developed by M3 is determined and then converted to a zero-one matrix. Afterward, the zero-one matrix is transposed. The permutation vector of the new zero-one matrix is the output of M4 which is supposed to differ from the original collection in a manner consistent with the concept of diversity previously employed.

5.7.3.4 Termination criteria

The algorithm stops under the following conditions: 1) when total computation time exceeds 180 minutes, 2) when the search process within the loops leads to no improvement on the objective function, 3) when no feasible solution in the neighborhood of solution is found, 4) when the number of iterations since the last improvement is larger than half of the door numbers, and 5) when evidence can be given that an optimum solution has been obtained

5.7.3.5 Tabu Search Framework

In the framework presented in Table 55, a Tabu search framework is elaborated which consists of diversification step, aspiration criteria, and termination condition. Instead of having termination condition at the end of algorithm, they are set in the middle of the search process to break the search process as soon as at least one of the termination conditions is met.

Table 55: Tabu search framework

```
1.  Use the best initial solution
    $X_{current} = X_{initial}$
    $Y_{current} = Y_{initial}$
    $Cost_{current} = Cost_{initial}$
2.  Generate a set of neighborhood solutions $N(X_{current}, Y_{current})$
3.  If an improvement happens in the neighborhood cost, then
    5.4 check aspiration criterial and see if tabu status can be removed from the tabu tenure list.
    5.5 $X_{current} = X_{new}$
        $Y_{current} = Y_{new}$
        $Cost_{current} = Cost_{new}$
    5.6 Update tabu tenure
    5.7 Check the termination condition
    5.8 Go to step 2;
6.  Check the termination condition
7.  If there is no improvement in the neighborhood cost
    7.1 Apply one of the diversification methods on $(X_{current}, Y_{current})$ and generate $X_{diversification}$ and
        $Y_{diversification}$
    7.2 $X_{current} = X_{diversification}$
        $Y_{current} = Y_{diversification}$
        $Cost_{current} = Cost_{Diversification}$
    7.3 Go to step 2;
```

5.8Numerical Example to evaluate total supply chain cost

A single I-shaped cross-dock distribution model (8 doors on each side) with a small case including 6 suppliers and 8 customers is illustrated in Figure 20 to demonstrate effectiveness of the mathematical model and the efficiency of the solution algorithm proposed in this research. Initially, 3 matrices of supplier-customer flow, supplier-customer distance, and fleet groups are generated and present in Table 56, Table 57, and Table 58 respectively.

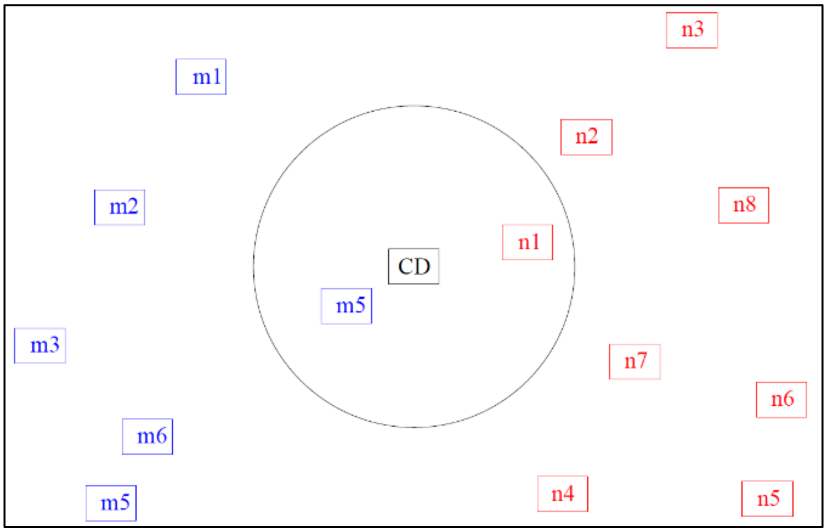


Figure 20: Graphical depiction of a single CD including 6 suppliers, and 8 customers

A set of 8 different trucks with different capacities, fixed costs, and variable costs is presented in Table 58 representing the transportation fleet for short-distance and long-distance product transportation. The basic fixed and variable costs are \$1000 and \$1 and are assigned for the 8th truck with the largest capacities. Also, truck capacities are assumed to be random numbers between 10 and 100. For instance, the second top truck's capacity equal to 75, and therefore, following Eq. 45 and Eq. 46, 7th truck's associated fixed and variable costs are $\$1000\times\frac{75}{90}=\$833$ and $\$1\times\frac{75}{90}=\$0.833$ respectively.

The right sub-table in Table 58 lists 8 truck types and their associated fixed and variable costs which are hired for long-distance transportation. In this instance, the top 20% of the trucks are assigned for the long-distance transportation while 100% of the fleet is hired for the short-distance product transportation between the nodes within CD's zone.

Table 56: Supplier-customer initial flow

---		Customers' Indices							
		N1	N2	N3	N4	N5	N6	N7	N8
Suppliers' Indices	M1	2259	4325	4706	3983	2928	4773	4837	3134
	M2	4930	6564	7844	7574	5791	9123	8767	6206
	M3	1463	3646	3586	3397	2381	4573	4406	2102
	M4	2266	4591	4549	4151	2652	5322	5471	2287
	M5	4975	7884	6911	7632	5922	9048	6806	5572
	M6	875	3305	3200	3265	2015	4480	4320	1605

Table 57: Supplier-customer original distances

---		Customers' Indices								CD
		N1	N2	N3	N4	N5	N6	N7	N8	
Suppliers' Indices	M1	3830	6319	5140	6271	3631	6554	7063	4617	3020
	M2	2259	4325	4706	3983	2928	4773	4837	3134	1580
	M3	4930	6564	7844	7574	5791	9123	8767	6206	4645
	M4	1463	3646	3586	3397	2381	4573	4406	2102	595
	M5	2266	4591	4549	4151	2652	5322	5471	2287	1395
	M6	4975	7884	6911	7632	5922	9048	6806	5572	4590
CD		875	3305	3200	3265	2015	4480	4320	1605	---

Table 58: Fleet characteristics for short and long-distance transportation

Fleet for short-distance transportation					Fleet for long-distance-transportation			
T. No.	Capacity	Fixed Costs	Var. Costs		T. No	Capacity	Fixed Costs	Var. Costs
T1	15	167	0.167		T1	15	Infinity	Infinity
T2	20	222	0.222		T2	20	Infinity	Infinity
T3	30	333	0.333		T3	30	Infinity	Infinity
T4	45	500	0.5		T4	45	Infinity	Infinity
T5	50	556	0.556		T5	50	Infinity	Infinity
T6	60	667	0.667		T6	60	Infinity	Infinity
T7	75	833	0.833		T7	75	833	0.833
T8	90	1000	1		T8	90	1000	1

5.8.1Numerical example of the 1st scenario: Cross-docking is included

5.9.1.1 Minimizing total transportation cost

Table 59 illustrates the direct FT product transportation from the suppliers → customers in 2 runs. In the first run, most products are transferred, and in the second run, just a few numbers of products are directly transferred, and the rest stay in the suppliers' sites until become consolidated at each supplier's site and then transferred to the cross-docking terminals. There are three coded acronyms including NT, R, and FT which are used in all the product transportation Table 59, Table 61, and Table 62. *NT* stands for "*No Transfer*" and it happens when no product transportation occurs between two nodes either due to zero number of products or impossibility of LTL product transportation. For instance, there is a long-distance product transportation from M1→N2, and their corresponding flows equals 25 product-unit which is lower than the smallest truck with capacity equals 75 and therefore no FT product transportation takes place; i.e., *No Transfer: 25* (see Table 58).

The second example is the product transportation from $M_1 \rightarrow N_3$ which its corresponding flow equals 955. Thus, the algorithm automatically selects 12 numbers of 7th truck with 75 product-unit capacity. By transferring 900 = 12×75 product-unit of 955 in the 1st run, in the 2nd run, the algorithm examines the possibility of direct transportation of R = 55 product-unit from $M_1 \rightarrow N_3$. In the 2nd run, the algorithm doesn't allow direct product transportation of 55 product-unit from $M_1 \rightarrow N_3$ since it is a long distance product transportation and 55 = 955-900 product-unit is less than the 7th truck capacity (75 product-unit) which is the smallest truck capacity in the corresponding fleet shown in Table 58.

The algorithm of direct transportation stops at 2nd run as all supplier-customer flows becomes less than the smaller truck capacity on their corresponding fleet shown in Table 58. Total FT product transportation cost at 1st and 2nd run is \$431,832.63 and \$11,369.44 respectively presented in Table 65.

Table 59: Supplier-customer FTL transportation (CD Included)

---		Customers' Indices							
1st Run		**N_1**	**N_2**	**N_3**	**N_4**	**N_5**	**N_6**	**N_7**	**N_8**
Suppliers' Indices	**M_1**	6×90=540→R: 605-540=65	No Transfer: 25	12×75=900→R: 955-900=55	No Transfer: 5	No Transfer: 10	1×75=75→R: 80-75=5	No Transfer: 35	75: Full Transfer with 75
	M_2	1×75=75→R: 95-75=20	No Transfer: 25	75: Full Transfer with 75	No Transfer: 5	8×90=720→R: 760-720=40	No Transfer: 70	9×90=810→R: 860-810=50	1×75=75→R: 80-75=5
	M_3	1×75=75→R: 95-75=20	7×90=630→R: 715-630=85	1×75=75→R: 95-75=20	1×75=75→R: 95-75=20	1×75=75→R: 80-75=5	No Transfer: 25	No Transfer: 5	No Transfer: 30
	M_4	1×30=30→R: 50-30=20	No Transfer: 25	No Transfer: 0	3×75=225→R: 290-225=65	No Transfer: 50	No Transfer: 35	No Transfer: 65	75: Full Transfer with 75
	M_5	No Transfer: 10	2×90=180→R: 260-180=80	No Transfer: 60	No Transfer: 60	No Transfer: 30	8×90=720→R: 770-720=50	No Transfer: 20	75: Full Transfer with 75
	M_6	No Transfer: 25	No Transfer: 10	No Transfer: 45	1×75=75→R: 95-75=20	10×75=750→R: 820-750=70	1×75=75→R: 85-75=10	No Transfer: 45	75: Full Transfer with 75
2nd Run		**N_1**	**N_2**	**N_3**	**N_4**	**N_5**	**N_6**	**N_7**	**N_8**
Suppliers' Indices	**M_1**	No Transfer: 65	No Transfer: 25	No Transfer: 55	No Transfer: 5	No Transfer: 10	No Transfer: 5	No Transfer: 35	No Transfer: 0
	M_2	No Transfer: 20	No Transfer: 25	No Transfer: 0	No Transfer: 5	No Transfer: 40	No Transfer: 70	No Transfer: 50	No Transfer: 5
	M_3	No Transfer: 20	1×75=75→R: 85-75=10	No Transfer: 20	No Transfer: 20	No Transfer: 5	No Transfer: 25	No Transfer: 5	No Transfer: 30
	M_4	1×15=15→R: 20-15=5	No Transfer: 25	No Transfer: 0	No Transfer: 65	No Transfer: 50	No Transfer: 35	No Transfer: 65	No Transfer: 0
	M_5	No Transfer: 10	1×75=75→R: 80-75=5	No Transfer: 60	No Transfer: 60	No Transfer: 30	No Transfer: 50	No Transfer: 20	No Transfer: 0
	M_6	No Transfer: 25	No Transfer: 10	No Transfer: 45	No Transfer: 20	No Transfer: 70	No Transfer: 10	No Transfer: 45	No Transfer: 0

Table 14 is matrix of supplier-customer LTL flows (all flows are less than the capacity of the smallest truck for both fleet shown Table 12) which are not worth being transferred directly from suppliers' sites to the customers' site.

Table 60: Supplier-customer LTLs' flows transferred via CD terminal

---		Customers' Indices								CD
		N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	
Suppliers' Indices	M_1	65	25	55	5	10	5	35	0	200
	M_2	20	25	0	5	40	70	50	5	215
	M_3	20	10	20	20	5	25	5	30	135
	M_4	5	25	0	65	50	35	65	0	245
	M_5	10	5	60	60	30	50	20	0	235
	M_6	25	10	45	20	70	10	45	0	225
CD		145	100	180	175	205	195	220	35	---

In order to transfer the remaining supplier→customer LTL products presented in Table 60, initially, all products at each supplier's site are consolidated (CD column in Table 60), and then transferred to the single CD. The consolidation of products at suppliers' sites helps increase the number of FT product transportation and decrease the number of LTL product transportation from suppliers' sites to the cross-docking terminal. After consolidation of products, the products initially are transferred from suppliers' sites to the cross-docking terminal using FT transportation (see the FT product transportation in Table 61). Afterward, the remaining LTL products at suppliers' sites are transferred to the terminal by appropriate trucks that minimize total LTL product transportation cost (see the LTL product transportation in Table 61).

On the other side of the terminal, the same policy is employed, and initially, the consolidated products at cross-docking terminal (CD row in Table 60) are transferred to the customers' sites using FT policy (see the FT product transportation in Table 62). The similar process of the transportation of the remaining LTL products from supplier→cross-docking terminal is applied for the LTL product transportation from the cross-docking terminal to each customer's site (see the LTL product transportation in Table 62). In the LTL sections of Table 61 and Table 62, the amount of each LTL flow is computed, and the amount of the products that a truck carries vacant is addressed as *empty*.

Table 61: Supplier→CD FTL and LTL product transportation

Supplier→CD FTL transportation		Supplier→CD LTL transportation	
1st Run	CD	Last	CD
M1	2×75=150→R: 200-150=50	M1	50 with 75 →Empty: 25
M2	2×75=150→R: 215-150=65	M2	65 with 75 →Empty: 10
M3	1×75=75→R: 135-75=60	M3	60 with 75 →Empty: 15
M4	2×90=180→R: 245-180=65	M4	No Transfer
M5	2×90=180→R: 235-180=55	M5	55 with 75 →Empty: 20
M6	2×90=180→R: 225-180=45	M6	45 with 75 →Empty: 30
NT: No/zero Transfer to next run, R: Remaining for the next run; FT: FT with Truck X that has zero remaining for the next run			

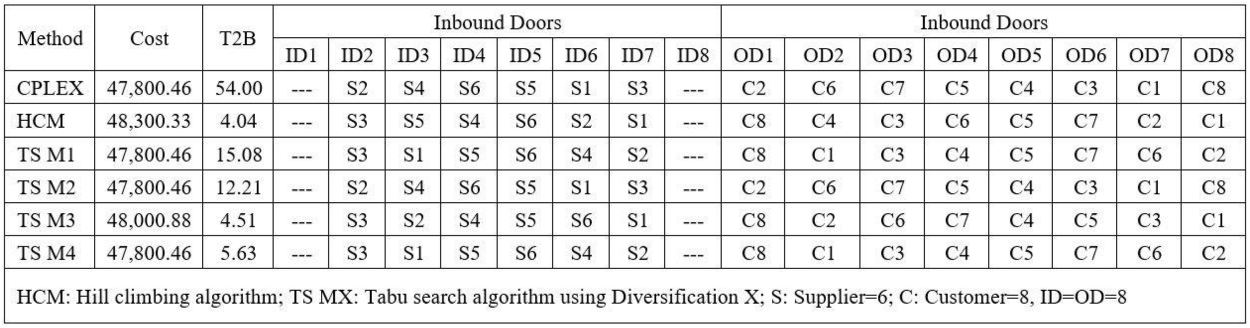
Table 62: CD→customer FTL and LTL product transportation

CD→customer FTL transportation				CD→customer LTL transportation	
1st Run	CD	2nd Run	CD	Last	CD
N1	1×75=75→R: 145-75=70	N1	1×45=45→R: 70-45=25	N1	No Transfer
N2	1×75=75→R: 100-75=25	N2	No Transfer: 25	N2	25 with 75 →Empty: 50
N3	2×75=150→R: 180-150=30	N3	No Transfer: 30	N3	30 with 75 → Empty: 45
N4	1×90=90→R: 175-90=85	N4	1×75=75→R: 85-75=10	N4	10 with 75 → Empty: 65
N5	2×75=150→R: 205-150=55	N5	No Transfer: 55	N5	55 with 75 → Empty: 20
N6	2×75=150→R: 195-150=45	N6	No Transfer: 45	N6	45 with 75 → Empty: 30
N7	2×75=150→R: 220-150=70	N7	No Transfer: 70	N7	70 with 75 → Empty: 5
N8	No Transfer: 35	N8	No Transfer: 35	N8	35 with 75 → Empty: 40
NT: No/zero Transfer to next run, R: Remaining for the next run; FT: FT with Truck X that has zero remaining for the next run					

5.9.1.2 Minimizing total cross-docking operating costs

The input flow of this section is the LTL flow matrix shown in Table 60. In this table, all flows are less that the smallest truck capacity on each fleet listed in Table 58. Assuming the cross-docking terminal's width and shift are 30 yards and 30 product-unit per hour, we try to find the permutation of the best truck-door assignment in a single cross-docking terminal.

To minimize the total cross-docking operating costs, 3 methods including computational enumeration method using ILOG CPLEX, hill-climbing method proposed by Tsui and Chen (1990) [30], and Tabu-search with four diversification methods are employed. The lowest cost associated with each of these methods is selected as the model's global cost, and the corresponding permutation would be the best truck-door assignment. The permutation results for each method is listed in Table 63. There, the global cost is $47,800.46 which is the optimum point as well. This is the sums up the total distance traveled from all receiving doors to shipping doors according to the distribution of flow shown in Table 60.



Method	Cost	T2B	Inbound Doors								Inbound Doors							
			ID1	ID2	ID3	ID4	ID5	ID6	ID7	ID8	OD1	OD2	OD3	OD4	OD5	OD6	OD7	OD8
CPLEX	47,800.46	54.00	---	S2	S4	S6	S5	S1	S3	---	C2	C6	C7	C5	C4	C3	C1	C8
HCM	48,300.33	4.04	---	S3	S5	S4	S6	S2	S1	---	C8	C4	C3	C6	C5	C7	C2	C1
TS M1	47,800.46	15.08	---	S3	S1	S5	S6	S4	S2	---	C8	C1	C3	C4	C5	C7	C6	C2
TS M2	47,800.46	12.21	---	S2	S4	S6	S5	S1	S3	---	C2	C6	C7	C5	C4	C3	C1	C8
TS M3	48,000.88	4.51	---	S3	S2	S4	S5	S6	S1	---	C8	C2	C6	C7	C4	C5	C3	C1
TS M4	47,800.46	5.63	---	S3	S1	S5	S6	S4	S2	---	C8	C1	C3	C4	C5	C7	C6	C2

HCM: Hill climbing algorithm; TS MX: Tabu search algorithm using Diversification X; S: Supplier=6; C: Customer=8, ID=OD=8

Table 63: Permutation results for the CPLEX, Hill-climbing, and Tabu search algorithm

5.8.2Numerical example of the 2nd scenario: Cross-docking is Excluded

Having all assumptions held, the supplier→customer FT product transportation is exactly similar to what we have done in previous section (when cross-docking is included in the supply chain. However, concerning the LTL product transportation (see Table 60) the best truck is selected for each route that help minimize the total LTL product transportation costs. Table 64 illustrates all direct LTL product transportation among suppliers and customers once cross-docking is excluded from the supply chain. There, *E* represents amount of empty product-unit on each truck.

Table 64: Supplier-customer LTL product transportation

Last		Customers’ Indices							
		N1	N2	N3	N4	N5	N6	N7	N8
Suppliers’ Indices	M1	65 with 75 →E: 10	25 with 75 →E: 50	55 with 75 →E: 20	5 with 75 →E: 70	10 with 75 →E: 65	5 with 75 →E: 70	35 with 75 →E: 40	No Transfer
	M2	20 with 75 →E: 55	25 with 75 →E: 50	No Transfer	5 with 75 →E: 70	40 with 75 →E: 35	70 with 75 →E: 5	50 with 75 →E: 25	5 with 75 →E: 70
	M3	20 with 75 →E: 55	10 with 75 →E: 65	20 with 75 →E: 55	20 with 75 →E: 55	5 with 75 →E: 70	25 with 75 →E: 50	5 with 75 →E: 70	30 with 75 →E: 45
	M4	No Transfer	25 with 75 →E: 50	No Transfer	65 with 75 →E: 10	50 with 75 →E: 25	35 with 75 →E: 40	65 with 75 →E: 10	No Transfer
	M5	10 with 75 →E: 65	5 with 75 →E: 70	60 with 75 →E: 15	60 with 75 →E: 15	30 with 75 →E: 45	50 with 75 →E: 25	20 with 75 →E: 55	No Transfer
	M6	25 with 75 →E: 50	10 with 75 →E: 65	45 with 75 →E: 30	20 with 75 →E: 55	70 with 75 →E: 5	10 with 75 →E: 65	45 with 75 →E: 30	No Transfer

5.8.3Model Efficiency

Table 65 and Table 66 list the total supply chain transportation costs calculated for each scenario.

Each table dichotomized the costs analysis into FT versus LTL analysis to deliver better insights. As it is presented in Table 65, 75.00% is related to the FT product transportation when cross-docking is included within the supply chain. The portion of FT product transportation costs drops considerably to 31.96% in the second scenario shown in Table 66.

As it is shown in Table 67, total transportation cost ratio (TTCR) equals 42.61% for the instance with 6 suppliers and 8 customers. Also, the total supply chain cost ratio (TSCCR) equals 46.01%. This result shows the significant advantage of practicing cross-docking to reduce the product-unit cost. This notable reduction is due to more FT product transportation (less LTL product transportation) in the first scenario and manifest itself in the decrease on the proportion FT product transportation costs when cross-docking is excluded from the supply chain.

Table 65: Transportation cost analysis when CD included

Route	Run No	Transportation	Cost Section		
			Cost/run	Cost	Cost %
S→C	1st Run	FT	$431,832.63	$443,202.07	75.00%
	2nd Run	FT	$11,369.44		
S→CD	1st Run	FT	$34,857.89	$53,038.11	8.98%
	Last	LTL	$18,180.23		
CD→C	1st Run	FT	$21,245.71	$94,682.98	16.02%
	2nd Run	FT	$4,490.25		
	Last	LTL	$68,947.03		
Total			$590,923.16		

Table 66: Transportation cost and mile analysis when CD excluded

Route	Run No	Transportation	Cost Section		
			Cost/run	Cost	Cost %
S→C	1st Run	FT	$431,832.63	$443,202.07	31.96%
	2nd Run	FT	$11,369.44		
S→C	Last	LTL	943,648.54	$943,648.54	68.04%
Total			1,386,850.61		

Table 67: Cost and mile product unit ratio

Scenario	**Total Transportation Cost (TTC)**	**Total Cross-docking operating costs (TCDC)**	**Total Supply Chain Cost (TSCC)**
CD Included	$590,923.16	$47,800.46	$638,723.62
CD Excluded	1,386,850.61	---	1,386,850.61
Ratio: $\frac{\textbf{CD Included}}{\textbf{CD Excluded}}$	**TTCR = 42.61%**	**---**	**TSCCR = 46.01%**

Aggregation of all FT and LTL product transportation costs presented in Table 65 and Table 66 are shown in Table 68. The comparison between two scenarios shows that the total transportation costs in the 1st scenario is much less than the total transportation costs for the 2nd scenario, and therefore, TCR ratios is less than 1 shown in Table 67. By looking at the portion of FT versus LTL at each scenario presented in Table 68, it is noted that 85.14% and 31.96% of the transportation cost belong to the FT transportation. In contrast, the portion of LTL product transportation cost (14.68%) for FT is much less than its counterpart in the 2nd scenario (68.04%).

Therefore, it turns out that the cross-docking as an intermediate transshipment node within the supply chain helps to have more FT product transportation and less LTL which indicate the signals of achieving economies of scale, less product unit costs, and higher quality usage of the roads.

Table 68: transportation cost (TTC) when CD included vs. excluded

Scenario	Transportation	Cost Section	
		Cost	Cost %
CD Included	FT	499,305.67	85.14%
	LTL	87,127.26	14.86%
CD Excluded	FT	443,202.07	31.96%
	LTL	943,648.54	68.04%

Another indicator that shows the efficiency and effectiveness of the proposed binary-linear programming model and results is the number of trucks that are used for FT product transportation against the LTL product transportation. According to the data shown in Table 69, in the 1st scenario, 106 trucks are hired for the FT product transportation and 83 FT product transportation in the 2nd scenario. Conversely, in the 1st scenario, we just hire 12 trucks for LTL product transportation and 41 trucks in the 2nd scenario. The number of LTL trucks is an indicator that shows the level of economies of scale within a supply chain. In fact, the higher (fewer) the number of FT (LTL) trucks, the higher (fewer) economies of scale is expected which results in less (higher) product-unit cost and higher (less) quality usage of the roads. By looking at the total number of trucks hired in each scenario; i.e.,118 trucks when cross-docking included and 124 trucks when cross-docking excluded, we showed that the proposed model is an efficient practice that not only helps minimize the total transportation costs, but also the increase the efficiency of the transportation network by reducing number of trucks from the network which results in reduction of pollution produced by the additional trucks in the networks. Also, Table 69 shows that the model emphasizes more on the trucks with larger capacities to handle product transportation between each two nodes.

Table 69: Number of truck assignment in each route between each two nodes

Truck	Cross-docking terminal Included							Cross-Dock Excluded	
	FT				LTL			FT	LTL
	S→C	S→CD	CD→C	Sum	S→CD	CD→C	Sum	S→C	S→C
15	1	---	---	1	---	---	---	1	---
20	---	---	---	0	---	---	---	---	---
30	1	---	---	1	---	---	---	1	---
45	---	---	---	0	---	---	---	---	---
50	---	---	---	0	---	---	---	---	---
60	---	---	---	0	---	---	---	---	---
75	40	5	11	56	5	7	12	40	41
90	41	6	1	48	---	---	---	41	---
Total	**83**	**11**	**12**	**106**	**5**	**7**	**12**	**83**	**41**

In the current example, the transportation cost ratio (TCR) is 42.61%. This indicates that, regardless of the operational costs of a cross-docking terminal, transportation cost is much lower when we involve CD terminal to take care of supplier→customer LTL product transportation. Nonetheless, depending on the size of the problem and the way we set up other parameters like initial fixed costs, initial variable costs, range of truck capacities, and percentage of trucks assigned for long-distance product transportation, this ratio can vary. The contribution of this study is to figure the best parameter settings to minimize these ratios.

5.9Numerical Example to check the Tabu search algorithm, efficiency

In order to evaluate the efficiency of the Tabu search framework shown in Table 55, nine sets of problems including 7×7×7×7, 10×10×10×10, 15×15×15×15, 20×20×20×20, 25×25×25×25, 30×30×30×30, 35×35×35×35, 40×40×40×40, and 45×45×45×45 are randomly generated. For simplicity, equal number of suppliers, customers, inbound and outbound doors are assumed, and each set is replicated for five times. Each experience is run using different methods for the problem-solving including enumeration method (CPLEX), hill-climbing technique, and Tabu search metaheuristic technique. Tabu search metaheuristic is implemented five times for each diversification method. The corresponding cost gap percentage and time-to-best (CPU time measured in seconds) are reported for each technique which are shown in Table 70. In the CPLEX section, the relative MIP gap tolerance (Gap %) which is a distance between upper and lower bound of the MIP solution is also reported. The desired value is the one that is closer to zero. As it is shown in Table 70, by the increase in the problem size, the relative MIP gap increases. Only for small cases, CPLEX converges and reaches the optimality; the relative MIP gap is lower than 20%. However, for larger size problems, CPLEX does not converge and does not reach optimality, and it reports "MIP starts not constructed because of out-of-memory status." And we see the relative MIP gap is observed to be greater than 60%, and for the largest problem size, it is almost 100% which indicates that the CPLEX stops right after it starts searching to find the first feasible points.

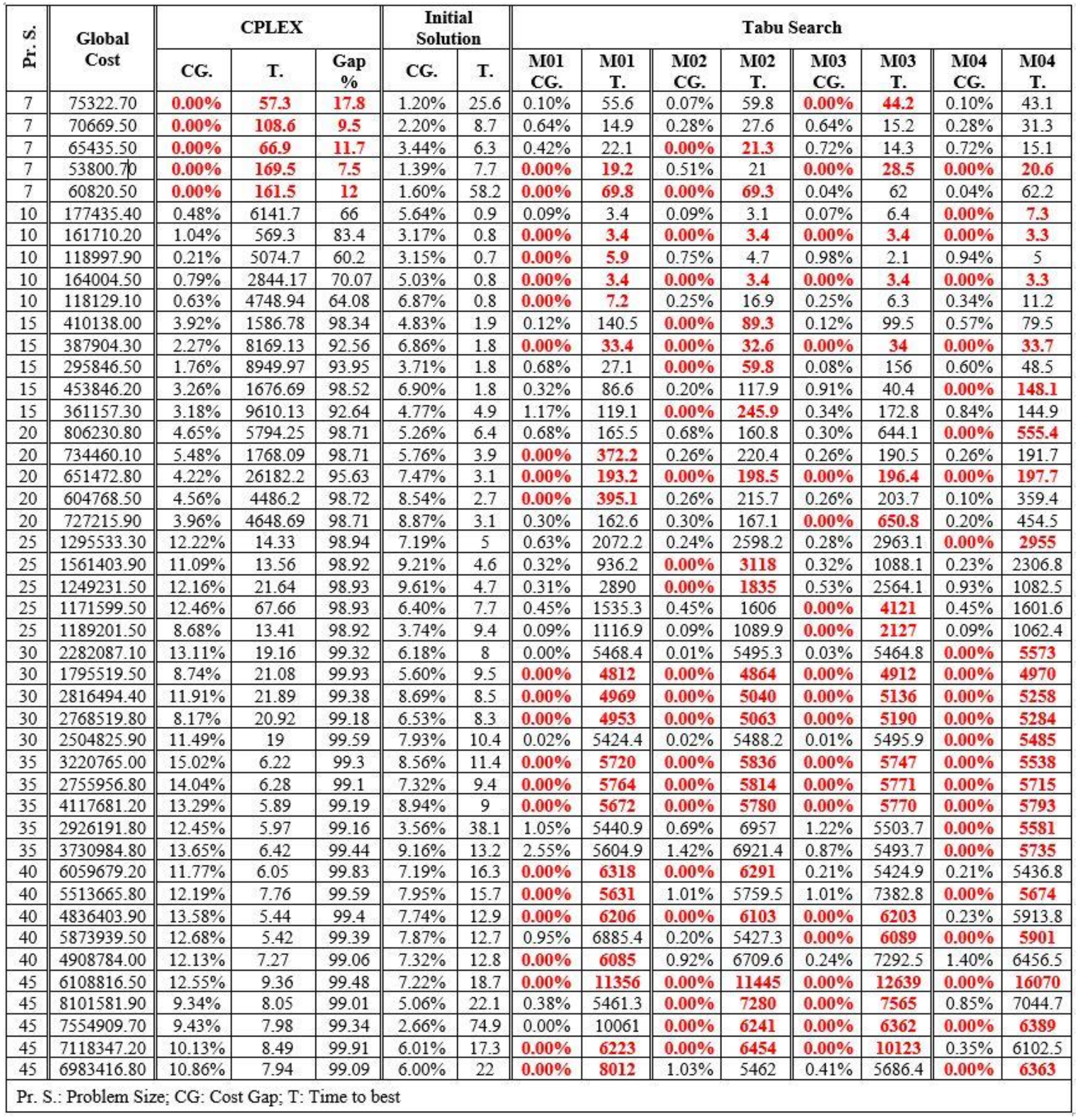
Following the hill-climbing algorithm described previously, in the initial solution section, a maximum of 200 local optimum solutions are generated, and the best one is selected as the best initial solution. In addition, the time reported in the initial solution section is the time that is spent to generate maximum 200 local optimum points. It is noteworthy to consider that the total time to generate maximum 200 local optimum points is well below the time CPLEX reports to reach the solution; i.e., either the optimal or non-optimal one.

As the initial solution to start TS is the best local optimum solution, time-to-best is added to generate the best initial solution to the TS time. For instance, when TS uses M1 diversification method for the first instance, TS's time-to-best (shown in Table 70) equals 55.60 seconds. So, 25.6 of 55.60 is spent to achieve maximum 200 solutions and 30 seconds for the TS process.

Excepting the 7×7×7×7 instances that reach optimality by CPLEX technique, in other instances, the red and bolded values indicate the global lowest solution which are not necessarily the optimum values. In all instances, none of the best initial solutions are the global points with the lowest costs. Moreover, looking at all TSs' columns, it can be observed that in all instances, except the 7×7×7×7, TS has superiority over the CPLEX not only from the cost perspective but also from the time-to-best standpoint.

Table 71 shows the average of the data presented in Table 70. For each problem set presented Table 70, the all methods are sorted and ranked in ascending order based on their cost gap percentage and time. The corresponding ranks for all methods are reported in Table 72. Overall, all tabu search techniques have remarkably significant advantages over the other two techniques; i.e., hill-climbing approach to achieve the best local optimal solutions and the enumeration technique using ILOG CPLEX.

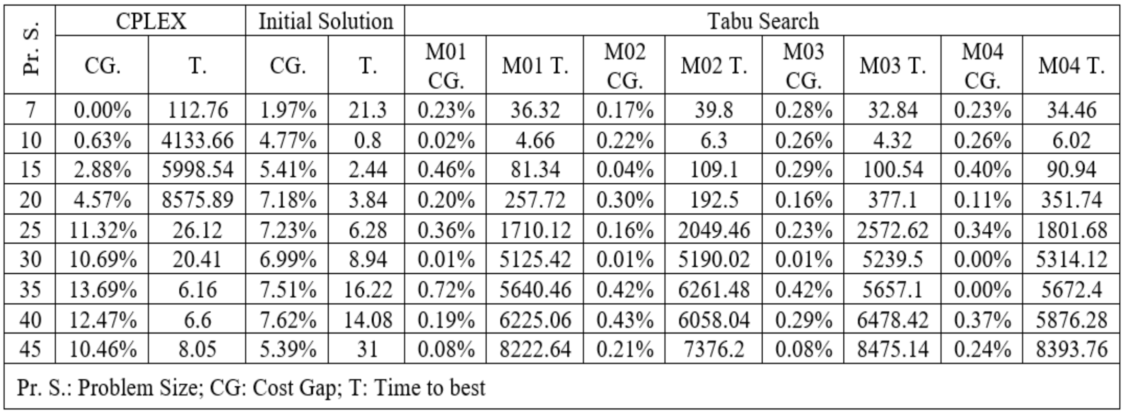
When the Tabu search technique is broken down to the diversification methods in Table 72, it was noticeable that the Tabu search with Permutation Mapping Diversification Method (M1) achieve the highest number of optimal solutions. The Recursive Permutation Mapping (M2) is the second-best alternative to solve the proposed model. The third lowest ranking corresponding to Recursive DivTS Restart Approach (M4) indicates the importance of M4 in problem solving with respect to M1 and M2. M3, the DivTS Restart Approach, receives the forth position of importance with respect the other 3 diversification methods. Therefore, the ranking from the best to the worst can be arranged as follows; Tabu search (M1, M2, M4, and M3), CPLEX, and then Best Initial Solution.



Pr. S.	Global Cost	CPLEX			Initial Solution		Tabu Search							
		CG.	T.	Gap %	CG.	T.	M01 CG.	M01 T.	M02 CG.	M02 T.	M03 CG.	M03 T.	M04 CG.	M04 T.
7	75322.70	**0.00%**	**57.3**	**17.8**	1.20%	25.6	0.10%	55.6	0.07%	59.8	**0.00%**	**44.2**	0.10%	43.1
7	70669.50	**0.00%**	**108.6**	**9.5**	2.20%	8.7	0.64%	14.9	0.28%	27.6	0.64%	15.2	0.28%	31.3
7	65435.50	**0.00%**	**66.9**	**11.7**	3.44%	6.3	0.42%	22.1	**0.00%**	**21.3**	0.72%	14.3	0.72%	15.1
7	53800.70	**0.00%**	**169.5**	**7.5**	1.39%	7.7	**0.00%**	**19.2**	0.51%	21	**0.00%**	**28.5**	**0.00%**	**20.6**
7	60820.50	**0.00%**	**161.5**	**12**	1.60%	58.2	**0.00%**	**69.8**	**0.00%**	**69.3**	0.04%	62	0.04%	62.2
10	177435.40	0.48%	6141.7	66	5.64%	0.9	0.09%	3.4	0.09%	3.1	0.07%	6.4	**0.00%**	**7.3**
10	161710.20	1.04%	569.3	83.4	3.17%	0.8	**0.00%**	**3.4**	**0.00%**	**3.4**	**0.00%**	**3.4**	**0.00%**	**3.3**
10	118997.90	0.21%	5074.7	60.2	3.15%	0.7	**0.00%**	**5.9**	0.75%	4.7	0.98%	2.1	0.94%	5
10	164004.50	0.79%	2844.17	70.07	5.03%	0.8	**0.00%**	**3.4**	**0.00%**	**3.4**	**0.00%**	**3.4**	**0.00%**	**3.3**
10	118129.10	0.63%	4748.94	64.08	6.87%	0.8	**0.00%**	**7.2**	0.25%	16.9	0.25%	6.3	0.34%	11.2
15	410138.00	3.92%	1586.78	98.34	4.83%	1.9	0.12%	140.5	**0.00%**	**89.3**	0.12%	99.5	0.57%	79.5
15	387904.30	2.27%	8169.13	92.56	6.86%	1.8	**0.00%**	**33.4**	**0.00%**	**32.6**	**0.00%**	**34**	**0.00%**	**33.7**
15	295846.50	1.76%	8949.97	93.95	3.71%	1.8	0.68%	27.1	**0.00%**	**59.8**	0.08%	156	0.60%	48.5
15	453846.20	3.26%	1676.69	98.52	6.90%	1.8	0.32%	86.6	0.20%	117.9	0.91%	40.4	**0.00%**	**148.1**
15	361157.30	3.18%	9610.13	92.64	4.77%	4.9	1.17%	119.1	**0.00%**	**245.9**	0.34%	172.8	0.84%	144.9
20	806230.80	4.65%	5794.25	98.71	5.26%	6.4	0.68%	165.5	0.68%	160.8	0.30%	644.1	**0.00%**	**555.4**
20	734460.10	5.48%	1768.09	98.71	5.76%	3.9	**0.00%**	**372.2**	0.26%	220.4	0.26%	190.5	0.26%	191.7
20	651472.80	4.22%	26182.2	95.63	7.47%	3.1	**0.00%**	**193.2**	**0.00%**	**198.5**	**0.00%**	**196.4**	**0.00%**	**197.7**
20	604768.50	4.56%	4486.2	98.72	8.54%	2.7	**0.00%**	**395.1**	0.26%	215.7	0.26%	203.7	0.10%	359.4
20	727215.90	3.96%	4648.69	98.71	8.87%	3.1	0.30%	162.6	0.30%	167.1	**0.00%**	**650.8**	0.20%	454.5
25	1295533.30	12.22%	14.33	98.94	7.19%	5	0.63%	2072.2	0.24%	2598.2	0.28%	2963.1	**0.00%**	**2955**
25	1561403.90	11.09%	13.56	98.92	9.21%	4.6	0.32%	936.2	**0.00%**	**3118**	0.32%	1088.1	0.23%	2306.8
25	1249231.50	12.16%	21.64	98.93	9.61%	4.7	0.31%	2890	**0.00%**	**1835**	0.53%	2564.1	0.93%	1082.5
25	1171599.50	12.46%	67.66	98.93	6.40%	7.7	0.45%	1535.3	0.45%	1606	**0.00%**	**4121**	0.45%	1601.6
25	1189201.50	8.68%	13.41	98.92	3.74%	9.4	0.09%	1116.9	0.09%	1089.9	**0.00%**	**2127**	0.09%	1062.4
30	2282087.10	13.11%	19.16	99.32	6.18%	8	0.00%	5468.4	0.01%	5495.3	0.03%	5464.8	**0.00%**	**5573**
30	1795519.50	8.74%	21.08	99.93	5.60%	9.5	**0.00%**	**4812**	**0.00%**	**4864**	**0.00%**	**4912**	**0.00%**	**4970**
30	2816494.40	11.91%	21.89	99.38	8.69%	8.5	**0.00%**	**4969**	**0.00%**	**5040**	**0.00%**	**5136**	**0.00%**	**5258**
30	2768519.80	8.17%	20.92	99.18	6.53%	8.3	**0.00%**	**4953**	**0.00%**	**5063**	**0.00%**	**5190**	**0.00%**	**5284**
30	2504825.90	11.49%	19	99.59	7.93%	10.4	0.02%	5424.4	0.02%	5488.2	0.01%	5495.9	**0.00%**	**5485**
35	3220765.00	15.02%	6.22	99.3	8.56%	11.4	**0.00%**	**5720**	**0.00%**	**5836**	**0.00%**	**5747**	**0.00%**	**5538**
35	2755956.80	14.04%	6.28	99.1	7.32%	9.4	**0.00%**	**5764**	**0.00%**	**5814**	**0.00%**	**5771**	**0.00%**	**5715**
35	4117681.20	13.29%	5.89	99.19	8.94%	9	**0.00%**	**5672**	**0.00%**	**5780**	**0.00%**	**5770**	**0.00%**	**5793**
35	2926191.80	12.45%	5.97	99.16	3.56%	38.1	1.05%	5440.9	0.69%	6957	1.22%	5503.7	**0.00%**	**5581**
35	3730984.80	13.65%	6.42	99.44	9.16%	13.2	2.55%	5604.9	1.42%	6921.4	0.87%	5493.7	**0.00%**	**5735**
40	6059679.20	11.77%	6.05	99.83	7.19%	16.3	**0.00%**	**6318**	**0.00%**	**6291**	0.21%	5424.9	0.21%	5436.8
40	5513665.80	12.19%	7.76	99.59	7.95%	15.7	**0.00%**	**5631**	1.01%	5759.5	1.01%	7382.8	**0.00%**	**5674**
40	4836403.90	13.58%	5.44	99.4	7.74%	12.9	**0.00%**	**6206**	**0.00%**	**6103**	**0.00%**	**6203**	0.23%	5913.8
40	5873939.50	12.68%	5.42	99.39	7.87%	12.7	0.95%	6885.4	0.20%	5427.3	**0.00%**	**6089**	**0.00%**	**5901**
40	4908784.00	12.13%	7.27	99.06	7.32%	12.8	**0.00%**	**6085**	0.92%	6709.6	0.24%	7292.5	1.40%	6456.5
45	6108816.50	12.55%	9.36	99.48	7.22%	18.7	**0.00%**	**11356**	**0.00%**	**11445**	**0.00%**	**12639**	**0.00%**	**16070**
45	8101581.90	9.34%	8.05	99.01	5.06%	22.1	0.38%	5461.3	**0.00%**	**7280**	**0.00%**	**7565**	0.85%	7044.7
45	7554909.70	9.43%	7.98	99.34	2.66%	74.9	0.00%	10061	**0.00%**	**6241**	**0.00%**	**6362**	**0.00%**	**6389**
45	7118347.20	10.13%	8.49	99.91	6.01%	17.3	**0.00%**	**6223**	**0.00%**	**6454**	**0.00%**	**10123**	0.35%	6102.5
45	6983416.80	10.86%	7.94	99.09	6.00%	22	**0.00%**	**8012**	1.03%	5462	0.41%	5686.4	**0.00%**	**6363**

Pr. S.: Problem Size; CG: Cost Gap; T: Time to best

Table 70:Cost gap percentage and time-to-best report for 45 instances



Pr. S.	CPLEX		Initial Solution		Tabu Search							
	CG.	T.	CG.	T.	M01 CG.	M01 T.	M02 CG.	M02 T.	M03 CG.	M03 T.	M04 CG.	M04 T.
7	0.00%	112.76	1.97%	21.3	0.23%	36.32	0.17%	39.8	0.28%	32.84	0.23%	34.46
10	0.63%	4133.66	4.77%	0.8	0.02%	4.66	0.22%	6.3	0.26%	4.32	0.26%	6.02
15	2.88%	5998.54	5.41%	2.44	0.46%	81.34	0.04%	109.1	0.29%	100.54	0.40%	90.94
20	4.57%	8575.89	7.18%	3.84	0.20%	257.72	0.30%	192.5	0.16%	377.1	0.11%	351.74
25	11.32%	26.12	7.23%	6.28	0.36%	1710.12	0.16%	2049.46	0.23%	2572.62	0.34%	1801.68
30	10.69%	20.41	6.99%	8.94	0.01%	5125.42	0.01%	5190.02	0.01%	5239.5	0.00%	5314.12
35	13.69%	6.16	7.51%	16.22	0.72%	5640.46	0.42%	6261.48	0.42%	5657.1	0.00%	5672.4
40	12.47%	6.6	7.62%	14.08	0.19%	6225.06	0.43%	6058.04	0.29%	6478.42	0.37%	5876.28
45	10.46%	8.05	5.39%	31	0.08%	8222.64	0.21%	7376.2	0.08%	8475.14	0.24%	8393.76

Pr. S.: Problem Size; CG: Cost Gap; T: Time to best

Table 71:The average summary of cost gap and time for 45 instances for nine categories

Problem Size	CPLEX	Initial Solution	Tabu Search			
			M1	M2	M3	M4
7	1	6	4	2	5	3
10	5	6	1	2	3	4
15	5	6	4	1	2	3
20	5	6	3	4	2	1
25	6	5	1	1	2	3
30	6	5	2	3	4	1
35	6	5	4	3	2	1
40	6	5	1	4	2	3
45	6	5	1	2	3	4
Average	5.11	5.44	2.33	2.44	2.78	2.56
Overall Rank	5	6	1	2	4	3

Table 72: Methods’ comparison based on their ranking for each instance

5.10Limitation of The Study

The limitations encountered during the study are as follows;

1) Concerning the binary-linear programming model, we perceive no limitation concerning the memory or speed.
2) The bilinear-quadratic assignment problem developed in this study; i.e., XQY, is the general format of the common quadratic assignment problem of XQX. Based on our research, there is no available sample on the internet to check the efficiency of the algorithm with their results. And all other studies have just reported their final output results, as well.

3) The proposed heuristic and meta-heuristic algorithms are coded in the Visual Studio C# 2017, and in this study, parallel programing method was implemented in which many calculations or the execution of processes are carried out simultaneously. Also, in order to increase the efficiency of memory usage , SQL Server 2014 is employed to store the output data in each run of the algorithms. In addition, some parts of the coding for this study was developed in the Matlab and used the Matlab dll files in the main program developed in VS C#. Due to complexity of the main software, there was no chance to install it on a super computer to test problems sizes larger than 45×45×45×45.
4) Concerning complete enumeration approaches, solvers like ILOG CPLEX give up finding the optimum solution due to lack of memory on a personal laptop; like one with a processor “Intel(R) Core (TM) i7-6500U CPU @ 2.50 GHz 2.60 GHz” and an installed memory of 12.00 GB. It is noteworthy that we didn’t change the CPLEX default setting and the results are generated using the settings offer by the CPLEX

5.11Conclusion

This work considers the problem of satisfying transportation requests from a set of suppliers to a set of customers. Instead of commonly approach of direct-shipping of products, an intermediate transshipment point – cross-docking terminal – is hired to handle the LTL product transportation. For this purpose, a multi-stage binary-linear programming is proposed to minimize total supply chain transportation costs and transportation miles. In that, initially, the FT product transportation policy is implemented to handle FT product transportation from the suppliers to the customers. Once the FT transportation becomes impossible at each suppliers’ sites, then the remaining products are consolidated and the second stage of the transportation network which is the transportation of products from suppliers to cross-docking terminal is activated. Again, initially products are transferred to the terminal using FT trucks, and for the rest LTL products at each supplier’s site, an appropriate truck is hired that minimize the total LTL transportation costs.

Concerning the product transshipment in the cross-docking terminal, a bilinear-quadratic assignment model is developed. Concerning solving the quadratic model, the results showed that the advantages of using heuristic (hill-climbing) and meta-heuristic (Tabu search) methods outweighed their disadvantages (getting trapped in the local optimum solution) in contrast with the enumeration techniques that seek optimality.

The contribution of this study is listed as follows;

1. By establishing an imaginary zone, we facilitate short-distance and long-distance product transportation.
2. This study not only focuses on transportation product-unit costs but also on the transportation product-unit miles.
3. Practicing cross-docking helps reduce transportation mile and transportation costs.
4. The assumption of dynamic fixed costs and variable costs is another contribution of this study. The trucks' variable costs vary by the capacity of the trucks. However, the variable cost of transportation in the proposed objective functions are functions of the distances that each truck travel plus the number of products that they carry. In fact, the more they carry, the less is paid for the variable costs. Also, they shorter they travel the less is paid for the variable costs. This helps achieve the economy of scale of choosing the best and appropriate truck that minimizes transportations variable costs. Although, the fixed costs for the larger trucks are higher than the smaller ones, the more the bigger trucks carry, the fewer variable costs are supposed to be paid.
5. The transportation cost are the indicators that are developed to show the significance of cross-docking within a transportation network when cross-docking is practiced comparing the time that it is excluded from the network.

6. The findings shown in Table 70, Table 71, and Table 72 confirmed that Tabu search outperforms the hill-climbing technique and CPLEX from both cost and time perspectives. The efficiency of the developed algorithm manifests itself when the time-to-best of TS was compared with the time-to-best reported by the hill-climbing and CPLEX. Even, the TS time-to-best was significantly lower than CPLEX time-to-best when CPLEX returned optimality in the small size problems; i.e., 7×7×7×7. For instance, CPLEX reached optimality of the last 7×7×7×7 instance at 161st second while Tabu search reached that in around 70th second.

In the future, the researcher plans to consider meta-heuristic methods or evolutionary optimization approaches to solve even larger size problems (few hundred doors and thousands of orders) in a fast and efficient way. Thus, same coding must be developed in the Python platform in order to run the coding on a supercomputer.

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VITA

Vahid Ghomi

PhD of Business Administration (2014 – 2018)
Department of Marketing
School of Business Administration
University of Mississippi (Ole Miss)

Education

PhD of Business Administration: Marketing and Supply Chain Management
Master of Engineering: Engineering Design and Manufacture (Kuala Lumpur, Malaysia)
Bachelor of Engineering: Industrial and System Engineering (Tehran, Iran)

Email

vahid.ghomi@gmail.com

Website

LinkedIn
Google Scholar