# TWO-ECHELON DISTRIBUTION NETWORK DESIGN WITH COLLABORATION AMONG CARRIERS

by
İSMAİL GÖKAY DOĞAN

Submitted to the Graduate School of Engineering and Natural Sciences
in partial fulfilment of
the requirements for the degree of Master of Science

Sabancı University
October 2022

# ABSTRACT

TWO-ECHELON DISTRIBUTION NETWORK DESIGN WITH COLLABORATION AMONG CARRIERS

İSMAİL GÖKAY DOĞAN

Industrial Engineering, Master's Thesis, October 2022

Thesis Supervisor: Asst. Prof. Dr. Esra Koca

Keywords: distribution network design, two-echelon supply chain, collaborative supply chain, location-routing, mixed integer programming, cut-generation

Globalization, exponential growth of e-commerce and q-commerce industries, changing market habits and increased need of logistics services result in high competition among supply chain pillars. Collaboration is an effective strategy to pursue in this endeavour. We define a two-echelon distribution network design problem in which parties can collaborate to complete the last-mile delivery requests in the lower echelon. The objective is to minimize costs which arise from facility opening, transportation and transfer of goods between regional depots. In the upper echelon, goods are transferred from plants to regional depots via direct transportation. In the lower echelon, goods are delivered to the customers in a milk-run fashion from regional depots. We develop three mixed-integer linear programming models which differ in terms of modelling outbound routing decisions. Several valid inequalities are proposed to strengthen formulations. To solve a traditional vehicle-based formulation, a cut-generation based method is developed. For the path-based formulation, a heuristic route pool generation procedure which promotes collaboration is developed. Proposed models are tested with different problem sizes to examine solution qualities and computational times. Moreover, models are tested under different collaborative network settings in which main parameters of the problem such as number of common customers, demand amounts and number of common depots are varied in order to explore managerial insights such as savings due to collaboration.

# ÖZET

## TAŞIYICILAR ARASINDA İŞ BİRLİĞİ ALTINDA İKİ AŞAMALI DAĞITIM AĞI TASARIMI

İSMAİL GÖKAY DOĞAN

Endüstri Mühendisliği Yüksek Lisans Tezi, Ekim 2022

Tez Danışmanı: Dr. Öğretim Üyesi Esra Koca Paç

Anahtar Kelimeler: dağtım ağı tasarımı, iki kademeli tedarik zinciri, işbirlikçi tedarik zinciri, lokasyon-rotalama, tam sayılı doğrusal programlama, kesim üretimi

Küreselleşme, e-ticaret ve q-ticaret endüstrilerinin katlanarak büyümesi, değişen pazar alışkanlıkları ve artan lojistik hizmetleri ihtiyacı, tedarik zinciri paydaşları arasında yüksek rekabete neden olmaktadır. İş birliği, bu rekabet ortamında maliyetleri azaltmak için izlenebilecek etkili bir stratejidir. Bu çalışmada, alt kademedeki son teslimat etaplarını tamamlamak için tarafların iş birliği yapabileceği iki kademeli bir dağıtım ağı tasarım problemi tanımlıyoruz. Problemin amaç fonksiyonun hedefi tesis açılışı, nakliye ve bölgesel depolar arası mal transferinden kaynaklanan maliyetleri en aza indirmektir. Üst kademede mallar fabrikalardan doğrudan taşıma ile bölgesel depolara aktarılır. Alt kademede mallar, bölgesel depolardan süt dağıtımı şemasıyla (depodan çıkıp tüm teslimat noktalarına uğradıktan sonra depoya geri dönecek rotalarla) müşterilere teslim edilir. Alt kademedeki rotalama kararlarını modelleme açısından farklılık gösteren üç karma tam sayılı doğrusal programlama modeli geliştiriyoruz. Formülasyonları güçlendirmek için çeşitli geçerli eşitsizlikler önerilmiştir. Geleneksel araç bazlı formülasyonu çözmek için, kesim üretimi bazlı bir yöntem geliştirilmiştir. Rota tabanlı formülasyon için, iş birliğini destekleyecek türde rotalar oluşturan sezgisel bir prosedür geliştirilmiştir. Önerilen modeller, çözüm niteliklerini ve hesaplama sürelerini incelemek için farklı problem boyutlarıyla test edilmiştir. Ayrıca modeller, ortak müşteri sayısı, talep miktarları ve ortak depo sayısı gibi problemin ana parametrelerinin değiştirildiği farklı işbirlikçi dağıtım ağı senaryoları altında test edilerek, iş birliğinden kaynaklanan tasarruflar gibi yönetsel içgörüler keşfedilmiştir.

**ACKNOWLEDGEMENTS**

First and foremost, I would like to thank my previous advisor Prof. Güvenç Şahin, for his invaluable advice and support during my undergraduate and master's studies. I would not be at this stage of my career without his support and endless motivation. Moreover, I would like to thank my advisor Asst. Prof. Dr. Esra Koca Paç for her support in the last stages of my thesis. In addition to my thesis advisor, I would also like to thank my thesis jury members, Asst. Prof. Dr. Ezgi Karabulut Türkseven and Asst. Prof. Dr. Ahmed Burak Paç for their valuable time to spare in my thesis committee and for their precious comments, advice, and feedback.

I would like to thank colleagues and friends in that journey, Çağrı Doğuş İyican and and Sinan Emre Koşunda for being a great fellow and supporting me in any stage of my master's studies.

I would like to thank my cousin, Hüseyin Tufan Usta for supporting me, believing in me and being there for me whenever I needed.

I am grateful to Alperen, Cengizhan, Serhan, Sina, Çağhan and many others for their friendship throughout the years in high school and university.

Finally, but most importantly, I would like to thank my parents Gülay and Gençay, and my brother Güray and my girlfriend İrem for their unconditional love and endless support. I would not come that far without their support and the sacrifices they made.

*To my family...*
*Aileme...*

**TABLE OF CONTENTS**

**LIST OF TABLES**

## LIST OF FIGURES

## LIST OF ABBREVIATIONS

# 1. INTRODUCTION

Network design is one of the key pillars of the modern supply chains. In addition to traditional supply requirements, exponential growth of e-commerce and q-commerce industries, changing market habits and increased need of micro logistics services promote competition among parties. Into the bargain, growing logistics needs also come along with social and environmental issues such as pollution, noise, traffic and congestion. Thus, promoting cost efficient supply networks become more important because of the increased competitiveness, and companies try to find new strategies for their logistics operations to cope with the sustainability issues and high competitiveness of the market (Aloui, Derrouiche, Hamani & Delahoche, 2020).

One strategy that can be followed by the parties of supply chains is collaboration. Collaboration between parties indeed promises positive outcomes such as decreased costs for businesses, companies, service providers, or increased environmental standards for community such as decreased pollution levels, noise and congestion. Hence, improving efficiencies via collaboration in logistics design and planning processes may have a great impact on environment and social welfare in society (Rao, Goh, Zhao & Zheng, 2015).

In this study, we address a two echelon centralized collaborative strategic network design problem in which companies are allowed to cooperate in the lower echelon within the scope of last mile delivery operations. The two echelon network consists of plants where products are produced, regional depots where goods are stored, and customers. Deliveries from plants to regional depots are conducted as direct transportation and called inbound transportation. Deliveries from regional depots to the customers are conducted in a milk-run fashion and called outbound transportation. Our goal is to determine the number and locations of regional depots, required inbound capacity and outbound routes as well as transfer lines between depots. Our problem includes strategic decisions such as facility decisions as well as tactical and operational decisions such are vehicle routing and transfer line construction decisions. The objective is to minimize total cost of the whole system due to both strategic, tactical and operational decisions.

To represent a collaborative distribution network, a single period strategic network design problem, in which parties can interchange demands, is defined.

We define a single period strategic network design problem in which parties can interchange demands to represent a collaborative distribution network. We develop three mathematical models which differ from each other in terms of modelling outbound routing operations.

Depending on the type and cause of computational challenges, the resulting mixed-integer linear programming formulations require different solution methods. We conduct computational experiments with different sizes of problem instances under three different collaborative network scenarios, and also two different demand settings. Our contributions can be summarized as follows:

- A centralized network design problem is defined in which parties can collaborate to satisfy other companies' demands in the outbound routing operations.
- Three mixed-integer linear programming formulations are proposed.
- A cut generation based method to solve one of the formulations is developed.
- Route pool generation procedure which employs five heuristic algorithms and promotes collaboration is proposed.
- Different valid inequalities are developed for each formulation in order to improve the solution performance.
- Impact of different collaborative network structures is investigated.

This thesis is organized as follows. Chapter 2 consists of a literature review. Problem definition and mathematical models are presented in Chapter 3. A vehicle-based formulation approach and related solution methodologies are presented in Chapter 4 together with computational results. Similarly, load-based and path-based formulation approaches and related solution methodologies as well as computational results are presented in Chapter 5 and Chapter 6, respectively. Finally, we conclude with our findings and future research directions in Chapter 7.

# 2. LITERATURE REVIEW

The literature review focuses on two aspects: strategic distribution network design problems and the effect of collaboration among parties that operate over the same network. Strategic distribution network design problems include two main decisions, locations of the facilities and transportation decisions. Both of these decisions can be presented under different optimization problem classes, such as facility location problems (FLP), and vehicle routing problems (VRP). Collaboration is a strategy that is utilized by the companies to increase service levels and decrease the costs. In the beginning of this literature review, we focus on FLP. In the later parts, collaborative approaches are explained.

Facility location problem is a combinatorial optimization problem, and its objective is to determine the number and locations of a set of facilities (warehouses, cross-docks, etc.) and assign customers to these facilities in such a way that the demands of the customers are satisfied, and the total cost is minimized (Wu, Zhang & Zhang, 2006). On the other hand, vehicle routing problem aims to decide on a set of vehicle routes to satisfy all or some transportation requests of the customers with the given vehicle fleet at minimum cost (Toth & Vigo, 2014).

In a distribution network, making location and routing decisions independently may lead to highly sub-optimal planning results (Salhi & Rand, 1989). Thus, making those decisions simultaneously pledges better outcomes. Location-routing problems (LRP) emerge from this basis. Given a set of possible depot locations, a set of vehicles, and a set of customers, LRP consists of simultaneous decision-making of opening a subset of depots, creating routes that depart from opened depots, and assigning customers to constructed routes of vehicles to minimize total cost including depot opening costs and transportation costs (Prodhon & Prins, 2014). The main difference between LRP and VRP is not only routing decisions, in addition to that, the optimal depot locations must be determined concurrently (Marinakis, 2009).

By the virtue of the complex logistics and distribution infrastructure requirements of modern-day supply chains, many distribution systems are designed as multi-echelon systems. In multi-echelon distribution systems, delivery of the goods from origin to the final destination is extended through intermediate facilities such as warehouses, cross-docks, etc. where goods are stored, changed, packed, unpacked, merged, or consolidated. Every single level of the distribution network refers to an echelon (Cuda, Guastaroba & Speranza, 2015).

Two-echelon systems are very well studied in the literature because of their applicability to real-life instances and promising outcomes. Two-echelon distribution networks consist of three disjoint sets of nodes, depots (plants or origins), satellites which are intermediate facilities such as regional depots, consolidation points or cross docks, and customers (Cuda et al., 2015).

The two-echelon setting of LRPs (2E-LRP) tries to answer, how many depots and/or intermediate facilities should be opened to which locations, and which routes should be constructed in both echelons according to the given network structure and parameters (Cuda et al., 2015). In terms of new problem structures and methodological works, numerous research has been conducted. Jacobsen & Madsen (1980) is one of the earliest studies on 2E-LRP which is motivated by a newspaper distribution problem which finds the best locations the satellite facilities, and routes to be created in both echelons. The authors propose three different heuristic approaches. Boccia, Crainic, Sforza & Sterle (2010) study a 2E-LRP where homogeneous vehicles in both echelons have fixed capacities. To the best of our knowledge, this study is one of the earliest examples of capacitated 2E-LRP, i.e., 2E-CLRP. They utilize a tabu search (TS) based heuristic algorithm.

Boccia, Crainic, Sforza & Sterle (2011) introduce three different mixed-integer linear programming (MILP) formulations for 2E-CLRP. They conduct computational experiments by solving two of those models with a commercial solver on a data set which is generated Boccia et al. (2011). Contardo, Hemmelmayr & Crainic (2012) propose a branch and cut (B&C) algorithm to solve 2E-LRP. They introduce a new two-index formulation that is used in B&C. They are able to solve small and medium-sized instances to optimality. Schwengerer, Pirkwieser & Raidl (2012) propose a Variable Neighborhood Search (VNS) for 2E-CLRP and conduct computational study on three sets of instances which are proposed by Contardo et al. (2012). The authors show that VNS is not able to outperform the B&C algorithm of Contardo et al. (2012).

Over the last few years, globalization changed logistics operations, as well as it has transformed many aspects of the modern world. Because of the exponential growth of e-commerce and q-commerce industries, micro logistics needs have been expanded and altered. Concerns about competitiveness and sustainability require reformer methods and models for planning logistics operations (Aloui, Hamani, Derrouiche & Delahoche, 2021). Therefore, companies try to find new strategies for their logistics operations to cope with the sustainability issues and high competitiveness of the market (Aloui et al., 2020). In addition to these issues, inefficient logistics operations in urban areas also create congestion, carbon emission, noise, and space consumption problems (Cleophas, Cottrill, Ehmke & Tierney, 2019).

Collaboration may facilitate new approaches to cope with these new problems. In the context of supply chains, collaboration is realized when “two or more independent companies work jointly to plan and execute supply chain operations with greater success than when acting in isolation” (Simatupang & Sridharan, 2002). As Gonzalez-Feliu & Salanova (2012) suggest, logistics stakeholders have been led to examine collaborative strategies to curtail costs of the supply processes. Collaboration between the businesses or companies indeed promises positive outcomes for all pillars of the logistics industry such as service providers, customers, citizens, and the community itself. Collaboration among the parties may lead to more efficient transportation operations in terms of fewer vehicles, less pollution, decreased transportation costs, and lower prices for end products (Cleophas et al., 2019). Thus, increased efficiencies via collaboration in logistics design and planning processes may have a great impact on social welfare and peace in society (Rao et al., 2015).

In terms of collaboration, parties can collaborate on two dimensions: horizontal and vertical. In vertical scheme, different levels of the supply network cooperate such as manufacturers, customers, suppliers, and distributors (Saenz, Ubaghs & Cuevas, 2014). In horizontal collaboration, stakeholders acting at the same level of the supply chain cooperate. Those stakeholders may or may not be competitors of each other, i.e, they may be part of the same supply chain network or not (Soysal, Bloemhof-Ruwaard, Haijema & Vorst, 2018). Different types of collaboration can be seen in Figure 2.1.

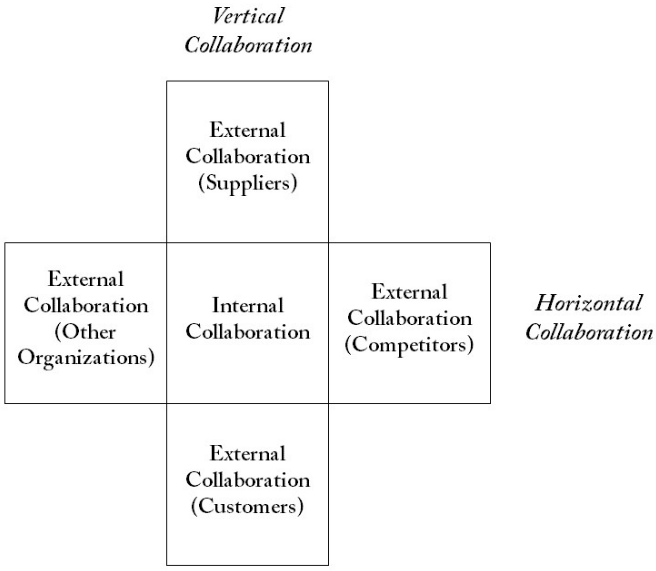


Figure 2.1 Collaboration Types (Barratt, 2004)

In the recent years, both academic research and professional practice have focused on horizontal collaboration in logistics systems because of the promised outcomes in terms of multiple benefits such as decreased costs and emissions, increased customer satisfaction rates, and profits (Pan, Trentesaux, Ballot & Huang, 2019). Horizontal collaboration can be utilized at different decision-making levels. As Defryn, Sörensen & Dullaert (2019) indicate, most of the previous work in the context of horizontal collaboration, focused on transportation optimization at the operational and tactical levels. According to Verdonck, Beullens, Caris, Ramaekers & Janssens (2016), research that focuses on the strategic level aims to design common supply networks to achieve economies of scale, but the number of such studies is not sufficient. The majority of the studies that focus on all different levels try to minimize costs or maximize profits.

Two common approaches are used for horizontal collaboration problems which focus on the operational level, capacity-sharing, and order-sharing (Verdonck, Caris, Ramaekers & Janssens, 2013). In the capacity sharing, stakeholders i.e., carriers or shippers, try to decide on whether they will share their vehicle capacities with the other parties or not (Defryn et al., 2019). In the second approach, all or some of the orders can be shared with the other parties so that they can satisfy those orders. According to Aloui et al. (2021), most of the studies at the operational level are related to variants of VRP. The main motivation behind those studies coincides with the findings of Chabot, Bouchard, Legault-Michaud, Renaud & Coelho (2018) who claim that outcomes of joint route planning or collaborative strategies through horizontal collaborative schemes pledge better economic benefits and environmental gains.

In terms of collaborative vehicle routing (VRP-C), there exist different strategies to collaborate. Fusion or merging is one of those strategies in which two or more tasks are merged into one single task. According to Weng & Xu (2014), merging pledges lower costs. Exchanging demand is another method of collaboration; parties can swap, exchange, or transfer their demand requests to other carriers so that the overall cost of the network or single parties can be minimized. According to Pan et al. (2019), there exist two major approaches to exchange demand, auctions, and side payments. Berger & Bierwirth (2010) propose an arrangement mechanism-based MIP model for exchanging transportation requests to maximize the profit of the whole network without decreasing the individual profits of stakeholders and they report that in highly competitive environments, horizontal collaboration leads to increased profits. Özener, Ergun & Savelsbergh (2011) establish a lane exchange approaches for long-haul transportation problems to provide a decentralized demand transfer mechanism.

Hernández & Peeta (2011) focus on a time-dependent carrier collaboration problem where capacity varies over time so that carriers can utilize or provide capacity during routing. They model the problem as a minimum cost flow problem and use B&C to solve the problem. Another paradigm for collaboration is resource pooling where resources such as vehicles, warehouses, cross-docks etc., are pooled for the use of collaborators. Wang, Zhang, Guan, Peng, Wang, Liu & Xu (2020) solve a multi depot (MD) collaborative location network planning problem with time windows. They utilize a hybrid heuristic algorithm which consists of non-dominated sorting genetic algorithm, K-means clustering, and Clarke-Wright savings algorithm, to solve the problem and they conclude that the collaborative approach increase the efficiency. Lin (2008) studies a real-life problem of a multi-national logistics company and modeled their problem as an exact integer programming formulation. The model is based on classical pickup and delivery with time windows (PDPTW) in which a vehicle is allowed travel to transfer goods to another vehicle that returns to the depot if time window constraints are not violated. The authors compared proposed models with a new insertion-based construction heuristic and reported that cooperative scenarios are more cost-effective when compared to non-cooperative scenarios. Sprenger & Mönch (2014) establish a decision tool in which production companies can pool their vehicles to reduce transportation costs. Fernández, Roca-Riu & Speranza (2018) define a multi-depot VRP variant in which several carriers on the same horizontal level can satisfy other carriers' demands if a customer has demand from both carriers. They define two MILP formulations for a centralized approach and derive valid inequalities for each formulation. The authors proposed a branch and cut algorithm to solve both formulations. They showed that collaboration among carriers leads to cost savings up to almost 21.2%.

Besides the operational and tactical levels, some studies focus on the strategic level as well. According to Aloui et al. (2021), strategic-level decisions are less studied in the context of collaborative planning despite the fact that they are the most essential part of supply chain management. The majority of the studies under the strategic-level section mainly focus on economic aspects. The number of studies that aim to optimize environmental or social aspects is narrow.

Hernández, Unnikrishnan & Awale (2012) define a multi-hub location problem with a centralized horizontal collaborative setting in which different Less-Than-Truckload (LTL) carriers can open joint consolidation transshipment points. The authors describe a new MILP which is a variant of $p$-hub location model and solved it via Lagrangian relaxation. They report that collaboration lead to cost savings, especially in small networks, and pledges more saving opportunities for small-sized LTL carriers. Pan, Ballot & Fontane (2013) investigate the environmental effect of the pooling of warehouses and distribution centers in a classical distribution network in which different companies shared their WHs and DCs for common usage. They provide a MILP formulation with two different objective functions depending on the transportation modes: road, and rail. They test their models with 2 real French companies' data. They report that pooling yields up to 14% savings in terms of carbon dioxide emissions. Fernández & Sgalambro (2020) define several models to investigate collaborative approaches for hub location problems in decentralized environments.

Nataraj et al. (2019), define a single echelon LRP in which the locations of urban consolidation centers and consequent routes are determined simultaneously. They utilized biased randomization (BR) technique to find good-quality solutions. They embedded BR into an Iterative Local Search (ILS) algorithm which they call BR-ILS. The authors investigate four different collaboration scenarios where collaboration level change. The results indicate that overall warehousing and maintenance costs decrease, service levels increase, and carbon emission levels decrease by the virtue of collaboration. Verdonck et al. (2016) describe a collaborative scheme and MILP for a 2E-FLP and takes into consideration that a carrier can prefer or not prefer to join cooperation. Only the carriers who are in cooperation can open joint depots. They conduct computational studies by using a commercial solver on a UK-based case study. They report that overall costs are decreased by 9.1% in average via collaboration. Tang, Lehuédé & Péton (2016) propose a MILP to solve a FLP for a centralized supply network to find the optimal locations for intermediate storage facilities, i.e., regional depots. In other words, all resources are pooled, and decisions are made in a centralized context in which all pillars act like one single entity. Ouhader & Kyal (2017) define a collaborative 2E-LRP in a full centralized manner in which the demand of each customer can be met from any opened intermediate satellite. All satellites and routes are constructed jointly. The authors have propose a MILP where the objective function consists of cost, carbon emissions, and created job opportunities that cover all pillars of sustainability. They showed that collaboration can lead to reduced costs and carbon emissions. However, as expected, collaboration can negatively affect the social aspects such as created job opportunities.

To the best of our knowledge, no work considers a two-echelon location routing problem in which carriers on the same horizontal level can complete other carriers' LTL delivery requests on the second echelon and first echelon deliveries are completed as direct shipments. Our goal is to provide a pragmatic definition of a distribution network design problem for a centralized collaborative scheme, present exact and matheuristic surrogate formulations as mixed integer-linear programming models, enhance those formulations with valid inequalities and solve them using a commercial solver. We examine the solutions not only in terms of computational aspects such as solution time and quality but also with respect to managerial insights like the effects of network structure, collaboration amount, joint facility decisions.

# 3. PROBLEM DEFINITION & MATHEMATICAL MODELS

We consider a distribution network design problem: multiple companies (carriers) operating over the same network are willing to collaborate to reduce costs. The network consists of plants where the goods are produced, regional depots where the goods are stored and customers which have demands from carriers. As Klibi, Martel & Guitouni (2016) indicate, w.l.o.g. goods are assumed to be aggregated as a single entity since they use same technology in terms of storing and handling.

Each company has one plant, numerous possible regional depot locations and customers. It is assumed that some of the customers have demand from multiple carriers; these customers are called *common* customers. In the context of collaboration, the demand of a common customer can be satisfied by one of the carriers which already has that customer in its own system. Demand from a customer can not be splitted among carriers. If a carrier is going to satisfy the demand of a customer which belongs to another carrier, then this carrier should satisfy the whole demand which emerges from other carrier. Goods are sent from plants to regional depots; then they are distributed from regional depots to customers. Transportation of the goods from plants to regional depots is direct and called inbound transportation. Transportation from regional depots to customers (outbound transportation) is conducted as milkrun shipments where vehicles follow routes in which several customers are visited in a specific order. For a carrier ($A$) to satisfy another carrier's ($B$) demand of a common customer from one of its depots, the goods should be sent from one of the regional depots of $B$ to this specific regional depot of $A$.

## 3.1 Problem Definiton

In the planning network, $N$ denotes the set of customers. $C$ represents the set of operating companies (i.e, carriers). $D$ denotes the candidate regional depot locations for the system where $D_r$ is the possible depot locations for carrier $r \in C$. $P$ is the set of all plants where $P_r$ is the set of plants of carrier $r$. $S_r$ is the set of carriers that has at least one common customer with carrier $r$, including $r$. In our case, each carrier $r \in C$ has a single plant. Let $G = (V, A)$ be the underlying network where $V = N \cup D \cup P$ represents the set of all vertices and $A = \{(V \times V) \setminus ((N \times P) \cup (P \times N))\}$ is the set of arcs connecting each pair of the vertices, except the ones which connect plant and customers. For each arc $(i, j) \in A$, there is a arc traversing cost $c_{ij}$. For each regional depot $d \in D_r$ of each carrier $r \in C$, there is a homogeneous fleet of vehicles with capacity $Q$. For any customer $i \in N$, $d_i^r$ represents the amount of demand of customer $i$ from carrier $r$. If $d_i^r > 0$ then $i$ is a customer of carrier $r \in C$. $N_r$ represents the set of customers which belong to carrier $r \in C$. On the other hand, $C_i$ is the set of carriers which has $i$ as a customer. Undoubtedly, if a customer $i \in N$ has a demand from carrier $r \in C$, then $i \in N_r$ and $r \in C_i$. A customer $i \in N$ can be visited in multiple routes. In other words, the demand that belong to a customer and emerge from different carriers can be satisfied by different routes.

If a customer only has a demand from one specific carrier (i.e $|C_i| = 1$ and $C_i = \{r^*\}$) than this demand should be satisfied in one of the routes which originates from one of depots of $r^*$: $d^* \in D_{r^*}$. In contrast, if a customer has demand from more than one carrier (i.e $|C_i| > 1$), then $d_i^r$ can be satisfied by one of the depots of these carriers $r \in C_i$. In other words, it can be satisfied from one of the depots of the carrier which demand is from, or it can be transferred to another carrier. For instance, carrier $A$ can serve customer $i$'s demand $d_i^B$ and carrier $B$ can serve customer $i$'s demand $d_i^A$, which means carriers are allowed to interchange demands, assuming that customer $i$ has demand from both carriers $A$ and $B$. A specific demand can not be splitted among carriers. If there exist a demand $d_i^r > 0$, then it must be completely delivered in one the routes of carrier $r \in C_i$.

In our problem, a carrier $r \in C$ can only visit the customers that already has demand from that carrier, i.e $N_r$. In any route which originates from any depot $d \in D_r$ of carrier $r$, only arcs that can be traversed are $A^{rd} = \{(i, j) \in A : i, j \in N_r$, or $(i = d$ and $j \in N_r)$, or $(i \in N_r$ and $j = d)\}$. If a demand is satisfied by another carrier, then this demand amount should be transferred between depots of those carriers. In order to transfer that amount, a transfer line between the corresponding depots must be established.

Among the strategic decisions involved in operating and managing such systems, we focus on determining number and location of regional depots and pairs of carrier depots between which transfer lines are to be established. In addition to that, direct transportation for inbound transportation and routing decisions for outbound transportation are also considered. Flow of goods from plants to depots, depots to other carriers' depots and depots to customers are determined as well. A general representation of the network structure can be found in Figure 3.1.

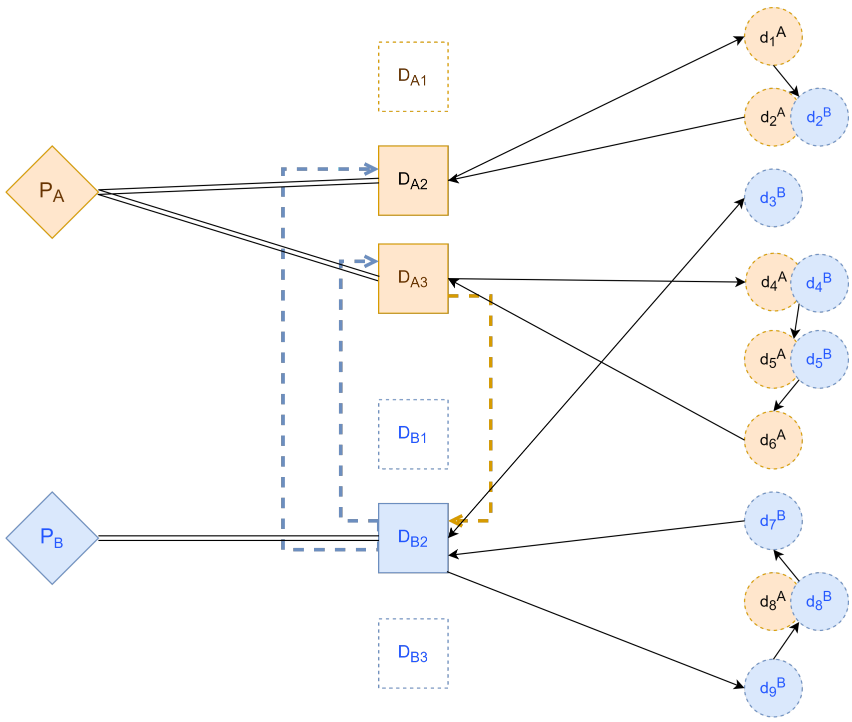


Figure 3.1 Sample network for two carriers

We illustrate the problem with an example and show how the carriers can collaborate. Figure 3.2 depicts a small example with 2 carriers: $A$ and $B$. Each carrier has one plant: $P_A$ and $P_B$ for carriers $A$ and $B$, respectively. Carrier $A$ has two possible depot locations, $D_A = \{1,2\}$ and carrier $B$ has only one possible depot location $D_B = \{3\}$. There are three customers, $N = \{4,5,6\}$. Customer 4 has only demand from carrier $A$, customers 5 and 6 have demand from both carriers. Related inbound line, transfer line and outbound route construction costs are depicted on arcs and based on distances between nodes. Regional depot opening and maintenance costs are shown above regional depots. Vehicle capacity $Q$ is 20 units.

Figure 3.3 (b) shows the result for the non-collaborative scenario. For the non-collaborative scenario, carrier $A$ opens depot 1 and constructs 2 routes from this depot. One route only serves to customer 4; another route serves customers 5 and 6. Carrier $B$ opens depot 3 and creates 2 routes for two customers, 5 and 6. Since $Q = 20$, $d_5^B = 11$ and $d_6^B = 14$ have to be delivered in different routes. In non-collaborative scenario, inbound line cost for carrier $A$ is 16, regional depot cost is 17, and outbound routing costs are 53; total cost of carrier $A = 16+17+53 = 86$. For carrier $B$, inbound line cost is 10, regional depot cost is 25, and outbound routing costs are 66; total cost of carrier $B = 10+25+66 = 101$. Therefore, total cost for

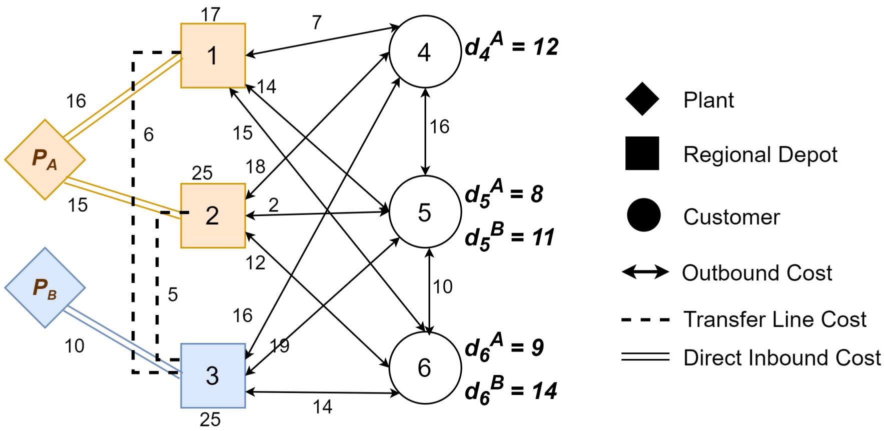


Figure 3.2 A small instance

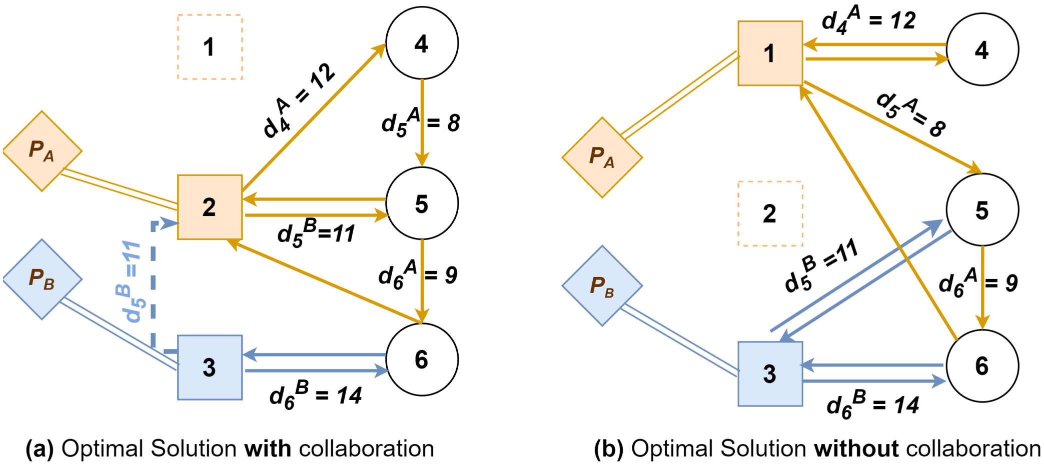


Figure 3.3 Results for collaborative and non-collaborative scenarios

non-collaborative scenario is 187.

Figure 3.3 (a) shows the result for a collaborative scenario. In this scenario carrier $A$ opens depot 2. Carrier $B$ opens depot 3 and creates a transfer line between depots 3 and 2. $B$ transfers $d_5^B$ to carrier $A$ and sends this amount to depot 2 which belongs to carrier $A$. Carrier $A$ constructs two routes from depot 2. In the first route, it serves its own demands for customers 4 and 5; $d_4^A$ and $d_5^A$. In the second route, it serves its own demand for customer 6 and customer 5's demand which is transferred from carrier $B$; i.e $d_6^A$ and $d_5^B$. Carrier $B$ constructs only one route to serve demand $d_6^B$. In collaborative scenario, for carrier $A$ inbound line cost is 15, regional depot cost is 25, and outbound routing costs are 60; total cost for carrier $A = 15 + 25 + 60 = 100$. For carrier $B$, inbound line cost is 10, regional depot cost is 25, and outbound routing costs are 28. In addition to that, transfer line cost is incurred to carrier $B$ since it constructed a transfer line between depots 3 and 2, which is equal to 5. Total cost of carrier $B = 10 + 25 + 28 + 5 = 68$. Therefore, total cost for collaborative scenario is 168. In this instance, collaboration led to cost savings up to approximately 10% for centralized system: 187 vs 168.

For the problem setting, we make the following assumptions:

- There are enough items in plants to satisfy demand.
- Regional depots has unlimited capacity for handling goods, but once one depot is used, opening and maintenance costs are incurred.
- All the locations for plants, candidate regional depots and customers and distances between those locations are known in advance.
- Demand for each customer is known in advance.
- Demand of each customer from each carrier is less than Q.
- Homogeneous vehicle fleets are used.
- The set of common customers is known in advance.
- There is a centralized decision making process.

The objective of this collaborative goods distribution network design problem is to minimize the costs which arise from regional depot opening and maintenance, direct inbound transportation, outbound transportation and transfer line construction between regional depots. Alternative mathematical models are proposed to solve this strategic network design problem. Mathematical models differ in terms of formulating outbound transportation operations.

Parameters and sets which are common for all models are defined in Table 3.2.

Table 3.1 Common notation for all three models

| Set | Definition | |
|---|---|---|
| $C$ | set of carriers | |
| $N$ | set of customers | |
| $P$ | set of plants | |
| $D$ | set of possible regional depot locations | |
| $D_r$ | set of possible regional depot locations for carrier $r$ | $\forall r \in C$ |
| $P_r$ | set of plants that belong to carrier $r$ | $\forall r \in C$ |
| $N_r$ | set of customers that have demand from carrier $r$ | $\forall r \in C$ |
| $C_i$ | set of carriers that have $i$ as a customer | $i \in N$ |
| $d_i^r$ | demand of customer $i$ from carrier $r$ | $i \in N, r \in C$ |
| $S_r$ | set of carriers that has at least one common | |
| | customer with carrier $r$, including $r$ | $r \in C$ |
| $V$ | vertex set including regional depots and customers | |
| | $V = N \cup D \cup P$ | |
| $A$ | arcs in the network: $A = \{(V \times V) \setminus ((N \times P) \cup (P \times N))\}$ | |
| $c_{ij}$ | cost of traversing arc $(i,j)$ | $(i,j) \in A$ |
| $B_{rd}$ | cost of opening and operating regional depot $d$ | |
| | of the carrier $r$ | $\forall r \in C, d \in D_r$ |
| $\Delta_{prd}$ | inbound transfer line construction cost | $\forall r \in C, d \in D_r$ |
| | from plant $p$ to depot $d$ of carrier $r$ | $p \in P_r$ |
| $F_{d,d'}$ | cost of constructing a transfer line between | |
| | regional depots $d$ to $d'$ $\quad \forall r \in C, d \in D_r, s \in S_r,$ | $d' \in D_s, r \neq s$ |
| $A^{rd}$ | possible arcs that can be traversed in a route | |
| | that is assigned to carrier $r$'s depot $d$ | |
| | $A^{rd} = \{(i,j) \in A : i,j \in N_r$, or $(i = d$ and $j \in N_r)$ | |
| | $(i \in N_r$ and $j = d)\}$ | $\forall r \in C, d \in D_r$ |

In all models $y_{rd}$, $v_{d'd}$, $\delta_{prd}$, $\pi_{d'd}$, $u_{prd}$ and $w_{srd}$ are common decision variables. The binary decision variable $y_{rd}$ is equal to 1 if regional depot $d$ which belongs to carrier $r$ is opened; 0, otherwise, $\forall r \in C, d \in D_r$. Binary decision variable $v_{d'd}$ is equal to 1 if a transfer line established between depots $d'$ and $d$ that belong to different carriers; 0, otherwise. The binary decision variable $\delta_{prd}$ is equal to 1 if a inbound transfer line is constructed between plant $p$ and regional depot $d$ of carrier $r$; 0, otherwise. Continuous decision variable $\pi_{d'd}$ represents the amount of goods transferred between regional depots $d'$ and $d$, $u_{prd}$ represents the amount of goods sent from plant $p$ to regional depot $d$ of carrier $r$. $w_{srd}$ denotes a continuous auxiliary decision variable used to calculate amount of demand of carrier $s$ which is satisfied by carrier $r$'s regional depot $d$. In the subsequent sections, additional new decision variables and parameters are defined depending on the mathematical model.

Table 3.2 Common decision variables for all three models

| **Dec. Var.** | **Definition** |
|---|---|
| $y_{rd}$ | 1 if regional depot $d$ which belongs to carrier $r$ is opened |
| $v_{d\prime d}$ | 1 if a transfer line established between depots $d\prime$ and $d$ that belong to different carriers; 0, otherwise |
| $\delta_{prd}$ | 1 if a inbound transfer line is constructed between plant $p$ and regional depot $d$ of carrier $r$; 0, otherwise |
| $\pi_{d\prime d}$ | amount of goods transferred between regional depots $d\prime$ and $d$ |
| $u_{prd}$ | amount of goods sent from plant $p$ to regional depot $d$ of carrier $r$ |
| $w_{srd}$ | amount of demand of carrier $s$ which is satisfied by carrier $r$'s regional depot $d$ |

### 3.2.1 Model 1: Vehicle-Based Formulation

In the first mathematical model, outbound routing decisions are denoted by decision variables which are representing arc traversals by vehicles. This model yields an exact solution to the problem. We define an additional parameter $K_{rd}$ for each depot $d \in D_r$ of carrier $r \in C$ which represents the set of vehicles that belong to depot $d$. We define two additional binary decision variables $z$ and $x$. $z^k_{irsd}$ is equal to 1 if demand $d^r_i$ is assigned to vehicle $k$ of depot $d$ which belongs to carrier $s$, for $i \in N, r \in C_i, s \in C_i, d \in D_s, k \in K_{sd}$; 0, otherwise. For each carrier $r \in C$ and depot $d \in D_r, k \in K_{rd}, (i,j) \in A^{rd}$, $x^k_{ij}$ is equal to 1, if arc $(i,j)$ is traversed by vehicle $k$, 0 otherwise. The resulting formulation becomes

$$\text{(3.1)} \quad \text{minimize} \quad \sum_{r\in C}\sum_{d\in D_r}\sum_{k\in K_{rd}}\sum_{(i,j)\in A^{rd}} c_{ij}x_{ij}^k + \sum_{r\in C}\sum_{d\in D_r} B_{rd}y_{rd} + \sum_{r\in C}\sum_{d\in D_r}\sum_{\substack{s\in S_r \\ s\neq r}}\sum_{d'\in D_s} F_{dd'}v_{dd'} + \sum_{r\in C}\sum_{d\in D_r}\sum_{p\in P_r} \Delta_{prd}\delta_{prd}$$

subject to

$$\text{(3.2)} \quad \sum_{s\in C_i}\sum_{d\in D_s}\sum_{k\in K_{sd}} z_{irsd}^k = 1 \qquad \forall i\in N, r\in C_i$$

$$\text{(3.3)} \quad \sum_{j\in N_r} x_{d,j}^k \leq 1 \qquad \forall r\in C, d\in D_r, k\in K_{rd}$$

$$\text{(3.4)} \quad \sum_{\substack{j\in N_r\cup\{d\} \\ i\neq j}} x_{j,i}^k - \sum_{\substack{j\in N_r\cup\{d\} \\ i\neq j}} x_{i,j}^k = 0 \quad \forall r\in C, d\in D_r, k\in K_{rd}, i\in N_r$$

$$\text{(3.5)} \quad \sum_{i\in N_r}\sum_{s\in C_i} z_{isrd}^{k-1} \geq \sum_{i\in N_r}\sum_{s\in C_i} z_{isrd}^k \qquad \forall r\in C, d\in D_r, k\in K_{rd}\setminus min\{k : k\in K_{rd}\}$$

$$\text{(3.6)} \quad \sum_{i\in W}\sum_{\substack{j\in N_r\setminus W \\ \cup\{d\}, i\neq j}} x_{i,j}^k \geq z_{isrd}^k \quad \forall r\in C, d\in D_r, k\in K_{rd}, s\in S_r, W\subset N_r, i\in W\cap N_s$$

$$\text{(3.7)} \quad \sum_{i\in N_r}\sum_{s\in C_i} d_i^s z_{isrd}^k \leq Q \qquad \forall r\in C, d\in D_r, k\in K_{rd}$$

$$\text{(3.8)} \quad y_{rd}\sum_{i\in N}\sum_{r\in C} d_i^r \geq \sum_{i\in N_r}\sum_{s\in C_i}\sum_{k\in K_{rd}} z_{isrd}^k \qquad \forall r\in C, d\in D_r$$

$$\text{(3.9)} \quad w_{srd} = \sum_{i\in N_s\cap N_r}\sum_{k\in K_{rd}} d_i^s z_{isrd}^k \qquad \forall r\in C, d\in D_r, s\in S_r$$

$$\text{(3.10)} \quad \sum_{i\in N}\sum_{r\in C} d_i^r \sum_{d'\in D_s} v_{d',d} \geq w_{srd} \qquad \forall r\in C, d\in D_r, s\in S_r, r\neq s$$

$$\text{(3.11)} \quad \sum_{d'\in D_s} v_{d',d} \leq 1 \qquad \forall r\in C, d\in D_r, s\in S_r, r\neq s$$

$$\text{(3.12)} \quad \sum_{d'\in D_s} \pi_{d',d} = w_{srd} \qquad \forall r\in C, d\in D_r, s\in S_r, r\neq s$$

$$\text{(3.13)} \quad v_{d',d}\sum_{i\in N}\sum_{r\in C} d_i^r \geq \pi_{d',d} \qquad \forall r\in C, d\in D_r, s\in S_r, d'\in D_s, r\neq s$$

$$\text{(3.14)} \quad |D||D|y_{rd} \geq \sum_{d'\in D_s} v_{d,d'} \qquad \forall r\in C, d\in D_r, s\in S_r, r\neq s$$

$$(3.15) \quad \delta_{prd} \sum_{i \in N} \sum_{r \in C} d_i^r \geq u_{prd} \qquad \forall r \in C, d \in D_r, p \in P_r$$

(3.16)

$$\sum_{p \in P_r} u_{prd} + \sum_{\substack{s \in S_r \\ s \neq r}} w_{srd} - \sum_{\substack{s \in S_r \\ s \neq r}} \sum_{d' \in D_s} \pi_{d,d'} = \sum_{i \in N_r} \sum_{s \in C_i} \sum_{k \in K_{rd}} d_i^s z_{isrd}^k \quad \forall r \in C, d \in D_r$$

$$(3.17) \quad x_{ij}^k \in \{0,1\} \qquad \forall r \in C, d \in D_r, k \in K_{rd}, (i,j) \in A^{rd}$$

$$(3.18) \quad z_{irsd}^k \in \{0,1\} \qquad \forall i \in N, r, s \in C_i, d \in D_s, k \in K_{sd}$$

$$(3.19) \quad y_{rd} \in \{0,1\} \qquad \forall r \in C, d \in D_r$$

$$(3.20) \quad v_{d',d} \in \{0,1\} \qquad \forall r \in C, d \in D_r, s \in S_r, d' \in D_s, r \neq s$$

$$(3.21) \quad \delta_{prd} \in \{0,1\} \qquad \forall r \in C, d \in D_r, p \in P_r$$

$$(3.22) \quad u_{prd} \in \mathbb{R}_+ \qquad \forall r \in C, d \in D_r, p \in P_r$$

$$(3.23) \quad \pi_{d',d} \in \mathbb{R}_+ \qquad \forall r \in C, d \in D_r, s \in S_r, d' \in D_s, r \neq s$$

$$(3.24) \quad w_{srd} \in \mathbb{R}_+ \qquad \forall r \in C, d \in D_r, s \in S_r$$

The objective function (3.1) minimizes total cost which arise from outbound transportation, opening and operating depots, inbound transportation and transfer line construction between depots. Constraints (3.2) guarantee that each demand that a customer has from its own carriers, is satisfied by a possible carrier (any carrier that has this customer) once. Constraints (3.3) guarantee that each vehicle can leave a depot at most one time. Constraints (3.4) ensure that a vehicle visiting a customer should leave that customer. Moreover, constraints (3.3) and (3.4) work together to describe flow equality in the vehicle routes. Constraints (3.5) depict that a vehicle with a higher index can not be utilized if another vehicle with a lower index is not utilized from a depot of the same carrier. In other words, the model orders used vehicles in ascending order. Constraints (3.6) guarantee two restrictions. For $W = \{i\}$, they ensure that if the demand $d_i^s$ is assigned to any vehicle $k \in K_{rd}$ of depot $d \in D_r$ of carrier $r \in C_i$, then this vehicle visits customer $i$. Moreover, they ensure that subtours are not generated since if a customer in set $W$ is visited by a vehicle $k \in K_{rd}$ then that vehicle use at least one arc which leaves set $W$. Constraints (3.7) guarantee that vehicle capacities is not exceeded. Constraints (3.8) indicate that demand can not be satisfied from a depot if the depot is not opened. Constraints (3.9) are used to calculate amount of demand that originally belongs to carrier $s \in C$ but satisfied from carrier $r$'s depot $d$. Constraints (3.10) guarantee that a transfer line should be constructed from one of the depots of the other carrier to the that depot if a carrier satisfied another carrier's demand from its depot. Constraints (3.11) work with constraints (3.10) to ensure that at most one transfer line can be constructed from a carrier's depots to another carriers' one specific depot. Constraints (3.12) calculates the amount that should be transferred between depots. Constraints (3.13) guarantee that there can not be any flow of goods between different carriers' depots if transfer line among these depots is not constructed. Constraints (3.14) ensure that a transfer line can not be constructed which originates from that depot if the depot is not opened. Constraints (3.15) guarantee that goods can not be transferred between a plant and a depot if inbound line is not constructed between a plant and a depot. Constraints (3.16) guarantee the flow balance of goods and ensure the enough amount of goods are transferred from plants to depots. Constraints (3.17), (3.18), (3.19), (3.20), (3.21), (3.22), (3.23) and (3.24) define the domains and ranges of the decision variables.

### 3.2.2 Model 2: Load-Based Formulation

In the second mathematical model, outbound routing decisions are modeled with decision variables representing amount of loads carried. Main motivation is to decrease high number of binary variables that are used to define outbound routing decisions (i.e., $x_{ij}^k$). Instead of using a binary decision variable to determine whether a vehicle which belongs to a depot of a carrier is using an arc or not, we define a new arc variable which uses an aggregated form of using arcs originating from a depot. If route originating from depot $d$ of carrier $r$, $r \in C, d \in D_r$, uses arc $(i,j) \in A^{rd}$, binary decision variable $x_{ij}^{rd}$ takes value 1; otherwise, it takes 0. Decreased number of binary variables $x$ is traded with new defined continuous variables $l$ which are used to control overall load of the routes on the traversed arcs. $l_{ij}^{rdh}$ represents the load carried on arc $(i,j) \in A^{rd}$ to serve customer $h \in N_r$ on a route originating from depot $d \in D_r$ of carrier $r \in C$. Lastly, as in the $x$ variables, vehicle index is dropped for allocation variable $z$ as well. New binary allocation variable $z_{irsd}$ is equal to 1 if $d_i^r$ is assigned to any route which originates from depot $d \in D_s$, $s \in C_i$; 0, otherwise. The resulting formulation becomes

$$\text{(3.25)} \quad \text{minimize} \quad \sum_{r\in C}\sum_{d\in D_r}\sum_{(i,j)\in A^{rd}} c_{ij}x_{ij}^{rd} + \sum_{r\in C}\sum_{d\in D_r} B_{rd}y_{rd} + \sum_{r\in C}\sum_{d\in D_r}\sum_{\substack{s\in S_r\\ s\neq r}}\sum_{d'\in D_s} F_{dd'}v_{dd'} + \sum_{r\in C}\sum_{d\in D_r}\sum_{p\in P_r}\Delta_{prd}\delta_{prd}$$

subject to

$$\text{(3.26)} \quad \sum_{s\in C_i}\sum_{d\in D_s} z_{irsd} = 1 \qquad \forall i\in N, r\in C_i$$

$$\text{(3.27)} \quad \sum_{\substack{j\in N_r\cup\{d\}\\ i\neq j}} x_{j,i}^{rd} - \sum_{\substack{j\in N_r\cup\{d\}\\ i\neq j}} x_{i,j}^{rd} = 0 \qquad \forall r\in C, d\in D_r, i\in N_r$$

$$\text{(3.28)} \quad \sum_{\substack{j\in N_s\cup\{d\}\\ i\neq j}} x_{i,j}^{sd} \geq z_{irsd} \qquad \forall i\in N, r,s\in C_i, d\in D_s$$

$$\text{(3.29)} \quad \sum_{j\in N_r} l_{d,j}^{rdi} = \sum_{s\in C_i} d_{is}z_{isrd} \qquad \forall r\in C, d\in D_r, i\in N_r$$

(3.30)

$$\sum_{\substack{j\in N_r\cup\{d\}\\ i\neq j}} l_{i,j}^{rdh} - \sum_{\substack{j\in N_r\cup\{d\}\\ i\neq j}} l_{j,i}^{rdh} = \begin{cases} -\sum_{s\in C_i} d_{is}z_{isrd} & \text{if } i=h \\ 0 & \text{if } i\neq h \end{cases} \qquad \forall r\in C, d\in D_r, i,h\in N_r$$

$$\text{(3.31)} \quad \sum_{h\in N_r} l_{i,j}^{rdh} \leq Qx_{i,j}^{rd} \qquad \forall r\in C, d\in D_r, (i,j)\in A^{rd}$$

$$\text{(3.32)} \quad y_{rd}\sum_{i\in N}\sum_{r\in C} d_i^r \geq \sum_{i\in N_r}\sum_{s\in C_i} z_{isrd} \qquad \forall r\in C, d\in D_r$$

$$\text{(3.33)} \quad w_{srd} = \sum_{i\in N_s\cap N_r} d_i^s z_{isrd} \qquad \forall r\in C, d\in D_r, s\in S_r$$

$$(3.10)-(3.15)$$

$$\text{(3.34)} \quad \sum_{p\in P_r} u_{prd} + \sum_{\substack{s\in S_r\\ s\neq r}} w_{srd} - \sum_{\substack{s\in S_r\\ s\neq r}}\sum_{d'\in D_s}\pi_{d,d'} = \sum_{i\in N_r}\sum_{s\in C_i} d_i^s z_{isrd} \qquad \forall r\in C, d\in D_r$$

$$\text{(3.35)} \quad x_{ij}^{rd}\in\{0,1\} \qquad \forall r\in C, d\in D_r, (i,j)\in A^{rd}$$

$$\text{(3.36)} \quad z_{irsd}\in\{0,1\} \qquad \forall i\in N, r,s\in C_i, d\in D_s$$

$$\text{(3.37)} \quad l_{ij}^{rdh}\in\mathbb{R}_+ \qquad \forall r\in C, d\in D_r, (i,j)\in A^{rd}, h\in N_r$$

$$(3.19) - (3.24)$$

Constraints (3.26) ensure that demand of each customer is satisfied by a possible carrier. Constraints (3.27) guarantee the flow equality of incoming and outgoing arcs to customers in an aggregated route which belongs to depot $d$ of carrier $r$. Constraints (3.28) ensure that at least one arc must be activated if any of that customer's demand is assigned to any route of depot $d$ of carrier $s$. In other words, if a demand is assigned to a route which originates from depot $d$, then the customer must be visited at least once. Constraints (3.29) ensure that amount of satisfied demand which belongs to customer $h$ in a route of depot $d$ leaves that depot $d$. Constraints (3.30) guarantee that required amount of assigned demands are delivered by the routes of depot $d$ to customer $h$ if $i = h$. They also guarantee that no load is served if $i \neq h$. Constraints (3.31) depicts that amount of load served in a route can not exceed the vehicle capacity. They also relate the variables $l$ and $x$ and ensure that any load can not be carried on an arc if the arc is not used. Constraints (3.32) indicate that any demand can not be satisfied from a regional depot if the depot is not opened. Constraints (3.33) are used to calculate amount of demand that originally belongs to carrier $s \in C$ but is satisfied from carrier $r$'s depot $d$. Constraints (3.34) guarantee the flow balance of goods and ensure that a sufficient amount of goods are transferred from plants to depots. Constraints (3.35), (3.36) and (3.37) define the domains and ranges of the decision variables.

### 3.2.3 Model 3: Path-Based Formulation

In the path-based formulation, outbound routes are not constructed within by the formulation. Instead, they are selected among heuristically pre-generated routes. We define an additional parameter $R$ which denotes the set of pre-generated routes. For the heuristic route creation, problem is decomposed for each carrier $r \in C$ and solved as a single depot VRP for each depot of each carrier $d \in D_r$. Then all routes in each solution are united into a master route list. Parameter $R_d$ represents the set of routes which belongs to depot $d \in D_r$. $\alpha^t_{ird}$ is the assignability parameter; it is equal to 1 if demand $d^r_i$ can be assigned to route $t \in R_d$, $r \in C, d \in D_r$; 0, otherwise. In other words, $\alpha^t_{ird}$ is 1 if customer $i$ is included in route $t$ and $i$ has demand from the carrier who owns this route. In this respect, we define the binary decision variable $x^t$ is equal 1 if route $t \in R$ is used and 0 otherwise. Binary allocation variable $z^t_{irsd}$ is equal to 1 if demand $d^r_i$ is assigned to route $t \in R_s$ which originates from depot

$d \in D_s$ of carrier $s \in C$. The cost parameter $c$ is altered as $c^t$ and denotes the length of route $t$.

$$\text{(3.38)} \qquad \text{minimize} \quad \sum_{t\in R} x^t c^t + \sum_{r\in C}\sum_{d\in D_r} B_{rd}y_{rd} + \sum_{r\in C}\sum_{d\in D_r}\sum_{\substack{s\in S_r\\ s\neq r}}\sum_{d'\in D_s} F_{dd'}v_{dd'} + \sum_{r\in C}\sum_{d\in D_r}\sum_{p\in P_r} \Delta_{prd}\delta_{prd}$$

subject to

$$\text{(3.39)} \qquad \sum_{s\in C_i}\sum_{d\in D_s}\sum_{t\in R_d} z^t_{irsd} = 1 \qquad \forall i \in N, r \in C_i$$

$$\text{(3.40)} \qquad x^t \geq z^t_{isrd} \qquad \forall i \in N, s, r \in C_i, d \in D_r, t \in R_d$$

$$\text{(3.41)} \qquad z^t_{isrd} \leq \alpha^t_{ird} \qquad \forall i \in Ns, r \in C_i, d \in D_r, t \in R_d$$

$$\text{(3.42)} \qquad \sum_{i\in N_r}\sum_{s\in C_i} d^s_i z^t_{isrd} \leq Q \qquad \forall r \in C, d \in D_r, t \in R_d$$

$$\text{(3.43)} \qquad y_{rd}\sum_{i\in N}\sum_{r\in C} d^r_i \geq \sum_{i\in N_r}\sum_{s\in C_i}\sum_{t\in R_d} z^t_{isrd} \qquad \forall r \in C, d \in D_r$$

$$\text{(3.44)} \qquad w_{srd} = \sum_{i\in N_s\cap N_r}\sum_{t\in R_d} d^s_i z^t_{isrd} \qquad \forall r \in C, d \in D_r, s \in S_r$$

$$(3.10) - (3.15)$$

$$\text{(3.45)} \quad \sum_{p\in P_r} u_{prd} + \sum_{\substack{s\in S_r\\ s\neq r}} w_{srd} - \sum_{\substack{s\in S_r\\ s\neq r}}\sum_{d'\in D_s} \pi_{d,d'} = \sum_{i\in N_r}\sum_{s\in C_i}\sum_{t\in R_d} d^s_i z^t_{isrd} \quad \forall r \in C, d \in D_r$$

$$\text{(3.46)} \qquad x^t \in \{0,1\} \qquad \forall r \in C, d \in D_r, t \in R_d$$

$$\text{(3.47)} \qquad z^t_{irsd} \in \{0,1\} \qquad \forall i \in N, r, s \in C_i, d \in D_s, t \in R_d$$

$$(3.19) - (3.24)$$

Constraints (3.39) guarantee that demand of each customer is satisfied by a possible carrier. Constraints (3.40) relate variables $x$ and $z$ and ensure that a route is used if a demand is assigned to that route. Constraints (3.41) ensure that a demand from a customer can be assigned to a route if and only if that route contains that customer. Constraints (3.42) guarantees that vehicle capacities are not exceeded. Constraints

(3.43) indicates any demand can not be satisfied from a regional depot if the depot is not opened. Constraints (3.44) are used to calculate amount of demand that originally belongs to carrier $s$ but it is satisfied from carrier $r$'s depot $d$. Constraints (3.45) guarantee the flow balance of goods and ensure that a sufficient amount is transferred from plants to depots. Constraints (3.46) and (3.47) define the domains and ranges of the decision variables.

# 4. VEHICLE-BASED FORMULATION

In the vehicle-based formulation, the number of sub-tour elimination constraints is exponential and the number of required binary variables for outbound routing is excessive. For the outbound routing decision variables, $x$, it is required to define $\sum_{r \in C} \sum_{d \in D_r} |K_{rd}||A^{rd}|$ many variables. This number is polynomial but increases the size significantly. In the original formulation, number of required constraints are polynomial except constraints (3.6). For the vehicle-based formulation, we propose an exact method for handling exponentially many constraints. The corresponding exact method is based on a cut generation scheme for sub-tour elimination constraints.

## 4.1 Cut generation for sub-tour elimination

Constraints (3.6) can be separated into two different constraints, one for connecting variables $x$ and $z$, and the other one to ensure that there are no sub-tours.

$$\sum_{\substack{j \in N_r \cup \{d\} \\ i \neq j}} x^k_{i,j} \geq z^k_{isrd} \qquad \forall i \in N, s \in C_i, r \in C_i, d \in D_r, k \in K_{rd} \tag{4.1}$$

$$\sum_{i \in W} \sum_{\substack{j \in W \\ j \neq i}} x^k_{i,j} \leq |W| - 1 \qquad \forall r \in C, d \in D_r, k \in K_{rd}, W \subseteq N_r \tag{4.2}$$

Constraints (4.1) ensure that a vehicle must visit a customer at least once if any demand of this customer is assigned to that vehicle. Constraints (4.2) guarantee that there is at least one arc which leaves customer set $W$ for each vehicle $K_{rd}$ so that it is ensured that no sub-tours are generated. Constraints (3.6) can be replaced with constraints (4.1) and (4.2).

We propose an exact method for handling exponentially many sub tour elimination constraints with the updated constraints (4.1) and (4.2). Initially, all sub-tour elimination constraints proposed in (4.2) are relaxed. Then, the relaxed version of the problem is solved. Using the active routing variables $\{x : x = 1\}$, a sub-graph $\bar{G}_x$ is constructed; all cycles in $\bar{G}_x$ are detected using the algorithm in Johnson (1975). Johnson's algorithm is used to detect all simple cycles in a graph since it has a time complexity of $\mathcal{O}((|V| + |E|)(C + 1)$, $C$ indicating all cycles in a given graph, which is polynomial. If there are no sub-tours in the solution, the method aborts the execution and reports the optimum solution. If there are sub-tours, current solution for variables $x$ is decomposed for each depot $d \in D_r, \forall r \in C$ while $x_d$ represents the active arcs which belong to any route of depot $d$. For each depot $d$, a sub-graph $\bar{G}_x^d$ is constructed. All simple cycles for each sub-graph $\bar{G}_x^d, \forall d \in D$, are identified using Johnson's algorithm. If any simple cycle includes depot $d$ itself, then nothing is identified. If there are sub-tours which do not include the depot, they are appended to a set $\Gamma$ which includes all sub-tours to be eliminated for the given depot $d$ in the current solution. Then sub-tour elimination constraints used to eliminate the sub-tours that are specific to the given depot are generated as in (4.3) and added to the model. Then, the model is resolved. As the iterations proceed, given solutions converges to a state in which no sub-tours are found. Flowchart of the method is represented in Figure 4.1.

$$\sum_{i \in \gamma} \sum_{\substack{j \in \gamma \\ j \neq i}} x_{ij}^k \leq |\gamma| - 1 \qquad \forall \gamma \in \Gamma \tag{4.3}$$

### 4.2 Valid Inequalities for Vehicle-Based Formulation

Number of required binary variables in the vehicle-based formulation is excessive. In order to strengthen the formulation and tighten the solution space several valid inequalities are proposed.

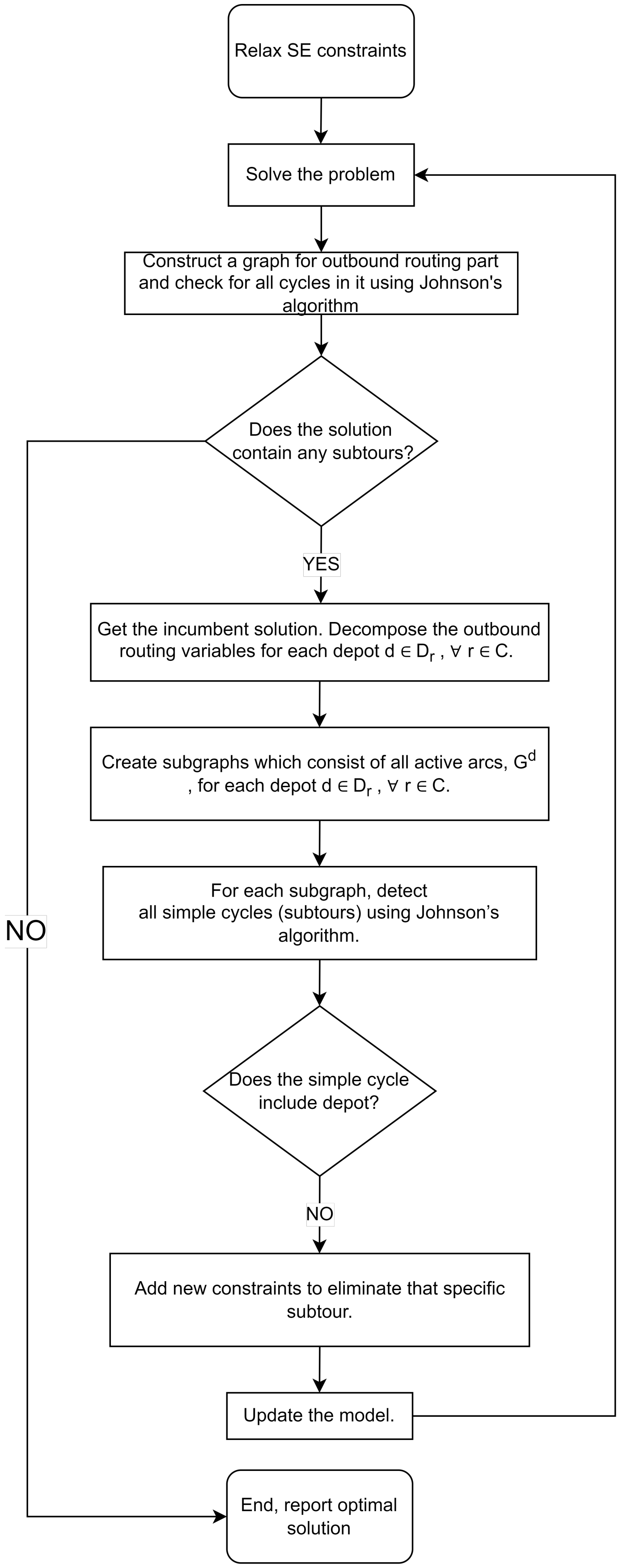


Figure 4.1 Cut generation method

### 4.2.1 Minimum Depot Valid Inequalities

For any instance, first echelon transportation operations are executed in a direct manner. In other words, inbound deliveries are conducted as direct transportation in which trucks do not ramble around depots. If there is collaboration among carriers than that collaboration must take place at the second echelon including transfer among depots and mutual routing. Consequently, each company has to open and operate at least one regional depot in the system, whether it participates in a collaboration or not. Therefore, inequalities (4.4) are valid for the vehicle-based formulation and impose that each carrier $r \in C$ must open at least one depot.

$$\sum_{d \in D_r} y_{rd} \geq 1 \qquad \forall r \in C \tag{4.4}$$

### 4.2.2 Two-Size Simple SEC Valid Inequalities

Sub-tour elimination is controlled by the constraints (3.6) in the original vehicle based formulation; they generate all constraints which eliminate all possible sub-tours. However, exponentially many constraints are required and a lower bound for required number of constraints is equal to $\sum_{r \in C} 2^{|N_r|}$ in the original formulation. So a cut generation based method proposed in Section 4.1 and in this method, sub-tour elimination constraints are relaxed; in each iteration, only required sub-tour elimination constraints are added to the model. In the early iterations, models are tend to create sub-tours of size 2. Inequalities (4.5) eliminate all two-size sub-tour possibilities. Thus, they also eliminate unnecessary iterations which are only conducted to eliminate two-size sub-tours.

$$x_{i,j}^{k} + x_{j,i}^{k} < 2 \quad \forall r \in C, d \in D_r, k \in K_{rd}, i, j \in N_r, i < j \tag{4.5}$$

### 4.2.3 Two-Size SEC Valid Inequalities

(4.6)

$$x^k_{i,j} + x^k_{j,i} \leq 2 - \left\lceil \frac{\sum_{s \in C_i} d^s_i z^k_{isrd} + \sum_{s \in C_j} d^s_j z^k_{jsrd}}{Q} \right\rceil \quad \forall r \in C, d \in D_r, k \in K_{rd}, i,j \in N_r, i < j$$

Extended version of (4.5) is proposed in (4.6) inequalities. If any demand of a customer $i$ or $j$ is assigned to a vehicle $k$, than this vehicle can travel only in one way among two different customer nodes i.e, $i$ and $j$. SECs are activated for customer pairs if some demand of these customers is assigned to a vehicle. The total amount of demand that is assigned to a vehicle can not exceed vehicle capacity $Q$. Inside of ceiling operator can take values between 0 and 1. If any demand which emerge from customers $i$ and $j$ are not assigned to vehicle $k$, then no SECs are generated; otherwise, required two-size SECs are added to model. The ceiling operator breaks the linear structure of the model. So inequalities (4.6) can be replaced with inequalities (4.7).

(4.7)

$$x^k_{i,j} + x^k_{j,i} \leq 2 - \frac{\sum_{s \in C_i} d^s_i z^k_{isrd} + \sum_{s \in C_j} d^s_j z^k_{jsrd}}{Q} \quad \forall r \in C, d \in D_r, k \in K_{rd}, i,j \in N_r, i < j$$

### 4.2.4 Symmetry Breaking Valid Inequalities

Distances and incurred cost for traversing arcs $(i,j) \in A$ between nodes (i.e plants, depots and customers) are symmetrical such that $c_{ij} = c_{ji}$. As a consequence, model produces two identical solutions for two different outbound routes, one for normal order, one for reversed order. In order to brake that symmetry to some extent, Archetti, Fernández & Huerta-Muñoz (2017)'s inequalities are adopted for the vehicle-based formulation.

(4.8) $$x^k_{j,d} \leq \sum_{\substack{i \in N_r \\ i < j}} x^k_{d,i} \qquad \forall r \in C, d \in D_r, k \in K_{rd}, j \in N_r$$

### 4.2.5 Outgoing Flow Valid Inequalities

Total amount of products shipped from the plants must be equal to the total amount of demand to conserve flow balance.

$$\sum_{r\in C}\sum_{p\in P_r}\sum_{d\in D_r} u_{prd} = \sum_{i\in N}\sum_{r\in C} d_i^r \tag{4.9}$$

### 4.2.6 Carrier Inbound Flow Valid Inequalities

For each carrier, amount of products shipped from plants to depots must be equal to the total amount of demand of that carrier which ensures the inbound flow balance for each carrier $r \in C$.

$$\sum_{p\in P_r}\sum_{d\in D_r} u_{prd} = \sum_{i\in N_r} d_i^r \qquad \forall r \in C \tag{4.10}$$

### 4.2.7 One Enterance Valid Inequalities

$$\sum_{i\in N_r} x_{i,d}^k \leq 1 \quad \forall r \in C, d \in D_r, k \in K_{rd} \tag{4.11}$$

Those inequalities are the counterpart of (3.3) constraints. These inequalities impose that a vehicle can enter a depot at most once. Constraints (3.4) guarantee that a vehicle can enter a depot at most one time by controlling entering and leaving arc numbers. However, inequalities (4.11) strengthen the formulation.

## 4.3 Experimental Design

Since we focus on a strategic model, computational experiments do not only aim to evaluate the computational challenges of the models and solution methods but also managerial aspects of the proposed centralized collaboration schema. Experimental design lies at the heart of the computational experiments and directly affects the results. Thus, it is of great importance to design experiments carefully.

In order to explore the impact of the problem size on given solution techniques and formulations, three different problem sets are used by (Ercan, 2019). The three data sets differ in terms of number of possible regional depots and customers as follows:

- 30 customers and 10 possible depot locations,
- 50 customers and 15 possible depot locations, and
- 100 customers and 30 possible depot locations

Each instance is constructed on a 100x100 coordinate system in which each carrier in the system $r \in C$ has one plant at the center of the coordinate system, $(50, 50)$. Customers are randomly distributed on the grid and candidate depot locations are determined using a k-means algorithm. Ten different instances are created for each problem size; locations of customers, candidate depot locations, and demand amounts differ in each problem instance. All distances between all nodes (plants, depots, customers) are calculated as Euclidean distances. Regional depot opening and maintenance costs are between 3000 and 6000. The cost of inbound transportation is a function of distance between plant and the regional depot. The outbound routing costs are calculated as a function of distance between travelled nodes. The transfer line cost is a function of distance between depots. Vehicle capacity $Q$ is set to 1000 for each instance and problem size.

Ercan (2019) provides a problem set for a single carrier. For our computational experiments, we use two carriers. In each instance, we distribute the customers and candidate depot locations among two carriers while some customers and some depot locations are common. Depending on the problem size and experimental setup, number of customers and depot locations change in three different scenarios as

- Original (O),
- Increased Common Customer (ICC), and

- No Common Depot (NCD).

Three different scenarios are used to observe the effect of parameters on the computational behaviour and collaboration activities. In the Original scenario, we have a moderate number of common customers and common depot locations to represent an average collaboration schema. In the Increased Common Customer scenario, in addition to the original common customers, we declare several other customer as "common" while keeping the original common customers. In the No Common Depot scenario, we do not declare any of the possible depot locations as common; in other words, each carrier has to open their depots to the unique locations in the coordinate system.

For each combination of problem size and scenario, the corresponding numbers of customers, depot locations, common depot locations, common customers and total depot locations are shown in Table 4.1.

Table 4.1 Experimental setup parameters

| | **30 Customers** | | | **50 Customers** | | | **100 Customers** | | |
|---|---|---|---|---|---|---|---|---|---|
| | *O* | *ICC* | *NCD* | *O* | *ICC* | *NCD* | *O* | *ICC* | *NCD* |
| *# Customers* | 30 | 30 | 30 | 50 | 50 | 50 | 100 | 100 | 100 |
| *# Depot Locations* | 10 | 10 | 10 | 15 | 15 | 15 | 30 | 30 | 30 |
| *# Common Depot Locations* | 4 | 4 | 0 | 4 | 4 | 0 | 8 | 8 | 0 |
| *# Common Customers* | 8 | 14 | 8 | 10 | 18 | 10 | 20 | 40 | 20 |
| *# Total Depot Locations* | 14 | 14 | 10 | 19 | 19 | 15 | 38 | 38 | 30 |

An example to the proposed instances can be found in Figure 4.2 with 30 customers and 10 candidate depot locations.

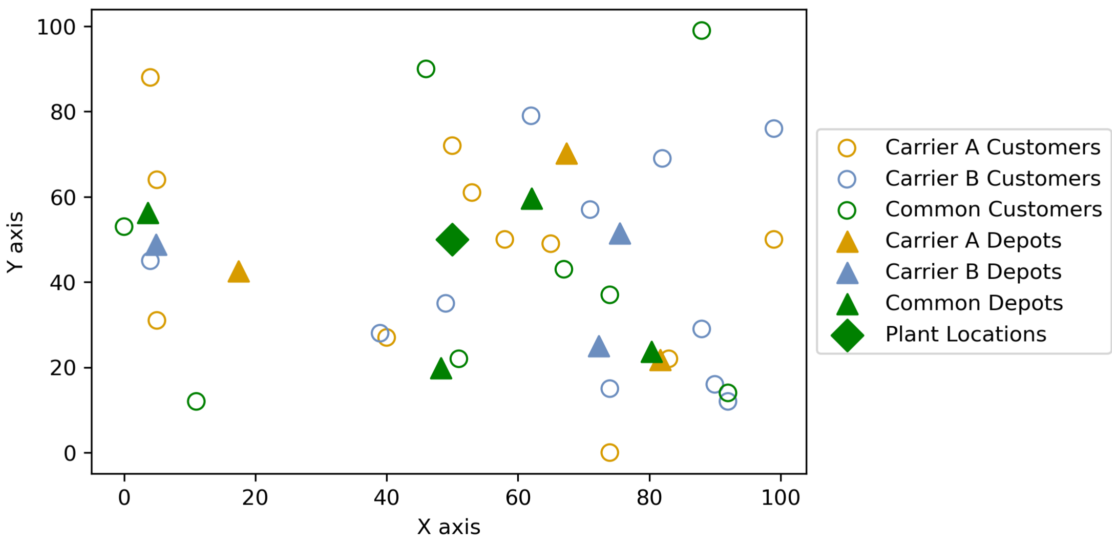


Figure 4.2 Instance 1 with 30 customers and 10 total candidate depot locations

The third dimension of our experimental setting is on the demand density. We conduct our experiments in two different demand settings: "Low Demand" and "High Demand". "Low Demand" setting depicts the initial demand setting in Ercan (2019) since we already divide demand of common customers between the two carriers. In the "High Demand" setting, we multiply all the demand by 2 to achieve a setup with higher demand density.

## 4.4 Computational Experiments

For the computational experiments, we utilize the commercial solver Gurobi. Since Gurobi or any commercial solver has limited capabilities to solve large instance problems, we apply different solution methodologies for each formulation approach. We utilized the High Performance Computing (HPC) server of the Sabancı University. HPC servers are equipped with Intel(R) Xeon(R) Gold 6140 CPU @ 2.30GHz X2 processors in each node. For each run, a partition from any node of the HPC is created with 4 cores, and 64 GBs of RAM and the partition had an 64 bit Linux operating system. Data manipulation and preperation is conducted through Python 3.8 using PyCharm and Spyder IDE's. Gurobi 9.1.2 is used throughout gurobipy API. The computational time limit is set to 8 hours for 30 customer instances, 16 hours for 50 customer instances and 48 hours for 100 customer instances.

Our computational experiments started with the most simple setup, original VB formulation of vehicle-based (VB) formulation we were not able to solve any of the instances with 30 customers in the original scenario since they did not fit into random access memory. Main reason is the number of constraints in (3.6) which eliminates sub-tours and couples variables $x$ and $z$. At least $2^{|N_r|}|K_{rd}|$ many constraints are generated which directly exceeds several million constraints.

Because of the space complexity of the original VB formulation, a cut generation procedure to eliminate sub-tours is proposed in Section 4.1. We repeat all the tests indicated above with the cut generation method in order to avoid out of memory issues and results of those runs can be found in Table 4.2.

Table 4.2 Results using the cut generation method with VB formulation for the instances with 30 customers

| **Ins.** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***T(s)*** | ***Gap*** |
|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 2 | 2 | 1 | 66085 | 25145 | 40940 | 28800 | 25.5% |
| **2** | 1 | 2 | 2 | 0 | 69977 | 27532 | 42445 | 28800 | 29.6% |
| **3** | - | - | - | - | - | - | - | 28800 | - |
| **4** | - | - | - | - | - | - | - | 28800 | - |
| **5** | - | - | - | - | - | - | - | 28800 | - |
| **6** | 2 | 1 | 1 | 2 | 67788 | 42946 | 24842 | 28800 | 30.7% |
| **7** | - | - | - | - | - | - | - | 28800 | - |
| **8** | - | - | - | - | - | - | - | 28800 | - |
| **9** | - | - | - | - | - | - | - | 28800 | - |
| **10** | 1 | 2 | 2 | 1 | 76991 | 34032 | 42959 | 28800 | 36.8% |

Using the cut generation method, we are able to create and run all the instances for the original scenario of 30 customers without having any memory related issues.

In Table 4.2, $F_A$ and $F_B$ show how many facilities opened by carriers $A$ and $B$, respectively. $T_A$ and $T_B$ indicate how many transfer lines are constructed by carriers $A$ and $B$, respectively. While $Obj$ shows the objective function value, $Obj_A$ and $Obj_B$ depict the cost separately for each carrier. $T(s)$ indicates the run time in seconds and $Gap$ indicates the percentage optimality gap reported by the solver. Rows with $-$'s represent that no feasible solution found within given time limit.

Within 8 hours of time limit, only 4 instances obtained a solution and the average gap for those four instances is 30.6%. For the rest of the instances, Gurobi was not able to find any feasible solution. Thus, in order to shrink the solution space and lower the gaps, several valid inequalities are proposed in Section 4.2. The valid inequalities (VI) are systematically added to the model in order to see the effect on the solution time and quality. Run results with different combinations of VIs can be found in Table 4.3. For all runs, time limit is set to 8 hours which is same with the previous tests.

Table 4.3 Effect of different combinations of valid inequalities to VB formulation

| | (4.8) | | (4.5) + (4.8) | | (4.7) + (4.8) | | (4.5) + (4.7) + (4.8) | | **All** | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Ins.** | ***Obj*** | ***Gap*** | ***Obj*** | ***Gap*** | ***Obj*** | ***Gap*** | ***Obj*** | ***Gap*** | ***Obj*** | ***Gap*** |
| ***1*** | 68814 | 28.3% | 68664 | 28.4% | 69287 | 28.1% | 68008 | 27.7% | 67683 | 27.4% |
| ***2*** | - | - | - | - | 72223 | 31.2% | - | - | - | - |
| ***3*** | 76424 | 37.8% | - | - | - | - | - | - | - | - |
| ***4*** | - | - | - | - | - | - | - | - | - | - |
| ***5*** | - | - | - | - | - | - | - | - | - | - |
| ***6*** | - | - | - | - | 73753 | 36.7% | - | - | - | - |
| ***7*** | - | - | - | - | - | - | - | - | - | - |
| ***8*** | - | - | - | - | - | - | - | - | - | - |
| ***9*** | 81462 | 36.3% | - | - | - | - | - | - | - | - |
| ***10*** | - | - | - | - | - | - | - | - | - | - |

Different combinations of VIs yield different results when compared to the results indicated in Table 4.2. In the first column, only symmetry braking inequalities (4.8) are added to the model. With those inequalities, solver found feasible results for instances 3 and 9. Without those inequalities, it was not able to find any solutions for these instances. However, solver could not find any solution for instances 2, 4 and 10. Nonetheless, it found solutions without those inequalities. Then two-size simple SEC inequalities (4.5) are added in addition to symmetry braking inequalities; only one instance was solved. Then, two-size simple SECs are swapped with two-size SEC inequalities (4.7); instance 6 was solved with this combination but solver was not able to find solutions for other instances which it found solutions before. Then both two-size SEC inequalities are added to the model in addition to the symmetry braking inequalities. With these 3 additional inequalities, only instance 1 is solved. For the last test, all proposed VIs in Section 4.2 is added to the model; the solver reported a solution for only instance 1.

While adding new inequalities, the model size is increasing and solver behaviour is changing. The solver was able to find new solutions which are previously not attained. On the other hand, since new constraints are added to the model, model size increases and search behaviour of the solver changes. Depending on the instance, solver may or may not be able to find good or any solutions when compared to cases in which no VIs are added. Also there is no significant change in the optimality gaps and still all the reported gaps are not close to 0.

As mentioned earlier , there are two main drivers which increase problem complexity in the VB formulation; number of binary variables for outbound routing decisions and handling sub-tour elimination constraints. To cope with those challenges, several methods are experimented with. In terms of space complexity issues, all the difficulties are solved. However, solution times still remain too high.

Consequently, a new load-based formulation is proposed in Section 3.2.2 in which outbound operations are controlled with continuous variables instead of a high number of binary variables. Details of load-based approach discussed in Section 5.

# 5. LOAD-BASED FORMULATION

In the load-based formulation, many continuous load variables are defined in the exchange of decreased number of binary variables. New valid inequalities are proposed for load-based formulation and their effects on solution times investigated. Then since instances become solvable, strategic analysis performed using load-based formulation.

## 5.1 Valid Inequalities for Load Based Formulation

For the load-based formulation, inequalities (4.4),(4.9) and (4.10) that are proposed in Section 4.2 are valid as well. Two different valid inequalities are proposed below for the load-based formulation.

### 5.1.1 Capacity Cut Valid Inequalities

In the load-based formulation, amount of load that leaves a depot for a customer is controlled by variables $l$ and constraints (3.28). Therefore, minimum number of arcs that must be used can be limited as well using inequalities (5.1) with a similar motivation that is proposed by Fernández et al. (2018).

$$\sum_{j \in N_r} x_{d,j}^{rd} \geq \lceil \frac{\sum_{i \in N_r} \sum_{s \in C_i} d_i^s z_{isrd}}{Q} \rceil \qquad \forall r \in C, d \in D_r \tag{5.1}$$

By the same convergence with (4.6), inequalities (5.1) destruct linear structure of the load based model. They can be replaced with (5.2).

$$\sum_{j \in N_r} x^{rd}_{d,j} \geq \frac{\sum_{i \in N_r} \sum_{s \in C_i} d^s_i z_{isrd}}{Q} \qquad \forall r \in C, d \in D_r \tag{5.2}$$

### 5.1.2 Symmetry Breaking Valid Inequalities

As indicated in Section 4.2.4, arc traversing costs for outbound routing are symmetric, i.e $c_{ij} = c_{ji}$. Model becomes indifferent between choosing a specific route and its reversely ordered form which lead to same objective function value. To break this tie, inequalities (5.3) are proposed.

$$x^{rd}_{j,d} \leq \sum_{\substack{i \in N_r \\ i<j}} x^{rd}_{d,i} \qquad \forall r \in C, d \in D_r, j \in N_r \tag{5.3}$$

## 5.2 Computational Experiments

Load-based (LB) formulation comes with the additionally defined continuous variables in exchange for binary variables and reduced number of indices on different variables as explained in Section 3.2.2. Fpr 30, 50, and 100 customer instances we set the time limit to 8, 16, and 48 hours, respectively.

In the tables given below, $F_A$ and $F_B$ show how many facilities opened by carriers $A$ and $B$, respectively. $T_A$ and $T_B$ indicate how many transfer lines are constructed by carriers $A$ and $B$, respectively as well. While $Obj$ shows the objective function value, $Obj_A$ and $Obj_B$ depict the cost for each carrier. $T(s)$ indicates the run time in seconds and $Gap$ indicates the percentage optimality gap reported.

We first consider the original scenario and low demand setting of 30 customers instances. Results can be found below in Table 5.1.

Within the given time limit, all instances were solved to reasonable gaps when compared to VB formulation and obtained a solution for each instance. Gaps deviate

Table 5.1 Summary of LB Formulation results with 30 customers and original scenario in low demand setting

| Ins. | $F_A$ | $F_B$ | $T_A$ | $T_B$ | *Obj* | $Obj_A$ | $Obj_B$ | *T(s)* | *Gap* |
|---|---|---|---|---|---|---|---|---|---|
| *1* | 1 | 1 | 1 | 1 | 58449 | 26680 | 31769 | 28800 | 7.5% |
| *2* | 1 | 1 | 1 | 1 | 61095 | 29329 | 31766 | 28800 | 6.1% |
| *3* | 1 | 1 | 1 | 1 | 61527 | 30436 | 31091 | 28800 | 4.0% |
| *4* | 1 | 1 | 1 | 1 | 52444 | 27409 | 25035 | 28800 | 4.2% |
| *5* | 1 | 1 | 1 | 1 | 57824 | 20603 | 37221 | 28800 | 8.5% |
| *6* | 1 | 1 | 1 | 1 | 59213 | 33838 | 25376 | 28800 | 7.6% |
| *7* | 1 | 1 | 1 | 1 | 57160 | 28020 | 29140 | 28800 | 5.0% |
| *8* | 1 | 1 | 1 | 1 | 56851 | 29001 | 27850 | 28800 | 5.3% |
| *9* | 1 | 1 | 1 | 1 | 66783 | 36342 | 30441 | 28800 | 8.8% |
| *10* | 1 | 1 | 1 | 1 | 61442 | 26724 | 34718 | 28800 | 8.1% |

between 4.0% and 8.5%. Average gap is 6.5% for the original scenario and low demand setting of 30 customer instances. In all the instances each carrier chose to open one facility and create one transfer line. In order to see the behaviour of the LB formulation with different data sets of different sizes, LB formulation is tested with the original scenario and high demand setting of 30 customer instances and the original scenario and high demand setting of 50 customer instances. Results can be found in Table 5.2.

Table 5.2 LB Formulation results with original scenario under high demand setting for 30 & 50 customers

| | 30 Customers High Demand | | | | | 50 Customers High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ins. | *Obj* | $Obj_A$ | $Obj_B$ | *T(s)* | *Gap* | *Obj* | $Obj_A$ | $Obj_B$ | *T(s)* | *Gap* |
| *1* | 82893 | 36519 | 46374 | 28800 | 11.4% | 110487 | 54658 | 55829 | 57600 | 9.3% |
| *2* | 86373 | 40967 | 45405 | 28800 | 8.9% | 116145 | 60624 | 55522 | 57601 | 10.1% |
| *3* | 87266 | 42203 | 45063 | 28800 | 8.0% | 115178 | 57232 | 57945 | 57600 | 12.7% |
| *4* | 69866 | 34477 | 35389 | 28800 | 8.6% | 113827 | 57719 | 56107 | 57600 | 11.4% |
| *5* | 78676 | 32031 | 46645 | 28800 | 8.5% | 119793 | 53929 | 65863 | 57600 | 10.9% |
| *6* | 81847 | 46273 | 35575 | 28800 | 7.8% | 115084 | 56188 | 58897 | 57600 | 10.5% |
| *7* | 77987 | 38321 | 39666 | 28800 | 10.1% | 116067 | 48423 | 67644 | 57600 | 10.8% |
| *8* | 75652 | 33655 | 41998 | 28801 | 8.7% | 131233 | 67436 | 63797 | 57600 | 9.9% |
| *9* | 88638 | 42530 | 46108 | 28800 | 10.2% | 111844 | 59768 | 52076 | 57600 | 11.1% |
| *10* | 80652 | 35424 | 45229 | 28800 | 6.1% | 132865 | 62753 | 70112 | 57600 | 11.0% |

Once problem size increases or problem instance gets harder because of increased demand structure, gaps increase on average. For the original scenario and high demand setting of 30 customer instances, gaps deviate between 6.1% and 11.4%. Average gap for ten instances is 8.8%. In the low demand setting average gap was 6.5%. For the original scenario and high demand setting of 50 customer instances, gaps deviate between 9.3% and 11.4%. Average gap for ten instances for this setup is 10.8%. Average gap was 8.8% in the 30 customer instances of this setting. As problem size increases, gaps increase as well.

Even though solutions are found for the 30 and 50 customer instances with optimality gaps, several other runs are completed to see the behaviour of the formulation with 100 customers. For this purpose, runs are completed with the 100 customer instances with original scenario and low demand setting. The time limit is set as 48 hours for each run. Results can be found in Table 5.3. In Table 5.3, M indicates that server run out of memory during branching or model creation phase and -1 indicates that no solution found within given time limit. As it can be interpreted from Table 5.3, with 100 customers problem grows exponentially and half of the instances do not fit into 64 gigabytes of random access memory because of the increased number of variables and size of the branching tree. Solutions are reported for only three instances within 48 hours of time limit, and the reported gaps are above 55% on average.

Table 5.3 LB Formulation results with original scenario and low demand setting of 100 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***T(s)*** | ***Gap*** |
|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 8 | 7 | 5 | 5 | 191879 | 97503.25 | 94375 | 172801 | 55.4% |
| ***2*** | M | M | M | M | M | M | M | M | M |
| ***3*** | 6 | 9 | 5 | 5 | 196658 | 92681.9 | 103976 | 172801 | 65.7% |
| ***4*** | M | M | M | M | M | M | M | M | M |
| ***5*** | M | M | M | M | M | M | M | M | M |
| ***6*** | - | - | - | - | | - | - | 172801 | |
| ***7*** | M | M | M | M | M | M | M | M | M |
| ***8*** | M | M | M | M | M | M | M | M | M |
| ***9*** | - | - | - | - | | - | - | 172800 | |
| ***10*** | 8 | 7 | 6 | 3 | 194335 | 98975.15 | 95360 | 172801 | 63.4% |

In order to tighten solution space and reduce gaps, valid inequalities are proposed in Section 5.1. There exists five different valid inequalities (VI) which applies to LB formulation. In favor of examining the effect of VIs on different data sets of different sizes, we conduct three experiments. In all three experiments, we utilize the original scenario of 30 and 50 customer data sets in both low and high demand environments to see the behaviour of VIs. First experiments are conducted with no additional VIs to have a basis for the comparison. Then, (5.2) and (5.3) added and experiments are repeated. Lastly, all proposed VIs in the Section 5.1 are added to the formulation and the experiments are repeated again. Results in which gaps of first and second experiments are compared, can be found in Table 5.4.

In the Table 5.4, columns $\Delta_O$ indicates original optimality gaps without any valid inequalities. Columns $\Delta_{VI}$ indicates the optimality gaps with the added VIs (5.2) and (5.3). A cell is highlighted with a green color if VIs yield a better solution in terms of lower gaps, highlighted with a red color otherwise. In the 30 customer instances, 17 out of 20 instances are solved with lower gaps with activated VIs. In 50 customer instances, 13 out of 20 instances are solved with lower gaps. In total,

Table 5.4 Gap comparison for LB Formulation with original formulation and additional (5.2) and (5.3) valid inequalities

| | **30 Customer** | | | | **50 Customer** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Low Demand** | | **High Demand** | | **Low Demand** | | **High Demand** | |
| ***Ins.*** | $\Delta_O$ | $\Delta_{VI}$ | $\Delta_O$ | $\Delta_{VI}$ | $\Delta_O$ | $\Delta_{VI}$ | $\Delta_O$ | $\Delta_{VI}$ |
| ***1*** | 7.5% | 8.4% | 11.4% | 11.1% | 11.7% | 11.4% | 9.3% | 9.5% |
| ***2*** | 6.1% | 4.8% | 8.9% | 8.3% | 10.6% | 10.6% | 10.1% | 9.2% |
| ***3*** | 4.0% | 4.8% | 8.1% | 8.0% | 14.4% | 13.7% | 12.7% | 12.0% |
| ***4*** | 4.2% | 3.4% | 8.6% | 7.8% | 12.2% | 11.3% | 11.4% | 10.9% |
| ***5*** | 8.5% | 8.1% | 8.5% | 9.0% | 10.5% | 10.6% | 10.9% | 11.5% |
| ***6*** | 7.6% | 6.0% | 7.8% | 7.0% | 11.1% | 10.2% | 10.5% | 10.0% |
| ***7*** | 5.0% | 4.4% | 10.1% | 10.0% | 13.2% | 11.4% | 10.8% | 10.8% |
| ***8*** | 5.3% | 4.9% | 8.7% | 7.9% | 12.6% | 12.5% | 9.9% | 9.0% |
| ***9*** | 8.8% | 7.3% | 10.2% | 9.4% | 14.1% | 14.4% | 11.1% | 10.4% |
| ***10*** | 8.1% | 6.8% | 6.1% | 5.9% | 12.8% | 12.5% | 11.0% | 11.8% |

30/40 instances are solved with lower gaps when the (5.2) and (5.3) VIs are added to the model. In some samples, the improvement is 0.1 percent, while in some samples, up to 1.8 percent improvement is observed.

To investigate the effect of all VIs, all proposed VIs in Section 5.1 are added to the model and experiments are repeated. Results can be found in Table 5.5 and Table 5.6 for 30 and 50 customers, respectively. $\Delta_O$ indicates original gaps without any valid inequalities. $\Delta_{(5.2)+(5.3)}$ demonstrates optimality gaps when only (5.2) and (5.3) VIs were added to the model. $\Delta_{All}$ indicates gaps when all valid inequalities are added to the model. Green cells report the best gap found, orange cells indicate medium gap and red cells report the worst gap found for the given instance.

Table 5.5 Gap comparison for LB Formulation with original formulation, (5.2) and (5.3) VIs, and all VIs for 30 customers in original scenario

| | **30 Customers** | | | | | |
|---|---|---|---|---|---|---|
| | **Low Demand** | | | **High Demand** | | |
| **Ins.** | $\Delta_O$ | $\Delta_{(5.2)+(5.3)}$ | $\Delta_{All}$ | $\Delta_O$ | $\Delta_{(5.2)+(5.3)}$ | $\Delta_{All}$ |
| ***1*** | 7.5% | 8.4% | 8.8% | 11.4% | 11.1% | 11.4% |
| ***2*** | 6.1% | 4.8% | 5.9% | 8.9% | 8.3% | 9.0% |
| ***3*** | 4.0% | 4.8% | 4.3% | 8.1% | 8.0% | 8.2% |
| ***4*** | 4.2% | 3.4% | 3.6% | 8.6% | 7.8% | 7.6% |
| ***5*** | 8.5% | 8.1% | 9.3% | 8.5% | 9.0% | 9.6% |
| ***6*** | 7.6% | 6.0% | 6.6% | 7.8% | 7.0% | 7.8% |
| ***7*** | 5.0% | 4.4% | 4.5% | 10.1% | 10.0% | 11.0% |
| ***8*** | 5.3% | 4.9% | 5.1% | 8.7% | 7.9% | 8.8% |
| ***9*** | 8.8% | 7.3% | 8.1% | 10.2% | 9.4% | 9.8% |
| ***10*** | 8.1% | 6.8% | 6.7% | 6.1% | 5.9% | 6.1% |

For the 30 customer instances, it is observed that still the best gaps are reported when only inequalities (5.2) and (5.3) are added to the model. When the other two experiments are compared in which no VIs are added or all VIs are added, in high demand environments, original formulation is solved with lower gaps. However, in low demand environments, formulation with all added VIs reported lower gaps. Nonetheless, there is not a strict distinction between those since still exceptional instances are observed.

Table 5.6 Gap comparison for LB Formulation with original formulation, (5.2) and (5.3) VIs, and all VIs for 50 customers in original scenario

| | 50 Customers | | | | | |
|---|---|---|---|---|---|---|
| | Low Demand | | | High Demand | | |
| **Ins.** | $\Delta_O$ | $\Delta_{(5.2)+(5.3)}$ | $\Delta_{All}$ | $\Delta_O$ | $\Delta_{(5.2)+(5.3)}$ | $\Delta_{All}$ |
| ***1*** | 11.7% | 11.4% | 11.9% | 9.3% | 9.5% | 9.1% |
| ***2*** | 10.6% | 10.6% | 10.7% | 10.1% | 9.2% | 11.6% |
| ***3*** | 14.4% | 13.7% | 15.3% | 12.7% | 12.0% | 12.6% |
| ***4*** | 12.2% | 11.3% | 12.7% | 11.4% | 10.9% | 12.4% |
| ***5*** | 10.5% | 10.6% | 10.9% | 10.9% | 11.5% | 11.6% |
| ***6*** | 11.1% | 10.2% | 10.9% | 10.5% | 10.0% | 10.4% |
| ***7*** | 13.2% | 11.4% | 17.1% | 10.8% | 10.8% | 10.7% |
| ***8*** | 12.6% | 12.5% | 12.0% | 9.9% | 9.0% | 9.5% |
| ***9*** | 14.1% | 14.4% | 13.1% | 11.1% | 10.4% | 10.5% |
| ***10*** | 12.8% | 12.5% | 13.1% | 11.0% | 11.8% | 11.5% |

Once the results for 50 customer instances are evaluated, again best gaps are resulted with inequalities (5.2) and (5.3). For the low demand setting, original formulation reported better results in terms of gaps when compared to all VIs added. On the other hand, in the high demand setting, formulation with all added VIs reported lower gaps.

When all results indicated above considered, best results are obtained when inequalities (5.2) and (5.3). As mentioned in earlier sections, this study proposes a new collaboration schema for a strategic network design problem. Despite the models are not solved to the optimality, with the LB formulation and proposed VIs, reasonable solutions are reported. So we investigated the strategic outcomes of the proposed models and collaboration schema using those results in the following Section 5.3. All runs are completed using LB formulation + inequalities (5.2) & (5.3) for the strategic analysis since this formulation reported best gaps as discussed above.

## 5.3 Managerial Insights

Proposed models comprise managerial aspects in addition to mathematical approaches. Given an instance, companies make decisions about number and place of the facilities, which routes and transportation lines should be defined, and which and how many transfer lines should be constructed under collaborative schema. As it is proposed in former sections, collaboration leads to cost savings. And the above decisions directly affect the cost realization of the whole system. In order to investigate strategic decisions which are given under collaboration, effect of different parameters such as common customer number or common depot number and effect of those parameters on collaboration amounts and gains come from collaboration, experiments are conducted under three different scenarios as explained in Section 4.3.

First set of experiments are conducted with *original* scenario setup for 30 customers in both low and high demand environments. The results can be found Table 5.7. Explanations of abbreviations of column names from $F_A$ to *Gap* is explained at the beginning of Section 5.2. Only four new columns added to new tables, namely, *RC, FC, TC, IC*. *RC* indicates outbound routing cost, *FC* indicates facility opening and maintenance cost, *TC* describes transfer line construction cost and lastly *IC* defines inbound transportation line construction cost.

Table 5.7 LB Formulation results of original scenario and low demand setting of 30 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 1 | 1 | 1 | 59178 | 26722 | 32457 | 8.4% | 49059 | 7029 | 0 | 3090 |
| ***2*** | 1 | 1 | 1 | 1 | 61095 | 27447 | 33648 | 4.8% | 49314 | 7029 | 0 | 4752 |
| ***I*** | 1 | 1 | 1 | 1 | 61527 | 30436 | 31091 | 4.8% | 46250 | 9413 | 452 | 5412 |
| ***4*** | 1 | 1 | 1 | 1 | 52444 | 27409 | 25035 | 3.4% | 39391 | 7065 | 522 | 5466 |
| ***5*** | 1 | 1 | 1 | 1 | 57719 | 26702 | 31017 | 8.1% | 44046 | 7065 | 259 | 6350 |
| ***6*** | 1 | 1 | 1 | 1 | 59213 | 33838 | 25376 | 6.0% | 46029 | 8334 | 298 | 4552 |
| ***7*** | 1 | 1 | 1 | 1 | 57181 | 28020 | 29161 | 4.4% | 44474 | 7065 | 478 | 5164 |
| ***8*** | 1 | 1 | 1 | 1 | 56851 | 29001 | 27850 | 4.9% | 42153 | 8530 | 523 | 5645 |
| ***9*** | 1 | 1 | 1 | 1 | 66615 | 34664 | 31951 | 7.3% | 51795 | 7669 | 614 | 6538 |
| ***10*** | 1 | 1 | 1 | 1 | 61106 | 29232 | 31875 | 6.8% | 47922 | 7065 | 522 | 5597 |

In the original scenario of 30 customer instances with low demand setting, each carrier chooses to open and maintain one facility in all instances. Also in each instance, transfer lines are constructed between opened depots for each carrier, which means collaboration exists. In instances 1 and 2, model chose to declare depots on same locations and create transfer line between them with no cost, which advances collaboration. Next, same experiments are conducted for high demand environment.

Results can be found in Table 5.8.

Table 5.8 LB Formulation results of original scenario and high demand setting of 30 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 2 | 2 | 1 | 82554 | 39774 | 42780 | 11.1% | 64073 | 10995 | 368 | 7118 |
| ***2*** | 1 | 1 | 1 | 1 | 86145 | 40060 | 46085 | 8.3% | 70892 | 8731 | 384 | 6139 |
| ***3*** | 1 | 2 | 2 | 1 | 87266 | 42203 | 45063 | 8.0% | 65143 | 12739 | 325 | 9059 |
| ***4*** | 1 | 1 | 1 | 1 | 69007 | 34748 | 34260 | 7.8% | 55954 | 7065 | 522 | 5466 |
| ***5*** | 1 | 2 | 2 | 1 | 78874 | 31340 | 47534 | 9.0% | 57403 | 10995 | 561 | 9915 |
| ***6*** | 2 | 1 | 1 | 2 | 81847 | 46273 | 35575 | 7.0% | 62660 | 10266 | 368 | 8553 |
| ***7*** | 2 | 1 | 1 | 1 | 78808 | 39394 | 39415 | 10.0% | 60127 | 10266 | 282 | 8133 |
| ***8*** | 1 | 1 | 1 | 1 | 75266 | 38078 | 37188 | 7.9% | 60568 | 8530 | 523 | 5645 |
| ***9*** | 2 | 2 | 2 | 1 | 88562 | 42584 | 45978 | 9.4% | 59361 | 15663 | 463 | 13074 |
| ***10*** | 1 | 2 | 2 | 1 | 80652 | 35424 | 45229 | 5.9% | 56439 | 12460 | 886 | 10867 |

Once the demand increased, carriers chose to open new facilities in order to deal with increased routing costs. Overall, costs are increased since number of routes should be created to satisfy increased demand is increased as well. Depending on the instance, number of constructed transfer lines is also increased. Augmentation rate of $RC$ is higher than other costs since increased demand mainly affects number of routes that must be constructed to satisfy increased demand. In high demand setting, instances 1 and 2, depots are opened in different locations as well in contrast to low demand setting.

In order to the see how much gains are achieved through collaboration, above instances are solved in individual environments in which no collaboration exists between carriers. To solve instances, individual load based formulation is used which is proposed in Appendix A which is formulated for a single carrier. For each carrier, time limit is set to 4 hours for 30 customer instances and 8 hours for 50 customer instances to equate total run times with collaborative scenarios. In the individual run results, $Obj$ shows the sum of separate objectives of each carrier $Obj_A$ and $Obj_B$ for carriers $A$ and $B$, respectively. $BB_A$ and $BB_B$ indicates the best bounds of the objective function value that is found by the solver for carriers $A$ and $B$, respectively and $BB_{Obj}$ indicates the sum of those value which is the OFV of integrated problem. $T_A(s)$ and $T_B(s)$ reports the run time for the given instance and $Gap_A$ and $Gap_B$ illustrates the reported lowest gap within given time limit for each carrier. Results for the 30 customer instances with original setting under low demand environment can be found in Table 5.9.

Instances which are solved until optimality are indicated with red color in Table 5.9. Five instances are solved to optimality. Rest is solved with lower gaps when compared to collaborative versions. However, in order to conduct an accurate comparison, best bounds are also compared with the collaborative solutions. Since best

Table 5.9 Individual LB Formulation results for original scenario and low demand setting of 30 customer instances

| ***Ins.*** | $Obj$ | $Obj_A$ | $Obj_B$ | $BB_{Obj}$ | $BB_A$ | $BB_B$ | $T_A(s)$ | $T_B(s)$ | $Gap_A$ | $Gap_B$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *1* | 65225 | 32188 | 33037 | 65225 | 32188 | 33037 | 1080 | 9587 | 0.0% | 0.0% |
| *2* | 67980 | 35502 | 32478 | 67980 | 35502 | 32478 | 3773 | 1312 | 0.0% | 0.0% |
| *3* | 70869 | 34267 | 36603 | 66351 | 32108 | 34244 | 14400 | 14400 | 6.3% | 6.4% |
| *4* | 58522 | 29866 | 28657 | 58522 | 29866 | 28657 | 2180 | 4372 | 0.0% | 0.0% |
| *5* | 65900 | 31679 | 34221 | 65511 | 31290 | 34221 | 14400 | 13516 | 1.2% | 0.0% |
| *6* | 66274 | 35616 | 30658 | 65133 | 34476 | 30658 | 14400 | 5907 | 3.2% | 0.0% |
| *7* | 63901 | 32540 | 31362 | 63901 | 32540 | 31362 | 9910 | 9916 | 0.0% | 0.0% |
| *8* | 61667 | 28201 | 33467 | 61667 | 28201 | 33467 | 2441 | 7336 | 0.0% | 0.0% |
| *9* | 73648 | 35447 | 38201 | 70154 | 33465 | 36689 | 14400 | 14400 | 5.6% | 4.0% |
| *10* | 65438 | 31330 | 34109 | 63361 | 31330 | 32031 | 3724 | 14400 | 0.0% | 6.1% |

bounds indicates the best achievable results for given individual instance, if the collaborative solutions with gaps still reports a better outcome against best bound of individual scenario, it means collaborative model indeed promises gains. Gains are identified in Figure 5.1 via comparing objective function values of non-collaborative and collaborative scenarios. In Figure 5.1, green bars indicate overall gain of the system, where orange and blue bars indicate gains of carrier $A$ and carrier $B$, respectively. Gains can be realized with $-$ coefficients which indicates loss.

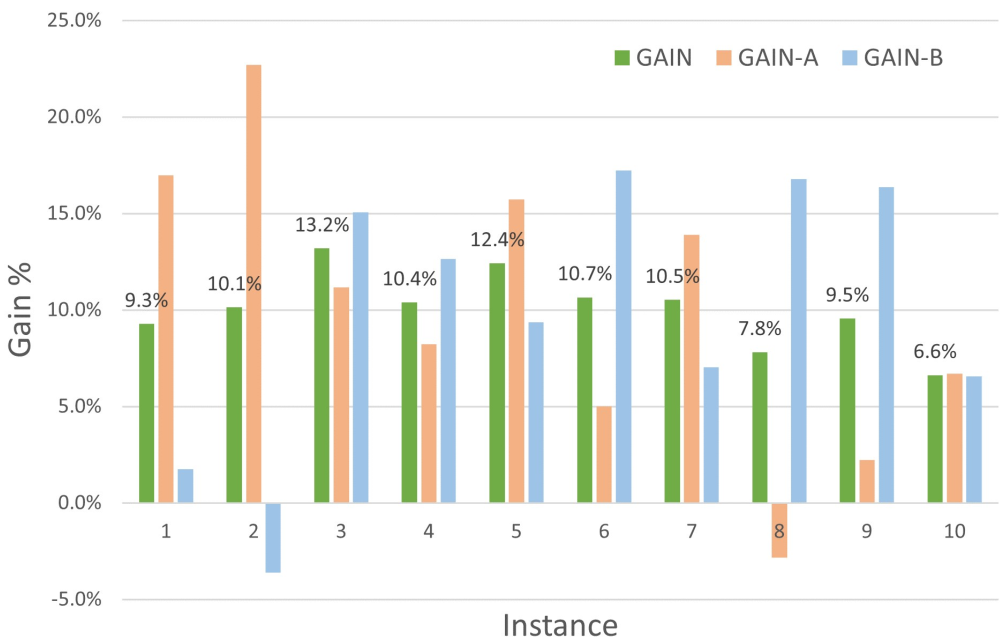


Figure 5.1 Gain comparison through OFVs for original scenario and low demand setting of 30 customer instances

When OFVs are compared in the low demand setting of original scenario with 30 customers, magnitude of the gains which arise from collaboration deviates between 6.6% and 13.2%. In average, overall gain of the whole system is 10.1%. As mentioned in earlier sections, proposed model assumes that there is a centralized decision making mechanism so that they minimize the total cost of the all network. So that individual carriers may suffer and worse cost realizations may occur when compared to individual scenarios. For the given examples, gains for carrier $A$ deviate between -2.8% and 22.7% where average gain for carrier $A$ is 10%. Gains for carrier $B$ deviate between -3.6% and 17.2% where average gain for carrier $B$ is 9.9%.In instance 2, carrier $B$ had a worse outcome when compared to individual scenario but gain of integrated system is 10.1%. On the contrary, in the instance 8, carrier $A$ had a worse outcome where overall gain realization was 7.8%. As mentioned in Table 5.9, not all individual instances are solved to optimality. Therefore, best bounds are also compared with the collaborative results to ensure and investigate the minimum amount of gains. Results are presented in Figure 5.2.

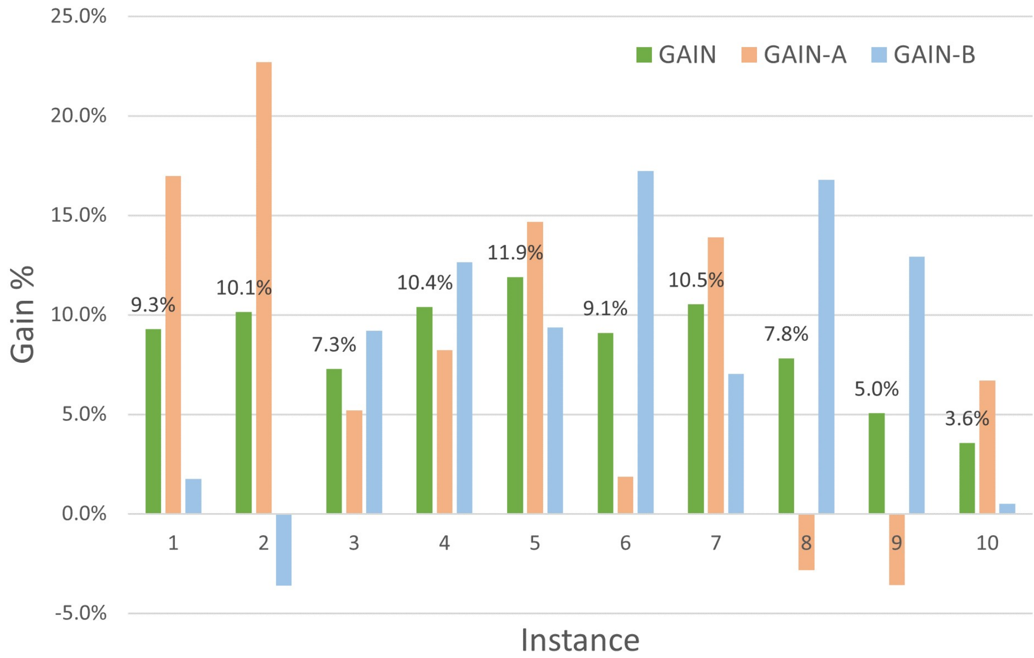


Figure 5.2 Gain comparison through best bounds for original scenario and low demand setting of 30 customer instances

Indeed gains reported in Figure 5.1 state an upper bound for the best bound results. On the other hand, gains reported in the best bound results hold a lower bound for the "real" gains since best bound represent the best theoretical results that can be achieved. Since some instances are solved with higher gaps, reported best bound may be far away from real optimum solution and OFV. When the best bounds of the individual scenario are compared with the collaborative solution, it is observed that gains deviate between 3.6% and 11.9% which indicates that despite gaps, collaborative scenario still provides a better cost realization. Average gain is 8.5%. For the given examples, gains for carrier $A$ deviate between -3.6% and 22.7% where average gain for carrier $A$ is 8.4%. Gains for carrier $B$ deviate between -3.6% and 17.2% where average gain for carrier $B$ is 8.4%.

In order to the see the effect of demand on problem and collaboration, same experiments are conducted for high demand environment of original scenario with 30 customers. Results can be found in Table 5.10

Table 5.10 Individual LB Formulation results for original scenario and high demand setting of 30 customers instances

| ***Ins.*** | ***Obj*** | $\boldsymbol{Obj_A}$ | $\boldsymbol{Obj_B}$ | $\boldsymbol{BB_{Obj}}$ | $\boldsymbol{BB_A}$ | $\boldsymbol{BB_B}$ | $\boldsymbol{T_A(s)}$ | $\boldsymbol{T_B(s)}$ | $\boldsymbol{Gap_A}$ | $\boldsymbol{Gap_B}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 89531 | 42193 | 47338 | 84942 | 41280 | 43663 | 14400 | 14400 | 2.2% | 7.8% |
| ***2*** | 91773 | 49064 | 42709 | 90047 | 47339 | 42709 | 14400 | 2491 | 3.5% | 0.0% |
| ***3*** | 92738 | 46788 | 45951 | 90634 | 44684 | 45951 | 14400 | 4814 | 4.5% | 0.0% |
| ***4*** | 77789 | 38617 | 39173 | 73886 | 36798 | 37088 | 14400 | 14400 | 4.7% | 5.3% |
| ***5*** | 87299 | 40988 | 46312 | 82738 | 39351 | 43388 | 14400 | 14400 | 4.0% | 6.3% |
| ***6*** | 90180 | 47948 | 42233 | 84576 | 45397 | 39179 | 14400 | 14400 | 5.3% | 7.2% |
| ***7*** | 84438 | 43178 | 41260 | 79481 | 40536 | 38945 | 14400 | 14400 | 6.1% | 5.6% |
| ***8*** | 84637 | 38809 | 45828 | 79355 | 36768 | 42587 | 14400 | 14400 | 5.2% | 7.1% |
| ***9*** | 94613 | 43824 | 50789 | 91511 | 43824 | 47687 | 5261 | 14400 | 0.0% | 6.1% |
| ***10*** | 88344 | 43196 | 45148 | 85843 | 40695 | 45148 | 14400 | 6838 | 5.8% | 0.0% |

When high demand scenarios are compared with the low demand scenarios, it is observed that the average gaps for individual scenarios are higher. None of the problems for both carriers solved to optimality. Individual results again compared with the collaborative scenario to see how much gains are obtained.

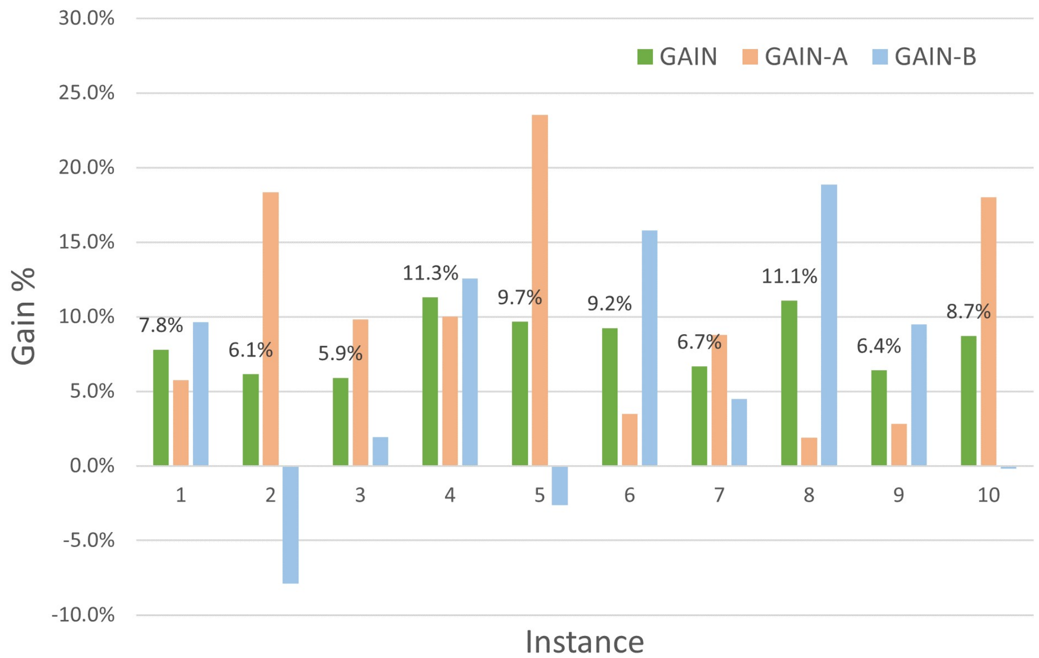


Figure 5.3 Gain comparison through OFVs for original scenario and high demand setting of 30 customer instances

When OFVs are compared for the centralized system, it is seen that gains deviate between 5.9% and 11.3% where average is 8.3%. In none of the instances, carrier $A$ reported a loss for the collaborative schema and reported gains deviate between

1.9% and 23.5%. Average gain amount for the carrier $A$ is 10.2%. For the carrier $B$, collaborative setup reported worse cost realizations for three instances. Gains for carrier $B$ deviate between -7.9% and 18.9% where average gain for $B$ is 6.2%. In order to the see the lower bound of the gains, best bounds of reported individual scenarios are also compared and the results can be found in Figure 5.4.

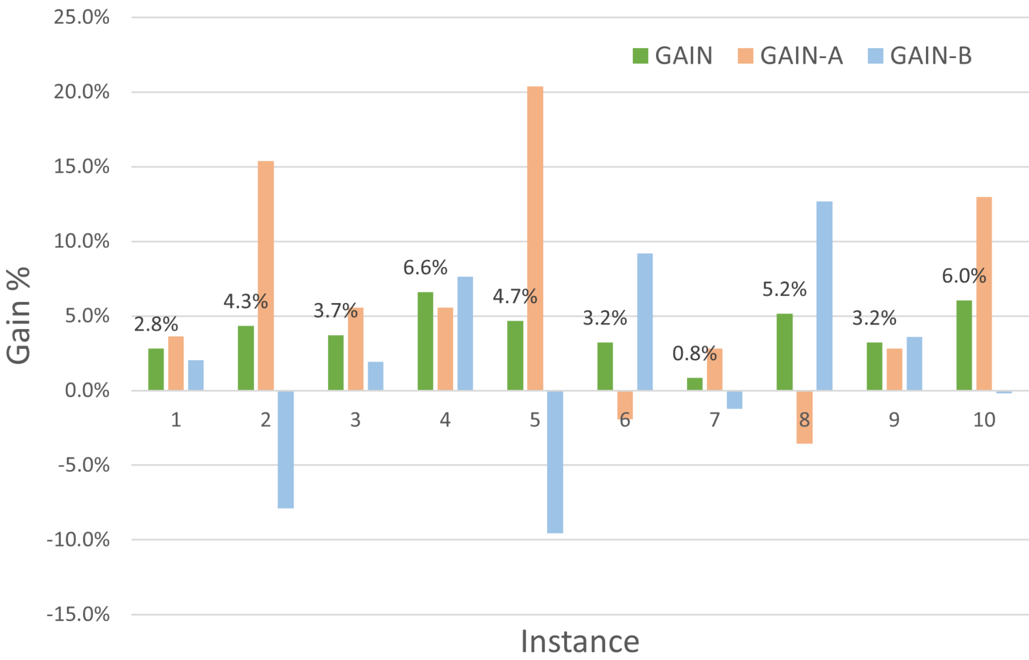


Figure 5.4 Gain comparison through best bounds for original scenario and high demand setting of 30 customer instances

When the gains are compared through best bounds for high demand setting of original scenario with 30 customers, it is seen that gains are lowered but still in all collaborative scenarios, a positive gain is reported. Gains for whole system vary between 0.8% and 6.6% and the average gain amount is 4.1%. For carrier $A$, average gain percentage is 6.4 where gains differ between -3.6% and 20.4%. For the carrier $B$, average gain percentage is 1.8 in which gains deviate between -9.6% and 12.7%.

Overall, in all experiments based on original scenario of 30 customers, proposed models report positive acquisitions. In most cases, both carriers benefit from the collaboration. However, there exist some instances in which one carrier reports a worse outcome when compared to individual scenario in favor of better outcome for whole system. To see the effect of common customer number on collaboration, above experiments, which are conducted to identify gain structure, are repeated. The setup, in which common customer numbers are increased, is called "Increased Common Customer" as mentioned in Section 4.3 and abbreviated as *ICC*. Collaboration occur if a customer is called *common*. If it is a common customer, then the demand which arise from this customer can be satisfied from either one of the carriers. When the number of common customers increase in the system, number of opportunities increase as well. On the contrary, once the number of common customer increases, complexity of problem increases as well since the number of possible opportunities to complete deliveries increase as well.

First experiments of ICC scenario is conducted with 30 customers and low demand environment. Results can be found in Table 5.11.

Table 5.11 LB Formulation results with ICC scenario and low demand setting of 30 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 1 | 1 | 1 | 59139 | 28287 | 30852 | 8.2% | 45771 | 9111 | 158 | 4099 |
| ***2*** | 1 | 1 | 1 | 1 | 60859 | 24108 | 36750 | 6.4% | 45895 | 8441 | 384 | 6139 |
| ***3*** | 1 | 1 | 1 | 1 | 62598 | 29455 | 33143 | 7.6% | 47356 | 9378 | 452 | 5412 |
| ***4*** | 1 | 1 | 1 | 1 | 49296 | 22490 | 26805 | 5.9% | 36191 | 7456 | 492 | 5157 |
| ***5*** | 1 | 1 | 1 | 1 | 57451 | 20065 | 37385 | 8.8% | 41731 | 9111 | 259 | 6350 |
| ***6*** | 1 | 1 | 1 | 1 | 55410 | 33115 | 22295 | 7.1% | 43104 | 7456 | 298 | 4552 |
| ***7*** | 1 | 1 | 1 | 1 | 56382 | 26823 | 29558 | 6.3% | 43440 | 7456 | 419 | 5067 |
| ***8*** | 1 | 1 | 1 | 1 | 52368 | 26016 | 26352 | 6.7% | 38905 | 7892 | 428 | 5144 |
| ***9*** | 1 | 1 | 1 | 1 | 65171 | 34556 | 30615 | 10.2% | 51047 | 7456 | 512 | 6156 |
| ***10*** | 1 | 1 | 1 | 1 | 62071 | 25848 | 36223 | 10.7% | 47630 | 7456 | 244 | 6741 |

In all instances all carriers chose to open one depot and construct one transfer line. Reported optimality gaps are higher when compared the low number of customers on average. To see the effect of high demand on this setup, same experiments are repeated for high demand environment. Results can be found in Table 5.12.

Table 5.12 LB Formulation results with ICC scenario and high demand setting of 30 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 3 | 3 | 1 | 82197 | 28165 | 54032 | 12.7% | 52235 | 16672 | 651 | 12639 |
| ***2*** | 2 | 1 | 1 | 2 | 81755 | 36503 | 45252 | 8.1% | 57605 | 13572 | 690 | 9888 |
| ***3*** | 2 | 3 | 3 | 2 | 85123 | 36376 | 48747 | 8.8% | 45362 | 19888 | 625 | 19247 |
| ***4*** | 1 | 1 | 1 | 1 | 65385 | 27469 | 37916 | 8.8% | 52280 | 7456 | 492 | 5157 |
| ***5*** | 1 | 2 | 2 | 1 | 76175 | 32307 | 43869 | 8.3% | 55266 | 10772 | 497 | 9640 |
| ***6*** | 2 | 2 | 2 | 2 | 75411 | 42314 | 33096 | 7.5% | 47368 | 14965 | 697 | 12380 |
| ***7*** | 1 | 1 | 1 | 1 | 77186 | 38752 | 38434 | 11.2% | 64244 | 7456 | 419 | 5067 |
| ***8*** | 1 | 2 | 2 | 1 | 65896 | 30849 | 35047 | 4.6% | 42350 | 13292 | 731 | 9523 |
| ***9*** | 2 | 2 | 2 | 2 | 85490 | 41236 | 44255 | 10.1% | 55448 | 14984 | 729 | 14329 |
| ***10*** | 1 | 2 | 2 | 1 | 80933 | 38737 | 42196 | 9.3% | 55631 | 13409 | 868 | 11025 |

Once the demand setting is switched to high, number of opened facilities and constructed transfer lines increased. Total costs are increased when compared to low demand setting. To see the effect of increased number of common customers on collaboration and identify gains from that collaboration, non-collaborative scenario experiments are completed for 30 customer ICC setting as well. Results can be found in Table 5.13.

Table 5.13 Individual LB Formulation results for ICC scenario and low demand setting of 30 customer instances

| ***Ins.*** | ***Obj*** | $Obj_A$ | $Obj_B$ | $BB_{Obj}$ | $BB_A$ | $BB_B$ | $T_A(s)$ | $T_B(s)$ | $Gap_A$ | $Gap_B$ |
|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 69703 | 35091 | 34612 | 69703 | 35091 | 34612 | 4559 | 2895 | 0.0% | 0.0% |
| ***2*** | 72538 | 37847 | 34691 | 69846 | 35155 | 34691 | 14400 | 8310 | 7.1% | 0.0% |
| ***3*** | 71499 | 33590 | 37909 | 65414 | 30885 | 34529 | 14400 | 14400 | 8.1% | 8.9% |
| ***4*** | 59526 | 30338 | 29188 | 59526 | 30338 | 29188 | 1256 | 1356 | 0.0% | 0.0% |
| ***5*** | 70753 | 35529 | 35224 | 68143 | 34207 | 33936 | 14400 | 14400 | 3.7% | 3.7% |
| ***6*** | 65553 | 35590 | 29964 | 63709 | 33746 | 29964 | 14400 | 2410 | 5.2% | 0.0% |
| ***7*** | 68737 | 34698 | 34040 | 65284 | 32538 | 32747 | 14400 | 14400 | 6.2% | 3.8% |
| ***8*** | 65577 | 31011 | 34566 | 61674 | 29324 | 32350 | 14400 | 14400 | 5.4% | 6.4% |
| ***9*** | 75511 | 36010 | 39501 | 70839 | 34215 | 36624 | 14400 | 14400 | 5.0% | 7.3% |
| ***10*** | 69502 | 35046 | 34456 | 65782 | 33681 | 32101 | 14400 | 14400 | 3.9% | 6.8% |

We compare the results of collaborative scenario with best reported objective function value of individual runs as well as best bounds found. Gains that are identified through the comparison of OFVs can be found in Figure 5.5.

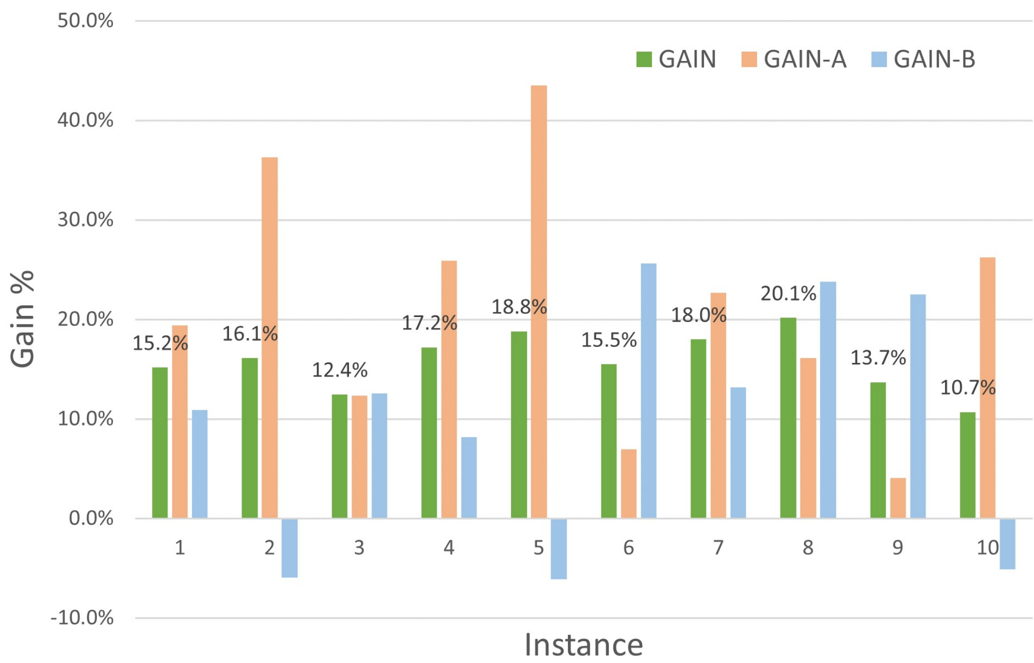


Figure 5.5 Gain comparisons through OFVs for ICC scenario and low demand setting of 30 customer instances

When the non-collaborative and collaborative scenarios are compared for low demand setting of ICC scenario with 30 customers, in all instances, collaborative scenario reports positive gains. For centralized system, gains deviate between 10.7% and 20.1% where average gain amount is 15.8%. For carrier $A$, average gain percentage is 21.3 where gains differ between 4% and 43.5%. 43.5% is an extreme example in which a carrier is decreased its cost almost by half with reported solutions. Carrier $A$ benefits from collaboration in all instances and reports a positive gain for each instance. For the carrier $B$, average gain percentage is 9.9 in which gains deviate between -6.1% and 25.6%. In three instances, carrier $B$ suffer from collaboration and reports increased cost. In order to the see the lower bound of the gains, best bounds of reported individual scenarios are also compared and the results can be found in Figure 5.6.

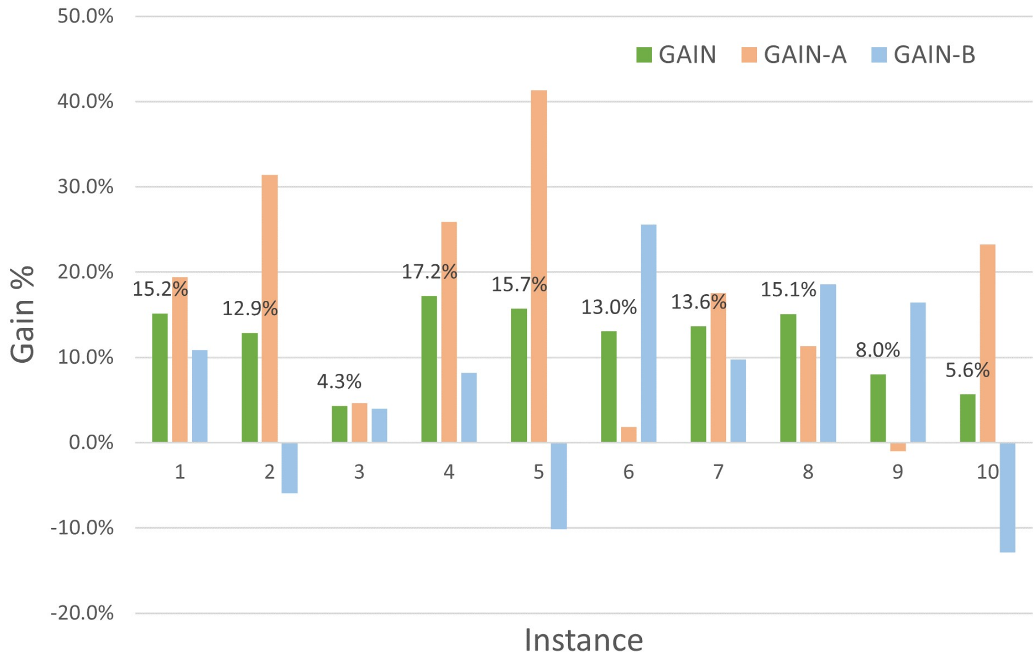


Figure 5.6 Gain comparisons through best bounds for ICC scenario and low demand setting of 30 customer instances

When the gains are compared through best bounds for low demand setting of ICC scenario with 30 customers, again in all instances, collaborative scenario yields better outcomes when contrasted with individual scenarios. Gains for whole system deviate between 4.3% and 17.2%. Average gain amount is 12.1%. Carrier $A$ reports positive gains for 9 out of 10 instances with an average of 17.6%. Gain percentages vary between -1% and 41.3% for carrier $A$. For carrier $B$ average gain is 6.4% where gains deviate between -12.8% and 25.6%.

The gains with ICC scenario with low demand are higher when compared to original scenario with low demand in average. To evaluate the effect of demand on collaboration levels, same experiments are conducted for high demand environment of ICC scenario with 30 customers. Results can be found in Table 5.14.

Similar to what we did for low demand instances of ICC, we compare the results of collaborative scenario with best reported OFV of individual runs as well as best bounds found. Gains that are identified through the comparison of OFVs can be found in Figure 5.7

When collaboration results are compared with individual results through best found

Table 5.14 Individual LB Formulation results for ICC scenario and high demand setting of 30 customer instances

| ***Ins.*** | ***Obj*** | $Obj_A$ | $Obj_B$ | $BB_{Obj}$ | $BB_A$ | $BB_B$ | $T_A(s)$ | $T_B(s)$ | $Gap_A$ | $Gap_B$ |
|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 95724 | 44646 | 51078 | 88974 | 42116 | 46859 | 14400 | 14400 | 5.7% | 8.3% |
| ***2*** | 97506 | 50609 | 46898 | 90242 | 47136 | 43106 | 14400 | 14400 | 6.9% | 8.1% |
| ***3*** | 93483 | 46193 | 47290 | 87853 | 42151 | 45702 | 14400 | 14400 | 8.8% | 3.4% |
| ***4*** | 78934 | 39894 | 39040 | 74652 | 37587 | 37066 | 14400 | 14400 | 5.8% | 5.1% |
| ***5*** | 92166 | 45135 | 47031 | 86278 | 43818 | 42460 | 14400 | 14400 | 2.9% | 9.7% |
| ***6*** | 89378 | 48610 | 40768 | 83216 | 44074 | 39142 | 14400 | 14400 | 9.3% | 4.0% |
| ***7*** | 90706 | 45668 | 45039 | 83603 | 42033 | 41571 | 14400 | 14400 | 8.0% | 7.7% |
| ***8*** | 84769 | 40685 | 44085 | 78787 | 37157 | 41630 | 14400 | 14400 | 8.7% | 5.6% |
| ***9*** | 99234 | 45922 | 53312 | 91314 | 43898 | 47416 | 14400 | 14400 | 4.4% | 11.1% |
| ***10*** | 95170 | 46892 | 48279 | 87907 | 43623 | 44284 | 14400 | 14400 | 7.0% | 8.3% |

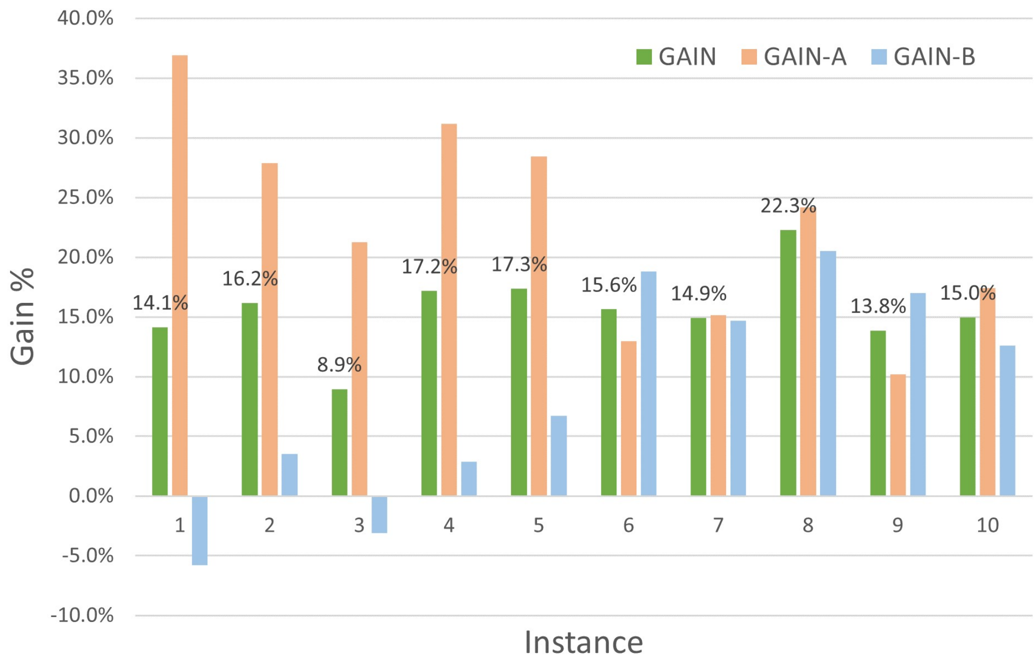


Figure 5.7 Gain comparisons through OFVs for ICC scenario and high demand setting of 30 customer instances

objective function values to evaluate gains for the high demand setup of ICC setting for 30 customers, it is seen that there is an average gain of 15.5%. For the integrated system gains vary between 8.9% and 22.3%. Carrier $A$ benefited from collaboration in all instances with an average gain amount of 22.3%. Carrier $A$ gained at least 10.2% from collaboration and 36.9% at most. On the other hand, carrier $B$ reported worse outcomes for 2 instances but for the rest of the instances it reported positive gains as well. Average gain of carrier $B$ is 8.8% where gains deviate between -5.8% and 20.5%.

Next, best bounds of individual scenarios are compared with the collaborative scenario results to asses lower bound on gains and the results can be found in Figure

5.8.

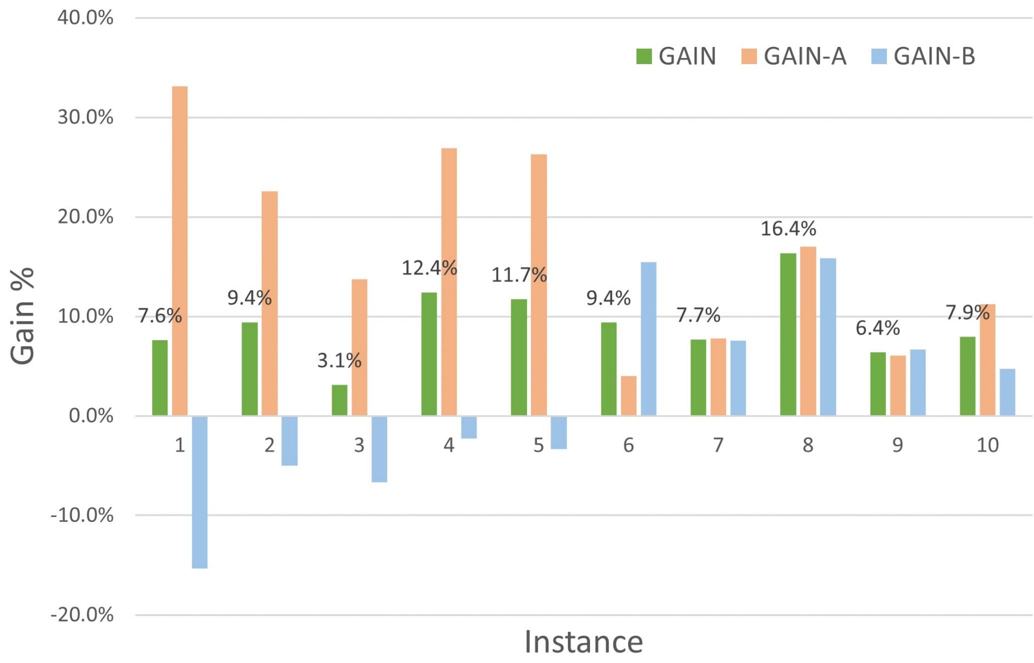


Figure 5.8 Gain comparisons through best bounds for ICC scenario and high demand setting of 30 customer instances

When the individual results are compared with collaborative results for the high demand setup of ICC scenario for 30 customers through best bounds, again all instances with collaboration reported a lower cost and more gains. Centralized system has a gain of 9.2% on average where gains vary between 3.1% and 16.4%. Carrier $A$ reported better outcomes in all cases which means collaboration was beneficial for carrier $A$ in all cases. Carrier $A$ gained 16.9% on average where gains of $A$ deviate between 4% and 33.1%. On the other hand, carrier $B$ realized higher costs in five instances with an average gain of 1.8%. Minimum gain of carrier $B$ is -15.3% and maximum gain of carrier $B$ is 15.8%.

When the results of high demand ICC setting is compared with high demand original scenario results, it is observed that gain percentages are higher in ICC scenarios. Those results overlap with the expected outcomes since increased number of common customers increase the collaboration possibility which may yield lower costs. In original scenario's best bound comparisons, average gains was reported as 4.1%, but in ICC setting it is reported as 9.2%.

Overall, all experiments which are conducted with ICC setting of 30 customers yielded positive gains. As explained in Section 4.3, in the original scenarios, carriers declare some of the possible regional depot locations as *common* and no cost incurred if a transfer line is constructed between two depots which share same location. Main

Table 5.15 LB Formulation results for NCD scenario and low demand setting of 30 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 1 | 1 | 1 | 60011 | 30863 | 29147 | 6.8% | 48222 | 7532 | 158 | 4099 |
| ***2*** | 1 | 1 | 1 | 1 | 64459 | 26433 | 38026 | 6.4% | 51165 | 7532 | 284 | 5478 |
| ***3*** | 1 | 1 | 1 | 1 | 63377 | 31338 | 32039 | 5.9% | 51274 | 7424 | 313 | 4366 |
| ***4*** | 1 | 1 | 1 | 1 | 54967 | 28233 | 26733 | 4.0% | 41837 | 6794 | 66 | 6270 |
| ***5*** | 1 | 1 | 1 | 1 | 58945 | 31605 | 27339 | 6.1% | 44804 | 7532 | 259 | 6350 |
| ***6*** | 1 | 1 | 1 | 1 | 61669 | 35543 | 26125 | 6.8% | 49183 | 7226 | 406 | 4854 |
| ***7*** | 1 | 1 | 1 | 1 | 61605 | 31436 | 30169 | 5.9% | 48431 | 7532 | 478 | 5164 |
| ***8*** | 1 | 1 | 1 | 0 | 58964 | 26534 | 32430 | 5.2% | 46263 | 7730 | 57 | 4915 |
| ***9*** | 1 | 1 | 1 | 1 | 62428 | 32707 | 29720 | 5.2% | 48825 | 6992 | 485 | 6126 |
| ***10*** | 2 | 1 | 1 | 2 | 63145 | 33361 | 29784 | 9.3% | 39776 | 10457 | 805 | 12107 |

motivation behind this is to incentivize collaboration between carriers. To see the effect of not opening depots on same locations, runs are repeated with "No Common Depot" (NCD) setting. When the number of common depots are decreased in the system, number of collaboration opportunities decrease as well.

Initial experiments of NCD scenario are conducted with 30 customers and low demand environment. Results can be found in Table 5.15.

Both carriers chose to open regional depot and create transfer lines even though the depots are not located in same geographical locations to promote collaboration. In order to evaluate the effect of high demand density on NCD setup, same experiments are conducted in high demand setting. Results can be found in Table 5.16.

Table 5.16 LB Formulation results for NCD scenario and high demand setting of 30 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 1 | 1 | 1 | 84202 | 43080 | 41122 | 9.4% | 69948 | 8999 | 361 | 4894 |
| ***2*** | 2 | 2 | 2 | 2 | 86447 | 40889 | 45558 | 5.8% | 57741 | 14396 | 920 | 13389 |
| ***3*** | 2 | 1 | 1 | 2 | 90193 | 48824 | 41369 | 8.2% | 68118 | 12525 | 552 | 8998 |
| ***4*** | 2 | 2 | 1 | 2 | 75341 | 39598 | 35742 | 9.1% | 49606 | 14524 | 82 | 11129 |
| ***5*** | 2 | 1 | 1 | 2 | 80076 | 47109 | 32967 | 8.5% | 57934 | 11767 | 489 | 9886 |
| ***6*** | 2 | 2 | 2 | 2 | 81810 | 43024 | 38785 | 7.2% | 55812 | 13658 | 665 | 11675 |
| ***7*** | 2 | 1 | 1 | 2 | 81736 | 42321 | 39415 | 8.5% | 62153 | 11125 | 326 | 8133 |
| ***8*** | 2 | 1 | 1 | 1 | 79613 | 39707 | 39905 | 8.1% | 60084 | 11017 | 213 | 8299 |
| ***9*** | 2 | 1 | 1 | 2 | 83058 | 39650 | 43407 | 8.6% | 61614 | 10457 | 815 | 10172 |
| ***10*** | 3 | 1 | 1 | 2 | 82731 | 45746 | 36984 | 8.4% | 53536 | 15150 | 546 | 13499 |

Once total demand in the system increases, carriers prefer to open more depots to cope with routing costs. And still, despite the fact that depots are not located in same locations, they prefer to establish transfer lines. To investigate the effect of decreased number of common depots to the gains, individual runs are completed in which carriers act as individuals and do not collaborate. Results for the individual runs of NCD setting for 30 customers with low demand density setting can be found in Table 5.17.

Table 5.17 Individual LB Formulation for NCD scenario and low demand setting of 30 customer instances

| ***Ins.*** | ***Obj*** | $Obj_A$ | $Obj_B$ | $BB_{Obj}$ | $BB_A$ | $BB_B$ | $T_A(s)$ | $T_B(s)$ | $Gap_A$ | $Gap_B$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *1* | 62972 | 30239 | 32734 | 62972 | 30239 | 32734 | 345 | 2805 | 0.0% | 0.0% |
| *2* | 69764 | 31921 | 37843 | 69764 | 31921 | 37843 | 5683 | 9589 | 0.0% | 0.0% |
| *3* | 69981 | 37386 | 32595 | 68092 | 35497 | 32595 | 14400 | 2238 | 5.1% | 0.0% |
| *4* | 57514 | 29861 | 27654 | 57139 | 29861 | 27279 | 1322 | 14400 | 0.0% | 1.4% |
| *5* | 65043 | 34757 | 30287 | 63759 | 33472 | 30287 | 14400 | 2896 | 3.7% | 0.0% |
| *6* | 67162 | 36233 | 30930 | 66141 | 35211 | 30930 | 14400 | 939 | 2.8% | 0.0% |
| *7* | 67295 | 34859 | 32437 | 66097 | 33661 | 32437 | 14400 | 1341 | 3.4% | 0.0% |
| *8* | 62871 | 33044 | 29827 | 62298 | 32472 | 29827 | 14400 | 1273 | 1.7% | 0.0% |
| *9* | 70567 | 36683 | 33884 | 69610 | 35726 | 33884 | 14400 | 734 | 2.6% | 0.0% |
| *10* | 67898 | 36593 | 31306 | 67529 | 36224 | 31306 | 14400 | 3282 | 1.0% | 0.0% |

As we did in ICC and original scenario instances, we compare the results of collaborative scenario with best reported objective function value of individual runs as well as best bounds found. Gains that are identified through the comparison of OFVs for NCD setting in low demand environment of 30 customers can be found in Figure 5.9.

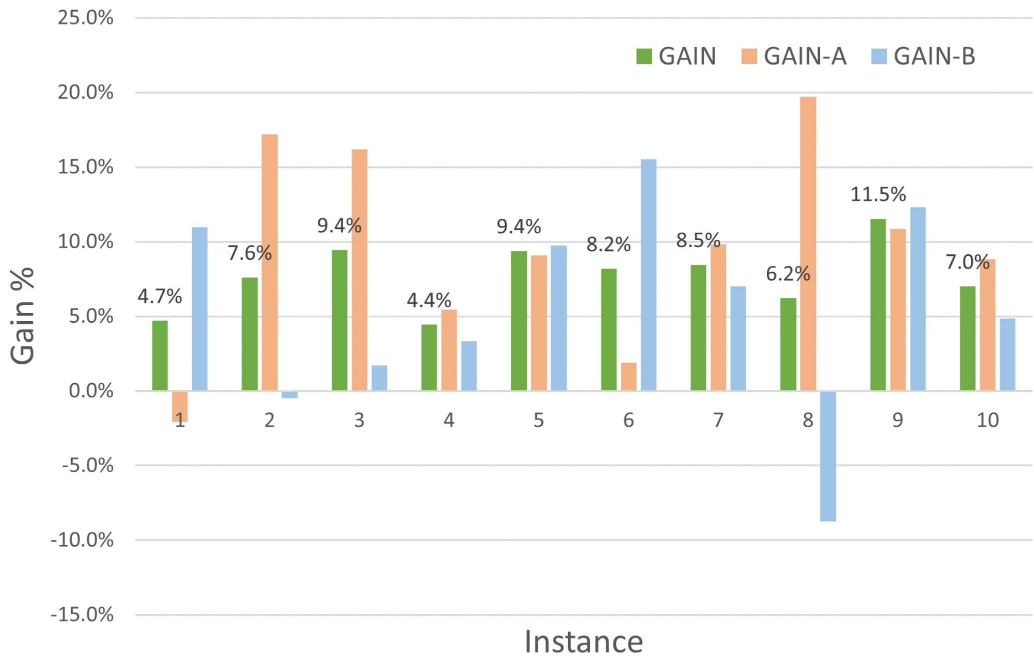


Figure 5.9 Gain comparisons through OFVs for NCD scenario and low demand setting of 30 customer instances

When costs of collaborative scenarios are compared with individual scenarios through OFVs, it is observed that all instances of NCD setting of low demand setup for 30 customers lead to positive gains. Gain amounts are lower than both original and ICC scenarios. Average gain percentage for centralized network is 7.7%

where gains deviate 4.4% and 11.5%. Carrier $A$ reported worse outcome for only one instance and average gain of carrier $A$ from collaboration is 9.7%. Gain percentages of carrier $A$ vary between -2.1 and 19.7. Carrier $B$ reports negative gains only for two instances. Gains for carrier $B$ deviate between -8.7% and 15.5% where average gain for $B$ is 5.6%. Best bounds of individual scenarios are also compared with the collaborative scenarios to investigate lower bounds on gains. Results can be found in figure 5.10.

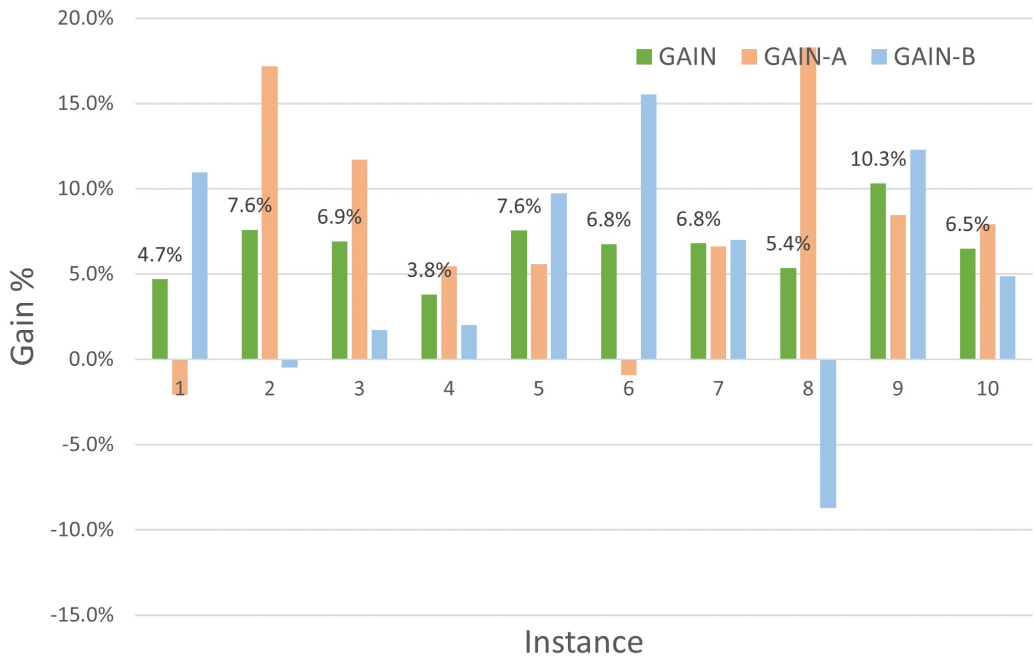


Figure 5.10 Gain comparisons through best bounds for NCD scenario and low demand setting of 30 customer instances

When the gains are compared through best bounds for NCD scenario of 30 customers with low demand setting, a similar outcome is observed with the comparison that is conducted through OFVs. In all instances, collaboration is beneficial for centralized system. Average gain through collaboration is 6.6%. Gains for collaborative system vary between 3.8% and 10.3%. For two instances carrier $A$ reported increased costs when compared with the individual scenario. Average gain of carrier $A$ is 7.8% where gains deviate between -2.1% and 18.3%. For carrier $B$, two instances resulted with worst outcomes but average gain of carrier $B$ is 5.5% where gains of $B$ deviate between -8.7% and 15.5%.

In order to see the effect of demand density on collaboration, NCD experiments with 30 customers are repeated under high demand environment. Results can be found in Table 5.18.

As we did in previous experiments, we compare gains for 30 customers and NCD

Table 5.18 Individual LB Formulation results for NCD scenario and high demand setting of 30 customer instances

| ***Ins.*** | $Obj$ | $Obj_A$ | $Obj_B$ | $BB_{Obj}$ | $BB_A$ | $BB_B$ | $T_A(s)$ | $T_B(s)$ | $Gap_A$ | $Gap_B$ |
|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 87660 | 43034 | 44626 | 83156 | 39841 | 43315 | 14400 | 14400 | 7.4% | 2.9% |
| ***2*** | 97832 | 43943 | 53890 | 92413 | 41787 | 50626 | 14400 | 14400 | 4.9% | 6.1% |
| ***3*** | 98572 | 53252 | 45320 | 92765 | 48858 | 43907 | 14400 | 14400 | 8.3% | 3.1% |
| ***4*** | 77764 | 40805 | 36960 | 74127 | 38593 | 35534 | 14400 | 14400 | 5.4% | 3.9% |
| ***5*** | 88225 | 49267 | 38959 | 82112 | 45469 | 36643 | 14400 | 14400 | 7.7% | 5.9% |
| ***6*** | 89788 | 47081 | 42707 | 87402 | 45673 | 41730 | 14400 | 14400 | 3.0% | 2.3% |
| ***7*** | 86779 | 44246 | 42533 | 84324 | 41791 | 42533 | 14400 | 10600 | 5.5% | 0.0% |
| ***8*** | 83816 | 44627 | 39189 | 80263 | 41868 | 38395 | 14400 | 14400 | 6.2% | 2.0% |
| ***9*** | 90951 | 46161 | 44791 | 90464 | 46161 | 44303 | 5409 | 14400 | 0.0% | 1.1% |
| ***10*** | 89321 | 45671 | 43651 | 87131 | 45671 | 41460 | 14244 | 14400 | 0.0% | 5.0% |

scenario in high demand setting through best found OFVs and best reported individual bounds. Gains that are identified through the comparison of OFVs can be found in figure 5.11.

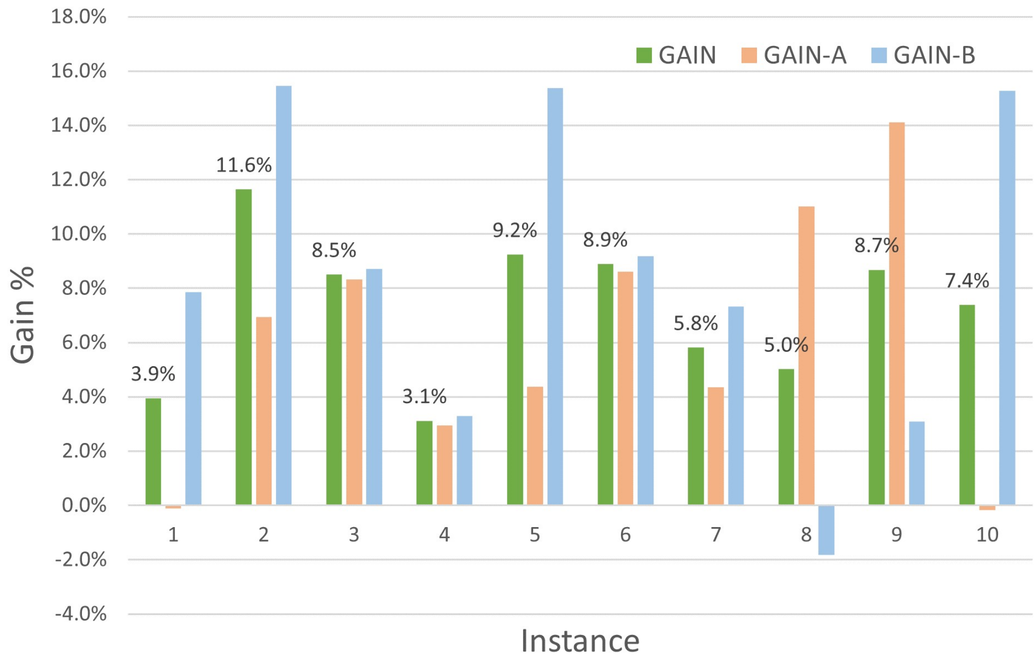


Figure 5.11 Gain comparisons through OFVs for NCD scenario and high demand setting o 30 customer instances

When the comparisons is are through OFVs, in parallel of previous findings, all instances yielded better results under collaborative scenarios. Average gain amount is 7.2% for centralized system where gains differ between 3.1% and 11.6%. For carrier $A$ all instances reported better values except for two instances. Average gain percentage for carrier $A$ is 6%. For carrier $A$, gains deviate between -0.2% and 14.1%. For carrier $B$ gains vary between -1.8% and 15.5% where average gain is 8.4%. Best bounds of individual scenarios are also compared with the collaborative scenarios to investigate lower bounds on gains. Results can be found in Figure 5.12

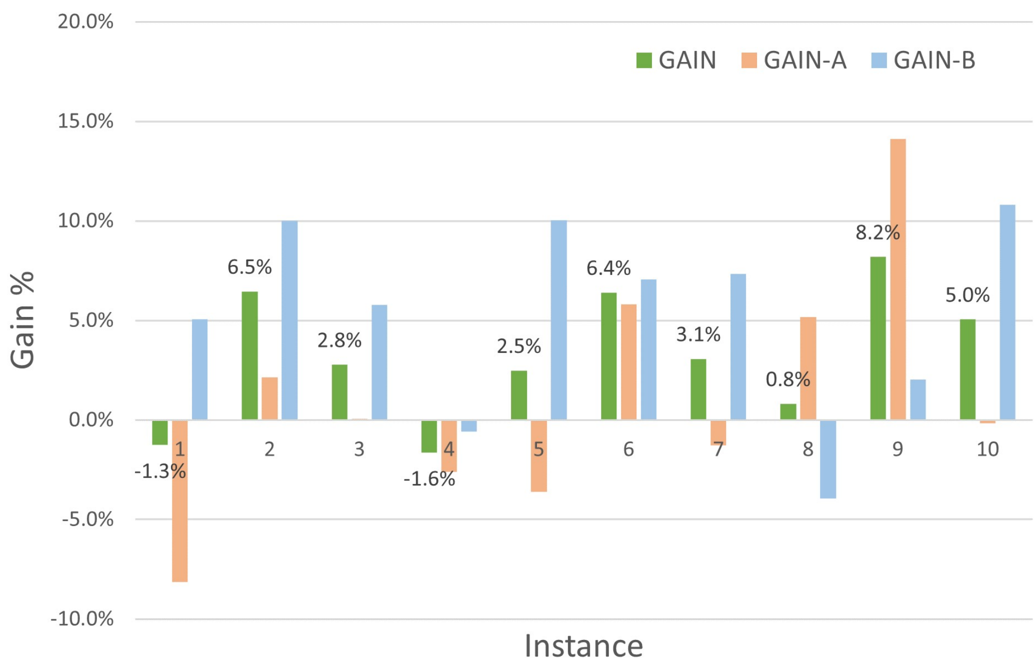


Figure 5.12 Gain comparison through best bounds for NCD scenario and high demand setting of 30 customer instances

When the comparison is conducted through best bounds for high demand setting of NCD scenario with 30 customers, all instances yielded better results under collaborative scenarios expect for two scenarios. Since all the models are solved relatively higher gaps, these two cases are exceptions with only approximately -1% deviation. Average gain for collaborative scenarios is 3.2% where gains deviate between -1.6% and 8.2%. Carrier *A* reported an average of 1.1% gain where gains vary between -8.1% and 14.1%. Average gain of carrier *B* is 5.4% where gains of *B* deviate between -3.9% and 10.8%.

Overall, all instances of all scenarios are solved under both low demand and high demand environments. LB formulation was able to find solutions for all instances with deviating gaps. To lower gaps several valid inequalities are proposed and their effects are investigated. All tests are continued with best found combination of proposed valid inequalities. From the managerial perspective, it is observed that in all scenarios, collaboration yielded better solutions even though the collaborative scenario instances are solved with gaps. Collaboration behaviour tested with all three scenarios proposed in Section 4.3, namely; original, ICC and NCD. When the original and ICC scenarios are compared, ICC instances yielded higher gains in average, as expected because of the increased number of opportunities for collaboration. When the original and NCD scenarios are compared, NCD instances yielded lower gains than original instances, since the collaboration gains are restricted through distanced facility declaration. Same experiments are conducted with 50 customer setups as well. Results can be found in Appendix A. However, since the reported gaps are higher in both collaborative and individual runs, comparing results do not promise reliable insights.

As indicated in previous sections, none of the collaborative instances solved until optimality. Moreover, solution times are 8 and 16 hours for 30 and 50 customer instances, respectively. 100 customer instances did not yield sensible results within 48 hour time limit.

Consequently, a new path-based formulation is proposed in Section 3.2.3 to solve problem with a path-based formulation approach in which outbound routes are selected pre-generated routes instead of creating optimum routes. As mentioned before, outbound routing decisions is one of the key reasons that increase time and space complexity of the problem. Via path-based method, time and space complexity of the model decreased in exchange of exact solutions. Details of path-based formulation approach discussed in Section 6.

# 6. PATH-BASED FORMULATION

The path-based formulation is different from the other two in the way routing decisions are modeled. Instead of constructing the routes through arc traversal decisions, the formulation selects a subset of the routes from a set of predetermined routes. As a matter of fact, the formulation requires these routes to be generated a priori, i.e., a pre-processing phase to generate routes is needed. Ideally, for the mathematical model to find the true optimal solution equivalent that can be found by either the VB formulation or the LB formulation, all possible feasible routes must have been generated by this pre-processing phase. Since the number of such routes are usually exponentially many, a possible approach is to generate a limited number of good routes.

In our approach, the set of routes are created by solving heuristically a series of single depot VRPs: a VRP for each depot $d \in D_r$ of each carrier $r \in C$. For each depot, the problem is solved with several different heuristic algorithms and the resulting routes are added to route pool. Then, demands of common customers are merged as if they are a single customer of that carrier: the new version of the problem is solved with all heuristic algorithms again. These routes are also, added to route pool. Main motivation behind the repetition and merging demands is to mimic creation of joint routes when the carriers collaborate and transfer their demand among themselves. 5 different well known heuristics are utilized:

- *Nearest Neighborhood (NNH)* (Tyagi, 1968)
- *Sweep* (Gillett & Miller, 1974)
- *Parallel Savings (PS)* (Clarke & Wright, 1964)
- *Gaskell-Savings (GS)* (Gaskell, 1967)
- *CMT Two-Phase Heuristic (CMT2P)* (Christofides, Mingozzi & P.Toth, 1979)

The working mechanisms of the heuristics or heuristic algorithm development is beyond the scope of this study. Different heuristic algorithms are utilized to generate different routes and increase the diversity among routes. Since demand transfer is allowed if vehicle capacity is not exceeded on that route, creation of sub-optimal routes in individual cases may be beneficial to incentivize collaboration as well. Flowchart of the route pool generation mechanism can be found in Figure 6.1.

During root pool generation, firstly an empty master route list $R$ is defined. Then for each depot $d \in D_r$ of each carrier $r \in C$, problem is reduced to a single depot VRP and a list $R_d = \{\}$ is initialized which denotes the routes belong to depot $d$ and a parameter $iter = 1$. Then problem is solved by NNH, Sweep, PS, GS and CMT2P heuristics separately and all found routes are appended to $R_d$. Then all generated identical routes eliminated from $R_d$, if there is any, to break possible symmetry. Append $R_d$ to $R$. If $iter = 1$, then demand of other common customers which emerge from other carriers assigned to that customer and $iter$ is updated to 2. All reduced problem steps are repeated for this depot. Then master route list $R$ is used as "possible route list" for outbound routes in path-based formulation.

For the path-based formulation, inequalities (4.4),(4.9) and (4.10) that are proposed under Section 4.2 are valid as well. One extra valid inequality is proposed for path-based model.

$$\sum_{t \in R} x^t \geq \lceil \frac{\sum_{i \in N} \sum_{r \in C} d_i^r}{Q} \rceil \tag{6.1}$$

Since the total demand and vehicle capacities are known and vehicles are homogeneous, a lower bound on the number of routes that should be used can be forced by inequalities (6.1). Note that since (6.1) are non-linear, it can be replaced with (6.2).

$$\sum_{t \in R} x^t \geq \frac{\sum_{i \in N} \sum_{r \in C} d_i^r}{Q} \tag{6.2}$$

## 6.1 Computational Experiments

Path-based (PB) formulation reduces the problem size and consequently time and space complexity drastically. Therefore, for 30 customer instances, time limit is set

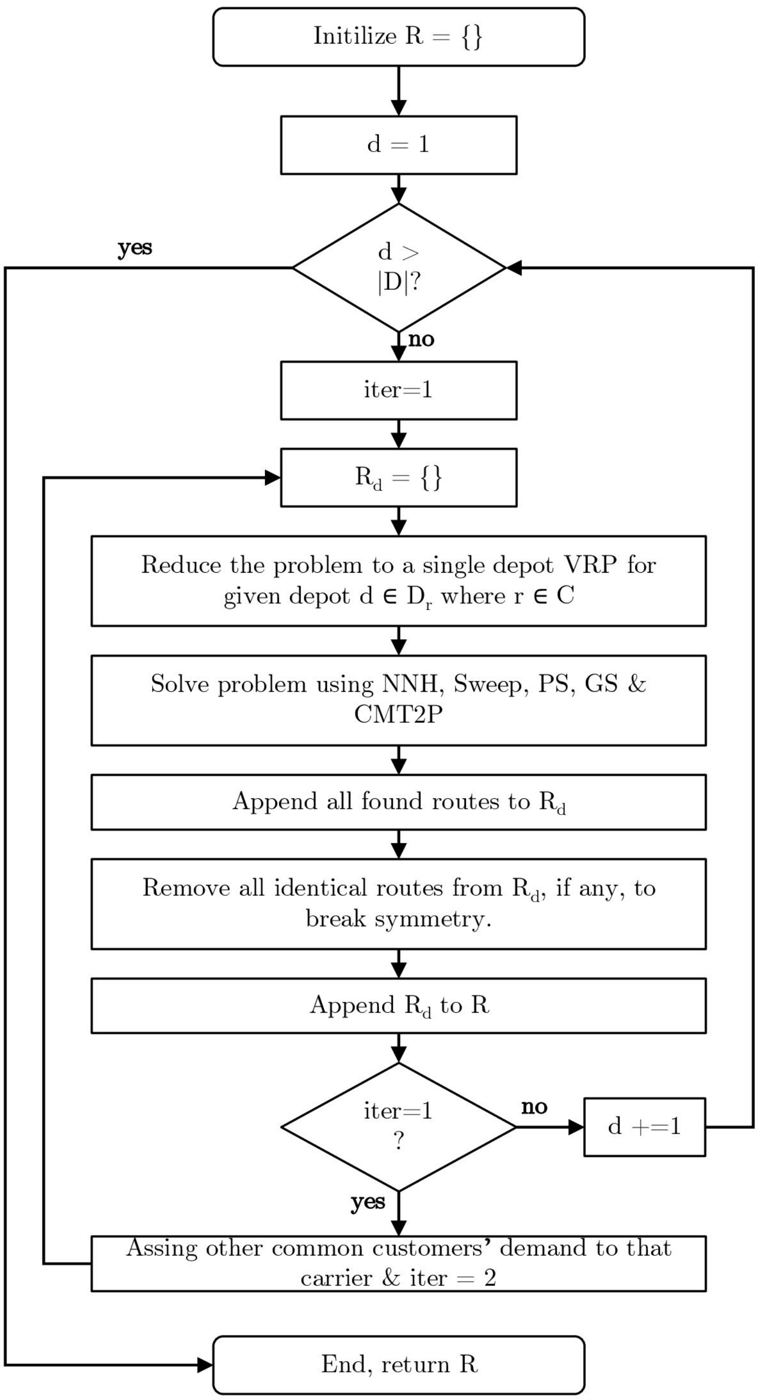


Figure 6.1 Heuristic route pool generation

as 2 hours, 50 customer instances 4 hours and 100 customer instances 16 hours. Note that route generation process takes no more than 2 minutes even for biggest instances, so they are not included in solution times.

For all results tables, $R_A$ and $R_B$ columns indicate the number of used routes in optimum solution. Rest of the column names explained at the beginning of Section 5.2.

In PB approach, computational experiments are started with original scenario and low demand setting of 30 customer instances. Before going into details of the run results, information on number of pre-generated routes in original scenarios presented in Table 6.1. As it can be interpreted from Table 6.1, number of possible routes per carrier deviate between 245 and 6344 depending on the problem size and demand structure. In Table 6.1, $TR_A$ and $TR_B$ depicts the number of pre-generated routes for each carrier, respectively.

Table 6.1 Pre-generated route numbers for original scenario

| | **30 Customer** | | | | **50 Customer** | | | | **100 Customer** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Low Dem.** | | **High Dem.** | | **Low Dem.** | | **High Dem.** | | **Low Dem.** | | **High Dem.** | |
| **Ins.** | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ |
| **1** | 315 | 379 | 622 | 785 | 690 | 603 | 1265 | 1093 | 2819 | 2678 | 6177 | 5774 |
| **2** | 371 | 320 | 784 | 679 | 798 | 705 | 1489 | 1284 | 2780 | 2855 | 5466 | 5500 |
| **3** | 380 | 323 | 662 | 617 | 749 | 649 | 1389 | 1166 | 2627 | 2522 | 5708 | 5450 |
| **4** | 245 | 359 | 532 | 793 | 785 | 726 | 1405 | 1326 | 2672 | 2575 | 5286 | 4927 |
| **5** | 328 | 357 | 712 | 722 | 763 | 733 | 1400 | 1336 | 2619 | 2779 | 5652 | 6020 |
| **6** | 358 | 315 | 767 | 678 | 712 | 713 | 1312 | 1305 | 2836 | 2737 | 5485 | 5255 |
| **7** | 357 | 316 | 753 | 664 | 696 | 714 | 1338 | 1312 | 2838 | 2858 | 4618 | 4644 |
| **8** | 315 | 315 | 588 | 615 | 807 | 701 | 1570 | 1281 | 2769 | 2851 | 6156 | 6344 |
| **9** | 315 | 353 | 622 | 787 | 684 | 668 | 1479 | 1402 | 2814 | 2682 | 4582 | 4343 |
| **10** | 315 | 356 | 529 | 667 | 767 | 700 | 1416 | 1273 | 2870 | 2715 | 5573 | 5331 |

Results of the path-based formulation for 30 customers under original scenario and low demand setting can be found in Table 6.2.

Table 6.2 PB Formulation results for original scenario and low demand setting of 30 customer instances

| *Ins.* | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | *Obj* | $Obj_A$ | $Obj_B$ | T(s) | *RC* | *FC* | *TC* | *IC* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | 1 | 1 | 1 | 1 | 4 | 5 | 59212 | 28374 | 30838 | 2 | 49093 | 7029 | 0 | 3090 |
| *2* | 1 | 1 | 1 | 1 | 9 | 4 | 63258 | 31251 | 32007 | 6 | 51477 | 7029 | 0 | 4752 |
| *3* | 1 | 1 | 1 | 1 | 9 | 4 | 66487 | 35099 | 31389 | 4 | 53486 | 9073 | 105 | 3928 |
| *4* | 1 | 1 | 1 | 1 | 3 | 5 | 56495 | 28600 | 27894 | 2 | 42512 | 8334 | 492 | 5157 |
| *5* | 1 | 1 | 1 | 1 | 4 | 5 | 59675 | 23104 | 36571 | 5 | 46002 | 7065 | 259 | 6350 |
| *6* | 1 | 1 | 1 | 1 | 4 | 4 | 62773 | 35704 | 27069 | 4 | 50294 | 7065 | 382 | 5033 |
| *7* | 1 | 1 | 1 | 1 | 5 | 4 | 60823 | 29770 | 31053 | 3 | 48116 | 7065 | 478 | 5164 |
| *8* | 1 | 1 | 1 | 1 | 3 | 4 | 59838 | 27162 | 32675 | 5 | 45140 | 8530 | 523 | 5645 |
| *9* | 1 | 1 | 1 | 1 | 4 | 4 | 71090 | 34649 | 36441 | 6 | 55295 | 8938 | 333 | 6525 |
| *10* | 1 | 1 | 1 | 1 | 4 | 5 | 63738 | 29752 | 33986 | 3 | 50554 | 7065 | 522 | 5597 |

Within seconds, all of the instances are solved with 0 gap. Maximum run time is

6 seconds. When the results are compared with the LB formulation results, both carriers open one depot and create one transfer line between depots. Number of total selected routes in PB formulation results deviate between 7 and 13. Same experiments are conducted for high demand environment as well. Results can be found in Table 6.3.

Table 6.3 PB Formulation results for original scenario and high demand setting of 30 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 2 | 2 | 1 | 7 | 11 | 84655 | 37917 | 46738 | 10 | 66736 | 11299 | 181 | 6439 |
| ***2*** | 2 | 1 | 1 | 2 | 18 | 7 | 87762 | 49155 | 38607 | 6 | 66925 | 12130 | 192 | 8515 |
| ***3*** | 2 | 2 | 2 | 2 | 15 | 22 | 81829 | 41689 | 40140 | 2 | 50744 | 17032 | 362 | 13691 |
| ***4*** | 2 | 1 | 1 | 2 | 7 | 9 | 72874 | 35897 | 36977 | 5 | 53427 | 10266 | 327 | 8854 |
| ***5*** | 1 | 2 | 2 | 1 | 8 | 9 | 80099 | 33351 | 46748 | 7 | 59982 | 11440 | 448 | 8229 |
| ***6*** | 2 | 2 | 2 | 2 | 8 | 10 | 87084 | 44873 | 42211 | 8 | 59309 | 14641 | 692 | 12442 |
| ***7*** | 2 | 1 | 1 | 1 | 10 | 7 | 80806 | 44932 | 35874 | 15 | 62124 | 10266 | 282 | 8133 |
| ***8*** | 1 | 1 | 1 | 1 | 8 | 6 | 78296 | 42119 | 36177 | 18 | 63598 | 8530 | 523 | 5645 |
| ***9*** | 2 | 2 | 1 | 2 | 8 | 8 | 91513 | 46544 | 44970 | 29 | 62523 | 15967 | 166 | 12857 |
| ***10*** | 1 | 2 | 2 | 1 | 6 | 10 | 79527 | 37881 | 41646 | 4 | 55314 | 12460 | 886 | 10867 |

In high demand environment, all instances are solved under 30 seconds as well. Maximum solution time is 29 seconds and average solution time is 10 seconds. Number of selected routes deviate between 14 and 37.

Since outbound routes are created heuristically, results of exact solutions which are achieved through LB formulation, are compared with PB solutions in order to evaluate how much PB formulation deviate from optimality. Since not all LB formulation examples are solved to optimality, we compare both best found objective values within 8 hour limit and best bounds found by solver. Deviation amounts for original scenario of 30 customer instances can be found in Table 6.4.

Table 6.4 PB deviation percentages for original scenario of 30 customer instances

| | **Low Demand** | | **High Demand** | |
|---|---|---|---|---|
| **Ins** | $\Delta_{OFV}$ | $\Delta_{BB}$ | $\Delta_{OFV}$ | $\Delta_{BB}$ |
| **1** | 0.1% | 8.4% | 2.5% | 13.3% |
| **2** | 3.4% | 8.1% | 1.8% | 9.9% |
| **3** | 7.5% | 11.9% | -6.6% | 7.0% |
| **4** | 7.2% | 10.3% | 5.3% | 12.7% |
| **5** | 3.3% | 11.1% | 1.5% | 10.4% |
| **6** | 5.7% | 11.3% | 6.0% | 12.6% |
| **7** | 6.0% | 10.1% | 2.5% | 12.2% |
| **8** | 5.0% | 9.6% | 3.9% | 11.4% |
| **9** | 6.3% | 13.1% | 3.2% | 12.3% |
| **10** | 4.1% | 10.7% | -1.4% | 4.5% |

In deviation tables, $\Delta_{OFV}$ indicates the percentage difference between the objective function value of PB formulations run results and the best reported objective function value of LB formulation. In other words, it shows that how far PB solution is away from the best found exact solution reported by LB model within 8 hours for 30 customer instances. Similarly, $\Delta_{BB}$ reports the difference percentage between the objective function value of PB model results and the best reported bound by LB formulation. A negative sign (-) means that PB method reported a better solution.

In low demand environment of original scenario of 30 customer instances, PB formulation deviates 4.8% on average when comparison is conducted through best found OFVs of LB formulation. Minimum deviation is 0.1% which means that PB formulation found a solution almost as good as exact formulation, within seconds. On the other hand maximum deviation is 7.5%. When deviations compared through best bounds, average difference in 10.5% where minimum variance is 8.1% and maximum variance is 13.1%.

When best found OFVs are compared with PB formulation results for high demand environment of the original scenario of 30 customers, it is observed that PB model reported better outcomes for two instances. In average, PB formulation deviates 1.9% and deviation range is between -6.6% and 6%. When deviations compared through best bounds, average difference is 10.6% where minimum variance is 4.5% and maximum variance is 13.3%.

Overall, when the original setting of 30 customer instances investigated, PB approach deviates 3.4% in average when OFVs are compared and 10.5% on average when bests bounds are compared. Same experiments are repeated with 50 customer instances. PB formulation run results for low demand setting and original scenario of 50 customer instances can be found in Table 6.5.

Table 6.5 PB Formulation results for original scenario and low demand setting of 50 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 2 | 2 | 2 | 1 | 6 | 6 | 89476 | 43608 | 45868 | 12 | 58555 | 17069 | 147 | 13706 |
| ***2*** | 2 | 1 | 1 | 0 | 6 | 8 | 90619 | 44855 | 45764 | 21 | 67563 | 13406 | 239 | 9411 |
| ***3*** | 1 | 1 | 1 | 1 | 7 | 6 | 84881 | 40609 | 44273 | 37 | 70557 | 10386 | 285 | 3653 |
| ***4*** | 2 | 2 | 2 | 2 | 7 | 8 | 87623 | 42465 | 45158 | 29 | 60775 | 15664 | 396 | 10788 |
| ***5*** | 2 | 1 | 1 | 2 | 7 | 8 | 87197 | 46103 | 41094 | 13 | 68541 | 11894 | 370 | 6392 |
| ***6*** | 1 | 1 | 1 | 1 | 6 | 7 | 86500 | 43433 | 43067 | 22 | 75813 | 8590 | 181 | 1916 |
| ***7*** | 1 | 1 | 1 | 1 | 7 | 6 | 86940 | 46419 | 40521 | 21 | 76263 | 8032 | 223 | 2422 |
| ***8*** | 2 | 2 | 2 | 2 | 7 | 7 | 104264 | 50686 | 53579 | 44 | 72608 | 17306 | 584 | 13766 |
| ***9*** | 1 | 2 | 1 | 1 | 6 | 8 | 90836 | 45053 | 45783 | 92 | 69787 | 11430 | 43 | 9576 |
| ***10*** | 2 | 2 | 2 | 2 | 8 | 8 | 103262 | 51673 | 51589 | 32 | 71436 | 19049 | 692 | 12085 |

In low demand environment, all instances are solved under two minutes. Maximum solution time is 92 seconds and average solution time is 32 seconds. Number of selected routes deviate between 14 and 16.

The experiments are repeated for the for high demand environment and original scenario setting of 50 customers. Results can be found in Table 6.6.

Table 6.6 PB Formulation results for original scenario and high demand setting of 50 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 2 | 2 | 2 | 2 | 11 | 12 | 107793 | 53111 | 54682 | 12 | 76724 | 17069 | 294 | 13706 |
| ***2*** | 2 | 2 | 2 | 2 | 13 | 13 | 112120 | 60779 | 51341 | 38 | 77212 | 19656 | 827 | 14424 |
| ***3*** | 2 | 2 | 1 | 2 | 13 | 11 | 111125 | 52967 | 58159 | 80 | 83610 | 17700 | 145 | 9671 |
| ***4*** | 2 | 3 | 1 | 2 | 14 | 12 | 108818 | 56296 | 52523 | 18 | 70451 | 22130 | 417 | 15820 |
| ***5*** | 2 | 3 | 2 | 2 | 12 | 13 | 115084 | 52583 | 62501 | 45 | 78273 | 20106 | 874 | 15832 |
| ***6*** | 3 | 3 | 2 | 2 | 10 | 14 | 110016 | 53199 | 56818 | 14 | 66996 | 23449 | 218 | 19353 |
| ***7*** | 2 | 2 | 2 | 2 | 12 | 15 | 114594 | 50365 | 64229 | 41 | 84984 | 17822 | 567 | 11222 |
| ***8*** | 3 | 2 | 2 | 3 | 16 | 11 | 129866 | 70035 | 59832 | 18 | 87191 | 21068 | 712 | 20896 |
| ***9*** | 3 | 3 | 2 | 3 | 14 | 13 | 116189 | 59813 | 56376 | 15 | 72337 | 22778 | 323 | 20751 |
| ***10*** | 3 | 2 | 1 | 2 | 14 | 13 | 128774 | 61819 | 66955 | 64 | 89393 | 22311 | 560 | 16510 |

In high demand environment, all instances are solved under two minutes as well. Maximum solution time is 80 seconds and average run time is 35 seconds. As we did in 30 customer setting, deviations are compared with the best reported OFVs and best bounds of LB formulation. Results can be found in Table 6.7

Table 6.7 PB deviations for original scenario of 50 customer instances

| | **Low Demand** | | **High Demand** | |
|---|---|---|---|---|
| **Ins** | $\Delta_{OFV}$ | $\Delta_{BB}$ | $\Delta_{OFV}$ | $\Delta_{BB}$ |
| **1** | 1.4% | 12.7% | -2.9% | 6.9% |
| **2** | 8.5% | 18.2% | -3.3% | 6.1% |
| **3** | 3.5% | 16.7% | -3.2% | 9.2% |
| **4** | 2.7% | 13.7% | -4.4% | 6.9% |
| **5** | 2.6% | 12.9% | -5.0% | 7.1% |
| **6** | 6.4% | 15.9% | -4.3% | 6.1% |
| **7** | 2.1% | 13.2% | -1.3% | 9.7% |
| **8** | 5.1% | 17.0% | -0.3% | 8.7% |
| **9** | 3.6% | 17.4% | 4.0% | 13.9% |
| **10** | 3.2% | 15.3% | -4.3% | 7.9% |

In low demand and original scenario of 50 customer instances, PB formulation results deviate 3.9% on average when comparisons are conducted through the best found OFVs of LB formulation's 16 hour runs. Average run time for PB formulation is in the order of seconds. Minimum deviation is 1.4% and maximum deviation is 8.5%. When deviations compared through best bounds, average deviation is 15.3% where minimum deviation is 12.7% and maximum deviation is 18.2%. Since LB formulations solved with optimality gaps for 50 customer instances, deviation rate $\Delta_{BB}$ reports an upper bound for deviation amount.

In high demand environment, when the best OFVs are compared, average deviation turns out to be -2.5% where minimum deviation is -5% and maximum deviation is 4%. Furthermore, PB formulation found better results within seconds for 9 out of 10 instances. When deviations are compared through best bounds, average deviation is 8.2% where maximum deviation is 13.9%.

Overall, when the original setting of 50 customer instances investigated, PB approach deviates 0.7% in average when OFVs are compared and 11.8% in average when bests bounds are compared.

Since solution times decreased for 30 and 50 customer instances under original scenario, 100 customer instances are solved with PB formulation as well. For the 100 customer instances, only 3 solutions are found by LB formulation within 48 hours of run time, and average gap of those instances are 61.5%. Other instances were not be able to solved because of memory issues or no feasible solutions are reported within given time limit. Experiments are repeated with original scenario of 100 customer instances for PB formulation. PB formulation run results for low demand and original scenario of 100 customer instances can be found in Table 6.8.

Table 6.8 PB Formulation results for original scenario and low demand setting of 100 customer instances

| ***Ins*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 3 | 2 | 2 | 3 | 15 | 12 | 130086 | 67529 | 62556 | 676 | 98570 | 18080 | 413 | 13022 |
| ***2*** | 2 | 2 | 2 | 2 | 13 | 14 | 134553 | 65329 | 69224 | 4035 | 109531 | 15958 | 469 | 8595 |
| ***3*** | 2 | 3 | 3 | 2 | 12 | 13 | 134803 | 70106 | 64697 | 1955 | 95940 | 21309 | 674 | 16880 |
| ***4*** | 2 | 2 | 2 | 2 | 14 | 12 | 132917 | 66092 | 66826 | 1738 | 107289 | 14054 | 391 | 11183 |
| ***5*** | 2 | 2 | 2 | 2 | 13 | 13 | 139164 | 69815 | 69349 | 3543 | 118193 | 14318 | 247 | 6406 |
| ***6*** | 2 | 2 | 2 | 2 | 13 | 14 | 130353 | 64118 | 66236 | 730 | 109035 | 13525 | 307 | 7486 |
| ***7*** | 2 | 3 | 2 | 2 | 15 | 14 | 138534 | 69514 | 69020 | 1929 | 102812 | 21847 | 246 | 13629 |
| ***8*** | 2 | 3 | 3 | 2 | 14 | 13 | 135919 | 71045 | 64874 | 669 | 100961 | 17639 | 658 | 16661 |
| ***9*** | 3 | 2 | 2 | 3 | 14 | 14 | 138389 | 69475 | 68914 | 2698 | 104155 | 19929 | 705 | 13600 |
| ***10*** | 2 | 2 | 2 | 2 | 14 | 14 | 137148 | 71254 | 65894 | 1604 | 110825 | 15548 | 658 | 10118 |

Using PB formulation, all instances are solved to optimality. For original scenario and low demand setting of 100 customer instances, average run time turns out to be 1958 seconds which is approximately half an hour. Maximum run time is 3543 seconds and minimum run time is 669 seconds. Carriers started to open more depots and declare more transfer lines. Number of total selected routes increased either for both carriers. Since all instances are solved with no gaps, same experiments are repeated for the high demand setting. Results can be found in Table 6.9.

For original scenario and high demand setting of 100 customer instances, average run time is 1189 seconds which is under 20 minutes. Conversely, the deviation between max run time and min run time is higher when compared to low demand scenario. For the high demand scenario, minimum run time is 328 seconds and maximum run time is 6010 seconds. In the high demand scenario, carriers prefer to open more depot and transfer lines between depots. Number of used routes increased as well and deviate between 45 and 59.

Table 6.9 PB Formulation results for original scenario and high demand setting of 100 customer instances

| *Ins* | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | *Obj* | $Obj_A$ | $Obj_B$ | T(s) | *RC* | *FC* | *TC* | *IC* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | 4 | 5 | 5 | 2 | 27 | 31 | 179192 | 81451 | 97741 | 358 | 117208 | 32436 | 383 | 29165 |
| *2* | 3 | 4 | 4 | 3 | 24 | 28 | 175510 | 82049 | 93461 | 921 | 124757 | 27080 | 770 | 22902 |
| *3* | 4 | 3 | 3 | 3 | 26 | 27 | 172583 | 89524 | 83059 | 495 | 117288 | 25220 | 659 | 29416 |
| *4* | 4 | 4 | 3 | 4 | 26 | 23 | 171736 | 90075 | 81661 | 535 | 113552 | 30924 | 814 | 26445 |
| *5* | 4 | 4 | 4 | 4 | 27 | 28 | 184279 | 93553 | 90726 | 350 | 128324 | 29172 | 842 | 25941 |
| *6* | 4 | 3 | 2 | 4 | 26 | 24 | 173623 | 89068 | 84555 | 1143 | 127297 | 26668 | 623 | 19035 |
| *7* | 3 | 3 | 3 | 2 | 24 | 21 | 165411 | 83634 | 81777 | 1298 | 122132 | 23824 | 427 | 19027 |
| *8* | 4 | 3 | 3 | 4 | 32 | 27 | 187854 | 99803 | 88052 | 446 | 136635 | 27551 | 852 | 22816 |
| *9* | 4 | 3 | 3 | 3 | 23 | 21 | 171977 | 84453 | 87524 | 6010 | 119259 | 26977 | 572 | 25170 |
| *10* | 4 | 4 | 4 | 3 | 25 | 29 | 174801 | 90015 | 84786 | 328 | 114162 | 32381 | 606 | 27651 |

All instances of original scenario are solved till optimality with PB formulation and therefore all experiments are repeated with ICC and NCD scenarios to see the effect of data structure on problem. Initially, experiments are started with the 30 customer and low demand setup of ICC scenario.

Before going into details of the experiment results, information on number of pre-generated routes in ICC scenarios presented in Table 6.10. As it can be concluded from the Table 6.10, number of possible routes per carrier deviate between 282 and 6682 depending on the problem size and demand structure.

Table 6.10 Pre-generated route numbers for ICC scenarios

| | **30 Customer** | | | | **50 Customer** | | | | **100 Customer** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Low Dem.** | | **High Dem.** | | **Low Dem.** | | **High Dem.** | | **Low Dem.** | | **High Dem.** | |
| **Ins.** | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ |
| *1* | 346 | 368 | 705 | 800 | 748 | 659 | 1384 | 1174 | 2978 | 2901 | 6525 | 6308 |
| *2* | 383 | 360 | 817 | 769 | 857 | 759 | 1841 | 1611 | 3054 | 3047 | 5950 | 5874 |
| *3* | 366 | 358 | 678 | 670 | 783 | 707 | 1696 | 1508 | 2842 | 2727 | 6110 | 5919 |
| *4* | 282 | 365 | 605 | 774 | 881 | 725 | 1617 | 1297 | 2835 | 2843 | 5452 | 5485 |
| *5* | 359 | 354 | 773 | 743 | 784 | 794 | 1440 | 1456 | 2804 | 3012 | 6080 | 6570 |
| *6* | 377 | 348 | 818 | 719 | 802 | 752 | 1457 | 1376 | 2995 | 3017 | 5801 | 5804 |
| *7* | 370 | 347 | 818 | 715 | 797 | 754 | 1476 | 1382 | 3036 | 3066 | 4899 | 4960 |
| *8* | 334 | 338 | 654 | 646 | 909 | 763 | 1702 | 1371 | 2967 | 3044 | 6540 | 6682 |
| *9* | 349 | 370 | 703 | 837 | 747 | 707 | 1598 | 1504 | 2985 | 2933 | 4844 | 4726 |
| *10* | 322 | 384 | 596 | 710 | 784 | 776 | 1471 | 1411 | 3096 | 2828 | 6119 | 5563 |

Results of PB formulation runs for 30 customer instances under original and low demand scenario can be found in Table 6.11.

Under two minutes, all of the instances all solved to optimality. Maximum run time is 98 seconds and minimum run time is 9 seconds. Average run time is 27 seconds for the PB formulation results with 30 customers and ICC scenario in low demand setting. In all instances, both carriers chose to open one depot and declare one transfer line. Number of total selected routes vary between 8 and 12. Same experiment is conducted for high demand environment as well. Results can be

Table 6.11 PB Formulation results for ICC scenario and low demand setting of 30 customer instances

| ***Ins*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 1 | 1 | 1 | 4 | 4 | 61617 | 30649 | 30968 | 18 | 48249 | 9111 | 158 | 4099 |
| ***2*** | 1 | 1 | 1 | 1 | 6 | 6 | 66917 | 28582 | 38335 | 27 | 51542 | 10623 | 0 | 4752 |
| ***3*** | 1 | 1 | 1 | 1 | 4 | 6 | 64793 | 30357 | 34436 | 9 | 50906 | 9208 | 313 | 4366 |
| ***4*** | 1 | 1 | 1 | 1 | 4 | 4 | 52718 | 28585 | 24133 | 19 | 39614 | 7456 | 492 | 5157 |
| ***5*** | 1 | 1 | 1 | 1 | 4 | 5 | 61008 | 24980 | 36028 | 25 | 45289 | 9111 | 259 | 6350 |
| ***6*** | 1 | 1 | 1 | 1 | 5 | 3 | 58756 | 37667 | 21089 | 22 | 46450 | 7456 | 298 | 4552 |
| ***7*** | 1 | 1 | 1 | 1 | 5 | 4 | 62069 | 32040 | 30029 | 17 | 49127 | 7456 | 419 | 5067 |
| ***8*** | 1 | 1 | 1 | 1 | 4 | 4 | 54596 | 27326 | 27270 | 16 | 39947 | 7963 | 594 | 6092 |
| ***9*** | 1 | 1 | 1 | 1 | 3 | 5 | 69495 | 30289 | 39206 | 98 | 52908 | 10005 | 237 | 6345 |
| ***10*** | 1 | 1 | 1 | 1 | 4 | 5 | 65380 | 31796 | 33584 | 19 | 50773 | 6929 | 606 | 7073 |

found in Table 6.12.

Table 6.12 PB Formulation results with 30 customers and ICC scenario in high demand setting

| ***Ins*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 2 | 2 | 1 | 6 | 12 | 82493 | 29554 | 52939 | 27 | 60454 | 12973 | 449 | 8618 |
| ***2*** | 3 | 1 | 1 | 3 | 21 | 5 | 85637 | 51811 | 33825 | 20 | 53441 | 16324 | 1038 | 14834 |
| ***3*** | 1 | 2 | 2 | 1 | 12 | 22 | 80740 | 35753 | 44987 | 42 | 58286 | 12471 | 487 | 9497 |
| ***4*** | 1 | 1 | 1 | 1 | 6 | 10 | 68220 | 29142 | 39078 | 27 | 55116 | 7456 | 492 | 5157 |
| ***5*** | 1 | 2 | 2 | 1 | 6 | 11 | 77020 | 25294 | 51726 | 17 | 55371 | 12973 | 448 | 8229 |
| ***6*** | 2 | 2 | 2 | 2 | 9 | 9 | 77171 | 42707 | 34464 | 14 | 49129 | 14965 | 697 | 12380 |
| ***7*** | 1 | 2 | 2 | 1 | 9 | 9 | 79263 | 38681 | 40582 | 91 | 58602 | 11318 | 545 | 8798 |
| ***8*** | 1 | 2 | 2 | 1 | 7 | 8 | 68111 | 30198 | 37913 | 13 | 44566 | 13292 | 731 | 9523 |
| ***9*** | 2 | 2 | 2 | 2 | 9 | 10 | 88169 | 41383 | 46786 | 61 | 58127 | 14984 | 729 | 14329 |
| ***10*** | 2 | 2 | 2 | 2 | 7 | 9 | 79354 | 35915 | 43438 | 26 | 46707 | 15420 | 617 | 16610 |

Optimum results for PB formulation are reported under two minutes for high demand setting. Average run time is 34 seconds where run times deviate between 17 and 91 seconds. Once the demand setting switched to high, carriers started to open more depots and define more transfer lines. Number of total selected routes vary between and 16 and 34. When the ICC experiments with 30 customers compared with the original scenario experiments with 30 customers, it is observed that solution times increased with ICC setup. Run time comparisons can be found in Table 6.13. Run times are indicated in terms of seconds.

Table 6.13 Original vs ICC scenario run times with 30 customer instances under PB formulation

| | ***Instance*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | ***7*** | ***8*** | ***9*** | ***10*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Low Demand** | **Original** | 2 | 6 | 4 | 2 | 5 | 4 | 3 | 5 | 6 | 3 |
| | **ICC** | 18 | 27 | 9 | 19 | 25 | 22 | 17 | 16 | 98 | 19 |
| **High Demand** | **Original** | 10 | 6 | 2 | 5 | 7 | 8 | 15 | 18 | 29 | 4 |
| | **ICC** | 27 | 20 | 42 | 27 | 17 | 14 | 91 | 13 | 61 | 26 |

When the results compared in Table 6.13, it is observed that ICC setting increases solution times. Since number of possibilities for assignment and collaboration increases with the ICC scenario, solution times are increased as well.

As we did in original scenario instances, deviations are compared with the best reported OFVs and best bounds of LB formulation for ICC scenario. Results can be found in Table 6.14.

Table 6.14 PB deviations for ICC scenario of 30 customer instances

| | **Low Demand** | | **High Demand** | |
|---|---|---|---|---|
| **Ins** | $\Delta_{OFV}$ | $\Delta_{BB}$ | $\Delta_{OFV}$ | $\Delta_{BB}$ |
| **1** | 4.0% | 11.9% | 0.4% | 13.0% |
| **2** | 9.1% | 14.9% | 4.5% | 12.3% |
| **3** | 3.4% | 10.7% | -5.4% | 3.9% |
| **4** | 6.5% | 12.0% | 4.2% | 12.6% |
| **5** | 5.8% | 14.1% | 1.1% | 9.3% |
| **6** | 5.7% | 12.4% | 2.3% | 9.6% |
| **7** | 9.2% | 14.9% | 2.6% | 13.6% |
| **8** | 4.1% | 10.5% | 3.3% | 7.7% |
| **9** | 6.2% | 15.8% | 3.0% | 12.8% |
| **10** | 5.1% | 15.2% | -2.0% | 7.4% |

In low demand environment of ICC scenario of 30 customer instances, PB model deviates 5.9% in average when comparison is conducted through best found OFVs. Minimum deviation is 3.4% and maximum deviation is 9.2%. When deviations compared through best bounds, average difference is 13.2% where minimum variance is 10.5% and maximum variance is 15.8%.

When best found OFVs are compared with PB formulation results for high demand environment of the ICC scenario of 30 customers, it is observed that PB model reported better outcomes for two instances; instance 3 and instance 10. On average, PB formulation deviates 1.4% and deviation range is between -5.4% and 4.5%. When deviations compared through best bounds, average difference in 10.2% where minimum variance is 3.9% and maximum variance is 13.6%.

Overall, when the ICC setting of 30 customer instances investigated, PB approach deviates 3.6% in average when OFVs are compared and 11.7% in average when bests bounds are compared. Same experiments are repeated with 50 customer instances. PB formulation run results for low demand and ICC scenario of 50 customer instances can be found in Table 6.15.

In low demand environment, all instances are solved under 360 seconds. Minimum run time is 29 seconds and maximum run time is 345 seconds where average run time is 186 seconds. Number of selected routes deviate between 13 and 17. In order to see the effect of demand, experiments are repeated under high demand setup. Results can be found in Table 6.16.

Table 6.15 PB Formulation results for ICC scenario and low demand setting of 50 customer instances

| ***Ins*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 2 | 2 | 2 | 2 | 7 | 6 | 85884 | 44174 | 41710 | 29 | 54284 | 17699 | 326 | 13575 |
| ***2*** | 2 | 1 | 1 | 2 | 9 | 6 | 92657 | 54120 | 38538 | 265 | 67974 | 12211 | 738 | 11734 |
| ***3*** | 1 | 1 | 1 | 1 | 7 | 6 | 82663 | 42731 | 39932 | 151 | 69393 | 9332 | 285 | 3653 |
| ***4*** | 2 | 1 | 1 | 2 | 8 | 7 | 88608 | 45647 | 42961 | 170 | 66577 | 12832 | 592 | 8607 |
| ***5*** | 2 | 1 | 1 | 2 | 7 | 7 | 86911 | 45951 | 40961 | 36 | 67778 | 12372 | 370 | 6392 |
| ***6*** | 1 | 1 | 1 | 1 | 7 | 6 | 84591 | 45736 | 38854 | 120 | 73652 | 8842 | 181 | 1916 |
| ***7*** | 1 | 1 | 1 | 1 | 6 | 8 | 90956 | 39374 | 51581 | 328 | 79345 | 8966 | 223 | 2422 |
| ***8*** | 2 | 2 | 2 | 2 | 9 | 8 | 100368 | 50299 | 50070 | 237 | 65580 | 17352 | 863 | 16574 |
| ***9*** | 2 | 2 | 1 | 2 | 7 | 7 | 89009 | 41119 | 47890 | 176 | 57755 | 18467 | 110 | 12677 |
| ***10*** | 2 | 1 | 1 | 2 | 8 | 7 | 101852 | 50555 | 51297 | 345 | 78985 | 14221 | 570 | 8076 |

Table 6.16 PB Formulation results for ICC scenario and high demand setting of 50 customer instances

| ***Ins*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 3 | 2 | 2 | 2 | 12 | 11 | 102624 | 50198 | 52426 | 61 | 63609 | 20525 | 560 | 17930 |
| ***2*** | 3 | 2 | 2 | 3 | 15 | 15 | 118839 | 63005 | 55833 | 51 | 76689 | 21427 | 929 | 19794 |
| ***3*** | 2 | 2 | 2 | 2 | 16 | 11 | 113558 | 60556 | 53002 | 128 | 84758 | 17668 | 532 | 10600 |
| ***4*** | 2 | 2 | 2 | 2 | 16 | 10 | 103221 | 58861 | 44360 | 51 | 73093 | 16999 | 701 | 12427 |
| ***5*** | 2 | 2 | 2 | 2 | 13 | 13 | 111538 | 54013 | 57525 | 159 | 78150 | 17162 | 977 | 15249 |
| ***6*** | 2 | 3 | 3 | 2 | 9 | 15 | 107299 | 48336 | 58964 | 136 | 72376 | 19854 | 615 | 14455 |
| ***7*** | 3 | 2 | 2 | 3 | 14 | 11 | 112998 | 58003 | 54995 | 174 | 74384 | 21660 | 797 | 16157 |
| ***8*** | 3 | 2 | 2 | 3 | 15 | 11 | 120297 | 64610 | 55687 | 42 | 77345 | 20598 | 656 | 21698 |
| ***9*** | 3 | 2 | 1 | 3 | 16 | 11 | 110823 | 55383 | 55441 | 88 | 70363 | 21726 | 834 | 17900 |
| ***10*** | 3 | 2 | 2 | 3 | 14 | 12 | 122948 | 63880 | 59069 | 146 | 79999 | 22598 | 910 | 19442 |

In high demand environment, all instances are solved under three minutes. Maximum solution time is 159 seconds and average run time is 104 seconds. When the demand setting is high, companies started to open more depots and transfer lines overall. Number of selected routes vary between 23 and 30. When the ICC experiments with 50 customers compared with the original scenario experiments with 50 customers, it is observed that solution times increased with ICC setup. Runtime comparisons can be found in Table 6.17. Run times are indicated in terms of seconds.

Table 6.17 Original vs ICC scenario run times with 50 customer instances under PB formulation

| | ***Instance*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | ***7*** | ***8*** | ***9*** | ***10*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Low Demand** | **Original** | 12 | 21 | 37 | 29 | 13 | 22 | 21 | 44 | 92 | 32 |
| | **ICC** | 29 | 265 | 151 | 170 | 36 | 120 | 328 | 237 | 176 | 345 |
| **High Demand** | **Original** | 12 | 38 | 80 | 18 | 45 | 14 | 41 | 18 | 15 | 64 |
| | **ICC** | 61 | 51 | 128 | 51 | 159 | 136 | 174 | 42 | 88 | 146 |

When the results compared in Table 6.17, it is observed that ICC setting increases solution times which is get along with the findings in 30 customer experiments. Since number of possibilities for assignment and collaboration increases with the ICC scenario, solution times are increased as well.

As we did in 30 customer setting, deviation amounts from exact solutions are compared with the best reported OFVs and best bounds of LB formulation. Results can be found in Table 6.18.

Table 6.18 PB deviations for ICC scenario of 50 customers

| | **Low Demand** | | **High Demand** | |
|---|---|---|---|---|
| **Ins** | $\Delta_{OFV}$ | $\Delta_{BB}$ | $\Delta_{OFV}$ | $\Delta_{BB}$ |
| **1** | 3.1% | 13.9% | -0.8% | 8.1% |
| **2** | 8.9% | 19.4% | 4.4% | 14.6% |
| **3** | 0.6% | 18.6% | 3.8% | 15.5% |
| **4** | 8.5% | 18.6% | -6.1% | 6.5% |
| **5** | 3.5% | 13.4% | -2.7% | 7.4% |
| **6** | 5.7% | 16.1% | -6.5% | 6.8% |
| **7** | 9.2% | 19.0% | -6.8% | 8.0% |
| **8** | 6.7% | 17.7% | -5.4% | 8.0% |
| **9** | 5.9% | 18.5% | 4.4% | 13.6% |
| **10** | 3.7% | 18.2% | -3.2% | 8.7% |

PB formulation deviates 5.6% in average when ICC scenario of 50 customer instances are compared in low demand setup through best found OFVs. Minimum deviation is 0.6% and maximum deviation is 9.2%. When deviations compared through best bounds, average difference is 17.3% where minimum variance is 13.4% and maximum variance is 19.4%.

When best found OFVs are compared with PB formulation results for high demand environment of the ICC scenario of 50 customers, it is observed that PB formulation reported better outcomes for seven out of ten instances, except instances 2,3 and 9. PB formulation deviates -1.9% in average which means that PB formulation reported better outcomes than 16 hour exact LB formulation runs within few minutes. When deviations compared through best bounds, average difference in 9.7% where minimum variance is 6.5% and maximum variance is 15.5%.

Overall, when the ICC setting of 50 customer instances investigated, PB approach deviates 1.8% in average when OFVs are compared and 13.5% in average when best bounds are compared.

Experiments are continued with ICC setting of 100 customer instances in order to see the effect of number of increased customers to solution times and managerial aspects with the biggest available instances. PB formulation run results for low demand and ICC scenario of 100 customer instances can be found in Table 6.19.

All ICC and low demand scenario instances of 100 customer setting, are solved to optimality. With the increased number of common customers, problem became harder to solve and run times increase. Average run time for those instances is 14105 seconds which is approximately 4 hours. Minimum run time is 5335 seconds and

Table 6.19 PB Formulation results for ICC scenario and low demand setting of 100 customer instances

| ***Ins*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 2 | 2 | 2 | 2 | 12 | 15 | 128694 | 56056 | 72638 | 9604 | 101259 | 15477 | 758 | 11200 |
| ***2*** | 2 | 3 | 3 | 2 | 13 | 15 | 129742 | 57798 | 71945 | 14403 | 97217 | 19042 | 480 | 13004 |
| ***3*** | 2 | 3 | 3 | 2 | 12 | 14 | 127583 | 63829 | 63755 | 3010 | 90843 | 20495 | 810 | 15435 |
| ***4*** | 3 | 1 | 1 | 3 | 14 | 11 | 128180 | 69858 | 58322 | 7291 | 100630 | 15392 | 696 | 11462 |
| ***5*** | 3 | 1 | 1 | 3 | 14 | 12 | 136663 | 70309 | 66353 | 15057 | 113408 | 14004 | 484 | 8767 |
| ***6*** | 2 | 3 | 3 | 2 | 13 | 15 | 129174 | 55453 | 73721 | 15271 | 99443 | 18035 | 244 | 11452 |
| ***7*** | 2 | 2 | 2 | 2 | 15 | 13 | 132599 | 68772 | 63827 | 14852 | 105916 | 14650 | 183 | 11850 |
| ***8*** | 2 | 3 | 3 | 2 | 13 | 14 | 138466 | 67378 | 71088 | 5335 | 104122 | 21636 | 457 | 12252 |
| ***9*** | 3 | 2 | 2 | 3 | 15 | 12 | 138107 | 70187 | 67920 | 28791 | 100601 | 22208 | 657 | 14640 |
| ***10*** | 3 | 2 | 2 | 3 | 15 | 13 | 139141 | 75873 | 63268 | 27424 | 104668 | 20243 | 606 | 13624 |

maximum run time is 28791 seconds which is almost 8 hours. Genuinely run times increase with the ICC scenario. As it is anticipated, number of opened and created depots are increased as well. In order to see the effect of demand amount on the problem, same experiments are repeated under high demand setting. Results can be found in Table 6.20.

Table 6.20 PB Formulation results for ICC scenario and high demand setting of 100 customer instances

| ***Ins*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 4 | 4 | 4 | 4 | 29 | 27 | 171710 | 77686 | 94024 | 5044 | 112140 | 31268 | 938 | 27364 |
| ***2*** | 4 | 4 | 4 | 4 | 29 | 25 | 163346 | 79945 | 83401 | 1933 | 103554 | 33093 | 856 | 25843 |
| ***3*** | 4 | 3 | 3 | 4 | 25 | 28 | 162491 | 81949 | 80542 | 587 | 107552 | 26793 | 1023 | 27123 |
| ***4*** | 3 | 4 | 4 | 3 | 24 | 24 | 162973 | 80907 | 82066 | 4796 | 113570 | 26477 | 1045 | 21882 |
| ***5*** | 4 | 4 | 3 | 4 | 29 | 27 | 182783 | 95253 | 87531 | 5725 | 121098 | 32309 | 920 | 28457 |
| ***6*** | 5 | 3 | 3 | 5 | 27 | 24 | 165413 | 79464 | 85949 | 4175 | 110697 | 29908 | 733 | 24075 |
| ***7*** | 3 | 3 | 3 | 3 | 21 | 22 | 158518 | 75119 | 83399 | 2538 | 119674 | 23424 | 402 | 15018 |
| ***8*** | 5 | 3 | 3 | 5 | 36 | 25 | 185498 | 100967 | 84531 | 15071 | 125966 | 31420 | 955 | 27157 |
| ***9*** | 4 | 4 | 4 | 4 | 22 | 22 | 159548 | 79042 | 80505 | 7730 | 99803 | 32197 | 801 | 26747 |
| ***10*** | 5 | 3 | 3 | 5 | 29 | 22 | 175915 | 94526 | 81389 | 3938 | 114106 | 35257 | 964 | 25588 |

In high demand environment, all instances are solved to optimality. Maximum solution time is 15071 seconds and average run time is 5154 seconds. When the demand setting is high, companies started to open more depots and transfer lines overall. Number of selected routes vary between 43 and 61. When the ICC experiments with 100 customers compared with the original scenario experiments with 100 customers, it is observed that solution times increased with ICC setup. Runtime comparisons can be found in Table 6.21. Run times are indicated in terms of seconds.

When the run times compared in Table 6.21, it is observed that ICC setting increase run times which is also in parallel to previous findings in the 30 and 50 customer experiments. Consequently, it can be concluded that increased number of common customers increases the time complexity of the model.

As explained in Section 5.3, experiments are repeated with NCD setting with PB

Table 6.21 Original vs ICC scenario run times with 100 customer instances under PB formulation

| | ***Instance*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | ***7*** | ***8*** | ***9*** | ***10*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Low Dem.** | **Original** | 676 | 4035 | 1955 | 1738 | 3543 | 730 | 1929 | 669 | 2698 | 1604 |
| | **ICC** | 9604 | 14403 | 3010 | 7291 | 15057 | 15271 | 14852 | 5335 | 28791 | 27424 |
| **High Dem.** | **Original** | 358 | 921 | 495 | 535 | 350 | 1143 | 1298 | 446 | 6010 | 328 |
| | **ICC** | 51 | 1933 | 587 | 4796 | 5725 | 4175 | 2538 | 15071 | 7730 | 3938 |

formulation in which carriers do not have any common depot declaration opportunities. Main motivation behind those experiments is to see the effect of opening depots on same location on collaboration and centralized gains as well as effect on problem complexity in terms of run times and gaps. Experiments started with the simplest setup again, 30 customers and low demand environment.

Before going into details of the experiment results, information on number of pre-generated routes in NCD scenarios presented in Table 6.22. As it can be interpreted from the Table 6.22, number of possible routes per carrier deviate between 179 and 4949 depending on the problem size and demand structure. When the total route numbers compared with original and ICC scenarios it is observed that total created route numbers under NCD setup is less because of the decreased amount of candidate depot locations.

Table 6.22 Pre-generated route numbers for NCD scenarios

| | **30 Customer** | | | | **50 Customer** | | | | **100 Customer** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Low Dem.** | | **High Dem.** | | **Low Dem.** | | **High Dem.** | | **Low Dem.** | | **High Dem.** | |
| **Ins.** | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ | $TR_A$ | $TR_B$ |
| ***1*** | 225 | 268 | 478 | 572 | 620 | 456 | 1334 | 922 | 2023 | 2194 | 4438 | 4798 |
| ***2*** | 262 | 225 | 554 | 505 | 639 | 561 | 1349 | 1188 | 2312 | 2125 | 4473 | 4055 |
| ***3*** | 267 | 252 | 462 | 461 | 588 | 523 | 1272 | 1137 | 1971 | 2075 | 4238 | 4434 |
| ***4*** | 179 | 240 | 396 | 513 | 671 | 506 | 1244 | 918 | 2106 | 2021 | 4043 | 3911 |
| ***5*** | 276 | 234 | 569 | 490 | 584 | 605 | 1055 | 1099 | 2062 | 2136 | 4461 | 4695 |
| ***6*** | 226 | 233 | 469 | 528 | 584 | 533 | 1034 | 1004 | 2151 | 2190 | 4180 | 4207 |
| ***7*** | 229 | 241 | 476 | 539 | 584 | 529 | 1047 | 1015 | 2254 | 2199 | 3694 | 3529 |
| ***8*** | 226 | 202 | 440 | 416 | 706 | 555 | 1345 | 977 | 2262 | 2139 | 4949 | 4761 |
| ***9*** | 225 | 229 | 481 | 510 | 602 | 487 | 1263 | 1040 | 2108 | 2239 | 3428 | 3566 |
| ***10*** | 235 | 231 | 469 | 436 | 620 | 529 | 1150 | 948 | 2149 | 2325 | 4109 | 4666 |

Run results of 30 customer instances in low demand and NCD setting can be found in Table 6.23.

Within 10 seconds, all instances are solved to optimality. Maximum run time is 6 seconds and average run time is 3 seconds for the PB Formulation results with 30 customers and NCD scenario in low demand setting. As it occurred in previous scenario settings, almost all carriers opened one depot. However, in one of the instances, instance 9, carrier $B$ opened two depots. Moreover, in instance 4, carrier $B$ does not prefer to create a transfer line. These results overlap with our motiva-

Table 6.23 PB Formulation results for NCD scenario and low demand setting of 30 customer instances

| ***Ins*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 1 | 1 | 1 | 4 | 4 | 62373 | 30610 | 31762 | 1 | 50584 | 7532 | 158 | 4099 |
| ***2*** | 1 | 1 | 1 | 1 | 5 | 4 | 68354 | 31458 | 36897 | 2 | 55060 | 7532 | 284 | 5478 |
| ***3*** | 1 | 1 | 1 | 1 | 5 | 6 | 69004 | 36390 | 32614 | 5 | 56901 | 7424 | 313 | 4366 |
| ***4*** | 1 | 1 | 1 | 0 | 3 | 5 | 56480 | 28615 | 27866 | 2 | 43383 | 6794 | 33 | 6270 |
| ***5*** | 1 | 1 | 1 | 1 | 5 | 4 | 62815 | 33996 | 28818 | 2 | 48674 | 7532 | 259 | 6350 |
| ***6*** | 1 | 1 | 1 | 1 | 4 | 4 | 63365 | 35077 | 28287 | 2 | 50879 | 7226 | 406 | 4854 |
| ***7*** | 1 | 1 | 1 | 1 | 4 | 4 | 66503 | 32122 | 34381 | 4 | 52825 | 7730 | 123 | 5825 |
| ***8*** | 1 | 1 | 1 | 1 | 4 | 4 | 63489 | 32684 | 30805 | 4 | 50925 | 6992 | 428 | 5144 |
| ***9*** | 1 | 2 | 1 | 1 | 4 | 4 | 67429 | 34404 | 33024 | 4 | 46650 | 10931 | 526 | 9322 |
| ***10*** | 1 | 1 | 1 | 1 | 4 | 4 | 66736 | 35860 | 30876 | 6 | 53085 | 7532 | 522 | 5597 |

tion in which it is assumed that NCD obstructs collaboration. Number of selected routes vary between 8 and 11. Same instances experimented under high demand environment as well. Results can be found in Table 6.24.

Table 6.24 PB Formulation results for NCD scenario and high demand setting of 30 customer instances

| ***Ins*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | T(s) | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 1 | 1 | 1 | 1 | 8 | 8 | 86322 | 44535 | 41787 | 7 | 72068 | 8999 | 361 | 4894 |
| ***2*** | 2 | 2 | 2 | 2 | 10 | 8 | 89328 | 41463 | 47866 | 2 | 57931 | 15863 | 888 | 14647 |
| ***3*** | 2 | 1 | 1 | 2 | 9 | 12 | 85718 | 47741 | 37977 | 2 | 63643 | 12525 | 552 | 8998 |
| ***4*** | 2 | 2 | 2 | 2 | 7 | 9 | 76847 | 39792 | 37055 | 3 | 51097 | 14524 | 97 | 11129 |
| ***5*** | 2 | 1 | 1 | 2 | 10 | 8 | 81508 | 47715 | 33794 | 4 | 59367 | 11767 | 489 | 9886 |
| ***6*** | 2 | 2 | 2 | 2 | 8 | 10 | 83165 | 43643 | 39522 | 1 | 57168 | 13658 | 665 | 11675 |
| ***7*** | 1 | 2 | 2 | 1 | 8 | 10 | 82852 | 41615 | 41237 | 4 | 60759 | 12398 | 441 | 9254 |
| ***8*** | 2 | 1 | 1 | 1 | 7 | 8 | 81581 | 39435 | 42146 | 5 | 62053 | 11017 | 213 | 8299 |
| ***9*** | 2 | 1 | 1 | 2 | 9 | 8 | 85209 | 45088 | 40121 | 4 | 63765 | 10457 | 815 | 10172 |
| ***10*** | 3 | 1 | 1 | 3 | 10 | 6 | 82206 | 42062 | 40143 | 4 | 52217 | 14284 | 730 | 14975 |

Optimum results are found under 10 seconds for each instance of NCD and high demand setting of 30 customer instances. Maximum run time is 7 seconds and average run time is 4 seconds. As a result of increased demand density, carriers started to open more depots and construct more transfer lines. Number of total selected routes vary between 16 and 21. When the NCD experiments are compared with original scenario experiments, for the low demand setting, there is no distinct effect on run times. For the high demand setting, there exist some instances which are solved faster under NCD setting. Run time comparisons can be found in Table 6.25. Run times are indicated in terms of seconds.

When the run time results examined in Table 6.25, there is no solid distinction between low demand scenarios. In high demand setting, original scenario instances are solved with higher run times which may be explained by decreased number of possibilities for collaboration. But still, difference is not distinct.

Similar to what we did in original scenario and ICC scenario instances, deviations

Table 6.25 Original vs NCD scenario run times with 30 customer instances under PB formulation

| | ***Instance*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | ***7*** | ***8*** | ***9*** | ***10*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Low Demand** | **Original** | 2 | 6 | 4 | 2 | 5 | 4 | 3 | 5 | 6 | 3 |
| | **NCD** | 1 | 2 | 5 | 2 | 2 | 2 | 4 | 4 | 4 | 6 |
| **High Demand** | **Original** | 10 | 6 | 2 | 5 | 7 | 8 | 15 | 18 | 29 | 4 |
| | **NCD** | 7 | 2 | 2 | 3 | 4 | 1 | 4 | 5 | 4 | 4 |

from the exact solutions are compared with the best reported OFVs and best bounds of LB formulation for NCD scenario. Results can be found in Table 6.26.

Table 6.26 PB deviations for NCD scenario of 30 customers

| | **Low Demand** | | **High Demand** | |
|---|---|---|---|---|
| **Ins** | $\Delta_{OFV}$ | $\Delta_{BB}$ | $\Delta_{OFV}$ | $\Delta_{BB}$ |
| **1** | 3.8% | 10.3% | 2.5% | 11.6% |
| **2** | 5.7% | 11.7% | 3.2% | 8.8% |
| **3** | 8.2% | 13.6% | -5.2% | 4.8% |
| **4** | 2.7% | 6.6% | 2.0% | 10.9% |
| **5** | 6.2% | 11.9% | 1.8% | 10.1% |
| **6** | 2.7% | 9.3% | 1.6% | 8.7% |
| **7** | 7.4% | 12.8% | 1.3% | 9.7% |
| **8** | 7.1% | 11.9% | 2.4% | 10.4% |
| **9** | 7.4% | 12.3% | 2.5% | 11.0% |
| **10** | 5.4% | 14.2% | -0.6% | 7.8% |

When the deviations are compared through best OFVs in low demand environment for NCD scenario, it is observed that model deviates 5.6% on average. Minimum deviation is 2.7% and maximum deviation is 8.2%. When deviations compared through best bounds, average deviation is 11.5% where minimum deviation is 6.6% and maximum deviation is 14.2%. As mentioned before, since LB formulation instances are not solved to optimality, comparisons through $\Delta_{BB}$ denotes an upper bound for deviation amount.

In high demand environment of NCD scenario of 30 customer instances, PB formulation deviates 4.8% in average when comparison is conducted through best found OFVs of LB formulation. For two instances, instance 3 and 10, PB formulation reported lower costs within seconds. In average, PB formulation deviates 1.1% and deviation range is between -5.2% and 3.2%. On the other hand, when deviations compared through best bounds, average deviation is 9.4% where minimum deviation is 4.8% and maximum variance is 11.6%. Same experiments for NCD scenario are repeated for 50 customer instances. PB formulation run results for low demand and NCD scenario of 50 customer instances can be found in Table 6.27.

Within a minute, all 50 customer instances with low demand scenario solved to optimality. Maximum solution time is 57 seconds where average is 19 seconds.

Table 6.27 PB Formulation results for NCD scenario and low demand setting of 50 customer instances

| *Ins* | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | *Obj* | $Obj_A$ | $Obj_B$ | T(s) | *RC* | *FC* | *TC* | *IC* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | 2 | 2 | 2 | 1 | 7 | 7 | 87908 | 43486 | 44422 | 16 | 56711 | 17461 | 218 | 13518 |
| *2* | 2 | 2 | 2 | 1 | 7 | 9 | 92528 | 45972 | 46557 | 57 | 61754 | 15663 | 687 | 14424 |
| *3* | 1 | 1 | 1 | 1 | 7 | 6 | 82109 | 41232 | 40877 | 8 | 69605 | 8154 | 269 | 4081 |
| *4* | 2 | 1 | 1 | 2 | 8 | 7 | 88358 | 46828 | 41530 | 7 | 68300 | 12686 | 481 | 6891 |
| *5* | 1 | 1 | 1 | 1 | 7 | 8 | 93751 | 45423 | 48328 | 14 | 81762 | 9307 | 201 | 2481 |
| *6* | 1 | 1 | 1 | 1 | 7 | 7 | 85270 | 44321 | 40949 | 6 | 74134 | 9039 | 181 | 1916 |
| *7* | 1 | 1 | 1 | 1 | 7 | 7 | 90827 | 43085 | 47742 | 20 | 78875 | 9307 | 223 | 2422 |
| *8* | 2 | 1 | 1 | 2 | 7 | 7 | 102740 | 52825 | 49914 | 19 | 77749 | 14511 | 470 | 10009 |
| *9* | 2 | 2 | 2 | 1 | 6 | 8 | 89349 | 40514 | 48835 | 19 | 59126 | 17492 | 85 | 12646 |
| *10* | 2 | 1 | 1 | 2 | 7 | 7 | 103108 | 53742 | 49366 | 29 | 81728 | 11103 | 550 | 9728 |

The number of opened depots increased when compared to 30 customer instances. Moreover, they declared more transfer lines. Number of total selected routes change between 13 and 16. To see how increased demand density affect the outcomes, experiments are repeated under high demand setup. Results can be found in Table 6.28.

Table 6.28 PB Formulation results for NCD scenario and high demand setting of 50 customer instances

| *Ins* | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | *Obj* | $Obj_A$ | $Obj_B$ | T(s) | *RC* | *FC* | *TC* | *IC* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | 3 | 2 | 2 | 1 | 15 | 14 | 115718 | 58034 | 57685 | 9 | 75086 | 22861 | 374 | 17398 |
| *2* | 2 | 3 | 3 | 1 | 13 | 18 | 116431 | 54685 | 61746 | 5 | 73736 | 22010 | 892 | 19794 |
| *3* | 2 | 2 | 1 | 2 | 15 | 13 | 115473 | 55665 | 59808 | 19 | 87080 | 16217 | 243 | 11933 |
| *4* | 2 | 2 | 1 | 2 | 15 | 11 | 114511 | 61551 | 52960 | 7 | 86743 | 16385 | 321 | 11062 |
| *5* | 1 | 3 | 3 | 1 | 9 | 16 | 124417 | 53764 | 70653 | 17 | 92246 | 17861 | 752 | 13558 |
| *6* | 3 | 3 | 2 | 2 | 13 | 13 | 110843 | 57115 | 53729 | 13 | 66503 | 24343 | 385 | 19612 |
| *7* | 2 | 2 | 2 | 2 | 12 | 14 | 114360 | 51852 | 62509 | 8 | 84596 | 15878 | 682 | 13204 |
| *8* | 3 | 2 | 1 | 3 | 17 | 10 | 124894 | 72843 | 52052 | 12 | 81695 | 20982 | 687 | 21530 |
| *9* | 3 | 3 | 3 | 3 | 16 | 13 | 117288 | 59698 | 57590 | 7 | 68396 | 26772 | 691 | 21429 |
| *10* | 2 | 2 | 1 | 2 | 15 | 11 | 126785 | 67859 | 58926 | 14 | 93700 | 15472 | 813 | 16799 |

In the high demand setting, all instances are solved under 20 seconds. Maximum solution time is 19 seconds and average is 11 seconds. Overall, number of opened depots, transfer lines and selected depots increased when compared to low demand setting. Number of selected routes vary between 25 and 31. When the NCD experiments with 50 customers compared with the original scenario experiments with 50 customers, it is observed that solution times of NCD scenarios are less than original scenarios. Run time comparisons can be found in Table 6.29. Note that run times are indicated in terms of seconds.

When run times examined in Table 6.29, it is observed that run times are shorter under NCD setting under both low and high demand environments. Since NCD eliminates the number of opportunities that can rise from joint depot opening decisions, instances may become more distinguishable from the perceptive of optimum

Table 6.29 Original vs NCD scenario run times with 50 customer instances under PB formulation

| | *Instance* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Low Demand** | **Original** | 12 | 21 | 37 | 29 | 13 | 22 | 21 | 44 | 92 | 32 |
| | **NCD** | 16 | 57 | 8 | 7 | 14 | 6 | 20 | 19 | 19 | 29 |
| **High Demand** | **Original** | 12 | 38 | 80 | 18 | 45 | 14 | 41 | 18 | 15 | 64 |
| | **NCD** | 9 | 5 | 19 | 7 | 17 | 13 | 8 | 12 | 7 | 14 |

depot locations. Next, deviations from exact solutions which are reported by LB formulation experiments are compared with the best reported OFVs and best bounds of LB formulation for NCD scenario. Results can be found in Table 6.30.

Table 6.30 PB deviations for NCD scenario of 50 customers

| | **Low Demand** | | **High Demand** | |
|---|---|---|---|---|
| **Ins** | $\Delta_{OFV}$ | $\Delta_{BB}$ | $\Delta_{OFV}$ | $\Delta_{BB}$ |
| **1** | 0.5% | 11.6% | 3.9% | 12.5% |
| **2** | 5.0% | 14.9% | 2.9% | 12.0% |
| **3** | 5.7% | 17.8% | 5.1% | 15.1% |
| **4** | 3.8% | 14.8% | -3.0% | 9.8% |
| **5** | 5.5% | 14.6% | -6.0% | 6.9% |
| **6** | 4.0% | 13.2% | -3.9% | 6.2% |
| **7** | 5.1% | 16.5% | -4.5% | 8.5% |
| **8** | 2.6% | 15.4% | -3.5% | 7.9% |
| **9** | 4.6% | 16.2% | 1.9% | 13.5% |
| **10** | 6.2% | 16.9% | -4.9% | 8.0% |

When the deviations from exact solutions compared in low demand setting through best OFVs of LB formulation, PB formulation deviates 4.3% in average. Maximum deviation is 6.2% and minimum deviation is 0.5% which means that PB approach found a solution which is almost good as 16 hours of LB formulation within seconds. When deviations compared through best bounds, minimum deviation is 11.6% and maximum deviation is 17.8% where average deviation is 15.2%.

In high demand environment of NCD scenario of 50 customer instances, PB model deviates -1.2% in average when comparison is conducted through best found OFVs of LB formulation. In other words, PB formulation reports better outcomes when compared to 16 hour runs of exact LB formulation for five instances. Maximum deviation is 5.1% and minimum deviation is -6%. On the other hand, when deviations compared through best bounds, average deviation is 10.0% where minimum deviation is 6.2% and maximum variance is 15.1%.

Consequently, when the NCD setting of 50 customer instances investigated, PB formulation deviates 1.5% on average when OFVs are compared and 12.6% on average when best bounds are compared.

Experiments continued with 100 customer NCD instances in order to see the effect of number of customers to solution times and vital aspects of problem. PB formulation run results for low demand and NCD scenario of 100 customer instances can be found in Table 6.31.

Table 6.31 PB Formulation results for NCD scenario and low demand setting of 100 customer instances

| *Ins* | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | *Obj* | $Obj_A$ | $Obj_B$ | T(s) | *RC* | *FC* | *TC* | *IC* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | **2** | **3** | **2** | **2** | 12 | 16 | 136420 | 62995 | 73425 | 628 | 100790 | 22870 | 133 | 12628 |
| ***2*** | 2 | 2 | 2 | 2 | 14 | 14 | 133221 | 62212 | 71008 | 1243 | 108422 | 15595 | 478 | 8726 |
| ***3*** | 2 | 3 | 2 | 2 | 12 | 13 | 134427 | 68625 | 65802 | 326 | 101546 | 20144 | 65 | 12672 |
| ***4*** | 2 | 2 | 2 | 2 | 13 | 12 | 134611 | 66603 | 68008 | 1697 | 113003 | 13596 | 459 | 7553 |
| ***5*** | 2 | 3 | 3 | 2 | 12 | 14 | 140476 | 70739 | 69737 | 2373 | 105887 | 20936 | 646 | 13007 |
| ***6*** | 2 | 2 | 2 | 2 | 14 | 14 | 133781 | 63293 | 70489 | 1372 | 110044 | 15437 | 371 | 7929 |
| ***7*** | 2 | 2 | 1 | 2 | 14 | 14 | 138358 | 67052 | 71305 | 696 | 112043 | 15950 | 241 | 10123 |
| ***8*** | 2 | 3 | 3 | 2 | 13 | 14 | 140567 | 64549 | 76019 | 1704 | 107112 | 18706 | 586 | 14163 |
| ***9*** | 3 | 2 | 2 | 2 | 14 | 14 | 141770 | 69315 | 72455 | 1716 | 104238 | 21249 | 491 | 15792 |
| ***10*** | 2 | 3 | 3 | 2 | 12 | 15 | 143327 | 67682 | 75645 | 1180 | 107312 | 20511 | 818 | 14686 |

All of the 100 customer instances are solved with no gap under NCD and low demand setting. Average run time is 1294 seconds where maximum run time is 2373 seconds and minimum run time is 326 seconds. Number of transfer lines, depots and selected routes increased when compared to 50 customer instances. Since all instances are solved with no gaps, same experiments are repeated for the high demand density setting. Results can be found in Table 6.32.

Table 6.32 PB Formulation results for NCD scenario and high demand setting of 100 customer instances

| *Ins* | $F_A$ | $F_B$ | $T_A$ | $T_B$ | $R_A$ | $R_B$ | *Obj* | $Obj_A$ | $Obj_B$ | T(s) | *RC* | *FC* | *TC* | *IC* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***1*** | 4 | 4 | 3 | 4 | 27 | 40 | 182381 | 84717 | 97663 | 135 | 122699 | 34744 | 535 | 24403 |
| ***2*** | 3 | 5 | 4 | 3 | 25 | 28 | 171402 | 76676 | 94726 | 331 | 110805 | 32665 | 918 | 27013 |
| ***3*** | 4 | 4 | 4 | 3 | 25 | 30 | 178360 | 90850 | 87510 | 288 | 117369 | 33478 | 860 | 26652 |
| ***4*** | 4 | 3 | 3 | 4 | 26 | 21 | 171617 | 86116 | 85501 | 585 | 121356 | 26729 | 783 | 22749 |
| ***5*** | 3 | 5 | 5 | 3 | 25 | 31 | 184627 | 89863 | 94764 | 388 | 123940 | 31495 | 1069 | 28123 |
| ***6*** | 3 | 4 | 4 | 2 | 24 | 28 | 172335 | 78350 | 93985 | 450 | 124531 | 27472 | 688 | 19643 |
| ***7*** | 4 | 3 | 3 | 3 | 23 | 21 | 169075 | 82562 | 86512 | 205 | 119725 | 26961 | 700 | 21689 |
| ***8*** | 3 | 5 | 5 | 2 | 26 | 32 | 193339 | 93195 | 100144 | 298 | 134502 | 32781 | 708 | 25348 |
| ***9*** | 3 | 3 | 2 | 3 | 20 | 22 | 167551 | 80449 | 87102 | 402 | 118269 | 27624 | 483 | 21174 |
| ***10*** | 3 | 5 | 4 | 3 | 25 | 27 | 182750 | 85297 | 97453 | 446 | 119823 | 33242 | 550 | 29135 |

In high demand environment, all instances are solved to optimality. Maximum solution time is 15071 seconds and average run time is 353 seconds. When the demand setting is high, companies started to open more depots and transfer lines overall. Number of selected routes vary between 42 and 67.

When the NCD experiments with 100 customers compared with the original scenario experiments with 100 customers, it is observed that solution times decreased with NCD setup. Run time comparisons can be found in Table 6.33. Run times are indicated in terms of seconds.

Table 6.33 Original vs NCD scenario run times with 100 customer instances under PB formulation

| | ***Instance*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | ***7*** | ***8*** | ***9*** | ***10*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Low Demand** | **Original** | 676 | 4035 | 1955 | 1738 | 3543 | 730 | 1929 | 669 | 2698 | 1604 |
| | **NCD** | 628 | 1243 | 326 | 1697 | 2373 | 1372 | 696 | 1704 | 1716 | 1180 |
| **High Demand** | **Original** | 358 | 921 | 495 | 535 | 350 | 1143 | 1298 | 446 | 6010 | 328 |
| | **NCD** | 135 | 331 | 288 | 585 | 388 | 450 | 205 | 298 | 402 | 446 |

When the run times of 100 customer instances of original and NCD scenarios under low demand environment are compared, 8 out 10 instances are solved faster with NCD scenario which coincides with the finding in previous experiments. In average, NCD instances are solved 33% faster. When the run times compared for high demand setting experiments, similar behavior is observed, NCD instances get solved faster in average.

Overall, all instances of all scenarios are solved under both low demand and high demand environments to optimality with PB formulation. In some instances it reported better outcomes with the 8 or 16 hours of run results of LB formulation solutions with gaps, within seconds or few minutes. As mentioned in Section 5.2, this study focuses on joint strategic network design in which parties may collaborate. Consequently, we investigated managerial outcomes via PB formulation results in Section 6.2.

## 6.2 Managerial Insights

In order to investigate gains achieved thorough collaboration, to see how many percent of customers' demand is transferred among carriers and the effect of collaboration on the number of created routes, individual runs are completed with PB formulation. In the individual runs, both carriers act individually in which there is no possibility for collaboration. In other words, problem is solved as a traditional LRP for each carrier. Individual experiments started with original scenario of 30 customer instances. Results can be found in Table 6.34.

In both low demand and high demand settings, collaboration yield better solutions in terms of lower costs. Gain amounts in terms of percentages can be found in Table 6.35.

When the gains are compared for original scenario instances, in low demand envi-

Table 6.34 Individual PB Formulation results for original scenario of 30 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Individual | | | Collaboration | | | Individual | | | Collaboration | | |
| **Ins** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** |
| **1** | 66388 | 32595 | 33793 | 59212 | 28374 | 30838 | 90528 | 43009 | 47519 | 84655 | 37917 | 46738 |
| **2** | 68956 | 36256 | 32700 | 63258 | 31251 | 32007 | 95109 | 50647 | 44462 | 87762 | 49155 | 38607 |
| **3** | 71805 | 34816 | 36989 | 66487 | 35099 | 31389 | 89502 | 45145 | 44357 | 81829 | 41689 | 40140 |
| **4** | 59756 | 30425 | 29331 | 56495 | 28600 | 27894 | 81507 | 39854 | 41653 | 72874 | 35897 | 36977 |
| **5** | 67529 | 32644 | 34885 | 59675 | 23104 | 36571 | 91368 | 43381 | 47988 | 80099 | 33351 | 46748 |
| **6** | 66488 | 35616 | 30872 | 62773 | 35704 | 27069 | 92182 | 49204 | 42978 | 87084 | 44873 | 42211 |
| **7** | 64561 | 33172 | 31389 | 60823 | 29770 | 31053 | 86870 | 44286 | 42584 | 80806 | 44932 | 35874 |
| **8** | 63114 | 29647 | 33467 | 59838 | 27162 | 32675 | 85608 | 38881 | 46727 | 78296 | 42119 | 36177 |
| **9** | 74007 | 35668 | 38339 | 71090 | 34649 | 36441 | 96850 | 44863 | 51987 | 91513 | 46544 | 44970 |
| **10** | 65777 | 31669 | 34109 | 63738 | 29752 | 33986 | 86586 | 42803 | 43784 | 79527 | 37881 | 41646 |

Table 6.35 Gain comparison for original scenario of 30 customer instances

| | Low Demand | | | High Demand | | |
|---|---|---|---|---|---|---|
| **Ins** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** |
| **1** | 10.8% | 13.0% | 8.7% | 6.5% | 11.8% | 1.6% |
| **2** | 8.3% | 13.8% | 2.1% | 7.7% | 2.9% | 13.2% |
| **3** | 7.4% | -0.8% | 15.1% | 8.6% | 7.7% | 9.5% |
| **4** | 5.5% | 6.0% | 4.9% | 10.6% | 9.9% | 11.2% |
| **5** | 11.6% | 29.2% | -4.8% | 12.3% | 23.1% | 2.6% |
| **6** | 5.6% | -0.2% | 12.3% | 5.5% | 8.8% | 1.8% |
| **7** | 5.8% | 10.3% | 1.1% | 7.0% | -1.5% | 15.8% |
| **8** | 5.2% | 8.4% | 2.4% | 8.5% | -8.3% | 22.6% |
| **9** | 3.9% | 2.9% | 5.0% | 5.5% | -3.7% | 13.5% |
| **10** | 3.1% | 6.1% | 0.4% | 8.2% | 11.5% | 4.9% |
| **Avg.** | 6.7% | 8.8% | 4.7% | 8.0% | 6.2% | 9.7% |

ronment, collaboration yields 6.7% of savings on average for the centralized system. Minimum gain is 3.1% and maximum gain is 11.6%. For carrier $A$, average gain percentage is 8.8%. However, in two instances, carrier $A$ reported higher costs but the difference is 0.8% at most. On the other hand, carrier $A$, benefits from collaboration in 8 out of 10 instances in which it benefited from collaboration with up to 29.2% gains in some instances. Carrier $B$ reports worse outcomes only for once instance. Gains for carrier $B$ deviate between -4.8% and 15.1% where average gain for B is 4.7%.

For the high demand setting of original scenario instances, average gain is 8% where gains deviate between 5.5% and 12.3%. Carrier $A$ suffered from collaboration in terms of increased costs in 3 instances. For carrier $A$, average gain is 6.2%, minimum gain is -8.3% and maximum gain is 23.1%. For carrier $B$, average gain amount is 9.7%. For all instances, carrier $B$ benefits from collaboration. Minimum saving amount is 1.6% and maximum saving amount is 22.6%.

Another managerial outcome is amount of transferred goods. It is important to investigate how much of original demand is served by the other carriers in the system. In the transfer percentage comparison tables like Table 6.36, columns $\%TD_A$ and $\%TD_B$ indicates how much of the total demand which belongs to that carrier is transferred to other carriers, for carrier $A$ and $B$, respectively. Columns $\%TP_A$ and $\%TP_B$ depicts how much of the total possible transferable amount is transferred to other carrier, for carrier $A$ and $B$, respectively.

Table 6.36 Transfer percentages for original scenario of 30 customer instances of PB formulation experiments

| | Low Demand | | | | High Demand | | | |
|---|---|---|---|---|---|---|---|---|
| **Ins** | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ |
| **1** | 13.8% | 11.4% | 49.3% | 50.7% | 16.3% | 6.2% | 58.3% | 27.6% |
| **2** | 10.6% | 9.4% | 44.7% | 35.4% | 7.6% | 17.9% | 32.1% | 67.9% |
| **3** | 14.7% | 14.7% | 58.7% | 52.7% | 9.3% | 14.5% | 37.1% | 52.0% |
| **4** | 15.1% | 6.9% | 53.9% | 36.8% | 11.8% | 10.9% | 42.2% | 57.8% |
| **5** | 18.3% | 5.5% | 64.5% | 20.2% | 18.3% | 9.6% | 64.5% | 35.5% |
| **6** | 14.0% | 10.4% | 55.1% | 35.9% | 15.4% | 8.8% | 60.6% | 30.5% |
| **7** | 10.4% | 9.8% | 41.0% | 33.7% | 8.5% | 15.3% | 33.4% | 52.7% |
| **8** | 23.0% | 10.0% | 68.8% | 31.2% | 4.9% | 17.2% | 14.7% | 53.6% |
| **9** | 17.4% | 15.1% | 58.7% | 61.8% | 3.4% | 13.8% | 11.5% | 56.5% |
| **10** | 12.5% | 7.6% | 48.1% | 35.8% | 16.7% | 10.0% | 64.3% | 46.9% |
| **Avg** | 15.0% | 10.1% | 54.3% | 39.4% | 11.2% | 12.4% | 41.9% | 48.1% |

As Table 6.36 investigated, it is observed that for low demand setting, carrier $A$ transfers 15% of its total demand in average and carrier $B$ transfers 10.1% of its total demand on average. When total possible transfer amounts are compared, it is observed that carrier $A$ prefers to transfer more than half of shared demand on average. Carrier $B$ transferred 39% percent of the possible transferable amount. Note that, in instance 8, carrier $A$ transfer ed 68.8% of the total transferable amount, which means that model chose to serve most of common demand points by a route of carrier $B$.

For the high demand setting, carrier $A$ transfers 11.2% of its total demand on average and carrier $B$ transfers 12.4% of its total demand on average. When total possible transfer amounts are compared, carrier $A$ prefers to transfer 41.9% of shared demand on average. Carrier $B$ transferred 48.1% percent of the possible transferable amount. In some cases, model chose to transfer only 11.5% of transferable amount for a carrier. On the other hand, there are instances in which 67.9% of the transferable amount is transferred to other carrier.

Next, all those strategic aspects are investigated with 50 customer instances. Results of individual experiments with original scenario of 50 customer instances can be found in Table 6.37.

Gains which are calculated through comparison of OFVs of individual and collabo-

Table 6.37 Individual PB Formulation results for original scenario of 50 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Individual | | | Collaboration | | | Individual | | | Collaboration | | |
| **Ins** | ***Obj*** | $\boldsymbol{Obj_A}$ | $\boldsymbol{Obj_B}$ | ***Obj*** | $\boldsymbol{Obj_A}$ | $\boldsymbol{Obj_B}$ | ***Obj*** | $\boldsymbol{Obj_A}$ | $\boldsymbol{Obj_B}$ | ***Obj*** | $\boldsymbol{Obj_A}$ | $\boldsymbol{Obj_B}$ |
| **1** | 97095 | 50391 | 46704 | 89476 | 43608 | 45868 | 117833 | 59881 | 57952 | 107793 | 53111 | 54682 |
| **2** | 97762 | 54057 | 43705 | 90619 | 44855 | 45764 | 122749 | 68755 | 53994 | 112120 | 60779 | 51341 |
| **3** | 88869 | 40837 | 48032 | 84881 | 40609 | 44273 | 116031 | 52893 | 63138 | 111125 | 52967 | 58159 |
| **4** | 92287 | 46175 | 46112 | 87623 | 42465 | 45158 | 116826 | 57301 | 59526 | 108818 | 56296 | 52523 |
| **5** | 99933 | 49348 | 50585 | 87197 | 46103 | 41094 | 128829 | 61427 | 67402 | 115084 | 52583 | 62501 |
| **6** | 92755 | 45260 | 47495 | 86500 | 43433 | 43067 | 123198 | 63501 | 59697 | 110016 | 53199 | 56818 |
| **7** | 93369 | 44406 | 48963 | 86940 | 46419 | 40521 | 120204 | 56897 | 63308 | 114594 | 50365 | 64229 |
| **8** | 106786 | 53323 | 53464 | 104264 | 50686 | 53579 | 140040 | 68825 | 71215 | 129866 | 70035 | 59832 |
| **9** | 92756 | 46995 | 45762 | 90836 | 45053 | 45783 | 121594 | 60682 | 60912 | 116189 | 59813 | 56376 |
| **10** | 107412 | 53168 | 54244 | 103262 | 51673 | 51589 | 134679 | 65996 | 68684 | 128774 | 61819 | 66955 |

rative PB formulation experiments can be found in Table 6.38.

Table 6.38 Gain comparison for original scenario of 50 customer instances

| | Low Demand | | | High Demand | | |
|---|---|---|---|---|---|---|
| **Ins** | ***Gain*** | $\boldsymbol{Gain_A}$ | $\boldsymbol{Gain_B}$ | ***Gain*** | $\boldsymbol{Gain_A}$ | $\boldsymbol{Gain_B}$ |
| **1** | 7.8% | 13.5% | 1.8% | 8.5% | 11.3% | 5.6% |
| **2** | 7.3% | 17.0% | -4.7% | 8.7% | 11.6% | 4.9% |
| **3** | 4.5% | 0.6% | 7.8% | 4.2% | -0.1% | 7.9% |
| **4** | 5.1% | 8.0% | 2.1% | 6.9% | 1.8% | 11.8% |
| **5** | 12.7% | 6.6% | 18.8% | 10.7% | 14.4% | 7.3% |
| **6** | 6.7% | 4.0% | 9.3% | 10.7% | 16.2% | 4.8% |
| **7** | 6.9% | -4.5% | 17.2% | 4.7% | 11.5% | -1.5% |
| **8** | 2.4% | 4.9% | -0.2% | 7.3% | -1.8% | 16.0% |
| **9** | 2.1% | 4.1% | 0.0% | 4.4% | 1.4% | 7.4% |
| **10** | 3.9% | 2.8% | 4.9% | 4.4% | 6.3% | 2.5% |
| **Avg** | 5.9% | 5.7% | 5.7% | 7.0% | 7.3% | 6.7% |

In low demand environment and original scenario setting of 50 customer instances, collaboration reduces costs of centralized system by 5.9% on average. For centralized system, minimum gain amount is 2.1% and maximum gain amount is 12.7%. For both carriers $A$ and $B$ average gain amount is 5.7%. Carrier $A$ reports a worse outcome for only one instance where carrier $B$ reports two.

In In high demand environment and original scenario setting of 50 customer instances, average gain for collaborative schema is 7% in average. Gains deviate between 4.2% and 10.7%. For carrier $A$, only two instances reported a negative gain and on average carrier $A$ gains 7.3% from collaboration.Carrier $B$ reported a increased cost for only one instance and average gain of carrier $B$ is 6.7%.

Transfer amounts in percentages for original scenario of 50 customer instances can be found in Table 6.39.

In low demand setting, carrier $A$ transfers 8.5% of its total demand in average

Table 6.39 Transfer percentages for original setting of 50 customer instances of PB formulation experiments

| | Low Demand | | | | High Demand | | | |
|---|---|---|---|---|---|---|---|---|
| **Ins** | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ |
| **1** | 5.7% | 5.1% | 42.8% | 38.0% | 6.2% | 7.2% | 46.5% | 53.5% |
| **2** | 14.8% | 0.0% | 71.4% | 0.0% | 10.8% | 10.4% | 51.9% | 48.1% |
| **3** | 7.9% | 11.9% | 36.9% | 53.6% | 10.0% | 13.9% | 46.6% | 62.7% |
| **4** | 14.3% | 6.0% | 67.2% | 29.6% | 4.6% | 13.5% | 21.8% | 66.1% |
| **5** | 7.5% | 13.9% | 35.5% | 71.1% | 11.5% | 8.9% | 54.6% | 45.4% |
| **6** | 9.9% | 9.0% | 49.8% | 50.2% | 15.6% | 3.9% | 78.3% | 21.7% |
| **7** | 1.7% | 13.8% | 8.7% | 77.4% | 15.2% | 4.3% | 76.1% | 23.9% |
| **8** | 9.2% | 8.0% | 55.3% | 44.7% | 2.5% | 15.2% | 15.0% | 85.0% |
| **9** | 4.4% | 2.3% | 19.7% | 10.9% | 5.1% | 16.3% | 22.5% | 77.5% |
| **10** | 9.9% | 8.4% | 45.5% | 39.3% | 5.9% | 6.2% | 27.0% | 29.0% |
| **Avg** | 8.5% | 7.8% | 43.3% | 41.5% | 8.7% | 10.0% | 44.0% | 51.3% |

and carrier $B$ transfers 7.8% of its total demand in average. When total possible transfer amounts are compared, it is observed that carrier $A$ prefers to transfer 43.3% of shared demand in average. Carrier $B$ transferred 41.5% percent of the possible transferable amount in average.

For the high demand setting, carrier $A$ transfers 8.7% of its total demand in average and carrier $B$ transfers 10% of its total demand in average. When total possible transfer amounts are compared, it is observed that carrier $A$ prefers to transfer 44% of shared demand in average. Carrier B transferred 51.3% percent of the possible transferable amount. In some cases, PB formulation can transfer up 85% of the transferable amount. However, it may also choose to only transfer 15% of the transferable amount is transferred to other carrier.

Same experiments are repeated for original scenario with 100 customer instances. Results of individual experiments with original scenario of 100 customer instances can be found in Table 6.40.

Table 6.40 Individual PB Formulation results for original scenario of 100 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Individual | | | Collaboration | | | Individual | | | Collaboration | | |
| Ins | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ |
| **1** | 138661 | 69258 | 69403 | 130086 | 67529 | 62556 | 193969 | 94953 | 99016 | 179192 | 81451 | 97741 |
| **2** | 140693 | 69394 | 71299 | 134553 | 65329 | 69224 | 188494 | 92613 | 95881 | 175510 | 82049 | 93461 |
| **3** | 140428 | 74080 | 66349 | 134803 | 70106 | 64697 | 185322 | 98405 | 86917 | 172583 | 89524 | 83059 |
| **4** | 140481 | 70747 | 69734 | 132917 | 66092 | 66826 | 186592 | 93513 | 93080 | 171736 | 90075 | 81661 |
| **5** | 145953 | 74726 | 71228 | 139164 | 69815 | 69349 | 198227 | 103262 | 94965 | 184279 | 93553 | 90726 |
| **6** | 140161 | 71179 | 68982 | 130353 | 64118 | 66236 | 186127 | 94872 | 91255 | 173623 | 89068 | 84555 |
| **7** | 148899 | 73072 | 75827 | 138534 | 69514 | 69020 | 176171 | 87883 | 88288 | 165411 | 83634 | 81777 |
| **8** | 145403 | 73370 | 72034 | 135919 | 71045 | 64874 | 202033 | 99887 | 102146 | 187854 | 99803 | 88052 |
| **9** | 143928 | 73783 | 70145 | 138389 | 69475 | 68914 | 184902 | 94211 | 90691 | 171977 | 84453 | 87524 |
| **10** | 143895 | 77077 | 66818 | 137148 | 71254 | 65894 | 187466 | 99056 | 88410 | 174801 | 90015 | 84786 |

Gains through collaboration for the 100 customer instances of original setting can be found in Table 6.41.

Table 6.41 Gain comparison for original scenario of 100 customer instances

| | Low Demand | | | High Demand | | |
|---|---|---|---|---|---|---|
| **Ins** | ***Gain*** | $Gain_A$ | $Gain_B$ | ***Gain*** | $Gain_A$ | $Gain_B$ |
| **1** | 6.6% | 2.5% | 9.9% | 7.6% | 14.2% | 1.3% |
| **2** | 4.6% | 5.9% | 2.9% | 6.9% | 11.4% | 2.5% |
| **3** | 4.2% | 5.4% | 2.5% | 6.9% | 9.0% | 4.4% |
| **4** | 5.7% | 6.6% | 4.2% | 8.0% | 3.7% | 12.3% |
| **5** | 4.9% | 6.6% | 2.6% | 7.0% | 9.4% | 4.5% |
| **6** | 7.5% | 9.9% | 4.0% | 6.7% | 6.1% | 7.3% |
| **7** | 7.5% | 4.9% | 9.0% | 6.1% | 4.8% | 7.4% |
| **8** | 7.0% | 3.2% | 9.9% | 7.0% | 0.1% | 13.8% |
| **9** | 4.0% | 5.8% | 1.8% | 7.0% | 10.4% | 3.5% |
| **10** | 4.9% | 7.6% | 1.4% | 6.8% | 9.1% | 4.1% |
| **Avg** | 5.7% | 5.8% | 4.8% | 7.0% | 7.8% | 6.1% |

In low demand and original setting of 100 customer instances, average gain amount for centralized system is 5.7% where gains deviate between 4.2% and 7.5%. For carrier $A$ and $B$, average gain percentages are 5.8 and 4.8, respectively. None of the carriers reported a loss. In high demand setting, for collaborative system, average gain amount is 7%. Carrier $A$ and $B$ have an average gain of 7.8% and 6.1%, respectively. Again, in all instances, both carriers benefited from the collaboration.

Transfer amounts in percentages for original scenario of 100 customer instances can be found in Table 6.42.

Table 6.42 Transfer percentages for original setting of 100 customer instances of PB formulation experiments

| | Low Demand | | | | High Demand | | | |
|---|---|---|---|---|---|---|---|---|
| **Ins** | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ |
| **1** | 6.7% | 13.5% | 33.7% | 63.8% | 13.1% | 3.9% | 65.5% | 18.6% |
| **2** | 10.4% | 9.7% | 50.1% | 47.9% | 10.6% | 7.7% | 50.9% | 37.9% |
| **3** | 12.9% | 8.0% | 64.4% | 38.3% | 11.4% | 6.5% | 56.9% | 31.0% |
| **4** | 11.0% | 6.7% | 49.6% | 28.8% | 9.2% | 12.8% | 41.5% | 55.3% |
| **5** | 9.7% | 10.9% | 43.7% | 52.4% | 11.0% | 8.1% | 49.8% | 38.8% |
| **6** | 12.7% | 9.3% | 55.2% | 39.2% | 7.8% | 10.9% | 33.8% | 46.0% |
| **7** | 9.2% | 9.2% | 42.2% | 42.4% | 10.8% | 12.3% | 49.4% | 57.1% |
| **8** | 8.1% | 12.1% | 37.6% | 57.8% | 5.5% | 13.8% | 25.5% | 65.5% |
| **9** | 9.7% | 9.1% | 50.9% | 44.8% | 10.0% | 7.8% | 52.3% | 38.6% |
| **10** | 8.5% | 7.1% | 51.0% | 39.6% | 9.9% | 6.2% | 59.4% | 34.5% |
| **Avg** | 9.9% | 9.5% | 47.8% | 45.5% | 9.9% | 9.0% | 48.5% | 42.3% |

In low demand setting, carrier $A$ transfers 9.9% of its total demand in average and carrier $B$ transfers 9.5% of its total demand in average. When total possible transfer amounts are compared, it is observed that carrier $A$ prefers to transfer

47.8% of shared demand in average. Carrier $B$ transferred 45.5% percent of the possible transferable amount in average.

For the high demand setting, carrier $A$ transfers 9.9% of its total demand in average and carrier $B$ transfers 9% of its total demand in average. When total possible transfer amounts are compared, it is observed that carrier A prefers to transfer 48.5% of shared demand in average. Carrier $B$ transferred 42.3% percent of the possible transferable amount. In some cases, PB formulation can transfer up 65.5% of the transferable amount. However, it may also choose to only transfer 18.6% of the transferable amount is transferred to other carrier.

In order to see the effect of common customer number on collaboration, above experiments, which are conducted to identify gain structure and transfer amounts, are repeated with ICC setting.

Initial individual experiments of ICC scenario is conducted with 30 customer instances. Results can be found in Table 6.43.

Table 6.43 Individual PB Formulation results for ICC scenario of 30 customer instances

| | **Low Demand** | | | | | | **High Demand** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Individual** | | | **Collaboration** | | | **Individual** | | | **Collaboration** | | |
| **Ins** | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ |
| ***1*** | 70328 | 35307 | 35021 | 61617 | 30649 | 30968 | 97998 | 45222 | 52776 | 82493 | 29554 | 52939 |
| ***2*** | 74657 | 39033 | 35625 | 66917 | 28582 | 38335 | 101297 | 52859 | 48438 | 85637 | 51811 | 33825 |
| ***3*** | 73008 | 34690 | 38318 | 64793 | 30357 | 34436 | 89891 | 45085 | 44807 | 80740 | 35753 | 44987 |
| ***4*** | 61915 | 32667 | 29248 | 52718 | 28585 | 24133 | 80651 | 40683 | 39968 | 68220 | 29142 | 39078 |
| ***5*** | 71877 | 35933 | 35944 | 61008 | 24980 | 36028 | 94990 | 47262 | 47729 | 77020 | 25294 | 51726 |
| ***6*** | 67086 | 36828 | 30258 | 58756 | 37667 | 21089 | 90078 | 49075 | 41003 | 77171 | 42707 | 34464 |
| ***7*** | 68922 | 34731 | 34192 | 62069 | 32040 | 30029 | 91384 | 46059 | 45325 | 79263 | 38681 | 40582 |
| ***8*** | 67771 | 31759 | 36012 | 54596 | 27326 | 27270 | 86110 | 42038 | 44072 | 68111 | 30198 | 37913 |
| ***9*** | 75577 | 36075 | 39503 | 69495 | 30289 | 39206 | 102797 | 47158 | 55639 | 88169 | 41383 | 46786 |
| ***10*** | 70475 | 35417 | 35058 | 65380 | 31796 | 33584 | 95391 | 47771 | 47620 | 79354 | 35915 | 43438 |

Identified saving amounts which are calculated through comparison of optimum solutions of individual and collaborative PB formulation experiments can be found in Table 6.44.

In low demand environment and ICC scenario setting of 30 customer instances, average gain amount is 12.1% for centralized system. Carrier $A$ benefits an average gain amount of 14.1% where carrier $B$ gains 10.3% on average. Carrier $A$ reported increased costs only for one instance and loss percentage when compared to non-collaborative scenario is 2.3%. Maximum gain reported by carrier $A$ is 30.5%. Carrier $B$ suffered from collaboration in two instances. Maximum gain reported by

Table 6.44 Gain comparison for ICC scenario of 30 customer instances

| | Low Demand | | | High Demand | | |
|---|---|---|---|---|---|---|
| **Ins** | $Gain$ | $Gain_A$ | $Gain_B$ | $Gain$ | $Gain_A$ | $Gain_B$ |
| **1** | 12.4% | 13.2% | 11.6% | 15.8% | 34.6% | -0.3% |
| **2** | 10.4% | 26.8% | -7.6% | 15.5% | 2.0% | 30.2% |
| **3** | 11.3% | 12.5% | 10.1% | 10.2% | 20.7% | -0.4% |
| **4** | 14.9% | 12.5% | 17.5% | 15.4% | 28.4% | 2.2% |
| **5** | 15.1% | 30.5% | -0.2% | 18.9% | 46.5% | -8.4% |
| **6** | 12.4% | -2.3% | 30.3% | 14.3% | 13.0% | 15.9% |
| **7** | 9.9% | 7.7% | 12.2% | 13.3% | 16.0% | 10.5% |
| **8** | 19.4% | 14.0% | 24.3% | 20.9% | 28.2% | 14.0% |
| **9** | 8.0% | 16.0% | 0.8% | 14.2% | 12.2% | 15.9% |
| **10** | 7.2% | 10.2% | 4.2% | 16.8% | 24.8% | 8.8% |
| **Avg** | 12.1% | 14.1% | 10.3% | 15.5% | 22.6% | 8.8% |

carrier $B$ is 30.3%.

When gains are compared in high demand setting, average gain amount for collaborative schema turns out to be 15.5%, which is higher than the low demand environment. Average gain of carrier $A$ is 22.6% and average gain of carrier $B$ is 8.8%. For all instances, carrier $A$ benefited from collaboration. Maximum gain amount reported by carrier $A$ is 46.5% which means cost of carrier $A$ is almost cut in half. On the contrary, carrier $B$ reported worse outcomes for three instances. Maximum loss amount of carrier $B$ is 8.4% and maximum gain amount is 30.2%.

Transfer amounts in percentages for ICC scenario of 30 customer instances can be found in Table 6.45.

Table 6.45 Transfer percentages for ICC setting of 30 customer instances of PB formulation experiments

| | Low Demand | | | | High Demand | | | |
|---|---|---|---|---|---|---|---|---|
| **Ins** | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ |
| **1** | 17.1% | 19.6% | 36.5% | 47.7% | 32.6% | 6.0% | 69.6% | 14.6% |
| **2** | 38.1% | 6.7% | 79.1% | 13.0% | 7.0% | 44.0% | 14.6% | 85.4% |
| **3** | 24.2% | 12.3% | 60.8% | 30.3% | 30.1% | 9.9% | 75.6% | 24.4% |
| **4** | 15.4% | 18.1% | 33.0% | 51.2% | 30.2% | 12.5% | 64.6% | 35.4% |
| **5** | 23.3% | 17.0% | 54.6% | 40.1% | 36.8% | 5.8% | 86.4% | 13.6% |
| **6** | 15.3% | 34.8% | 35.4% | 70.0% | 23.2% | 20.4% | 53.7% | 41.0% |
| **7** | 21.6% | 24.9% | 50.0% | 50.0% | 24.2% | 21.8% | 56.1% | 43.9% |
| **8** | 21.1% | 29.6% | 39.9% | 54.2% | 28.8% | 19.9% | 54.5% | 36.5% |
| **9** | 39.2% | 10.3% | 71.8% | 22.0% | 22.6% | 24.5% | 41.3% | 52.4% |
| **10** | 26.4% | 19.4% | 54.2% | 48.4% | 21.8% | 22.2% | 44.7% | 55.3% |
| **Avg** | 24.2% | 19.3% | 51.5% | 42.7% | 25.7% | 18.7% | 56.1% | 40.3% |

In low demand and ICC setting of 30 customer instances, carrier $A$ transfers 24.2% of its total demand in average and carrier $B$ transfers 19.3% of its total demand in average. Which means, on average, approximately 20% of demands are exchanged by carriers. In average, carrier $A$ chose to transfer 51.5% of transferable amount where carrier $B$ chose to transfer 42.7% of total transferable amount.

On high demand setting, a similar behaviour to low demand setting is observed. When the transfer amount is compared through total demand amounts, in average, carrier $A$ transferred 25.7% of its total demand and carrier $B$ transferred 18.7% of its total demand. In average, carrier $A$ chose to transfer 56.1% of transferable amount where carrier $B$ chose to transfer 40.3% of total transferable amount.

Later, in order to investigate strategic aspects discussed above and to see the effect of problem size, experiments are repeated with 50 customer instances. Results of individual experiments with ICC scenario of 50 customer instances can be found in Table 6.46.

Table 6.46 Individual PB Formulation results for ICC scenario of 50 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Individual | | | Collaboration | | | Individual | | | Collaboration | | |
| Ins | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ |
| *1* | 100838 | 51836 | 49002 | 85884 | 44174 | 41710 | 118874 | 60095 | 58780 | 102624 | 50198 | 52426 |
| *2* | 103434 | 56241 | 47193 | 92657 | 54120 | 38538 | 138557 | 74733 | 63824 | 118839 | 63005 | 55833 |
| *3* | 89020 | 43118 | 45902 | 82663 | 42731 | 39932 | 132008 | 60282 | 71726 | 113558 | 60556 | 53002 |
| *4* | 97620 | 49403 | 48218 | 88608 | 45647 | 42961 | 123757 | 61935 | 61822 | 103221 | 58861 | 44360 |
| *5* | 103322 | 50243 | 53080 | 86911 | 45951 | 40961 | 135243 | 62410 | 72833 | 111538 | 54013 | 57525 |
| *6* | 95436 | 46227 | 49210 | 84591 | 45736 | 38854 | 125312 | 62932 | 62380 | 107299 | 48336 | 58964 |
| *7* | 99122 | 48470 | 50652 | 90956 | 39374 | 51581 | 130543 | 63153 | 67390 | 112998 | 58003 | 54995 |
| *8* | 112711 | 59168 | 53544 | 100368 | 50299 | 50070 | 137451 | 70227 | 67224 | 120297 | 64610 | 55687 |
| *9* | 98097 | 47944 | 50153 | 89009 | 41119 | 47890 | 126161 | 60892 | 65270 | 110823 | 55383 | 55441 |
| *10* | 109700 | 53069 | 56631 | 101852 | 50555 | 51297 | 140978 | 68176 | 72803 | 122948 | 63880 | 59069 |

Gain amounts achieved through collaboration can be found for PB Formulation results with 50 customers and ICC scenario in Table 6.47.

In low demand environment of ICC scenario setting of 50 customer instances, average gain amount by centralized collaboration schema is 10.4%. Average gain for carrier $A$ is 8.9% where maximum gain amount is 18.8%. For carrier $B$ average gain amount is 12% and maximum gain amount is 22.8%. Carrier $A$ benefited from collaboration in all instances. Similarly, carrier $B$ benefited from collaboration in 9 out of 10 instances, it only reported a worse outcome for only one instance.

In high demand environment and ICC scenario setting of 50 customer instances, average gain for collaborative schema is 14.1%. Minimum gain amount is 12.2% and maximum gain amount is 17.5%. Overall, it can be identified that saving amounts are higher in high demand environments when compared to low demand

Table 6.47 Gain comparison for ICC scenario of 50 customer instances

| | Low Demand | | | High Demand | | |
|---|---|---|---|---|---|---|
| **Ins** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** |
| **1** | 14.8% | 14.8% | 14.9% | 13.7% | 16.5% | 10.8% |
| **2** | 10.4% | 3.8% | 18.3% | 14.2% | 15.7% | 12.5% |
| **3** | 7.1% | 0.9% | 13.0% | 14.0% | -0.5% | 26.1% |
| **4** | 9.2% | 7.6% | 10.9% | 16.6% | 5.0% | 28.2% |
| **5** | 15.9% | 8.5% | 22.8% | 17.5% | 13.5% | 21.0% |
| **6** | 11.4% | 1.1% | 21.0% | 14.4% | 23.2% | 5.5% |
| **7** | 8.2% | 18.8% | -1.8% | 13.4% | 8.2% | 18.4% |
| **8** | 11.0% | 15.0% | 6.5% | 12.5% | 8.0% | 17.2% |
| **9** | 9.3% | 14.2% | 4.5% | 12.2% | 9.0% | 15.1% |
| **10** | 7.2% | 4.7% | 9.4% | 12.8% | 6.3% | 18.9% |
| **Avg** | 10.4% | 8.9% | 12.0% | 14.1% | 10.5% | 17.4% |

environments. Carrier $A$ reported higher costs for one instance. Average gain of carrier $A$ is 10.5% where maximum gain of $A$ is 23.2%. On the other hand, carrier $B$ benefited from collaboration in all instances with an average gain amount of 17.4% and maximum gain amount of 28.2%.

Transfer amounts in percentages for ICC scenario of 50 customer instances can be found in Table 6.48.

Table 6.48 Transfer percentages for ICC setting of 50 customer instances of PB formulation experiments

| | Low Demand | | | | High Demand | | | |
|---|---|---|---|---|---|---|---|---|
| **Ins** | ***%$TD_A$*** | ***%$TD_B$*** | ***%$TP_A$*** | ***%$TP_B$*** | ***%$TD_A$*** | ***%$TD_B$*** | ***%$TP_A$*** | ***%$TP_B$*** |
| **1** | 9.5% | 18.6% | 29.2% | 55.8% | 12.9% | 17.0% | 39.6% | 50.9% |
| **2** | 12.0% | 20.6% | 31.7% | 51.9% | 18.9% | 17.2% | 49.9% | 43.4% |
| **3** | 9.6% | 18.7% | 24.7% | 48.7% | 9.7% | 25.2% | 24.8% | 65.7% |
| **4** | 16.5% | 21.3% | 47.5% | 55.9% | 9.3% | 25.3% | 26.8% | 66.3% |
| **5** | 13.9% | 18.2% | 37.5% | 56.6% | 16.7% | 17.0% | 45.1% | 52.9% |
| **6** | 13.3% | 25.4% | 33.6% | 67.1% | 28.5% | 4.8% | 72.0% | 12.7% |
| **7** | 28.1% | 12.6% | 70.8% | 33.4% | 14.7% | 22.6% | 37.0% | 59.8% |
| **8** | 17.8% | 20.1% | 47.8% | 48.6% | 15.3% | 24.0% | 40.9% | 57.9% |
| **9** | 19.2% | 22.2% | 46.7% | 57.5% | 7.2% | 27.1% | 17.6% | 70.3% |
| **10** | 18.0% | 13.8% | 43.4% | 36.9% | 16.1% | 24.1% | 38.8% | 64.1% |
| **Avg** | 15.8% | 19.2% | 41.3% | 51.2% | 14.9% | 20.4% | 39.2% | 54.4% |

In low demand and ICC setting of 50 customer instances, carrier $A$ transfers 15.2% of its total demand in average and carrier $B$ transfers 19.2% of its total demand in average. When the transfer percentages are compared through total shared amounts, carrier $A$ transfers 41.3% of transferable amount and carrier $B$ transfers 51.2% of transferable amount. For given instances, PB model may choose to transfer up to

70.8% of transferable amount.

For the high demand setting, carrier A transfers 14.9% of its total demand in average and carrier B transfers 20.4% of its total demand on average. When total possible transfer amounts are compared, it is observed that carrier $A$ prefers to transfer 39.2% of shared demand on average. Carrier $B$ transferred 54.4% percent of the possible transferable amount.

Last set of experiments for ICC scenario, conducted with 100 customers. Results of individual experiments with original scenario of 100 customer instances can be be found in Table 6.49.

Table 6.49 Individual PB Formulation results for ICC scenario of 100 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Individual | | | Collaboration | | | Individual | | | Collaboration | | |
| **Ins** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** |
| ***1*** | 148042 | 70690 | 77352 | 128694 | 56056 | 72638 | 198320 | 94339 | 103982 | 171710 | 77686 | 94024 |
| ***2*** | 145072 | 68416 | 76656 | 129742 | 57798 | 71945 | 190706 | 90288 | 100418 | 163346 | 79945 | 83401 |
| ***3*** | 145428 | 74912 | 70517 | 127583 | 63829 | 63755 | 191213 | 103207 | 88006 | 162491 | 81949 | 80542 |
| ***4*** | 145760 | 72830 | 72930 | 128180 | 69858 | 58322 | 191715 | 93040 | 98675 | 162973 | 80907 | 82066 |
| ***5*** | 148116 | 71702 | 76415 | 136663 | 70309 | 66353 | 204090 | 100317 | 103773 | 182783 | 95253 | 87531 |
| ***6*** | 143813 | 69715 | 74098 | 129174 | 55453 | 73721 | 186545 | 89488 | 97057 | 165413 | 79464 | 85949 |
| ***7*** | 148928 | 71957 | 76972 | 132599 | 68772 | 63827 | 179781 | 86361 | 93420 | 158518 | 75119 | 83399 |
| ***8*** | 151678 | 73904 | 77774 | 138466 | 67378 | 71088 | 207525 | 100603 | 106922 | 185498 | 100967 | 84531 |
| ***9*** | 148456 | 72846 | 75610 | 138107 | 70187 | 67920 | 185733 | 92038 | 93695 | 159548 | 79042 | 80505 |
| ***10*** | 155737 | 81753 | 73985 | 139141 | 75873 | 63268 | 205438 | 105278 | 100160 | 175915 | 94526 | 81389 |

For the 100 customer instances, gains are compared in Table 6.50.

Table 6.50 Gain comparison for ICC scenario of 100 customer instances

| | Low Demand | | | High Demand | | |
|---|---|---|---|---|---|---|
| **Ins** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** |
| **1** | 13.1% | 20.7% | 6.1% | 13.4% | 17.7% | 9.6% |
| **2** | 10.6% | 15.5% | 6.1% | 14.3% | 11.5% | 16.9% |
| **3** | 12.3% | 14.8% | 9.6% | 15.0% | 20.6% | 8.5% |
| **4** | 12.1% | 4.1% | 20.0% | 15.0% | 13.0% | 16.8% |
| **5** | 7.7% | 1.9% | 13.2% | 10.4% | 5.0% | 15.7% |
| **6** | 10.2% | 20.5% | 0.5% | 11.3% | 11.2% | 11.4% |
| **7** | 11.0% | 4.4% | 17.1% | 11.8% | 13.0% | 10.7% |
| **8** | 8.7% | 8.8% | 8.6% | 10.6% | -0.4% | 20.9% |
| **9** | 7.0% | 3.6% | 10.2% | 14.1% | 14.1% | 14.1% |
| **10** | 10.7% | 7.2% | 14.5% | 14.4% | 10.2% | 18.7% |
| **Avg** | 10.3% | 10.2% | 10.6% | 13.0% | 11.6% | 14.3% |

In low demand setup of ICC setting of 100 customer instances, average gain amount for centralized is 10.3%. For carrier $A$ average gain is 10.2% and for carrier $B$ average gain amount is 10.6%. None of the carriers suffer from collaboration. In high demand setup, average gains are higher for centralized system and both carriers. Average saving through collaboration in joint system is 13% where average gain for carrier $A$ is 11.6% and average gain for carrier $B$ is 14.3%.

Transfer amount information for 100 customer and ICC setting can be found in Table 6.51.

Table 6.51 Transfer percentages for ICC setting of 100 customer instances of PB formulation experiments

| | **Low Demand** | | | | **High Demand** | | | |
|---|---|---|---|---|---|---|---|---|
| **Ins** | **$\%TD_A$** | **$\%TD_B$** | **$\%TP_A$** | **$\%TP_B$** | **$\%TD_A$** | **$\%TD_B$** | **$\%TP_A$** | **$\%TP_B$** |
| **1** | 27.1% | 12.0% | 69.8% | 30.2% | 17.5% | 20.0% | 45.2% | 50.3% |
| **2** | 23.1% | 18.0% | 57.7% | 44.6% | 17.8% | 23.8% | 44.4% | 58.9% |
| **3** | 21.8% | 15.9% | 55.8% | 39.0% | 23.8% | 15.0% | 61.0% | 36.9% |
| **4** | 15.1% | 26.5% | 36.1% | 63.5% | 18.2% | 21.8% | 43.4% | 52.2% |
| **5** | 16.8% | 24.1% | 39.2% | 61.3% | 16.8% | 23.4% | 39.2% | 59.4% |
| **6** | 29.4% | 15.1% | 68.7% | 35.6% | 20.2% | 23.4% | 47.0% | 55.1% |
| **7** | 15.3% | 26.5% | 39.6% | 69.5% | 18.3% | 18.3% | 47.3% | 48.0% |
| **8** | 19.3% | 20.0% | 49.1% | 52.2% | 10.1% | 26.6% | 25.8% | 69.7% |
| **9** | 16.1% | 21.7% | 42.9% | 56.4% | 17.9% | 19.0% | 47.6% | 49.5% |
| **10** | 12.0% | 21.4% | 38.6% | 61.8% | 11.8% | 21.2% | 37.9% | 61.1% |
| **Avg** | 19.6% | 20.1% | 49.7% | 51.4% | 17.2% | 21.3% | 43.9% | 54.1% |

In low demand and ICC setting of 100 customer instances, carrier $A$ and carrier $B$ transfers 19.6% and 20.1% of their total demands in average, respectively. Carrier $A$ transfers 49.7% of total possible transferable amount in average. Carrier $B$ transfers 51.4% of its possible transferable amount in average. In short, carriers preferred to transfer approximately half of their shared demand with other carriers. In high demand environment, carrier $A$ and carrier $B$ transfers 17.2% and 21.3% of their total demands on average, respectively. Moreover, carrier $A$ and carrier $B$ transfers 43.9% and 54.1% of their total possible transferable demand in average, respectively.

Last set of experiments for PB formulation are conducted under NCD setting in which carriers do not have a chance to setup facilities in same location, in order to see the effect of common depot declaration on saving and transfer amounts. First, individual experiments of NCD scenario is conducted with 30 customer instances. Results can be found in Table 6.52.

Gain amounts achieved through collaboration can be found for PB Formulation

Table 6.52 Individual PB Formulation results for NCD scenario of 30 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Individual | | | Collaboration | | | Individual | | | Collaboration | | |
| Ins | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** | ***Obj*** | ***$Obj_A$*** | ***$Obj_B$*** |
| ***1*** | 64144 | 30955 | 33189 | 62373 | 30610 | 31762 | 90329 | 43764 | 46565 | 86322 | 44535 | 41787 |
| ***2*** | 72674 | 34678 | 37996 | 68354 | 31458 | 36897 | 102565 | 45504 | 57061 | 89328 | 41463 | 47866 |
| ***3*** | 70390 | 37605 | 32786 | 69004 | 36390 | 32614 | 94154 | 49138 | 45017 | 85718 | 47741 | 37977 |
| ***4*** | 57988 | 30122 | 27866 | 56480 | 28615 | 27866 | 80325 | 42479 | 37846 | 76847 | 39792 | 37055 |
| ***5*** | 65891 | 34768 | 31123 | 62815 | 33996 | 28818 | 91543 | 50978 | 40565 | 81508 | 47715 | 33794 |
| ***6*** | 68806 | 36851 | 31955 | 63365 | 35077 | 28287 | 91172 | 47993 | 43179 | 83165 | 43643 | 39522 |
| ***7*** | 68239 | 35120 | 33119 | 66503 | 32122 | 34381 | 89316 | 44992 | 44324 | 82852 | 41615 | 41237 |
| ***8*** | 63647 | 33056 | 30591 | 63489 | 32684 | 30805 | 87075 | 46628 | 40447 | 81581 | 39435 | 42146 |
| ***9*** | 71054 | 37170 | 33884 | 67429 | 34404 | 33024 | 94107 | 47745 | 46362 | 85209 | 45088 | 40121 |
| ***10*** | 69119 | 37504 | 31616 | 66736 | 35860 | 30876 | 89077 | 44556 | 44521 | 82206 | 42062 | 40143 |

results with 30 customers and NCD scenario in Table 6.53.

Table 6.53 Gain comparison for NCD scenario of 30 customer instances

| | Low Demand | | | High Demand | | |
|---|---|---|---|---|---|---|
| **Ins** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** |
| **1** | 2.8% | 1.1% | 4.3% | 4.4% | -1.8% | 10.3% |
| **2** | 5.9% | 9.3% | 2.9% | 12.9% | 8.9% | 16.1% |
| **3** | 2.0% | 3.2% | 0.5% | 9.0% | 2.8% | 15.6% |
| **4** | 2.6% | 5.0% | 0.0% | 4.3% | 6.3% | 2.1% |
| **5** | 4.7% | 2.2% | 7.4% | 11.0% | 6.4% | 16.7% |
| **6** | 7.9% | 4.8% | 11.5% | 8.8% | 9.1% | 8.5% |
| **7** | 2.5% | 8.5% | -3.8% | 7.2% | 7.5% | 7.0% |
| **8** | 0.2% | 1.1% | -0.7% | 6.3% | 15.4% | -4.2% |
| **9** | 5.1% | 7.4% | 2.5% | 9.5% | 5.6% | 13.5% |
| **10** | 3.4% | 4.4% | 2.3% | 7.7% | 5.6% | 9.8% |
| **Avg** | 3.7% | 4.7% | 2.7% | 8.1% | 6.6% | 9.5% |

In low demand environment of NCD scenario setting of 30 customer instances, average gain amount by centralized collaboration schema is 3.7%. For carriers $A$ and $B$ average gain amounts are 4.7% and 2.7%, respectively. Carrier $A$ benefited from collaboration in all instances. Carrier $B$ reported worse OFVs in two instances. Moreover, carrier $B$ reported a 0% gain for instance 4, which means that carrier $B$ was impartial for collaboration or non-collaboration. In high demand environment, average gain for collaborative schema is 8.1% which is higher than the low demand setting. For carriers $A$ and $B$ average gain amounts are 6.6% and 9.6%, respectively. Next transfer amounts are investigated for NCD setting and 30 customer instances. Results can be found in Table 6.54.

In low demand setting, carrier $A$ transfers 11.4% of its total demand in average and carrier $B$ transfers 12.2% of its total demand in average. When total possible

Table 6.54 Transfer percentages for NCD setting of 30 customer instances of PB formulation experiments

| | Low Demand | | | | High Demand | | | |
|---|---|---|---|---|---|---|---|---|
| **Ins** | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ |
| **1** | 8.1% | 12.9% | 29.1% | 57.0% | 10.4% | 15.5% | 31.1% | 55.9% |
| **2** | 9.5% | 13.3% | 39.8% | 50.2% | 8.4% | 19.8% | 33.7% | 71.1% |
| **3** | 11.0% | 21.1% | 43.9% | 75.6% | 4.3% | 24.8% | 15.4% | 84.6% |
| **4** | 13.2% | 0.0% | 46.9% | 0.0% | 12.9% | 7.1% | 58.2% | 41.8% |
| **5** | 9.9% | 10.6% | 35.0% | 39.0% | 15.6% | 14.2% | 56.2% | 43.8% |
| **6** | 12.2% | 15.4% | 48.0% | 53.2% | 10.6% | 15.2% | 39.5% | 60.5% |
| **7** | 11.2% | 12.3% | 44.1% | 42.6% | 12.6% | 13.3% | 47.1% | 52.9% |
| **8** | 12.7% | 14.3% | 37.9% | 44.5% | 14.5% | 6.6% | 58.5% | 24.6% |
| **9** | 11.3% | 12.2% | 38.0% | 50.0% | 10.5% | 13.1% | 43.2% | 56.8% |
| **10** | 14.8% | 10.1% | 56.7% | 47.3% | 9.1% | 18.8% | 35.1% | 64.9% |
| **Avg** | 11.4% | 12.2% | 41.9% | 45.9% | 10.9% | 14.8% | 41.8% | 55.7% |

transfer amounts are compared, it is observed that carrier $A$ prefers to transfer 41.9% of shared demand in average. Carrier $B$ transferred 45.9% percent of the possible transferable amount in average.

For the high demand setting, carrier $A$ transfers 10.9% of its total demand in average and carrier $B$ transfers 14.8% of its total demand in average. When total possible transfer amounts are compared, it is observed that carrier $A$ prefers to transfer 41.5% of shared demand in average. Carrier B transferred 55.7% percent of the possible transferable amount. In some cases, PB formulation can transfer up to 71.1% of the transferable amount of a carrier. However, it may also choose to only transfer 15.4% of the transferable amount is transferred to other carrier.

In order to investigate strategic aspects discussed above and to see the effect of problem size, experiments are repeated with 50 customer instances. Results of individual experiments with NCD scenario of 50 customer instances can be found in Tabla 6.55.

Table 6.55 Individual PB Formulation results for NCD scenario of 50 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Individual | | | Collaboration | | | Individual | | | Collaboration | | |
| Ins | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ |
| *1* | 98108 | 51103 | 47005 | 87908 | 43486 | 44422 | 127383 | 68869 | 58514 | 115718 | 58034 | 57685 |
| *2* | 96776 | 52645 | 44131 | 92528 | 45972 | 46557 | 134949 | 72823 | 62126 | 116431 | 54685 | 61746 |
| *3* | 87745 | 40949 | 46796 | 82109 | 41232 | 40877 | 125823 | 59783 | 66040 | 115473 | 55665 | 59808 |
| *4* | 94543 | 48953 | 45591 | 88358 | 46828 | 41530 | 124192 | 64327 | 59865 | 114511 | 61551 | 52960 |
| *5* | 99148 | 47848 | 51300 | 93751 | 45423 | 48328 | 133502 | 64852 | 68650 | 124417 | 53764 | 70653 |
| *6* | 91933 | 44378 | 47555 | 85270 | 44321 | 40949 | 117556 | 57716 | 59841 | 110843 | 57115 | 53729 |
| *7* | 92244 | 43109 | 49135 | 90827 | 43085 | 47742 | 122323 | 55541 | 66782 | 114360 | 51852 | 62509 |
| *8* | 111217 | 58671 | 52546 | 102740 | 52825 | 49914 | 134755 | 69539 | 65216 | 124894 | 72843 | 52052 |
| *9* | 98252 | 49279 | 48973 | 89349 | 40514 | 48835 | 130183 | 64601 | 65582 | 117288 | 59698 | 57590 |
| *10* | 105640 | 55298 | 50342 | 103108 | 53742 | 49366 | 134333 | 66933 | 67400 | 126785 | 67859 | 58926 |

Gain amount in which individual and collaborative scenarios of NCD setting of 50 customer instances can be found in Table 6.56.

Table 6.56 Gain comparison for NCD scenario of 50 customer instances

| | Low Demand | | | High Demand | | |
|---|---|---|---|---|---|---|
| **Ins** | ***Gain*** | $Gain_A$ | $Gain_B$ | ***Gain*** | $Gain_A$ | $Gain_B$ |
| **1** | 10.4% | 14.9% | 5.5% | 9.2% | 15.7% | 1.4% |
| **2** | 4.4% | 12.7% | -5.5% | 13.7% | 24.9% | 0.6% |
| **3** | 6.4% | -0.7% | 12.6% | 8.2% | 6.9% | 9.4% |
| **4** | 6.5% | 4.3% | 8.9% | 7.8% | 4.3% | 11.5% |
| **5** | 5.4% | 5.1% | 5.8% | 6.8% | 17.1% | -2.9% |
| **6** | 7.2% | 0.1% | 13.9% | 5.7% | 1.0% | 10.2% |
| **7** | 1.5% | 0.1% | 2.8% | 6.5% | 6.6% | 6.4% |
| **8** | 7.6% | 10.0% | 5.0% | 7.3% | -4.8% | 20.2% |
| **9** | 9.1% | 17.8% | 0.3% | 9.9% | 7.6% | 12.2% |
| **10** | 2.4% | 2.8% | 1.9% | 5.6% | -1.4% | 12.6% |
| **Avg** | 6.1% | 6.7% | 5.1% | 8.1% | 7.8% | 8.2% |

For the low demand and NCD setting of 50 customer instances, average gain amount for centralized system is 6.1%. Carrier $A$ and $B$ gains from the collaboration by 6.7% and 5.1%, respectively. Both carriers suffer from collaboration in only one instance. Maximum gain amount for carrier $A$ is 17.8% and for carrier $B$ 13.9%. For the high demand setting, average gain amount is 8.1%. Average gain for carrier $A$ is 7.8% and 8.2% for carrier $B$. Gain amounts deviate between -4.8% and 24.9% for independent carriers depending on instance.

Transfer amounts in percentages for NCD scenario of 50 customer instances can be found in Table 6.57.

Table 6.57 Transfer percentages for NCD setting of 50 customer instances of PB formulation experiments

| | Low Demand | | | | High Demand | | | |
|---|---|---|---|---|---|---|---|---|
| **Ins** | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ | $\%TD_A$ | $\%TD_B$ | $\%TP_A$ | $\%TP_B$ |
| **1** | 14.1% | 8.7% | 72.2% | 36.2% | 11.1% | 4.3% | 56.7% | 17.9% |
| **2** | 13.9% | 6.9% | 57.2% | 28.2% | 18.9% | 3.2% | 77.5% | 13.0% |
| **3** | 10.8% | 13.1% | 44.4% | 55.6% | 4.6% | 16.2% | 19.0% | 68.8% |
| **4** | 3.0% | 4.7% | 19.3% | 26.2% | 2.4% | 11.9% | 15.9% | 66.7% |
| **5** | 9.8% | 11.4% | 41.3% | 56.8% | 20.0% | 1.5% | 84.7% | 7.4% |
| **6** | 4.9% | 10.8% | 27.6% | 63.9% | 4.2% | 8.1% | 23.5% | 48.2% |
| **7** | 1.2% | 8.2% | 6.8% | 48.8% | 7.0% | 10.2% | 39.3% | 60.7% |
| **8** | 7.6% | 10.6% | 30.1% | 36.9% | 1.3% | 22.2% | 5.2% | 77.5% |
| **9** | 17.0% | 5.4% | 77.1% | 22.9% | 7.3% | 15.9% | 32.9% | 67.1% |
| **10** | 12.2% | 11.5% | 59.1% | 54.7% | 3.0% | 11.3% | 14.4% | 53.5% |
| **Avg** | 9.4% | 9.1% | 43.5% | 43.0% | 8.0% | 10.5% | 36.9% | 48.1% |

In low demand setting, carrier $A$ transfers 9.4% of its total demand in average and carrier $B$ transfers 9.1% of its total demand in average. When total possible transfer amounts are compared, it is observed that carrier $A$ prefers to transfer 43.5% of shared demand in average. Carrier B transferred 43% percent of the possible transferable amount in average.

On high demand setting, when the transfer amount is compared through total demand amounts, in average, carrier $A$ transferred 8% of its total demand and carrier B transferred 10.5% of its total demand. In average, carrier $A$ chose to transfer 36.9% of transferable amount where carrier B chose to transfer 48.1% of total transferable amount.

Last experiments are conducted with 100 customer instances. Results of individual runs of NCD scenario can be found in Table 6.58.

Table 6.58 Individual PB Formulation results for NCD scenario of 100 customer instances

| | **Low Demand** | | | | | | **High Demand** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Individual** | | | **Collaboration** | | | **Individual** | | | **Collaboration** | | |
| Ins | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ | $Obj$ | $Obj_A$ | $Obj_B$ |
| *1* | 141730 | 65537 | 76194 | 136420 | 62995 | 73425 | 197742 | 92353 | 105389 | 182381 | 84717 | 97663 |
| *2* | 139075 | 66240 | 72835 | 133221 | 62212 | 71008 | 183439 | 85872 | 97567 | 171402 | 76676 | 94726 |
| *3* | 144115 | 71444 | 72671 | 134427 | 68625 | 65802 | 191746 | 98309 | 93437 | 178360 | 90850 | 87510 |
| *4* | 140281 | 68358 | 71923 | 134611 | 66603 | 68008 | 183993 | 88281 | 95712 | 171617 | 86116 | 85501 |
| *5* | 147374 | 73295 | 74079 | 140476 | 70739 | 69737 | 196348 | 99911 | 96437 | 184627 | 89863 | 94764 |
| *6* | 138240 | 65170 | 73071 | 133781 | 63293 | 70489 | 181345 | 90101 | 91245 | 172335 | 78350 | 93985 |
| *7* | 146086 | 72181 | 73905 | 138358 | 67052 | 71305 | 181354 | 89804 | 91550 | 169075 | 82562 | 86512 |
| *8* | 147093 | 72534 | 74560 | 140567 | 64549 | 76019 | 205265 | 105431 | 99834 | 193339 | 93195 | 100144 |
| *9* | 146372 | 70927 | 75445 | 141770 | 69315 | 72455 | 177792 | 87156 | 90636 | 167551 | 80449 | 87102 |
| *10* | 148446 | 71113 | 77333 | 143327 | 67682 | 75645 | 193820 | 91883 | 101937 | 182750 | 85297 | 97453 |

Gains that are achieved through collaboration for NCD setting of 100 customer instances can be identified in Table 6.59.

Table 6.59 Gain comparison for NCD scenario of 100 customer instances

| | Low Demand | | | High Demand | | |
|---|---|---|---|---|---|---|
| **Ins** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** | ***Gain*** | ***$Gain_A$*** | ***$Gain_B$*** |
| **1** | 3.7% | 3.9% | 3.6% | 7.8% | 8.3% | 7.3% |
| **2** | 4.2% | 6.1% | 2.5% | 6.6% | 10.7% | 2.9% |
| **3** | 6.7% | 3.9% | 9.5% | 7.0% | 7.6% | 6.3% |
| **4** | 4.0% | 2.6% | 5.4% | 6.7% | 2.5% | 10.7% |
| **5** | 4.7% | 3.5% | 5.9% | 6.0% | 10.1% | 1.7% |
| **6** | 3.2% | 2.9% | 3.5% | 5.0% | 13.0% | -3.0% |
| **7** | 5.3% | 7.1% | 3.5% | 6.8% | 8.1% | 5.5% |
| **8** | 4.4% | 11.0% | -2.0% | 5.8% | 11.6% | -0.3% |
| **9** | 3.1% | 2.3% | 4.0% | 5.8% | 7.7% | 3.9% |
| **10** | 3.4% | 4.8% | 2.2% | 5.7% | 7.2% | 4.4% |
| **Avg** | 4.3% | 4.8% | 3.8% | 6.3% | 8.7% | 3.9% |

In low demand and NCD setting of 100 customer instances, average gain amount for centralized system is 4.3% where gains deviate between 3.1% and 6.7%. For carriers $A$ and $B$, average gain percentages are 4.8 and 3.8, respectively. Only one instance of carrier $B$ reported a loss. In high demand setting, for collaborative system, average gain amount is 6.3%. Carrier $A$ and $B$ have an average gain of 8.7% and 3.9%, respectively. Maximum gain amount in collaborative system is 7.8%. Again, in high demand setting, gain average is higher than the low demand environment.

Transfer amounts in percentages for NCD scenario of 100 customer instances can be found in Table 6.60.

Table 6.60 Transfer percentages for NCD setting of 100 customer instances of PB formulation experiments

| | Low Demand | | | | High Demand | | | |
|---|---|---|---|---|---|---|---|---|
| **Ins** | ***$\%TD_A$*** | ***$\%TD_B$*** | ***$\%TP_A$*** | ***$\%TP_B$*** | ***$\%TD_A$*** | ***$\%TD_B$*** | ***$\%TP_A$*** | ***$\%TP_B$*** |
| **1** | 8.3% | 6.4% | 46.7% | 38.9% | 8.0% | 8.3% | 44.6% | 49.9% |
| **2** | 12.0% | 10.7% | 58.6% | 48.6% | 13.2% | 7.1% | 64.6% | 32.1% |
| **3** | 5.9% | 9.1% | 32.8% | 53.1% | 10.9% | 5.4% | 60.9% | 31.6% |
| **4** | 9.7% | 9.0% | 46.4% | 41.7% | 4.7% | 13.0% | 22.8% | 60.0% |
| **5** | 8.5% | 7.5% | 43.7% | 40.0% | 13.5% | 7.1% | 69.7% | 37.7% |
| **6** | 8.8% | 9.3% | 43.8% | 46.5% | 8.9% | 4.8% | 44.1% | 24.1% |
| **7** | 7.3% | 7.1% | 39.7% | 37.5% | 7.0% | 7.3% | 38.0% | 38.6% |
| **8** | 12.9% | 4.8% | 69.1% | 24.7% | 12.3% | 4.9% | 66.3% | 25.0% |
| **9** | 9.4% | 6.0% | 46.3% | 31.2% | 10.1% | 8.6% | 49.6% | 44.7% |
| **10** | 12.4% | 7.9% | 54.3% | 37.8% | 11.4% | 11.4% | 50.0% | 54.2% |
| **Avg** | 9.5% | 7.8% | 48.1% | 40.0% | 10.0% | 7.8% | 51.0% | 39.8% |

In low demand setting, carrier $A$ transfers 9.5% of its total demand in average and carrier $B$ transfers 7.8% of its total demand in average. When total possible transfer amounts are compared, it is observed that carrier $A$ prefers to transfer 48.1% of shared demand in average. Carrier $B$ transferred 40% of the possible transferable amount in average.

On high demand setting, when the transfer amount is compared through total demand amounts, in average, carrier $A$ transferred 10% of its total demand and carrier $B$ transferred 7.8% of its total demand. In average, carrier $A$ chose to transfer 51% of transferable amount where carrier $B$ chose to transfer 39.8% of total transferable amount. It is observed that, in some instances carriers chose to transfer up to 69.7% of transferable amount.

Table 6.61 Summary of gain averages

| | **Low Demand** | | | **High Demand** | | |
|---|---|---|---|---|---|---|
| | **30** | **50** | **100** | **30** | **50** | **100** |
| ***O*** | 6.7% | 5.9% | 5.7% | 8.0% | 7.0% | 7.0% |
| ***ICC*** | 12.1% | 10.4% | 10.3% | 15.5% | 14.1% | 13.0% |
| ***NCD*** | 3.7% | 6.1% | 4.3% | 8.1% | 8.1% | 6.3% |

Overall, when the Table 6.61 examined, it can be concluded that collaborative schema yield gains. Minimum average gain amount is 3.7% in NCD and low demand setting of 30 customer instances. On the other hand, collaboration resulted with 15.5% gains in average for ICC and high demand setting of 30 customer instances. Under all scenario types of all problem sizes, collaboration reported higher savings in high demand environments. Moreover, ICC scenario is always reported a higher gain percentage in average for all experiments.

# 7. CONCLUSION

We study a two echelon strategic network design problem in which more than two firms (or carriers) simultaneously make decisions to collaborate in their distribution activities under a centralized schema. While there is no collaboration opportunity at the upper echelon transportation, firms can collaborate at the lower echelon and a firm can deliver the demand of a common customer for both itself and the other carrier(s). Three different mixed-integer linear programming models are proposed. Two of these models provide exact solutions to the problem whereas third model relies on a restricted solution space. The objective is to minimize the total cost arising from opening and operating regional depots, constructing transfer lines between depots and establishing both inbound and outbound routes.

Proposed MILP models differ in terms of modelling the decisions on outbound transportation, i.e., routing operations. In the VB model, outbound transportation decision modelling is derived from the traditional CVRP formulations and routing decisions are controlled over vehicles. In the LB model, outbound routing decisions are represented through load amounts carried on arcs. Both VB and LB formulations yield an exact solution to the problem. In the PB model, routes are selected from heuristically pre-generated route pool which does not necessarily include all theoretically possible routes.

To solve the proposed models various methods are used. A cut generation approach is utilized to control exponentially many sub-tour elimination constraints in the VB formulation. Several valid inequalities are proposed for all three formulations. In the PB model, a route pool is generated through well known five different heuristics to create diversity among routes in an iterative approach to mimic collaborative behaviour. In order to test effects of solution techniques and valid inequalities, models are tested under different collaboration scenarios and demand density for different problem sizes.

From a methodological point of view, results showed that the VB formulation has a high space and time complexity. Proposed cut generation method solves the space complexity problem and decreases solution times. Despite the decreased time complexity, the LB formulation still outperforms the VB formulation. The LB formulation is strengthened with valid inequalities; two of the proposed valid inequalities for the LB formulation successfully decrease the optimality gaps within limited solution time. Even tough the LB formulation was able to solve instances, solution times were still high and some gaps are reported. The PB formulation was able to solve all instances of all problem sizes to optimality. Deviations of the PB formulation solutions from the best bounds of LB formulation solutions vary between 3.9% and 19.4%. In some cases, the PB formulation yield better solutions than LB formulation within given time limits, when best solutions are compared.

From a managerial point of view, proposed collaborative scheme definitely reduces total distribution and facility costs. Depending on different parameters such as the number of candidate depot locations, common customers, problem size and customer distribution, the cost saving differ. When different scenarios are compared to identify the effect above parameters on collaboration, ICC setting yield more savings than the original setting on average. Hence, the savings due to collaboration increase as the number of common customers in the system increases. Higher demand density leads to higher gains on average when compared to low density. We emphasize that the proposed models aim to minimize total cost of a centralized system. In only few instances, individual carriers report worse outcomes in exchange of better integrated system outcomes.

In the future studies, this problem can be considered in a multi-period setting. Alternative exact solution methods can be implemented in order to solve larger instances to optimality. For the PB formulation, the route pool generation can be extended with other heuristic algorithms or meta-heuristic algorithms to create high quality routes in order to reduce deviation from the true optimal solutions. Moreover, other scenario types can be created such as clustered customers or high density customer regions to investigate the effect of geographical distribution of customers. Another challenging extension may be the increasing number of echelons in which parties can collaborate. The potential gains and collaboration behaviour can be tested with more than two carriers to study the effect of number of carriers in the system.

# BIBLIOGRAPHY

Aloui, A., Derrouiche, R., Hamani, N., & Delahoche, L. (2020). Collaboration horizontale durable des réseaux de transport de marchandises : état de l'art et perspectives.

Aloui, A., Hamani, N., Derrouiche, R., & Delahoche, L. (2021). Systematic literature review on collaborative sustainable transportation: overview, analysis and perspectives. *Transportation Research Interdisciplinary Perspectives*, *9*, 100291.

Archetti, C., Fernández, E., & Huerta-Muñoz, D. L. (2017). The flexible periodic vehicle routing problem. *Computers & Operations Research*, *85*, 58–70.

Barratt, M. (2004). Understanding the meaning of collaboration in the supply chain. *Supply Chain Management: An International Journal*, *9*(1), 30–42.

Berger, S. & Bierwirth, C. (2010). Solutions to the request reassignment problem in collaborative carrier networks. *Transportation Research Part E: Logistics and Transportation Review*, *46*(5), 627–638.

Boccia, M., Crainic, T. G., Sforza, A., & Sterle, C. (2010). A metaheuristic for a two echelon location-routing problem. In Festa, P. (Ed.), *Experimental Algorithms*, (pp. 288–301)., Berlin, Heidelberg. Springer Berlin Heidelberg.

Boccia, M., Crainic, T. G., Sforza, A., & Sterle, C. (2011). Location-routing models for designing a two-echelon freight distribution system.

Chabot, T., Bouchard, F., Legault-Michaud, A., Renaud, J., & Coelho, L. C. (2018). Service level, cost and environmental optimization of collaborative transportation. *Transportation Research Part E: Logistics and Transportation Review*, *110*, 1–14.

Christofides, N., Mingozzi, A., & P.Toth (1979). The vehicle routing problem, combinatorial optimization. (pp. 315–338). Wiley.

Clarke, G. & Wright, J. W. (1964). Scheduling of vehicles from a central depot to a number of delivery points. *Operations Research*, *12*(4), 568–581.

Cleophas, C., Cottrill, C., Ehmke, J. F., & Tierney, K. (2019). Collaborative urban transportation: Recent advances in theory and practice. *European Journal of Operational Research*, *273*(3), 801–816.

Contardo, C., Hemmelmayr, V., & Crainic, T. G. (2012). Lower and upper bounds for the two-echelon capacitated location-routing problem. *Computers & Operations Research*, *39*(12), 3185–3199.

Cuda, R., Guastaroba, G., & Speranza, M. (2015). A survey on two-echelon routing problems. *Computers & Operations Research*, *55*, 185–199.

Defryn, C., Sörensen, K., & Dullaert, W. (2019). Integrating partner objectives in horizontal logistics optimisation models. *Omega*, *82*, 1–12.

Ercan, H. (2019). On modeling the single period spare parts distribution system design problem by mixed integer linear optimization. Master's thesis.

Fernández, E., Roca-Riu, M., & Speranza, M. G. (2018). The shared customer collaboration vehicle routing problem. *European Journal of Operational Research*, *265*(3), 1078–1093.

Fernández, E. & Sgalambro, A. (2020). On carriers collaboration in hub location problems. *European Journal of Operational Research*, *283*(2), 476–490.

Gaskell, T. J. (1967). Bases for vehicle fleet scheduling. *Journal of the Operational Research Society*, *18*(3), 281–295.

Gillett, B. E. & Miller, L. R. (1974). A heuristic algorithm for the vehicle-dispatch problem. *Oper. Res.*, *22*(2), 340–349.

Gonzalez-Feliu, J. & Salanova, J.-M. (2012). Defining and evaluating collaborative urban freight transportation systems. *Procedia - Social and Behavioral Sciences*, *39*, 172–183. Seventh International Conference on City Logistics which was held on June 7- 9,2011, Mallorca, Spain.

Hernández, S. & Peeta, S. (2011). Centralized time-dependent multiple-carrier collaboration problem for less-than-truckload carriers. *Transportation Research Record: Journal of the Transportation Research Board*, *2263*(1), 26–34.

Hernández, S., Unnikrishnan, A., & Awale, S. S. (2012). Centralized carrier collaboration multihub location problem for less-than-truckload industry. *Transportation Research Record: Journal of the Transportation Research Board*, *2269*(1), 20–28.

Jacobsen, S. & Madsen, O. (1980). A comparative study of heuristics for a two-level routing-location problem. *European Journal of Operational Research*, *5*(6), 378–387.

Johnson, D. B. (1975). Finding all the elementary circuits of a directed graph. *SIAM Journal on Computing*, *4*(1), 77–84.

Klibi, W., Martel, A., & Guitouni, A. (2016). The impact of operations anticipations on the quality of stochastic location-allocation models. *Omega*, *62*(C), 19–33.

Lin, C. (2008). A cooperative strategy for a vehicle routing problem with pickup and delivery time windows. *Computers & Industrial Engineering*, *55*(4), 766–782.

Marinakis, Y. (2009). *Location routing problemLocation Routing Problem*, (pp. 1919–1925). Boston, MA: Springer US.

Ouhader, H. & Kyal, M. E. (2017). Combining facility location and routing decisions in sustainable urban freight distribution under horizontal collaboration: How can shippers be benefited? *Mathematical Problems in Engineering*, *2017*, 1–

18.

Özener, O. O., Ergun, O., & Savelsbergh, M. (2011). Lane-exchange mechanisms for truckload carrier collaboration. *Transportation Science*, *45*(1), 1–17.

Pan, S., Ballot, E., & Fontane, F. (2013). The reduction of greenhouse gas emissions from freight transport by pooling supply chains. *International Journal of Production Economics*, *143*(1), 86–94.

Pan, S., Trentesaux, D., Ballot, E., & Huang, G. Q. (2019). Horizontal collaborative transport: survey of solutions and practical implementation issues. *International Journal of Production Research*, *57*(15-16), 5340–5361.

Prodhon, C. & Prins, C. (2014). A survey of recent research on location-routing problems. *European Journal of Operational Research*, *238*(1), 1–17.

Rao, C., Goh, M., Zhao, Y., & Zheng, J. (2015). Location selection of city logistics centers under sustainability. *Transportation Research Part D: Transport and Environment*, *36*, 29–44.

Saenz, M. J., Ubaghs, E., & Cuevas, A. I. (2014). Vertical collaboration and horizontal collaboration in supply chain. In *Enabling Horizontal Collaboration Through Continuous Relational Learning* (pp. 7–10). Springer International Publishing.

Salhi, S. & Rand, G. K. (1989). The effect of ignoring routes when locating depots. *European Journal of Operational Research*, *39*(2), 150–156.

Schwengerer, M., Pirkwieser, S., & Raidl, G. R. (2012). A variable neighborhood search approach for the two-echelon location-routing problem. In Hao, J.-K. & Middendorf, M. (Eds.), *Evolutionary Computation in Combinatorial Optimization*, (pp. 13–24)., Berlin, Heidelberg. Springer Berlin Heidelberg.

Simatupang, T. M. & Sridharan, R. (2002). The collaborative supply chain. *The International Journal of Logistics Management*, *13*(1), 15–30.

Soysal, M., Bloemhof-Ruwaard, J. M., Haijema, R., & Vorst, J. G. (2018). Modeling a green inventory routing problem for perishable products with horizontal collaboration. *Computers & Operations Research*, *89*, 168–182.

Sprenger, R. & Mönch, L. (2014). A decision support system for cooperative transportation planning: Design, implementation, and performance assessment. *Expert Systems with Applications*, *41*(11), 5125–5138.

Tang, X., Lehuédé, F., & Péton, O. (2016). Location of distribution centers in a multi-period collaborative distribution network. *Electronic Notes in Discrete Mathematics*, *52*, 293–300.

Toth, P. & Vigo, D. (2014). *Vehicle routing: problems, methods, and applications.* SIAM.

Tyagi, M. S. (1968). A practical method for truck despatching problem.

Verdonck, L., Beullens, P., Caris, A., Ramaekers, K., & Janssens, G. K. (2016).

Analysis of collaborative savings and cost allocation techniques for the cooperative carrier facility location problem. *Journal of the Operational Research Society*, *67*(6), 853–871.

Verdonck, L., Caris, A., Ramaekers, K., & Janssens, G. K. (2013). Collaborative logistics from the perspective of road transportation companies. *Transport Reviews*, *33*(6), 700–719.

Wang, Y., Zhang, S., Guan, X., Peng, S., Wang, H., Liu, Y., & Xu, M. (2020). Collaborative multi-depot logistics network design with time window assignment. *Expert Systems with Applications*, *140*, 112910.

Weng, K. & Xu, Z. (2014). Flow merging and hub route optimization in collaborative transportation. *Journal of Applied Mathematics*, *2014*, 1–8.

Wu, L.-Y., Zhang, X.-S., & Zhang, J.-L. (2006). Capacitated facility location problem with general setup cost. *Computers & Operations Research*, *33*(5), 1226–1241.

# APPENDIX A

## Individual Load-Based Formulation

$$\text{minimize} \quad \sum_{d\in D}\sum_{(i,j)\in A^d} c_{ij}x_{ij}^d + \sum_{d\in D} B_d y_d + \sum_{d\in D}\sum_{p\in P} \Delta_{pd}\delta_{pd}$$

subject to

(A.1) $$\sum_{d\in D} z_{id} = 1 \qquad \forall i\in N$$

(A.2) $$\sum_{\substack{j\in N\cup\{d\}\\ i\neq j}} x_{j,i}^d - \sum_{\substack{j\in N\cup\{d\}\\ i\neq j}} x_{i,j}^d = 0 \qquad \forall d\in D, i\in N$$

(A.3) $$\sum_{\substack{j\in N\cup\{d\}\\ i\neq j}} x_{i,j}^d \geq z_{id} \qquad \forall i\in N, d\in D$$

(A.4) $$\sum_{j\in N} l_{d,j}^{dh} = d_h z_{hd} \qquad \forall d\in D, h\in N$$

(A.5) $$\sum_{\substack{j\in N\cup\{d\}\\ i\neq j}} l_{i,j}^{dh} - \sum_{\substack{j\in N\cup\{d\}\\ i\neq j}} l_{j,i}^{dh} = \begin{cases} -d_i z_{id} & \text{if } i=h \\ 0 & \text{if } i\neq h \end{cases} \qquad \forall d\in D, i,h\in N$$

(A.6) $$\sum_{h\in N} l_{i,j}^{dh} \leq Q x_{i,j}^d \qquad \forall d\in D, (i,j)\in A^d$$

(A.7) $$M * y_d \geq \sum_{i\in N} z_{id} \qquad \forall d\in D$$

(A.8) $$M * \delta_{pd} \geq u_{pd} \qquad \forall p\in P, d\in D$$

(A.9) $$u_{pd} = \sum_{i\in N} d_i z_{id} \qquad \forall d\in D, p\in P$$

(A.10) $$x_{ij}^d \in \{0,1\} \qquad \forall d\in D, (i,j)\in A^d$$

(A.11) $$z_{id} \in \{0,1\} \qquad \forall i\in N, d\in D$$

(A.12) $$l_{ij}^{dh} \in \mathbb{R}_+ \qquad \forall d\in D, (i,j)\in A^d, h\in N$$

(A.13) $$y_d \in \{0,1\} \qquad \forall d\in D$$

(A.14) $$\delta_{pd} \in \{0,1\} \qquad \forall p\in P, d\in D$$

(A.15) $$u_{pd} \in \mathbb{R}_+ \qquad \forall p\in P, d\in D$$

## Load-Based Formulation Results of 50 Customer Instances

Table A.1 LB results for original and low demand setting of 50 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***I1*** | 2 | 2 | 2 | 1 | 88184 | 43681 | 44503 | 11.4% | 57262 | 17069 | 147 | 13706 |
| ***I2*** | 1 | 1 | 1 | 1 | 82885 | 40724 | 42160 | 10.6% | 66884 | 9142 | 495 | 6364 |
| ***I3*** | 1 | 1 | 1 | 1 | 81902 | 41326 | 40576 | 13.7% | 68410 | 9142 | 269 | 4081 |
| ***I4*** | 2 | 1 | 1 | 2 | 85243 | 46276 | 38968 | 11.3% | 64079 | 11965 | 592 | 8607 |
| ***I5*** | 2 | 1 | 1 | 2 | 84943 | 46791 | 38153 | 10.6% | 66288 | 11894 | 370 | 6392 |
| ***I6*** | 1 | 1 | 1 | 1 | 80984 | 37730 | 43254 | 10.2% | 70297 | 8590 | 181 | 1916 |
| ***I7*** | 1 | 1 | 1 | 1 | 85120 | 43158 | 41962 | 11.4% | 74443 | 8032 | 223 | 2422 |
| ***I8*** | 2 | 2 | 2 | 2 | 98903 | 48413 | 50490 | 12.5% | 66231 | 15937 | 542 | 16193 |
| ***I9*** | 2 | 2 | 1 | 2 | 87599 | 47299 | 40300 | 14.4% | 59222 | 15292 | 104 | 12981 |
| ***I10*** | 2 | 2 | 2 | 1 | 99984 | 48377 | 51606 | 12.5% | 70284 | 17296 | 573 | 11831 |

Table A.2 LB results for original and high demand setting of 50 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***I1*** | 3 | 2 | 2 | 2 | 110932 | 55205 | 55727 | 9.5% | 70267 | 22175 | 560 | 17930 |
| ***I2*** | 2 | 2 | 2 | 1 | 115871 | 59294 | 56577 | 9.2% | 81104 | 19656 | 687 | 14424 |
| ***I3*** | 2 | 2 | 2 | 2 | 114703 | 55808 | 58894 | 12.0% | 84515 | 18822 | 536 | 10830 |
| ***I4*** | 2 | 3 | 1 | 2 | 113653 | 58611 | 55042 | 10.9% | 75897 | 20618 | 531 | 16607 |
| ***I5*** | 3 | 3 | 2 | 2 | 120797 | 55977 | 64820 | 11.5% | 77812 | 24735 | 640 | 17610 |
| ***I6*** | 3 | 3 | 2 | 3 | 114799 | 57141 | 57658 | 10.0% | 72813 | 21911 | 278 | 19797 |
| ***I7*** | 2 | 2 | 2 | 2 | 116067 | 48423 | 67644 | 10.8% | 86285 | 17008 | 603 | 12171 |
| ***I8*** | 3 | 3 | 3 | 2 | 130314 | 65564 | 64750 | 9.0% | 78841 | 24953 | 663 | 25857 |
| ***I9*** | 3 | 2 | 2 | 3 | 111563 | 59156 | 52407 | 10.4% | 75186 | 18939 | 323 | 17115 |
| ***I10*** | 3 | 3 | 3 | 2 | 134369 | 63328 | 71040 | 11.8% | 84999 | 25249 | 607 | 23514 |

Table A.3 LB results for ICC and low demand setting of 50 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***I1*** | 2 | 2 | 2 | 2 | 83263 | 41867 | 41396 | 11.2% | 52860 | 16216 | 703 | 13485 |
| ***I2*** | 1 | 1 | 1 | 1 | 84433 | 41961 | 42471 | 11.5% | 67339 | 10235 | 495 | 6364 |
| ***I3*** | 1 | 2 | 2 | 1 | 82198 | 35679 | 46519 | 18.2% | 64278 | 12164 | 222 | 5534 |
| ***I4*** | 2 | 1 | 1 | 2 | 81117 | 49619 | 31497 | 11.0% | 59086 | 12832 | 592 | 8607 |
| ***I5*** | 2 | 1 | 1 | 2 | 83847 | 45578 | 38269 | 10.2% | 64714 | 12372 | 370 | 6392 |
| ***I6*** | 1 | 1 | 1 | 1 | 79798 | 38442 | 41355 | 11.0% | 68859 | 8842 | 181 | 1916 |
| ***I7*** | 1 | 1 | 1 | 1 | 82583 | 39797 | 42785 | 10.8% | 70972 | 8966 | 223 | 2422 |
| ***I8*** | 3 | 1 | 1 | 3 | 93621 | 54920 | 38701 | 11.8% | 63875 | 14393 | 766 | 14587 |
| ***I9*** | 1 | 1 | 1 | 1 | 83780 | 39010 | 44770 | 13.4% | 67720 | 8790 | 650 | 6620 |
| ***I10*** | 2 | 1 | 1 | 2 | 98063 | 43747 | 54315 | 15.0% | 73757 | 14836 | 646 | 8824 |

Table A.4 LB results for ICC and high demand setting of 50 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***I1*** | 3 | 2 | 2 | 3 | 103423 | 53195 | 50227 | 8.9% | 64683 | 20202 | 739 | 17799 |
| ***I2*** | 3 | 2 | 2 | 3 | 113615 | 62804 | 50811 | 10.7% | 71466 | 21427 | 929 | 19794 |
| ***I3*** | 2 | 2 | 2 | 2 | 109297 | 57032 | 52265 | 12.2% | 80498 | 17668 | 532 | 10600 |
| ***I4*** | 2 | 2 | 2 | 2 | 109488 | 60968 | 48521 | 11.8% | 79361 | 16999 | 701 | 12427 |
| ***I5*** | 3 | 2 | 2 | 3 | 114577 | 52765 | 61812 | 9.9% | 75571 | 19514 | 1016 | 18477 |
| ***I6*** | 2 | 3 | 3 | 2 | 114308 | 50232 | 64077 | 12.6% | 77635 | 20700 | 588 | 15386 |
| ***I7*** | 3 | 3 | 2 | 3 | 120707 | 57080 | 63627 | 13.9% | 70266 | 28570 | 750 | 21121 |
| ***I8*** | 3 | 3 | 3 | 3 | 126826 | 64419 | 62407 | 12.7% | 78250 | 24822 | 917 | 22837 |
| ***I9*** | 3 | 2 | 2 | 3 | 105980 | 50572 | 55407 | 9.7% | 66916 | 19479 | 662 | 18923 |
| ***I10*** | 3 | 2 | 2 | 3 | 126826 | 65516 | 61310 | 11.5% | 82696 | 22071 | 1052 | 21007 |

Table A.5 LB results for NCD and low demand setting of 50 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***I1*** | 2 | 2 | 2 | 2 | 87427 | 45364 | 42063 | 11.1% | 56084 | 17461 | 364 | 13518 |
| ***I2*** | 2 | 1 | 1 | 1 | 87903 | 45916 | 41987 | 10.4% | 64789 | 11801 | 387 | 10926 |
| ***I3*** | 1 | 1 | 1 | 1 | 77400 | 39223 | 38176 | 12.8% | 64896 | 8154 | 269 | 4081 |
| ***I4*** | 2 | 1 | 1 | 2 | 84967 | 47538 | 37429 | 11.4% | 64909 | 12686 | 481 | 6891 |
| ***I5*** | 1 | 1 | 1 | 1 | 88593 | 43364 | 45229 | 9.6% | 76604 | 9307 | 201 | 2481 |
| ***I6*** | 1 | 1 | 1 | 1 | 81844 | 44080 | 37764 | 9.5% | 70708 | 9039 | 181 | 1916 |
| ***I7*** | 1 | 1 | 1 | 1 | 86221 | 41223 | 44998 | 12.0% | 74270 | 9307 | 223 | 2422 |
| ***I8*** | 2 | 2 | 2 | 2 | 100115 | 54480 | 45634 | 13.1% | 67175 | 18373 | 392 | 14175 |
| ***I9*** | 1 | 1 | 1 | 1 | 85280 | 40300 | 44980 | 12.2% | 69591 | 8830 | 543 | 6316 |
| ***I10*** | 2 | 1 | 1 | 2 | 96735 | 49987 | 46748 | 11.5% | 75160 | 11174 | 569 | 9832 |

Table A.6 LB results for NCD and high demand setting of 50 customer instances

| ***Ins.*** | $F_A$ | $F_B$ | $T_A$ | $T_B$ | ***Obj*** | $Obj_A$ | $Obj_B$ | ***Gap*** | ***RC*** | ***FC*** | ***TC*** | ***IC*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***I1*** | 3 | 2 | 2 | 2 | 111195 | 61098 | 50097 | 8.9% | 70763 | 21636 | 773 | 18023 |
| ***I2*** | 2 | 3 | 3 | 1 | 113047 | 53338 | 59709 | 9.3% | 72597 | 20319 | 831 | 19300 |
| ***I3*** | 2 | 2 | 1 | 2 | 109629 | 59971 | 49658 | 10.6% | 81236 | 16217 | 243 | 11933 |
| ***I4*** | 2 | 3 | 2 | 2 | 117987 | 61623 | 56364 | 12.4% | 80664 | 19888 | 479 | 16956 |
| ***I5*** | 2 | 3 | 3 | 2 | 131831 | 59639 | 72192 | 12.2% | 90509 | 23261 | 545 | 17516 |
| ***I6*** | 3 | 3 | 2 | 2 | 115120 | 56138 | 58982 | 9.7% | 71608 | 22928 | 565 | 20019 |
| ***I7*** | 2 | 2 | 2 | 2 | 119526 | 57679 | 61846 | 12.5% | 89761 | 15878 | 682 | 13204 |
| ***I8*** | 3 | 3 | 2 | 3 | 129326 | 72178 | 57148 | 11.0% | 76910 | 25997 | 564 | 25856 |
| ***I9*** | 2 | 3 | 3 | 1 | 115069 | 53155 | 61914 | 11.9% | 76101 | 20515 | 675 | 17778 |
| ***I10*** | 3 | 2 | 2 | 2 | 132982 | 68391 | 64591 | 12.3% | 90346 | 20603 | 872 | 21161 |

## Instance Data

Column explanations as follows; $N$ indicates the number of customers in the instance where $N_A$, $N_B$ and $N_C$ depict number of customers for carrier $A$, carrier $B$ and number of common customers, respectively. $d_A$ and $d_B$ indicate the demand of carriers $A$ and $B$, respectively. $d_A^S$ and $d_B^S$ depict the shared amount of demand for carriers $A$ and $B$. $d^T$ is the total demand.

Table A.7 Original scenario data for 30 customer instances

| | | | | | Low Demand | | | | | High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ins** | $N$ | $N_A$ | $N_B$ | $N_C$ | $d_A$ | $d_A^C$ | $d_B$ | $d_B^C$ | $d_T$ | $d_A$ | $d_A^C$ | $d_B$ | $d_B^C$ | $d_T$ |
| **1** | 30 | 19 | 19 | 8 | 3148 | 880 | 3895 | 880 | 7043 | 6297 | 1760 | 7790 | 1760 | 14087 |
| **2** | 30 | 19 | 19 | 8 | 3845 | 914 | 3458 | 914 | 7303 | 7690 | 1827 | 6917 | 1827 | 14607 |
| **3** | 30 | 19 | 19 | 8 | 3860 | 965 | 3460 | 965 | 7320 | 7720 | 1930 | 6920 | 1930 | 14640 |
| **4** | 30 | 19 | 19 | 8 | 2615 | 734 | 3889 | 734 | 6504 | 5230 | 1467 | 7778 | 1467 | 13008 |
| **5** | 30 | 19 | 19 | 8 | 3544 | 1007 | 3711 | 1007 | 7255 | 7089 | 2015 | 7421 | 2015 | 14510 |
| **6** | 30 | 19 | 19 | 8 | 3740 | 950 | 3281 | 950 | 7020 | 7480 | 1900 | 6561 | 1900 | 14041 |
| **7** | 30 | 19 | 19 | 8 | 3740 | 950 | 3281 | 950 | 7020 | 7480 | 1900 | 6561 | 1900 | 14041 |
| **8** | 30 | 19 | 19 | 8 | 3000 | 1004 | 3132 | 1004 | 6132 | 6000 | 2008 | 6264 | 2008 | 12263 |
| **9** | 30 | 19 | 19 | 8 | 3104 | 921 | 3764 | 921 | 6868 | 6208 | 1843 | 7529 | 1843 | 13737 |
| **10** | 30 | 19 | 19 | 8 | 3139 | 817 | 3834 | 817 | 6974 | 6279 | 1635 | 7669 | 1635 | 13947 |

Table A.8 Original scenario data for 50 customer instances

| | | | | | Low Demand | | | | | High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ins** | $N$ | $N_A$ | $N_B$ | $N_C$ | $d_A$ | $d_A^C$ | $d_B$ | $d_B^C$ | $d_T$ | $d_A$ | $d_A^C$ | $d_B$ | $d_B^C$ | $d_T$ |
| **1** | 50 | 30 | 30 | 10 | 5527 | 732 | 5465 | 732 | 10992 | 11054 | 1465 | 10930 | 1465 | 21985 |
| **2** | 50 | 30 | 30 | 10 | 6271 | 1303 | 6011 | 1303 | 12283 | 12543 | 2605 | 12023 | 2605 | 24566 |
| **3** | 50 | 30 | 30 | 10 | 5759 | 1231 | 5559 | 1231 | 11318 | 11517 | 2462 | 11118 | 2462 | 22635 |
| **4** | 50 | 30 | 30 | 10 | 6002 | 1276 | 6243 | 1276 | 12245 | 12004 | 2551 | 12486 | 2551 | 24490 |
| **5** | 50 | 30 | 30 | 10 | 5894 | 1243 | 6336 | 1243 | 12230 | 11789 | 2485 | 12671 | 2485 | 24460 |
| **6** | 50 | 30 | 30 | 10 | 5550 | 1105 | 6192 | 1105 | 11742 | 11101 | 2211 | 12384 | 2211 | 23485 |
| **7** | 50 | 30 | 30 | 10 | 5550 | 1105 | 6192 | 1105 | 11742 | 11101 | 2211 | 12384 | 2211 | 23485 |
| **8** | 50 | 30 | 30 | 10 | 6500 | 1080 | 6046 | 1080 | 12547 | 13000 | 2161 | 12093 | 2161 | 25093 |
| **9** | 50 | 30 | 30 | 10 | 5342 | 1206 | 5737 | 1206 | 11078 | 10683 | 2413 | 11473 | 2413 | 22157 |
| **10** | 50 | 30 | 30 | 10 | 5894 | 1280 | 5978 | 1280 | 11872 | 11789 | 2559 | 11955 | 2559 | 23744 |

Table A.9 Original scenario data for 100 customer instances

| | | | | | Low Demand | | | | | High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ins** | $N$ | $N_A$ | $N_B$ | $N_C$ | $d_A$ | $d_A^C$ | $d_B$ | $d_B^C$ | $d_T$ | $d_A$ | $d_A^C$ | $d_B$ | $d_B^C$ | $d_T$ |
| **1** | 100 | 60 | 60 | 20 | 11821 | 2357 | 11166 | 2357 | 22987 | 23642 | 4713 | 22331 | 4713 | 45973 |
| **2** | 100 | 60 | 60 | 20 | 11664 | 2425 | 11947 | 2425 | 23611 | 23328 | 4851 | 23895 | 4851 | 47223 |
| **3** | 100 | 60 | 60 | 20 | 11143 | 2234 | 10647 | 2234 | 21791 | 22287 | 4468 | 21295 | 4468 | 43581 |
| **4** | 100 | 60 | 60 | 20 | 11215 | 2475 | 10711 | 2475 | 21926 | 22429 | 4949 | 21422 | 4949 | 43852 |
| **5** | 100 | 60 | 60 | 20 | 10953 | 2426 | 11688 | 2426 | 22642 | 21906 | 4852 | 23377 | 4852 | 45283 |
| **6** | 100 | 60 | 60 | 20 | 11775 | 2705 | 11415 | 2705 | 23191 | 23550 | 5410 | 22831 | 5410 | 46381 |
| **7** | 100 | 60 | 60 | 20 | 11835 | 2587 | 11987 | 2587 | 23822 | 23670 | 5174 | 23974 | 5174 | 47644 |
| **8** | 100 | 60 | 60 | 20 | 11611 | 2516 | 11980 | 2516 | 23591 | 23222 | 5032 | 23959 | 5032 | 47182 |
| **9** | 100 | 60 | 60 | 20 | 11970 | 2292 | 11297 | 2292 | 23267 | 23940 | 4583 | 22594 | 4583 | 46534 |
| **10** | 100 | 60 | 60 | 20 | 12220 | 2047 | 11476 | 2047 | 23696 | 24440 | 4093 | 22953 | 4093 | 47393 |

Table A.10 ICC scenario data for 30 customer instances

| | | | | | Low Demand | | | | | High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ins** | $N$ | $N_A$ | $N_B$ | $N_S$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ |
| **1** | 30 | 22 | 22 | 14 | 3292 | 1540 | 3751 | 1540 | 7043 | 6584 | 3079 | 7502 | 3079 | 14087 |
| **2** | 30 | 22 | 22 | 14 | 3779 | 1818 | 3524 | 1818 | 7303 | 7558 | 3636 | 7049 | 3636 | 14606 |
| **3** | 30 | 22 | 22 | 14 | 3687 | 1470 | 3633 | 1470 | 7320 | 7373 | 2941 | 7267 | 2941 | 14640 |
| **4** | 30 | 22 | 22 | 14 | 2796 | 1308 | 3708 | 1308 | 6504 | 5591 | 2617 | 7417 | 2617 | 13008 |
| **5** | 30 | 22 | 22 | 14 | 3617 | 1541 | 3639 | 1541 | 7255 | 7233 | 3082 | 7277 | 3082 | 14510 |
| **6** | 30 | 22 | 22 | 14 | 3758 | 1623 | 3263 | 1623 | 7020 | 7515 | 3246 | 6525 | 3246 | 14041 |
| **7** | 30 | 22 | 22 | 14 | 3758 | 1623 | 3263 | 1623 | 7020 | 7515 | 3246 | 6525 | 3246 | 14041 |
| **8** | 30 | 22 | 22 | 14 | 3114 | 1647 | 3018 | 1647 | 6132 | 6227 | 3294 | 6036 | 3294 | 12263 |
| **9** | 30 | 22 | 22 | 14 | 3170 | 1730 | 3698 | 1730 | 6868 | 6341 | 3461 | 7396 | 3461 | 13737 |
| **10** | 30 | 22 | 22 | 14 | 3150 | 1535 | 3823 | 1535 | 6974 | 6301 | 3071 | 7646 | 3071 | 13947 |

Table A.11 ICC scenario data for 50 customer instances

| | | | | | Low Demand | | | | | High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ins** | $N$ | $N_A$ | $N_B$ | $N_S$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ |
| **1** | 50 | 34 | 34 | 18 | 5559 | 1811 | 5434 | 1811 | 10992 | 11117 | 3623 | 10867 | 3623 | 21985 |
| **2** | 50 | 34 | 34 | 18 | 6283 | 2380 | 6000 | 2380 | 12283 | 12566 | 4760 | 11999 | 4760 | 24566 |
| **3** | 50 | 34 | 34 | 18 | 5619 | 2184 | 5698 | 2184 | 11318 | 11238 | 4369 | 11397 | 4369 | 22635 |
| **4** | 50 | 34 | 34 | 18 | 6419 | 2225 | 5826 | 2225 | 12245 | 12837 | 4450 | 11653 | 4450 | 24490 |
| **5** | 50 | 34 | 34 | 18 | 5685 | 2108 | 6545 | 2108 | 12230 | 11370 | 4216 | 13090 | 4216 | 24460 |
| **6** | 50 | 34 | 34 | 18 | 5735 | 2274 | 6007 | 2274 | 11742 | 11470 | 4548 | 12015 | 4548 | 23485 |
| **7** | 50 | 34 | 34 | 18 | 5735 | 2274 | 6007 | 2274 | 11742 | 11470 | 4548 | 12015 | 4548 | 23485 |
| **8** | 50 | 34 | 34 | 18 | 6601 | 2461 | 5946 | 2461 | 12547 | 13201 | 4921 | 11892 | 4921 | 25093 |
| **9** | 50 | 34 | 34 | 18 | 5367 | 2204 | 5711 | 2204 | 11078 | 10735 | 4407 | 11422 | 4407 | 22157 |
| **10** | 50 | 34 | 34 | 18 | 5649 | 2337 | 6223 | 2337 | 11872 | 11298 | 4674 | 12446 | 4674 | 23744 |

Table A.12 ICC scenario data for 100 customer instances

| | | | | | Low Demand | | | | | High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ins** | $N$ | $N_A$ | $N_B$ | $N_S$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ |
| **1** | 100 | 70 | 70 | 40 | 11639 | 4515 | 11348 | 4515 | 22987 | 23277 | 9031 | 22696 | 9031 | 45973 |
| **2** | 100 | 70 | 70 | 40 | 11857 | 4745 | 11754 | 4745 | 23611 | 23714 | 9490 | 23508 | 9490 | 47223 |
| **3** | 100 | 70 | 70 | 40 | 11124 | 4339 | 10667 | 4339 | 21791 | 22247 | 8678 | 21334 | 8678 | 43581 |
| **4** | 100 | 70 | 70 | 40 | 10942 | 4587 | 10984 | 4587 | 21926 | 21885 | 9174 | 21967 | 9174 | 43852 |
| **5** | 100 | 70 | 70 | 40 | 10842 | 4645 | 11800 | 4645 | 22642 | 21683 | 9290 | 23600 | 9290 | 45283 |
| **6** | 100 | 70 | 70 | 40 | 11544 | 4949 | 11647 | 4949 | 23191 | 23087 | 9899 | 23294 | 9899 | 46381 |
| **7** | 100 | 70 | 70 | 40 | 11803 | 4575 | 12019 | 4575 | 23822 | 23606 | 9150 | 24037 | 9150 | 47644 |
| **8** | 100 | 70 | 70 | 40 | 11638 | 4570 | 11953 | 4570 | 23591 | 23276 | 9141 | 23905 | 9141 | 47182 |
| **9** | 100 | 70 | 70 | 40 | 11762 | 4419 | 11505 | 4419 | 23267 | 23524 | 8838 | 23010 | 8838 | 46534 |
| **10** | 100 | 70 | 70 | 40 | 12468 | 3890 | 11229 | 3890 | 23696 | 24936 | 7780 | 22457 | 7780 | 47393 |

Table A.13 NCD scenario data for 30 customer instances

| | | | | | Low Demand | | | | | High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ins** | $N$ | $N_A$ | $N_B$ | $N_S$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ |
| **1** | 30 | 19 | 19 | 8 | 3148 | 880 | 3895 | 880 | 7043 | 6393 | 2138 | 7694 | 2138 | 14087 |
| **2** | 30 | 19 | 19 | 8 | 3845 | 914 | 3458 | 914 | 7303 | 7708 | 1924 | 6898 | 1924 | 14606 |
| **3** | 30 | 19 | 19 | 8 | 3860 | 965 | 3460 | 965 | 7320 | 7479 | 2097 | 7160 | 2097 | 14640 |
| **4** | 30 | 19 | 19 | 8 | 2615 | 734 | 3889 | 734 | 6504 | 5649 | 1253 | 7359 | 1253 | 13008 |
| **5** | 30 | 19 | 19 | 8 | 3544 | 1007 | 3711 | 1007 | 7255 | 7825 | 2172 | 6685 | 2172 | 14510 |
| **6** | 30 | 19 | 19 | 8 | 3740 | 950 | 3281 | 950 | 7020 | 6780 | 1820 | 7261 | 1820 | 14041 |
| **7** | 30 | 19 | 19 | 8 | 3740 | 950 | 3281 | 950 | 7020 | 6780 | 1820 | 7261 | 1820 | 14041 |
| **8** | 30 | 19 | 19 | 8 | 3000 | 1004 | 3132 | 1004 | 6132 | 6352 | 1580 | 5912 | 1580 | 12263 |
| **9** | 30 | 19 | 19 | 8 | 3104 | 921 | 3764 | 921 | 6868 | 6683 | 1622 | 7054 | 1622 | 13737 |
| **10** | 30 | 19 | 19 | 8 | 3139 | 817 | 3834 | 817 | 6974 | 7362 | 1908 | 6585 | 1908 | 13947 |

Table A.14 NCD scenario data for 50 customer instances

| | | | | | Low Demand | | | | | High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ins** | $N$ | $N_A$ | $N_B$ | $N_S$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ |
| **1** | 50 | 30 | 30 | 10 | 6056 | 1185 | 4937 | 1185 | 10992 | 12111 | 2369 | 9873 | 2369 | 21985 |
| **2** | 50 | 30 | 30 | 10 | 6145 | 1497 | 6138 | 1497 | 12283 | 12290 | 2993 | 12276 | 2993 | 24566 |
| **3** | 50 | 30 | 30 | 10 | 5567 | 1350 | 5750 | 1350 | 11318 | 11135 | 2700 | 11500 | 2700 | 22635 |
| **4** | 50 | 30 | 30 | 10 | 6579 | 1011 | 5666 | 1011 | 12245 | 13159 | 2023 | 11331 | 2023 | 24490 |
| **5** | 50 | 30 | 30 | 10 | 5603 | 1325 | 6627 | 1325 | 12230 | 11206 | 2650 | 13254 | 2650 | 24460 |
| **6** | 50 | 30 | 30 | 10 | 5724 | 1015 | 6019 | 1015 | 11742 | 11447 | 2030 | 12037 | 2030 | 23484 |
| **7** | 50 | 30 | 30 | 10 | 5724 | 1015 | 6019 | 1015 | 11742 | 11447 | 2030 | 12037 | 2030 | 23484 |
| **8** | 50 | 30 | 30 | 10 | 6686 | 1677 | 5860 | 1677 | 12547 | 13372 | 3354 | 11721 | 3354 | 25093 |
| **9** | 50 | 30 | 30 | 10 | 5734 | 1267 | 5344 | 1267 | 11078 | 11469 | 2534 | 10688 | 2534 | 22157 |
| **10** | 50 | 30 | 30 | 10 | 5998 | 1238 | 5875 | 1238 | 11872 | 11995 | 2475 | 11749 | 2475 | 23744 |

Table A.15 NCD scenario data for 100 customer instances

| | | | | | Low Demand | | | | | High Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ins** | $N$ | $N_A$ | $N_B$ | $N_S$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ | $d_A$ | $d_A^S$ | $d_B$ | $d_B^S$ | $d_T$ |
| **1** | 100 | 60 | 60 | 20 | 11052 | 1974 | 11934 | 1974 | 22987 | 22104 | 3949 | 23869 | 3949 | 45973 |
| **2** | 100 | 60 | 60 | 20 | 12285 | 2507 | 11326 | 2507 | 23611 | 24571 | 5014 | 22652 | 5014 | 47223 |
| **3** | 100 | 60 | 60 | 20 | 10640 | 1914 | 11151 | 1914 | 21791 | 21280 | 3829 | 22302 | 3829 | 43581 |
| **4** | 100 | 60 | 60 | 20 | 11175 | 2328 | 10751 | 2328 | 21926 | 22351 | 4656 | 21501 | 4656 | 43852 |
| **5** | 100 | 60 | 60 | 20 | 11128 | 2160 | 11514 | 2160 | 22642 | 22256 | 4319 | 23027 | 4319 | 45283 |
| **6** | 100 | 60 | 60 | 20 | 11563 | 2327 | 11627 | 2327 | 23191 | 23126 | 4655 | 23255 | 4655 | 46381 |
| **7** | 100 | 60 | 60 | 20 | 12080 | 2217 | 11742 | 2217 | 23822 | 24160 | 4433 | 23484 | 4433 | 47644 |
| **8** | 100 | 60 | 60 | 20 | 12084 | 2249 | 11507 | 2249 | 23591 | 24168 | 4499 | 23014 | 4499 | 47182 |
| **9** | 100 | 60 | 60 | 20 | 11296 | 2294 | 11971 | 2294 | 23267 | 22592 | 4588 | 23942 | 4588 | 46534 |
| **10** | 100 | 60 | 60 | 20 | 11359 | 2593 | 12337 | 2593 | 23696 | 22719 | 5185 | 24674 | 5185 | 47393 |

**Transfer Information for Collaborative Scenario Experiments**

Columns $TA_A$ and $TA_B$ indicate the transfer amounts of carrier $A$ and $B$, respectively.

Table A.16 Transfer amounts for 30 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | O | | ICC | | NCD | | O | | ICC | | NCD | |
| **Ins** | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ |
| **1** | 434 | 446 | 562 | 735 | 225 | 268 | 1027 | 486 | 2144 | 449 | 478 | 572 |
| **2** | 409 | 323 | 1439 | 236 | 262 | 225 | 587 | 1240 | 532 | 3104 | 554 | 505 |
| **3** | 567 | 508 | 894 | 445 | 267 | 252 | 717 | 1004 | 2222 | 719 | 462 | 461 |
| **4** | 396 | 270 | 431 | 670 | 179 | 240 | 619 | 848 | 1689 | 927 | 396 | 513 |
| **5** | 650 | 204 | 842 | 618 | 276 | 234 | 1300 | 715 | 2662 | 420 | 569 | 490 |
| **6** | 524 | 341 | 575 | 1135 | 226 | 233 | 1150 | 579 | 1742 | 1331 | 469 | 528 |
| **7** | 389 | 320 | 811 | 812 | 229 | 241 | 635 | 1001 | 1821 | 1424 | 476 | 539 |
| **8** | 690 | 313 | 658 | 893 | 226 | 202 | 295 | 1076 | 1796 | 1203 | 440 | 416 |
| **9** | 541 | 569 | 1242 | 380 | 225 | 229 | 212 | 1041 | 1431 | 1814 | 481 | 510 |
| **10** | 393 | 292 | 833 | 743 | 235 | 231 | 1051 | 766 | 1374 | 1697 | 469 | 436 |

Table A.17 Transfer amounts for 100 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | O | | ICC | | NCD | | O | | ICC | | NCD | |
| **Ins** | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ |
| **1** | 314 | 278 | 529 | 1010 | 620 | 456 | 681 | 784 | 1433 | 1844 | 1334 | 922 |
| **2** | 931 | 0 | 755 | 1236 | 639 | 561 | 1352 | 1254 | 2374 | 2067 | 1349 | 1188 |
| **3** | 454 | 659 | 540 | 1065 | 588 | 523 | 1147 | 1544 | 1085 | 2869 | 1272 | 1137 |
| **4** | 857 | 378 | 1058 | 1243 | 671 | 506 | 557 | 1687 | 1193 | 2950 | 1244 | 918 |
| **5** | 441 | 884 | 790 | 1194 | 584 | 605 | 1356 | 1129 | 1901 | 2230 | 1055 | 1099 |
| **6** | 551 | 555 | 764 | 1526 | 584 | 533 | 1730 | 480 | 3273 | 576 | 1034 | 1004 |
| **7** | 96 | 855 | 1609 | 759 | 584 | 529 | 1682 | 528 | 1682 | 2720 | 1047 | 1015 |
| **8** | 597 | 483 | 1176 | 1195 | 706 | 555 | 324 | 1837 | 2013 | 2849 | 1345 | 977 |
| **9** | 238 | 131 | 1028 | 1267 | 602 | 487 | 543 | 1870 | 774 | 3100 | 1263 | 1040 |
| **10** | 583 | 503 | 1015 | 861 | 620 | 529 | 692 | 742 | 1814 | 2997 | 1150 | 948 |

Table A.18 Transfer amounts for 50 customer instances

| | Low Demand | | | | | | High Demand | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | O | | ICC | | NCD | | O | | ICC | | NCD | |
| **Ins** | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ | $TA_A$ | $TA_B$ |
| **1** | 793 | 1502 | 3150 | 1366 | 2023 | 2194 | 3086 | 875 | 4079 | 4546 | 4438 | 4798 |
| **2** | 1215 | 1161 | 2737 | 2116 | 2312 | 2125 | 2470 | 1838 | 4213 | 5592 | 4473 | 4055 |
| **3** | 1439 | 855 | 2420 | 1694 | 1971 | 2075 | 2541 | 1383 | 5296 | 3202 | 4238 | 4434 |
| **4** | 1229 | 713 | 1655 | 2913 | 2106 | 2021 | 2056 | 2735 | 3978 | 4793 | 4043 | 3911 |
| **5** | 1061 | 1270 | 1822 | 2849 | 2062 | 2136 | 2418 | 1882 | 3639 | 5522 | 4461 | 4695 |
| **6** | 1492 | 1062 | 3400 | 1762 | 2151 | 2190 | 1827 | 2488 | 4657 | 5455 | 4180 | 4207 |
| **7** | 1091 | 1097 | 1811 | 3179 | 2254 | 2199 | 2558 | 2954 | 4327 | 4388 | 3694 | 3529 |
| **8** | 946 | 1455 | 2245 | 2386 | 2262 | 2139 | 1283 | 3295 | 2359 | 6368 | 4949 | 4761 |
| **9** | 1167 | 1026 | 1894 | 2491 | 2108 | 2239 | 2399 | 1771 | 4204 | 4379 | 3428 | 3566 |
| **10** | 1044 | 811 | 1501 | 2403 | 2149 | 2325 | 2430 | 1413 | 2946 | 4756 | 4109 | 4666 |