# Mechanism Design for the City Logistics Alliance

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Submission for the degree of

**Doctor of Philosophy**

**Newcastle University Business School**

April 2022

# Abstract

In the field of city logistics, companies traditional make their own decisions unilaterally to deliver their own commodities to their own customers using their own vehicles. To improve the vehicle utilisation rate, increase the total profits, and reduce the environmental and noise pollution, promoting the collaboration between different logistics companies can be one of the most cost-effective measures. To implement the concept of collaboration in the city logistics industry, two problems need to be solved. One is how to form a stable logistics alliance involving the relevant logistics companies; the other is how to fairly allocate the total attainable profits to each member. This research focuses on solving the above two problems by designing reasonable contracts to allocate all the profits obtained from the grand alliance of logistics companies. The designed contracts will ensure that each member in the alliance is satisfied with the profit allocation. In other words, the profits allocated to each member is no less than the profits they could earn under non-collaborative and sub-collaborative situations.

Mathematical models are developed to measure the total profits each member can earn under the following three circumstances: non-collaboration, ideal collaboration and a logistics alliance with contracts. The cases of non-collaboration and ideal collaboration are solved using conventional Integer Programming method. Game theory is applied into the case of logistics alliance to design appropriate contracts that can fairly allocate the profits obtained by the grand alliance to each member. The capacity exchange costs between different logistics companies are proposed and then used as the main control parameters in the contract design. Inverse programming is then applied to determine the best values of the capacity exchange costs that can maximise the system profits and also ensure that each member in the logistics is better off than running their business individually.

After examining the outcomes of the above three models based on the extensive numerical case, it has been found that collaboration of logistics companies under reasonable contracts can generate higher profits than non-collaboration. What’s more, the members in the alliance are satisfied with the profit allocation plan under the majority of the circumstances. It is suggested that the contracts designed in this research can be applied to encourage logistics companies in practice to form a stable logistics alliance.

# Acknowledgement

First and foremost, I would like to express my deepest gratitude to all my supervisors, Professor Jingxin Dong, Dr. Ying Yang, and Professor Savvas Papagiannidis. My supervisors provided valuable advice and suggestions during my PhD study. I am gratefull to all my supervisors for their support. I also appreciate their concern and encouragement during all these years. Especially, I would like to show my gratitude to Professor Jingxin Dong, who suggested and supported me to learn C++ and CPLEX from the beginning. He taught me how to test a model and how to find errors in a project, which is the foundation of model building. Thanks again for all the support offered by all my supervisors, I appreciate their help very much.

Then, I would like to thank my colleges and friends who provided useful information and experience on what to do during the PhD study. I also thank them for providing encouragement during this long journey.

Last but not least, I am extremely grateful to my parents. I would like to express my appreciation to their care and encouragement. Many thanks for their suggestions not only on my study, but also on my life. Thanks to their financial support during my PhD study. Thanks again for their support and suggestions. I really appreciate their support, and I am so grateful for their patience and love.

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# Chapter 1 Introduction

## 1.1 Research Background

City logistics "*emphasise the need for an optimized consolidation of loads of different shippers and carriers within the same delivery vehicles and for the coordination of the resulting freight transportation activities within the city*." (Crainic, Ricciardi and Storchi, 2009, p. 2). It aims at "*reducing and controlling the number, dimensions, and characteristics of freight vehicles operating within city limits, improving the efficiency of freight movements, and reducing the number of empty vehicle kilometres*." (Crainic, 2008, p. 2; Ehmke, 2012, p. 14).

In traditional city logistics, all stakeholder, such as suppliers and transportation companies, usually service the orders of their own customers by utilizing their own vehicles on a regular basis (Cruijssen and Salomon, 2004). Logistics and freight transport not only provide a way to deliver commodities to meet the demand of the customers, but also make a great contribution to the employment as well as the development of the economy (Gonzalez-Feliu and Salanova, 2012). In spite of the significant contribution to the economy, there are some negative impacts on the environment, energy and the quality of life. For example, there is an increasing number of vehicles and a decreasing percentage of vehicle utilization with high empty hauling rates (Thompson and Hassall, 2012). This results in city traffic congestion, exhaust gas emission, noise pollution, and social nuisance, which negatively influences pedestrians, pollutes the environment, and affects the quality of life, especially in the city area. Due to these facts, city logistics need to consider how to improve the usage rate of vehicles, and reduce environmental and noise pollution (Crainic et al. 2012).

Apart from working independently, collaboration has already been taken into consideration in practice, where there are more than two stakeholders sharing their efforts to meet a common goal (Bahinipati, Kanda and Deshmukh, 2009; Dai and Chen, 2009). In the context of supply chain management, collaboration is mainly classified into two categories, vertical collaboration and horizontal collaboration (Mason, Lalwani, and Boughton, 2007).

Companies from different levels in supply chain management form a vertical collaboration. For example, efficient consumer response (ECR), vendor-managed inventory (VMI) and Collaborative planning, forecasting and replenishment (CPFR) are widely applied collaboration in supply chain management.

Companies from the same level in supply chain management form a horizontal collaboration. Fernandez, Fontana and Speranza (2016) summarized three situations for companies to form a horizontal collaboration.

- Companies can share a common inventory site
- Companies can hire a third-party logistics provider to deliver commodities in the same region
- Companies can exchange data (e.g. customer orders)

These collaboration can result in lower fixed costs, shorter travel distances, fewer empty returns, fewer vehicles used to deliver commodities, less environmental pollution and noise pollution (Frisk et al., 2010; Thompson and Hassall, 2012; Adenso-Diaz et al., 2014; de Souza et al. 2014; Chabot et al. 2018; Fernandez, Roca-Riu and Speranza, 2018; Algaba et al. 2019).

There is a collaboration in practice formed by eight sweet and candy producers. This Dutch Sweet Distribution hires a logistics service provider to deliver the commodities to their customers as there are altogether two hundred and fifty retail distribution centres, and the majority of the demand of the distribution centres must be satisfied on a daily basis. This Dutch Sweet Distribution was proved to be a successful collaboration to reduce the transportation costs as well as improving the service performance (Cruijssen, Dullaert and Fleuren, 2007). It was also turned out to be an environmentally friendly collaboration, which improves the utilization of vehicle and reduces the number of vehicles used. What’s more, it also decreases the total travel distances, environmental pollution and noise pollution (Frisk et al., 2010; Thompson and Hassall, 2012).

However, collaboration is not always successful and efficient. Gonzalez-Feliu and Salanova (2012) proposed a collaborative transport system and concluded that collaboration with all the members was not always the best result, and individual decisions were not always in accordance with the global decision. Pateman, Cahoon, and Chen (2016) pointed out that benefits, effects, outcomes and gains may be future incentives to encourage collaboration in logistics industry. Their research also showed that 65.6% expected to increase number of collaborations, 21.9% expected to stay the same, and 9.4% expected to decrease the number of collaboration in the next ten years in Australia.

## 1.2 Current Research

In order to increase total benefits (e.g. increase total profits or decrease total costs) and reduce negative impacts to the environment and the society, shippers and carriers can apply a set of current existing models to organize their daily service network. Vehicle routing problem (VRP) and its variants derived from travelling salesman problem (TSP), where there is a salesman must travel from the "*base city*" to all the other cities and back to this "*base city*". During the travel, "*base city*" must be visited fixed times, but there is no capacity limitation (Flood, 1956). Dantzig and Ramser (1959) introduced the TSP model to vehicle routing through adding capacity constraints. In this model, there is only one company making optimal decisions on a daily basis. This company owns a depot with sufficient supply (not necessary to make decisions on stock levels), a fleet of vehicles (with a finite capacity) to deliver commodities, and a number of customers whose orders must be satisfied. After that, more constraints were added to VRP models, e.g. distance constraint, time window constraint, backhaul constraint, loading and unloading constraint. This group of vehicle routing problems only focuses on the minimum total travel distances or total travel costs for one company.

Apart from improving the efficiency of city logistics for each logistics company individually, promoting the collaboration between logistics companies can also be a very effective way forward.

Guajardo and Ronnqvist (2016) pointed out two vital important issues faced by potential members who wish to form a logistics alliance.

- How to motivate members to form an alliance
- How to allocate total profits or costs to each member in the collaboration

One is how to motivate the members to form a stable alliance. Each member in the alliance aims at individual best solution, while the collaboration aims at global optimal solution. If one member receives less benefits from the collaboration, this member can choose to leave the collaboration and make this collaboration unstable. Thus, motivation mechanisms need to be applied to provide incentives.

The other is how to allocate the total attainable profits or total costs to each member in the alliance. Analogously, if one member is allocated less profits (or more costs) than the profits (or costs) they can obtain by themselves, it is not considered as a fair allocation. Thus, an allocation mechanism is needed to allocate total benefits to each member in a fair way, and each member is satisfied with the allocation.

For the purpose of forming a collaboration, a centralized collaboration and a decentralized collaboration were proposed. In a centralized collaboration, companies are willing to share all information, and there is a central decision maker making decisions with full information. While in a decentralized collaboration, companies prefer not to share all information, and information is shared individually in a decentralized way.

After forming an alliance, the remaining problem is to allocate the total benefit to each member in the alliance in a fair way. There are several existing allocation methods to allocate the total benefits to each member in the alliance, such as proportional methods, the core, Shapley value, Nucleolus, and equal profit method. These allocation methods are commonly applied allocation methods. Allocation method based on game theory sign and obey a binding agreement to allocate benefits to each member. However, implementation of optimal allocation plan is not considered.

As in a centralized collaboration, a central decision maker can make decisions for the alliance. It is obvious that this optimal solution is the best solution. However, members in practice prefer to form a decentralized collaboration as they prefer not to share full information. They can make decisions on their own with their own resources and sharing resources. Thus, a powerful contract is required to allocate benefits among members in a fair way. More importantly, this contract must guarantee the best benefit allocation plan can be adopted when each member in the alliance make decisions individually.

### 1.3 Research Aims and Questions

In this project, the collaboration between companies as a logistics alliance will be considered. The companies here include third party logistics companies or logistics departments affiliated with large manufacturing companies or e-retailers. Each of these companies has their own vehicle fleet, depot or warehouse and customers to be served. Within the logistics alliance, transport assets, including vehicle, depot and customer demand, will be shared. In other words, one company can use their own vehicles to serve another company’s customers. In this way, it is expected that the economy-of-scale effect can be achieved. For example, a member company may find that it might be more economical to use the other company’s return vehicle than using their own vehicles to serve their customers. However, realizing a logistics alliance of this kind relies on an appropriate cost/profit allocation mechanism. In fact, without such a mechanism, it is hard to form a logistics alliance.

In line with the above discussion, this study will focus on how to design cost/benefit allocation strategies and mechanisms for companies to form a sustainable logistics alliance. The mechanism should be specified in the agreement of the logistics alliance and obeyed by all the member companies. Designing the cost/profit allocation mechanism is tactical decision making, and will be affected by operational decision making, i.e., how the vehicles in the alliance will be utilized. Hence, a vehicle routing and allocation plan will also be considered in the project. To make the problem tractable, the existing vehicle routing problem (VRP) and its variants will be used to make decisions on the vehicle routing and allocation plan. Accordingly, the assumptions in the existing VRP and its variants will be followed in the study.

The aim of this study is to investigate the cost/profit allocation strategies and mechanisms of city logistics alliances on the tactical level by extending current existing VRP models. The strategy and mechanism will become a contract that the companies in a logistics alliance need to sign and obey. More specifically, there are four research questions to be answered:

Question 1: How to design the best vehicle routing plan on a daily basis for the non-collaborative city logistics industry where each individual company runs their business independently and makes decision unilaterally?

Question 2: How to determine the maximum overall profits of the grand alliance that is normally achieved under perfect collaboration?

Question 3: How to design a reasonable motivation mechanism that can 1) lead to the same profits as that under perfect collaboration, 2) fairly allocate the obtained profits to each member in the collaboration, and also 3) ensure that each company will be better off than the non-collaborative case? The designed mechanism is supposed to encourage logistics companies to form a stable alliance and share their resources, e.g. vehicles and customer orders. This research question deals with the motivation and allocation mechanisms, which are the two important issues proposed by Guajardo and Ronnqvist (2016) when forming an alliance.

Question 4: How to quantify the advantages of the logistics alliance over the traditional cases where each logistics company makes decisions independently?

## 1.4 Expected Contribution

From the perspective of theory, this study aims at developing reasonable profit allocation and motivation mechanisms. A collaborative model is proposed with non-collaborative situations, centralized collaborations, and decentralized collaborations. A centralized collaboration guarantee a best global routing plan. While a decentralized collaboration guarantees the optimal profit allocation plan. Under these circumstances, all the companies in a logistics alliance are better off than operating independently. Thus, with the help of these mechanisms, a logistics alliance can be formed and then a win-win situation can be realized. What's more, based upon these mechanisms, this study will lead to a better result arising from collaboration. In addition, this research will fill the research gaps.

From the perspective of practice, this research provides a reasonable mechanism to form a sustainable and stable logistics alliance with higher profits. As a result, it is expected that logistics companies can be encouraged to form logistics alliances with better services.

## 1.5 Structure of this Thesis

The remainder of the thesis is organized as follows.

In Chapter 2, literatures are critically reviewed with regard to collaborative city logistics, how to form an alliance (including model building and solving), and how to allocate benefits among members. More specifically, categories of collaboration, levels of collaboration, centralized collaboration, decentralized collaboration and key issues of collaborative city logistics are first reviewed. Then, the literature review focuses on how to build a collaboration, including how a single company makes decisions, how to form an alliance, relevant models and solution algorithms. After that, it focuses on how to share the benefits between the members in the alliance. Last, research gaps are proposed according to the literature review.

In Chapter 3, research methodology are introduced in details, including research design, data collection and analysis, research methods, and research ethics.

In Chapter 4, a contract is designed for logistics alliance where time window is taken into consideration. If the resources are shared among the members in the alliance, capacity exchange costs are charged according to the travel distances between customer and the depot. More specifically, the problem description and basic assumptions are first introduced. A service network is then designed for each logistics company in order to quantify the total profits they could earn on their own. Next, an ideal service network is designed without fees. Centralized collaboration is applied as there is a virtual central decision maker to make global decisions according to all the information from both companies and customers. After that, a reasonable service network is designed for each member in the logistics alliance where capacity exchange costs are taken into consideration. The capacity exchange costs are introduced to measure the value when they exchange their resources. Finally, cutting plane method is applied in order to measure the value of capacity exchange costs. As such, the profits allocated to each member can be obtained. Both motivation and allocation mechanisms are designed in this contract.

In Chapter 5, another contract is designed for a city logistics alliance. If one company delivers commodities for the other company, this company can charge capacity exchange costs according to the weight of the commodity.  In this chapter, problem description and basic assumptions are introduced in the first part. In the second part, it focuses on how to form an alliance. In the third part, it focuses on how to allocate total profits to each member in a fair way.

In Chapter 6, computational results are analysed in detail. A simple case study is first proposed to measure the optimal solutions in non-collaborative situation, ideal collaboration, and logistics alliance. The optimal solution of both non-collaborative situation and collaborative situation are quantified and compared. By comparing the result, it shows that collaboration is better than non-collaboration and profit allocation plans can keep a collaboration stable. Feasibility analysis and quality of results are then discussed.

In Chapter 7, a discussion is conducted to discuss the similarities and differences between two contracts in this research. A comparison is also made between findings of this research and previous researches on this topic.

In Chapter 8, conclusions are offered with main findings, main contributions, limitations and future research.

# Chapter 2 Literature Review

## 2.1 Introduction

In this chapter, literatures related to collaborative city logistics and mechanism design are critically reviewed.

In section 2.2, collaborative city logistics is reviewed according to the following aspects: 1) categories of logistics collaboration; 2) levels of collaboration; 3) centralized collaboration and decentralized collaboration; and 4) two key issues of logistics collaboration.

In section 2.3, literature related to how to form an alliance is reviewed, especially literatures related to collaborative model building and solving with regard to the following three aspects: 1) single carrier situation; 2) multiple carrier situation; and 3) solution algorithms. How each logistics company make daily decisions are reviewed before introducing collaborative model, as a single carrier plays an important role in the collaboration. The carrier can decide to join a collaboration if it is satisfied with the benefit allocation plan. Otherwise, the carrier can choose to quit a collaboration. In this study, to make the problem tractable, it is assumed that the members in logistics alliances follow existing vehicle routing problem models and their variants. Building collaboration is one of the key issues of collaboration, which provide motivation mechanisms to encourage potential members to form an alliance.

In section 2.4, literatures related to how to allocate benefit to each member in the alliance is reviewed through simple method, advanced methods and contract design. Benefit allocation is the other key issue of collaboration, which provide allocation mechanisms to build a stable and healthy alliance.

In section 2.5, research gaps are proposed according to the reviewed literatures.

In section 2.6, a summary is offered to summarize this chapter.

## 2.2 Collaborative City Logistics

In this part, literatures related to collaborative city logistics are critically reviewed according to the following aspects.

1) Categories of collaboration are reviewed in the context of supply chain, distribution channel and urban logistics.

2) Levels of collaboration are reviewed to show what resources one company can share when forming alliances.

3) Centralized collaboration and decentralized collaboration.

4) Key issues of logistics collaboration are reviewed.

### *2.2.1 Categories of Logistics Collaboration*

In this section, categories of collaboration is reviewed. The classification is based on whom a collaboration could be formed with. "*Collaboration is possible when at least two actors share their efforts to reach a common objective*" (Gonzalez-Feliu and Salanova, 2012, p.173).

In the context of supply chain management, collaboration is mainly classified into two categories, vertical collaboration and horizontal collaboration (Mason, Lalwani, and Boughton, 2007). This classification is based on the levels of supply chain management (Figure 2.1).

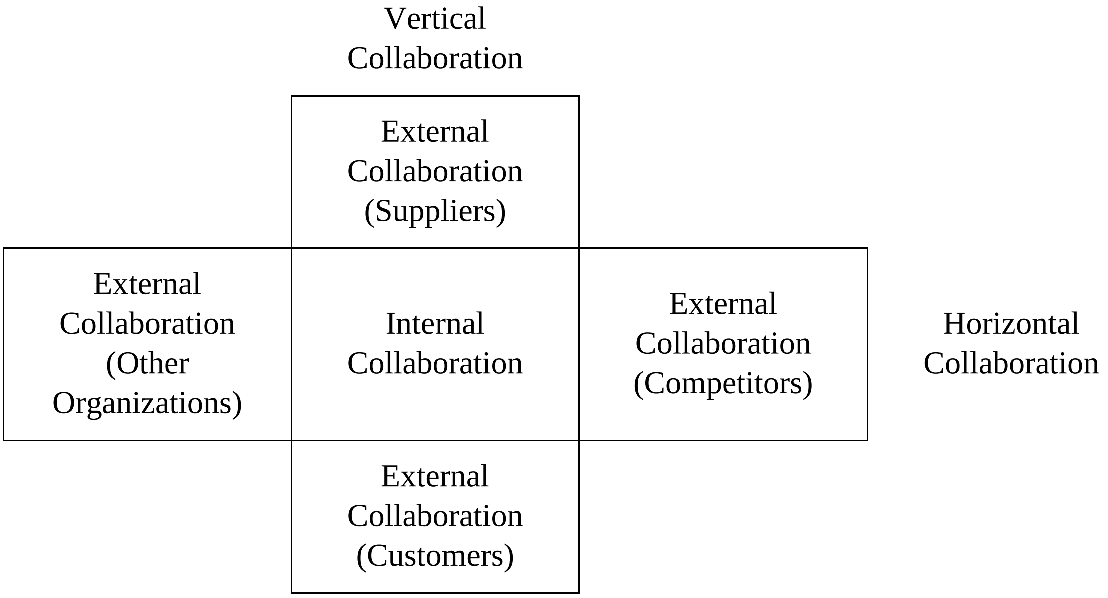

*Figure 2.1 The scope of collaboration: generally (Barrett, 2004, p.32)*

Vertical collaboration is *"collaboration with customers, internally (across function) and with suppliers"*, while horizontal collaboration is *"collaboration with competitors, internally and with non-competitors"* (Barratt, 2004, p.32). In other words, companies from different levels in supply chain management choose to form a vertical collaboration and companies from the same level choose to form a horizontal collaboration.

Horizontal collaboration and vertical collaboration can also be found in a distribution channel. A distribution channel provide a path for goods and services to travel from producers to customers (Khooban, 2001). Vertical collaboration in this distribution channel is classified into four groups, one group of direct channel, and three groups of indirect channels. While horizontal collaboration in this distribution channel is to form an alliance with the competitors (Figure 2.2).

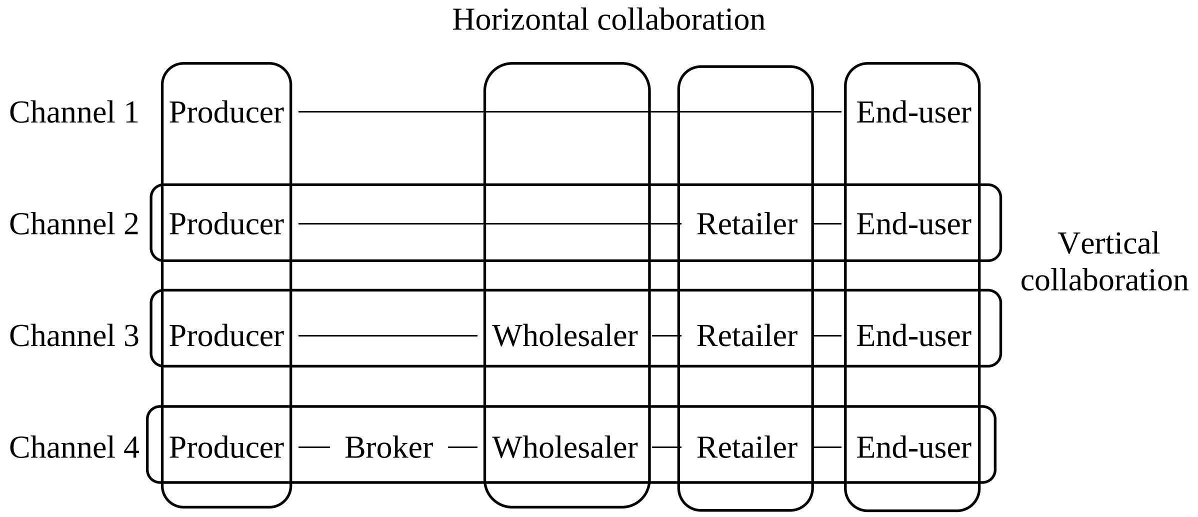

*Figure 2.2 Distribution channels and collaboration (Khooban, 2001, p.110)*

In the context of urban logistics, similar ideas of vertical and horizontal collaboration also exist. Khooban (2011) proposed that shippers and carriers were two basic participants in the transportation system. Then vertical collaboration was defined as “*when shippers and customers collaborate to help each other optimize their objective”*, while horizontal collaboration *“takes place when shippers collaborate among them (and/or the same do customers) at the same logistic level”* as well as carriers (Fernandez, Fontana and Speranza, 2016, p.121).

### *2.2.2 Levels of Collaboration*

In this section, what resources can be shared among members in the collaboration is reviewed. In a collaborative system, there are more than two companies sharing material and immaterial resources by means of signing and obeying a binding agreement (Cruijssen, Dullaert and Fleuren, 2007; Bahinipati, Kanda and Deshmukh, 2009). Three levels of interaction were introduced as follows (Gonzalez-Feliu and Morana, 2011).

Level 1: informational collaboration

Informational collaboration focuses on information exchange, which is "*the basis of cooperation between stakeholders*" (Gonzalez-Feliu et al., 2013, p.5). As a matter of fact, informational collaboration plays a vital important role in the collaboration and it is regarded as the core collaboration (Gonzalez -Feliu & Morana, 2011). Information is shared among members in the collaboration, such as stock levels, customer demands, time windows, transportation compatibility, time sensitivity, temperature regimes, visibility, and delivery times.

Information can be shared in two ways, a centralized way and a decentralized way (Fernandez, Fontana and Speranza, 2016). In a centralized collaboration scheme, there is a central decision maker who makes decisions for the members with access to all the information. It is expected that optimal results can be obtained by the collaboration. However, companies are not willing to share with others according to confidentiality issues, which can be an obstacle to form a collaboration (Gonzalez-Feliu et al., 2013). Thus, a compensation price is provided when sharing valuable information (Berger and Bierwirth, 2007). While in a decentralized collaboration scheme, companies change their information individually.

Level 2: transactional collaboration

Transactional collaboration aims at forming a collaboration with standardization and coordination. This type of collaboration provide an opportunity to exchange techniques, both material resources (e.g. facilities and equipment) and immaterial resources (e.g. information and data) can be shared by members in the alliances (Gonzalez-Feliu and Salanova, 2012).

Level 3: decisional collaboration

Decisional collaboration focuses on making decisions at various levels (Lambert, 2008). This type of collaboration is classified into three categories, strategic planning, tactical planning and operational planning (Rushton, Croucher and Banker, 2014, Gonzalez-Feliu and Salanova, 2012; Gonzalez-Feliu et al., 2013). This is in accordance with the three categories in logistics planning.

- Strategic planning focuses on long-term planning and makes decisions on resources allocation, such as facility location.
- Tactical planning focuses on middle-term planning, such as sharing decisions.
- Operational planning focuses on short-term planning and freight transportation belongs to operational planning.

### *2.2.3 Centralized Collaboration & Decentralized Collaboration*

*Centralized Collaboration*

In a centralized collaboration, there is a central decision maker who can make decisions for the members in the alliance, and members are willing to share all information. Thus, the central decision maker can get access to the full information.

The following two aspects are commonly researched in centralized collaboration:

- Collaborative gain assessment: comparing total benefits earned by non-collaborative situations and centralized collaboration.
- Methodological contributions: model innovation or solution innovation for centralized collaboration.

| **Articles** | **Contribution** |
|---|---|
| Montoya-Torres et al. (2016) | - collaborative routing<br>- quantified the effect<br>- improved 25.6% travel distance |
| Quintero-Araujo et al. (2016) | - stochastic demands<br>- cost reduction 4% |
| Sanchez et al. (2016) | - carbon emissions reduced by 60%<br>- cost savings nearly 55% |
| Soyasal et al. (2018) | - cost 4 – 24%<br>- emission 8 – 33% |
| Perez-Bernabeu et al. (2015) | - ecological<br>- reduce travel costs<br>- greenhouse gas emission |

*Table 2.1 A brief summary of studies on collaborative gain assessment*

| **Articles** | **Contribution** |
|---|---|
| Buijs et al. (2016) | decomposition strategies |
| Dai and Chen (2012) | joint route planning |
| Hernandez and Peeta (2011) | time-dependent centralized multiple carrier collaboration problem |
| Nadarajah and Bookbinder (2013) | decomposition strategies |
| Weng and Xu (2014) | open hub routing problem |
| Wang et al. (2014) | horizontal and vertical collaboration |

*Table 2.2 A brief summary of studies on methodological contribution*

*Decentralized Collaboration*

Compared with centralized collaboration, members in the alliance are not willing to share all the information. Thus, they can choose to form a decentralized collaboration, where the central decision maker cannot get access to full information.

The following three aspects are commonly researched:

- Partner selection: different partners may have different requirements, and different partners may result in different collaborative benefits.
- Request selection: carriers can select to share part of the requests, and carriers can deliver the rest of the requests individually; carriers can also select requests from requests shared by partners.
- Request exchange: exchange mechanism

| Articles | Type | Content |
|---|---|---|
| Berger and Bierwirth (2007) | Non-collaboration, centralized, decentralized | - information sharing<br>- profits increase |
| Wang and Kopfer (2014) | decentralized | Request Exchange |
| Cuervo et al. (2016) | Decentralized | Partner Selection |
| Wang et al. (2014) | Decentralized | Request Exchange |
| Hernandez and Peeta (2014) | Decentralized | Request Selection |
| Fernandez, Fontana and Speranza (2016) | Non-collaboration, decentralized collaboration, centralized collaboration | - timber transportation<br>- insufficient supply<br>- depot sharing<br>- information sharing |

*Table 2.3 A brief summary of studies on decentralized collaboration*

### 2.2.4 Key Issues of Logistics Collaboration

In the previous sections, categories of collaboration, levels of collaboration, centralized collaboration and decentralized collaboration are discussed. Potential members can identify the object to form an alliance, and the resources to share in an alliance. In this section, two key issues of logistics collaboration are reviewed for the purpose of forming a stable alliance.

When taking collaboration into consideration, there are usually two or more participants making decisions together. The alliance aims at global optimal solutions while the members aims at individual optimal solution. In a win-win condition, both participants and the collaboration can obtain optimal solutions. What’s more, members in the alliance can obtain more benefits than the individual benefits. However, if one member obtain less benefits from the alliance, there is not enough incentive to keep the member in the alliance. Thus, how to build an alliance, and how to allocate benefits to each member in the alliance are two key issues in collaborative logistics.

In order to achieve individual and global goals and to form a stable collaboration, cooperative game theory was introduced to collaborative logistics. As a branch of Game theory, it can also "*provides a powerful mathematical framework for modelling and analysing systems with multiple decision makers, referred to as players"* (Simchi-Levi, Chen and Bramel, 2014, p.45).

In a cooperative game theory, two or more players with common purpose need to sign and obey a binding agreement (Myerson, 1991). These binding agreements can be signed on the choice of strategies (cooperative strategic games) or on the distribution of payoffs (cooperative coalitional games). This cooperative coalitional game focuses on benefit allocation to each player.

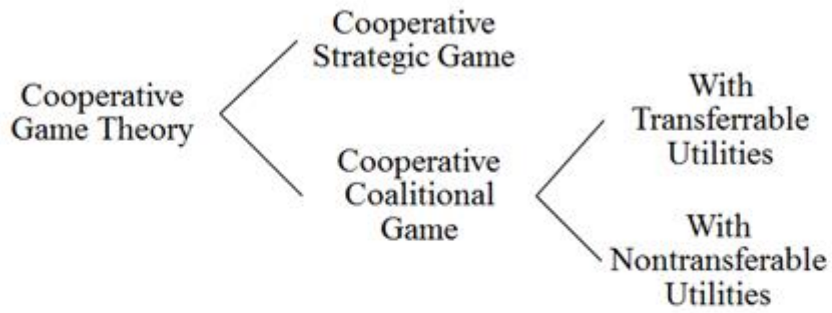

*Figure 2.3 Classification of Cooperative Game Theory (Simchi-Levi, Chen & Bramel, 2014)*

In a cooperative coalitional game with transferrable utilities, there is a set of players $N = \{1, 2, 3, \dots, n\}$ who wish to form a collaboration. A grand coalition is a collaboration with all the players, while a sub-coalition is a collaboration with part of the players or no players. In order to measure benefits and allocate benefits, there is a characteristic function $V$. Then, $V(N)$ stands for the total benefits earned by the grand alliance, $V(S)$ stands for the total benefits earned by the sub-coalition, and $V(\emptyset)$=0 as there is no players in the game.

As stated above, players in this game signed a binding agreement on the distribution of payoffs, thus, a feasible payoff vector $x = \{x_1, x_2, \dots, x_n\}$ is applied to measure the benefits allocated to each member in the alliance. The feasible payoff vector satisfies $V(S) \geq \sum_{i\in s} x_i$, that is, the total benefits allocated to each member is no more than the total benefits earned by the sub-coalition. Under this circumstance, there are numerous ways to allocate the benefits to each player.

Then, solution concept is applied to allocate benefits to players, and the core, Shapley value and Nucleolus are three commonly applied method. The following table listed part of properties for solution concept to follow.

| Properties | Formulation | Content |
|---|---|---|
| **Efficiency** | $x(N) = V(N)$ | All benefits earned by grand alliance can be allocated to each player |
| **Individual rationality** | $x_i \geq V(\{i\})$ | No player obtains less from the coalition |
| **Group rationality** | $x(S) \geq V(S)$ | No group of players obtain less from the coalition |
| **Symmetry** | $x_i = x_j$ | Two players with the same marginal contribution are allocated same benefit |
| **Null player** | $V(S \cup \{i\})$ = V(S) | Marginal contribution of the player is 0 |

*Table 2.4 Properties for solution concepts*

Efficiency property guarantee all benefits earned by grand alliance can be allocated to each member in the coalition. Individual rationality and group rationality guarantee that grand alliance is better than sub-coalitions, and this eliminate the opportunity for players to form a sub-coalition. Symmetry and null player guarantee a fair allocation.

## 2.3 How to Form an Alliance

In this section, how to build models for non-collaborative situation and collaborative situation are reviewed, followed by the relevant solution algorithms. It first focuses on a single-company situation, which is related to vehicle routing problem and its variants. These vehicle routing problems describe the one-company based routing problem, and "*lies at the heart of distribution management*" (Cordeau et al., 2007, p.367). In order to achieve the minimum costs or distances, vehicle routing problem aims at an optimal routing plan by building "*concise, comprehensive and clear"* mathematical models (Taniguchi and Thompson, 2001). It is one of the most significant combinatorial optimization problems (Liong et al., 2008), and is "*a lively field of applied mathematics, combining techniques from combinatorics, linear programming, and the theory of algorithms, to solve optimization problems over discrete structures*" (Cook et al., 1997, p. ix).

### *2.3.1 Single Carrier Situation*

Traditional vehicle routing problem proposed by Dantzig and Ramser (1959) can be described as follows: one company make decisions to deliver commodities to satisfy customer demands on a daily basis. The location of depot and customers are known and fixed, the stock is sufficient to meet all the demand, and the capacity of vehicles are identical. The daily task of the company is to make the most of the resources whilst delivering the supply to each customer and satisfy their demands. The objective is to minimize total travel costs or total travel distances, by satisfying the following assumptions (Kulkarni and Bhave, 1985; Laporte, 1992; Daneshzand, 2011):

- All customer demands must be satisfied;
- All customers must be visited exactly once by one vehicle;
- Each service route should start and end at the depot;
- Total demands each vehicle can deliver must be no more than its capacity.

Figure 2.4 shows possible service networks to deliver commodities to each customer using several vehicles. For example, if there is one company who owns six vehicles and six customers, it is obvious that each customer visited by each vehicle is a feasible service network. However, this network may be not efficient and effective. There are other feasible service routing plans, where fewer vehicles can be allocated to each route. Especially, there is a service network where six customers are serviced by only one vehicle as long as the capacity of the vehicle is large enough to deliver all the customer orders. All these service networks are feasible and all the above assumptions are satisfied.

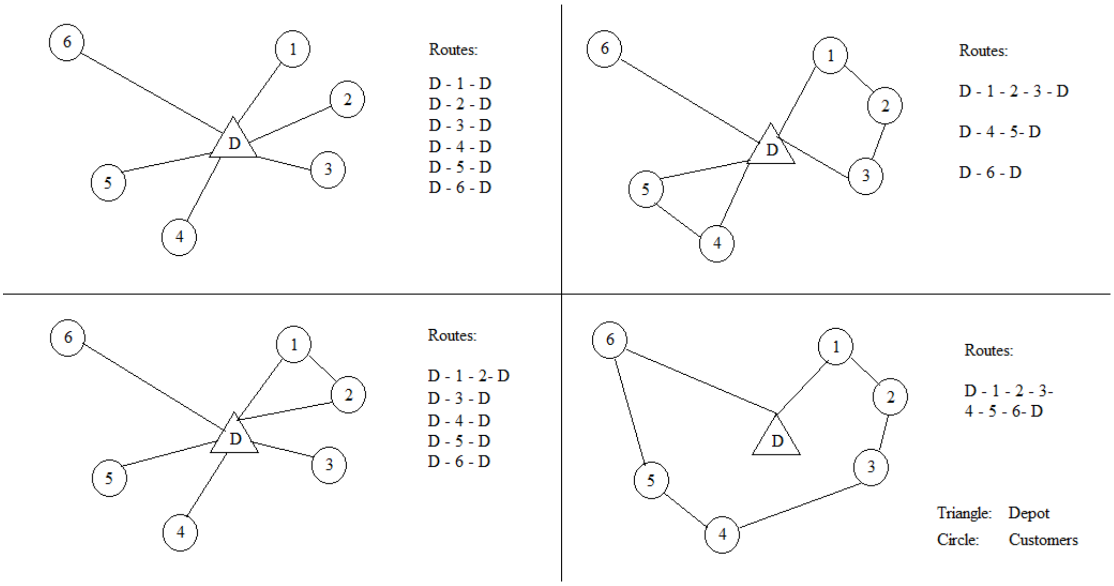

*Figure 2.4 Possible service routes for a situation with one company and six customers*

After introducing daily tasks and basic assumptions, mathematical model for vehicle routing problem can be built.

Let $G = (V, E)$ be a complete graph, where $V$ stands for a vertex set and $E$ stands for an edge set. $V = \{0, 1, 2, \dots, n\}$ is a vertex set consisting of all the nodes in the graph, where 0 stands for the depot and $\{1, 2, \dots, n\}$ stands for all the customers. As a result, the segment line between each pair of nodes is an edge, and the set $E$ consists of all the edges in the graph. Let $K$ be the total amount of vehicles, and capacity of each vehicle is $b_k$. Let $a_i \geq 0$ be the demand of each customer, and let $c_{ij}$ be the travel cost between each pair of nodes.

$$\min \sum_{ijk} c_{ij} x_{ijk} \tag{1}$$

$$s.t. \sum_{i} a_i y_{ik} \leq b_k \quad k = 1, \dots, K \tag{2}$$

$$\sum_{k} y_{ik} = \begin{cases} K, & i = 0 \\ 1, & i = 1, \dots, n \end{cases} \tag{3}$$

$$y_{ik} = 0 \; or \; 1, i = 0, \dots, n \tag{4}$$

$$\sum_{i} x_{ijk} = y_{jk} \quad j = 0, \dots, n; k = 1, \dots, K \tag{5}$$

$$\sum_{j} x_{ijk} = y_{ik} \quad i = 0, \dots, n; k = 1, \dots, K \tag{6}$$

$$\sum_{i,j \in S * S} x_{ijk} \leq |S| - 1 \quad S \subseteq \{1, \dots, n\}; 2 \leq |S| \leq n - 1; k = 1, \dots, K \tag{7}$$

$$x_{ijk} = 0 \; or \; 1 \quad i = 0, \dots, n; j = 0, \dots, n; k = 0, \dots, n \tag{8}$$

The above model (Fisher and Jaikumar, 1981) consists of decision variables (Eq. 4 and Eq. 8), an objective function (Eq. 1), and constraints (Eqs. 2-3 and Eqs. 5-7). $y_{ik}$ is a binary variable with two possible values 0 or 1. If the value equals 1, it indicates that customer $i$ is visited by vehicle $k$ in the optimal solution; on the contrary, if the value equals 0, it indicates that customer $i$ is not visited by vehicle $k$. For example, if $y_{51} = 1$ and $y_{52} = 0$ are in the optimal solution, it indicates that customer 5 is visited by vehicle 1 and not visited by vehicle 2. $x_{ijk}$ is also a binary variable with two possible values 0 or 1. If the value is 1, it shows that vehicle $k$ visited customer $j$ after directly visited customer $i$; otherwise, the value is 0. For example, if $x_{231} = 1, x_{251} = 0$ and $x_{351} = 1$ in the optimal solution, it shows that vehicle 1 visited node 2, node 3 and node 5 one after another.

The objective function of the model aims to minimize the total travel costs. The parameters in the objective function consist of a cost vector, which stands for the travel costs on each edge. Constraint (2) is a set of capacity constraint where there are altogether $K$ constraints. More specifically, the total customer demand each vehicle services must be less than or equal to the capacity of the vehicle. Constraint (3) shows the number of routes starts from or end at each nodes. For the depot, there are altogether $K$ routes starting from the depot, and there are altogether K routes ending at the depot. For each customer, there is only one route starting from each customer, and there is exactly one route ending at each customer. This set of constraints indicates that all the vehicles must be used to deliver customer orders. Constraint (5) and (6) show the relationship between two sets of binary variables. Constraint (5) consists of $n * k$ constraints. For each vehicle $k$, there is only one incoming arc on node $j$. Analogously, constraint (6) consists of $n * k$ constraints. For each vehicle $k$, there is only one outgoing arc on node $i$. Constraint (7) eliminate all sub cycle which are not start and end at the depot, as sub cycle is not a valid route.

For example, there is one depot and three customers $A$, $B$ and $C$. If these three customers are connected with each other and form a cycle ($A - B - C - A$), this cycle is a sub-tour without a depot in the route. This sub tour violate against basic assumptions. As a result, constraint (7) was introduced to make sure that all sub-tours are eliminated.

Apart from the above basic assumptions, a side constraint can also be added to vehicle routing problems. A side constraint stands for "*the variety of constraints that can be added for individual companies as faced in industry*." (Kilby and Shaw, 2006, p.803). As such, there are several variants of vehicle routing problems (Table 2.5).

In capacitated vehicle routing problem (CVRP), there is only one capacity constraint (Cordeau et al., 2007), which is the simplest vehicle routing problem. The capacity constraints guarantee that the total demand one vehicle can deliver should not exceed the capacity of the vehicle. In multi-depot vehicle routing problem (MDVRP), there are more than one depot with sufficient supply (Contardo and Martinelli, 2014). While in the vehicle routing problem, there is only one depot. In vehicle routing problem with time window (VRPTW), time constraint is considered (Cordeau et al., 2007). Each customer has a time window, and must be visited within this time interval. Early arrival is allowed, but have to wait until the start of the time range. Late arrival is not allowed, as customer demand cannot be satisfied. In vehicle routing problem with pickup and delivery (VRPPD), both pickup and delivery were considered (Kilby and Shaw, 2006). In a vehicle routing problem with backhauls (VRPB), return commodities are allowed (Toth and Vigo, 1997). In a distance vehicle routing problem (DVRP), travelling distances are minimized instead of travelling costs. Besides, there is a travel distance constraint (Weise, Podlich and Gorldt, 2009). The travel distance constraints make sure that the total distance travelled by one vehicle should not be more than the upper bound on travel distance. In periodic vehicle routing problem (PVRP), the planning period is expanded from one day to several days (Angelelli and Speranza, 2002). Customer demands are split into several parts, and customers can be visited more than once on different days. The figure below shows the relations between vehicle routing problem and its variants (Figure 2.5).

| **Category** | **Constraint** |
|---|---|
| **CVRP** | Capacity constraint of each vehicle |
| **MDVRP** | Multi-depot instead of one depot |
| **VRPTW** | Time window constraint of each customer |
| **VRPPD** | Both pickup and delivery are considered |
| **VRPB** | Return commodities are allowed |
| **DVRP** | Minimize travelling distances & travel distance constraints |
| **PVRP** | Extend planning period from one day to several days |

*Table 2.5 Side constraints of different vehicle routing problems*

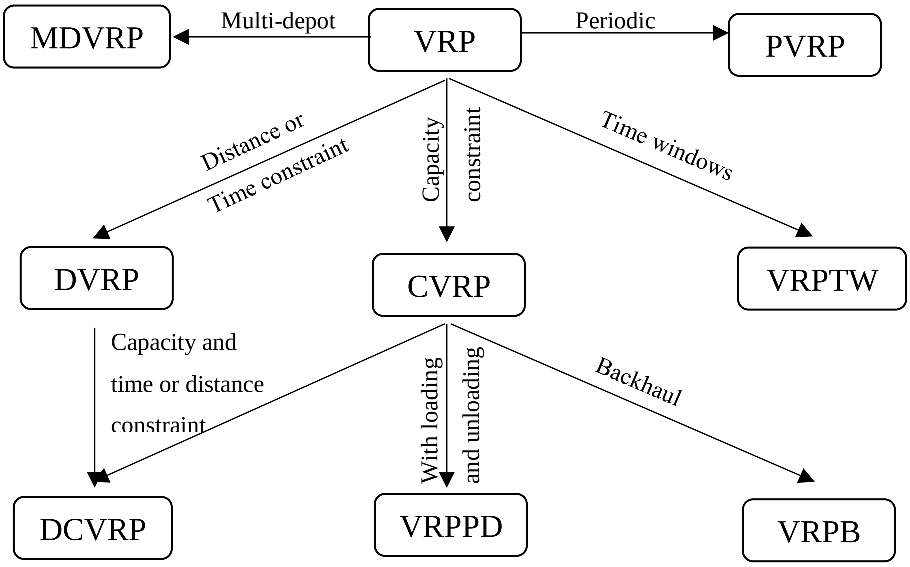

*Figure 2.5 Various vehicle routing problem models and their relations (Weise, Podlich and Gorldt, 2009, p.32)*

After introducing different models of vehicle routing problems, the algorithms, the dataset and the software applied to solve the models are then discussed.

For capacitated vehicle routing problems, Alba and Dorronsoro (2006) applied a cellular genetic algorithm to solve the problem, and used benchmark datasets proposed by Van Breedan, Golden et al. and Taillard respectively. Baldacci, Toth and Vigo (2007, 2010) applied branch-and-cut method, branch-and-cut-and-price method and set partitioning method as solution algorithms. Benchmark instances class A, B, E, M, P and F are applied as datasets. CPLEX software was applied to solve the problem. Analogously, Golden, Raghavan and Wasil (2008) also used benchmark instance class A, B, P, and E. Besides, there are two other groups of datasets, one proposed by Golden et al (1984) and the other proposed by Fischetti, Toth and Vigo (1994). They applied a robust branch-and-cut-and-price algorithm to solve the capacitated vehicle routing problem. Meanwhile, CPLEX 10.0 is used to solve the models. Some of the best solutions reported in the previous literature were improved by applying the above algorithms.

For multi-depot vehicle routing problems, Contardo and Martinelli (2014) applied cutting plane method and column-and-cut generation method as solution algorithms. They applied a dataset proposed by Cordeau, Gendreau and Laporte (1997). In addition, they also tested the algorithms by applying instances class A, B, E, F, M and P, which are widely used benchmark dataset by researchers. The software they use to solve the problem are CPLEX and C++.

For vehicle routing problem with time window, Solomon (1987) applied three heuristics methods as follows: saving heuristics, insertion heuristics and a time-oriented sweep heuristics. They used instances proposed by Mingozzi and Toth. They also used randomly generated dataset. Baldacci, Mingozzi and Roerti (2012) applied the data instances proposed by Solomon, where a branch-and-cut algorithm is applied to solve vehicle routing problem with time window. Similarly, Danna and Le Pape (2015) also used the dataset proposed by Solomon, while a branch-and-price algorithm is used to solve the problem. Kallehauge et al. (2005) applied column generation algorithm and brand-and-bound algorithm to solve vehicle routing problem with time window and used assumed data as dataset.

For vehicle routing problem with pickup and delivery, Dell’Amico, Righini and Salani (2006) applied column generation algorithm and a branch-and-price algorithm to obtain the optimal solution. They used benchmark instances classes 1, 2S, 2C, 3S, and 3C as the dataset.

To sum up, vehicle routing problem and its variants aims at identifying the optimal routing plan with the minimized travel costs or distances by satisfying both basic constraints and side constraints. These constraints can also be applied to individual companies. CPLEX is commonly used software to solve these optimization programming problem, and it can also applied together with C++. Assumed data and benchmark instances are commonly used data sources to test models.

It should be noted that the existing mathematical models related to vehicle routing problems are only applicable in the situation where there is only one company, and they are not suitable for collaborative city logistics situations. On one hand, vehicle routing problem and its variants have been developed based upon a single-company situation. More specifically, the fleet of vehicles, the set of customers, and the travel costs all belong to one company. On the other hand, in a logistics alliance, there need to be strategies or mechanisms to encourage them to collaborate, such as negotiation, auction mechanisms and profit sharing (Berger and Bierwirth, 2007). The existing one-company vehicle routing problem does not consider these mechanisms.

### *2.3.2 Multiple Carrier Situation*

Vornhusen, Wang and Kopfer (2014) proposed a mixed-integer programming model for carriers, where pickup and delivery, transfer, and time window were also considered. Liu et al. (2010) proposed a collaborative model for carriers based upon truckload transportation. In this model, carriers made decisions on whether to service the customers by utilizing their own vehicles or let other carriers to service the customer. Perez-Bernabeu et al. (2015) applied the multi-depot vehicle routing problem model, a metaheuristic algorithm and benchmark instances to the following three scenarios: a collaborative scenario, a non-collaborative clustered scenario and a non-collaborative scattered scenario. They concluded that transportation companies could form a collaboration to improve service, reduce costs, decrease delivery times and lessen greenhouse gas emissions. Li (2013) proposed a collaborative vehicle routing problem with pickup and delivery model aimed at minimising travel distance by satisfying the routing arrangement and vehicle availability constraint. Buijs et al. (2016) proposed a generalized pickup and delivery problem based upon a Dutch logistics service provider. Three situations were considered: a non-collaborative situation, a fixed geographical division and a variable geographical division. The data from this Dutch logistics service provider were applied to this problem. They concluded that both these two collaborations could reduce total travel distance compared with non-collaboration, and a variable geographical division was better than the fixed one.

Cruijssen and Salomon (2004) applied collaboration in transportation companies, where there are two transportation companies and a distribution centre. They considered order sharing, and concluded that order sharing was an effective way to reduce costs. Verstrepen, Cools, Cruijssen & Dullaert (2009) proposed a collaborative system in logistics with a dynamic framework. They stated that this framework has already been applied by Flanders Institute for Logistics, and successfully form a stable collaboration with four industrial companies.

Berger and Bierwirth (2010) proposed a collaborative carrier routing problem. They considered non-collaboration, centralized collaboration and decentralized collaboration. They considered information sharing, and concluded that information sharing could increase profits. Francois et al. (2017) proposed collaborative models for timber transportation, where there are two transport companies. They also considered non-collaboration, decentralized collaboration and centralized collaboration. They considered inefficient supply, depot sharing and information sharing in different scenarios, and concluded that a full collaboration can minimize total travel distances. Munoz-Villamiza, Montoya-Torres and Faulin (2017) proposed a collaborative transport network and took $CO_2$ emissions into consideration.

Bloos and Kopfer (2011) proposed a collaborative system with three modules, a cooperative framework, a re-allocation mechanism and profit sharing. They pointed out that this system could decrease costs and increase revenue by realizing mutual trust. Gonzalez-Feliu and Salanova (2012) proposed a collaborative transport system with six modules, a knowledge management system, a data processing tool, a risk factor, a transportation management system, an environmental module, and a decision support system. They focused on non-collaborative, collaboration with two members, and collaboration with all members. However, they concluded that collaboration with all members was not always the best result.

Fenandex, Fontana and Speranza (2016) proposed a collaborative incapacitated arc routing problem from a game theory perspective. They considered customer sharing, and classified customer into required customers and shared customers. Both non-collaborative and collaborative situations were taken into consideration, and they compared the optimal solution between these two situations and concluded that collaboration was effective to increase profits.

Wang and Kopfer (2014) proposed a request exchange mechanism for a collaborative model with pickup, delivery and time window, and a request exchange mechanism to solve the model. Chen (2016) studied an analogous situation and proposed a clock-proxy auction method to exchange information. Wang, Kopfer and Gendreau (2014) introduced subcontracting to request an exchange mechanism to reduce costs.

Some authors addressed collaboration according to profit or cost allocations, especially based on game theory. Krajewska et al. (2008) applied the Shapley value to allocate costs among freight carriers. Kimms and Kozeletskyi (2016) proposed an efficient core computation algorithm to allocate costs. Liu, Wu and Xu (2010) proposed a weight relative savings model to allocate profits among carriers fairly. They concluded this method was effective by comparing it with three other commonly used allocation methods, i.e. proportional allocation, the Shapley value and Nucleolus. Ozener (2014) proposed a duality-based method and applied the Shapley value to allocate transportation costs and $CO_2$ emissions among carriers.

Frisk et al. (2010) proposed collaborative transportation models on the operational level with cost allocation. Equal profit method was applied to allocate costs. They pointed out that backhauling could improve service performance, while geographical distribution could achieve savings. Audy, D'Amours and Rousseau (2011) proposed a cooperative transportation model with four furniture companies. Equal profit method and the alternative cost avoided method (ACAM) were applied to allocate costs. They concluded that collaboration could reduce costs as well as travel time.

| Authors | Content | |
|---|---|---|
| **Li (2013)** | Collaborative VRP with simultaneous pickup and delivery | Proposed a collaborative model |
| **Vornhusen, Wang and Kopfer (2014)** | Collaborative carrier vehicle routing | Proposed a mixed integer programming model |
| **Liu et al. (2010)** | Collaborative truckload transportation | Proposed a collaborative model |
| **Perez-Bernabeu et al. (2015)** | Collaboration in road transportation | Distances and emissions reduction |
| **Wang and Kopfer (2014)** | Collaborative transportation planning | Proposed request exchange methods |
| **Chen (2016)** | Carrier collaboration problem | Clock-proxy auction mechanism |
| **Wang, Kopfer and Gendreau (2014)** | Collaborative operational transportation planning | Request exchanging |
| **Krajewska et al. (2008)** | Freight carrier collaboration (game theory) | Request allocation<br>Profit sharing |

| | | |
|---|---|---|
| **Kimms and Kozeletskyi (2016)** | Cooperative travelling salesman problem | Cost allocation |
| **Liu, Wu and Xu (2010)** | Collaborative carrier alliance (game theory) | Proposed a profit allocation method |
| **Ozener (2014)** | Collaborative sustainable transportation planning (game theory) | Allocation mechanism |
| **Buijs et al. (2016)** | Collaborative transportation planning | Proposed solution methods |
| **Cruijssen and Salomon (2004)** | Collaboration among transportation companies | Order sharing |
| **Verstrepen, Cools, Cruijssen & Dullaert (2009)** | Horizontal cooperation in logistics | Dynamic framework |
| **Berger and Bierwirth (2010)** | Collaborative carrier routing problem | Information sharing |
| **Frisk et al. (2010)** | Collaborative transportation model | Cost allocation |
| **Audy, D'Amours and Rousseau (2011)** | Cooperative transportation | Cost allocation<br>Negotiation |
| **Fernandez, Fontana and Speranza (2016)** | Collaborative arc routing problem (game theory) | Profit improvement |
| **Francios et al. (2017)** | Collaborative model for timber transportation | Minimize total travel costs |
| **Munoz-Villamiza, Montoya-Torres and Faulin (2017)** | Collaborative transport network | Considered CO2 emission |
| **Bloos and Kopfer (2011)** | A collaborative system | Decrease costs and increase revenue by realizing mutual trust |
| **Gonzalez-Feliu and Salanova (2012)** | Collaborative transport system | Grand alliance was not always best |

*Table 2.6 A brief summary of studies*

### *2.3.3 Solution Algorithms*

*Commonly used algorithms:*

| **Model** | **Article** | **Solution algorithm** |
|---|---|---|
| **CVRP** | Fischetti, Toth and Vigo (1994), Toth and Vigo (2002) | Branch-and-bound |
| **CVRP** | Baldacci, Toth and Vigo (2007, 2010) | Branch-and-cut-and-price |
| | Golden, Raghavan and Wasil (2008) | Branch-and-cut-and-price |
| **MDVRP** | Contardo and Martinelli (2014) | Cutting plan method<br>Column and cut generation |
| | Solomon (1987) | Heuristics |
| | Baldacci, Mingozzi and Roerti (2012) | Brach-and-cut |
| | Danna and Le Pape (2015) | Branch-and-price |
| | Kallehauge et al. (2005) | Column generation |

|  |  |  |
|---|---|---|
| **VRPPD** | Dell'Amico, Rigini and Salani (2006) | Column generation<br>Branch-and-price |

*Table 2.7 Commonly applied solution algorithms*

Branch-and-bound method is one of the algorithms to solve vehicle routing problems. And it is still regarded as a state-of-the-art algorithm with exact solution (Cordeau et al, 2007; Montoya-Torres et al. 2015; Kallehauge et al. 2005).

Branch and cut algorithm, branch and cut and price method are also effective exact algorithms which are widely used exact algorithms to solve different variants of vehicle routing problem (Liong, et al., 2008).

Column generation is an effective heuristic method. Especially, it could solve linear programming with large columns.

### *Inverse Programming*

As reviewed in 2.3.1, cost vectors are usually parameters in the objective function. Analogously, when taking capacity exchange costs into consideration, this set of capacity exchange costs is also formulated in the objective function as a parameter to measure the total profits each member in the alliance can obtain. The set of binary variables are usually decision variables in vehicle routing problems. As such, these capacity exchange costs and binary variables are also parameters and decision variables respectively in non-collaborative model and ideal collaborative model. It is expected that the optimal solution to the ideal collaborative model is the optimal solution the grand alliance wish to achieve. That is, the optimal routing plan can be obtained before forming alliances. They applied inverse programming to solve the linear programming problems.

Inverse programming is usually applied to solve problems that the result of the problems can be measured or obtained by repeated experiments, while some parameters can not be easily achieved (Kirsch, 2010).

In inverse programming, there is an original optimization problem. Under current circumstance, the value of cost vector $c$ is known in advance, and the value of a set of feasible solutions $f^*$ can be obtained. After applying inverse programming algorithm, the feasible solution to the original problem turned out to be the optimal solution to the original problem with a new cost vector $d$ (Ahuja and Orlin, 2001; Taranotola, 2005; Kirsch, 2010; Bulut & Ralphs, 2015). Inverse programming algorithm also minimize the difference between $d$ and $c$.

As such, the variables in the original optimization problem turns out to be the parameters in the inverse programming problem, while the parameter (cost vector) in the original problem turns out to be the decision variables to the inverse problems. The purpose of inverse programming is to find the optimal cost coefficient in the objective function for the given optimal feasible solutions.

However, inverse programming can only be directly applied to linear programming problems. For mixed integer programming problems, a cutting plane method is then introduced by Wang (2009).

## 2.4 How to Allocate Benefits to Each Member

In this section, how to allocate benefits (profits or costs) to each member in the alliance is reviewed. Proportional allocation is first reviewed as a simple allocation method. Then, widely used advanced methods are also reviewed as follows: the core, Shapley value, nucleolus and equal profit methods. Last, contract design is discussed.

### *2.4.1 Simple Method*

Proportional method is a simple method to allocate total benefits to each member in the alliance proportionally according to different criteria. The simplest way to allocate total benefits is to share the benefits equally. Usually, proportional allocation allocates benefits according to the reasonable weight of each player. For example, the stand-alone costs (Ozener and Ergun, 2008; Ozener, 2014) and the quantities of customer orders (Massol and Tchung-Ming, 2010; Frisk, et al. 2010).

### *2.4.2 Advanced Methods*

The Core

The core is a solution concept in cooperative game theory. There are three important properties as follows:

- Efficiency: all benefits earned by grand alliance can be allocated
- Individual rationality: benefit allocated to each member is no less than the individual benefit (non-collaboration)
- Group rationality: benefit allocated to sub-coalition is more than or equal to the value earned by sub-coalition

The above properties guarantee that the grand coalition is the only and most stable collaboration (Kubo and Kasugai, 1992; Chalkiadakis, Elkind and Wooldridge, 2012).

However, it is possible that the core may be empty (Gilles, 2010), where there is no optimal solution under this circumstance. When the core is not empty, it is possible that the solution is not unique (Simchi-Levi, Chen and Bramel, 2014).

In a word, allocation in the core makes sure that the grand coalition is the only stable alliance formed by the players, and there is a high percentage chance of achieving optimal solutions.

### Shapley Value

Shapley value is another solution concept of cooperative game theory, which also follows the efficiency property (Hezarkhani, Slikker, and Woensel, 2015; Sun et al. 2015). In this method, marginal cost is calculated when one player enters one coalition (either sub-coalition or grand coalition). Thus, benefits earned by grand alliance is then allocated to each member according to the average of marginal costs (Engevall, Gothe-Lundgren and Varbrand, 2004). A special feature of Shapley value is that it is unique (Guajardo, Jornsten and Ronnqvist, 2015). However, the allocation is usually not in the core (Simchi-Levi, Chen and Bramel, 2014).

### Nucleolus

Nucleolus is also a solution concept of cooperative game theory. In this method, excess of coalition is applied to measure the differences between the attainable benefits obtained by sub-coalition and the sum of total benefits allocated to each member in the sub-coalition (Engevall, Gothe-Lundgren & Varbrand, 2004). This value represents the savings, and how satisfied the coalition is. Analogous to the Core and Shapley value, Nucleolus also follows the efficiency property, which can allocate all the benefits earned by grand alliance (Simchi-Levi, Chen and Bramel, 2014). More importantly, Nucleolus always exist and is unique (Frisk et al. 2010), and the nucleolus is in the core if the core is not empty (Lozano et al., 2013).

### Equal Profit Method (EPM)

Equal profit method is proposed by Frisk et al. (2006), as they expected to allocate nearly equal relative profit to each member. In this method, difference of relative savings are measured to allocate cost among players. Audy, D’Amous & Rousseau (2008) modified the equal profit method by introducing a minimum cost-saving percentage and three nontransferable costs for each member. They obtained a stable collaboration and a profitable collaboration, and all the players are satisfied with the allocation plan.

### *2.4.3 Contract Design*

As stated in section 2.2.4, binding agreements can be signed on the distribution of payoffs, and solution concepts reviewed in 2.4.2 allocate payoffs to each player in the alliance. However, these methods only allocate payoffs among members without the implementation of the allocation plan. More specifically, members can make decisions on individual resources and sharing resources in decentralized collaboration. Even if a member can receive more benefits from the alliance, it may not be in accordance with the individual decisions this member made. Thus, a strong contract need to be proposed to tackle with allocation and implementation.

Chu et al. (2020) designed a contract for a common agency model, where there is a common agency and several express companies. In their contract, they considered two aspects, reduce fairness concern during the collection of package and what factors influence an optimal contract. They designed this profit-sharing contract to guarantee the profit allocation plan.

In maritime transportation, there is also effective and efficient network design, where profit allocation plan was implemented. Agarwal and Ergun (2010) proposed a collaborative model where there is a central decision maker and multiple carriers to make decisions on optimal service routes. The central decision maker first make the global optimal solution (optimal routing plan and ship allocation plan) for the grand alliance. Then, single carriers make individual decisions on cargo selection as there is no need to deliver all cargos. Capacity exchange costs were introduced to measure the profits earned by carriers when exchange occurs. Their research aims at the optimal value of capacity exchange costs which satisfy both global optimal solution and individual optimal solution. Compared with existing allocation algorithms, profits are not simply allocated.

## 2.5 Research Gaps

In view of the above literatures on both collaborative city logistics and mechanism designs, the following research gaps in mechanism design for collaborative city logistics can be identified.

**Gap 1**: There is a lack of studies on designing motivation mechanisms for logistics alliance on the tactical level. More specifically, how logistics companies (such as transportation companies) can form an alliance and share their vehicles and customer information. A motivation mechanism is required to provide incentives for logistics companies to share their resources.

**Gap 2**: there is also a lack of studies on the contract design for logistics alliances. Existing studies allocated total profits or total costs to each member in the alliance applying current existing allocation methods. These allocation methods only focus on allocating benefits, and these methods cannot guarantee the implementation of allocation plan. Thus, designing a contract for logistics companies is required to not only allocate benefits to each member in a fair way, but also guarantee the allocation plan.

In recognition of these gaps, the PhD project will be positioned to investigate the cost/benefit allocation strategies and mechanisms of city logistics alliances on the tactical level by extending existing vehicle routing problem models. Two gaps are identified in the existing literature, and efforts will be made in the project to fill the gaps.

In order to fill the above research gaps, the following research questions are discussed.

**Research Question 1**: how to design service network for non-collaborative city logistics. Model can be built for individual company in order to figure out the vehicle routing plan with the highest profits. The maximum profits each company can earn plays an important role when making decisions to form a collaboration.

**Research Question 2**: how to achieve the highest profit by the grand alliance. This research question focuses on building a model for the ideal alliance. A central decision maker can make use of all the information and resources for the entire alliance. The maximum profits earned by ideal alliance is regarded as the maximum profits a collaboration can obtain.

**Research Question 3**: how to design motivation and allocation mechanisms for logistics alliance. This research question deals with the research gap 1 and 2. A decentralized collaboration is formed, as each member can make decisions individually. The members choose to form an alliance because of the common goal, while each member aims at individual optimal solution. This requires motivation mechanism to provide proper incentives, and also requires allocation mechanism to allocate maximum profits (achieved by answering research question 2) to each member in a fair way.

**Research Question 4**: how to quantify the results and make comparisons. Models are first solved with the optimal solutions. Then, results are compared between non-collaboration (related to research question 1) and ideal collaboration (related to research question 2). It is expected that collaboration can perform better than non-collaboration. After that, another comparison is made between non-collaboration (related to research question 1) and logistics alliance (related to research question3). It is expected that the profits allocated to each member is better than the profits each member can earn when working independently.

## 2.6 Summary

In this chapter, literatures related to collaborative city logistics, alliance forming (including model building and model solving) and benefit allocating are reviewed.

In section 2.1, a brief introduction is offered, followed by the structure of this chapter.

In section 2.2, collaborative city logistics is reviewed. Companies can identify with whom to form an alliance, and what resources can be shared in the alliance. Centralized collaboration and decentralized collaboration is reviewed, followed by two key issues of logistics collaboration.

In section 2.3, literatures related to how to form an alliance is reviewed. Alliance forming is one of the key issues of logistics collaboration. Literatures related to single player model (non-collaborative model) building, multiple players model (collaborative model) building, and relevant solution algorithms are reviewed.

In section 2.4, literatures related to how to allocate benefits to the members in the alliance is reviewed. Benefit allocation is also a key issue of logistics collaboration. Five allocation methods are reviewed, but these methods cannot ensure the allocation plan can be implemented. Thus, contract design is reviewed to guarantee an optimal allocation plan.

In section 2.5, two research gaps are proposed according to the previously reviewed literature. Research questions are discussed according to the research gaps.

# Chapter 3 Research Methodology

## 3.1 Introduction

In line with the research aims and the research questions, this study focuses on designing a reasonable contract for logistics alliances. This contract deals with the following two problems: 1) how each member can make daily decisions; and 2) how each member can share the overall benefits. Mathematical models are then built according to the contract. It is expected that this contract can encourage each member to form a stable logistics alliance. More specifically, it is expected that each member can satisfy with the benefits allocated to them. In order to achieve the research aims and answer the research questions, the research process is discussed in this chapter.

In section 3.2, how to design this research is presented according to the following aspects: 1) a brief introduction on how to answer each research questions; 2) a research framework on relevant models for four stages; and 3) basic assumptions of non-collaborative models and collaborative models.

In section 3.3, data collection and data analysis are discussed. Data collection is introduced based on the sources of data and the content of data. While data analysis is discussed in the light of the following aspects: 1) how to build a mathematical model; 2) how to solve a mathematical model (including relevant software); and 3) how to evaluate the results.

In section 3.4, the following two research methods are analysed, 1) cooperative game theory, and 2) cutting plane methods. The content of the above two methods are discussed, as well as how to apply these two methods to this research.

In section 3.5, research ethics are discussed.

In section 3.6, a brief summary of this chapter is offered.

## 3.2 Research Design

In this research, the objective is to investigate motivation and allocation mechanisms which are provided by the contract. More specifically, the motivation mechanism can provide incentives that each member can form and stay in an alliance, while the allocation mechanism can allocate total benefits among each member in a fair way. In other words, these two mechanisms guarantee a stable collaboration.

This research is conducted on the tactical level and based on the developed mathematical models. In other words, this is a tactical decision subject to low level operational decision, i.e. vehicle routing problem and its variants. In order to achieve the research aim, a quantitative method is then applied to this research by answering research questions.

*RQ1: design optimal vehicle routing plan for non-collaborative city logistics*

This research question focuses on individual decisions made by each company, and a mathematical model is built in order to answer this research question. More specifically, vehicle routing problem and its variants can be directly applied to this non-collaborative city logistics situation. In this research, vehicle routing problem with time window is taken into consideration in this stage.

Vehicle routing problem with time window clearly identified a single company routing problem with the following resources:

- A single depot with sufficient supply
- A fleet of vehicles with finite capacity
- A number of customers with different demands and different time windows

The daily task of one company is to design service routes by satisfying the following constraints.

- Each service route starts and ends at the depot
- Each customer is satisfied with the right demand and is visited once only within the time range

The optimal solution can be achieved by solving the model of vehicle routing problem with time window, and the optimal routing plan is the one with the maximum profits.

*RQ2: determine the maximum total profits of grand alliance*

This research question deals with the ideal collaboration, or the complete collaboration. In this collaboration, a virtual central decision maker can have access to all the information (the depot, the fleet of vehicles and the information of customers) held by individual members. As a result, all the members then work as a single company. It is clear that this ideal collaboration can achieve the most attainable profits without considering resources sharing and relevant costs.

In this stage, another mathematical model is built in order to answer this research question. Multi-depot vehicle routing problem can then be applied to this ideal collaboration with the following resources:

- Multiple depot with sufficient supply
- All fleets of vehicles with homogeneous capacity
- All customers with different demands and various time windows

The daily task of the central decision maker is to design service routes for the ideal collaboration by following the constraints below.

- Each depot is both the start and the end of each service route
- Each customer is visited once only by satisfying the right demand within the time window

After solving the model of multi-depot vehicle routing problem, the optimal solution can be achieved. The optimal service network is the one with the maximum profits, and then each company can deliver commodities to the relevant customers. As stated earlier, resources sharing is not taken into consideration in this ideal collaboration as the members are working as a single company in this centralized collaboration. In other words, companies do not charge each other when they deliver commodities for other companies. The optimal solution to this problem is regarded as the optimal solution of the grand alliance.

*RQ3: design reasonable motivation and allocation mechanisms to allocate total profits from grand alliance to each member in the logistics alliance in a fair way, and to keep this alliance stable.*

A logistics alliance is formed in order to answer this research question. Compared with the ideal collaboration, this logistics alliance is a decentralized collaboration. In other words, there is no central decision maker making decisions for the entire alliance. Each member in the logistics alliance can make own daily decisions. Each company can get access to own resources, e.g. the depot, a fleet of vehicles and own customers. Besides, each member can get access to the resources of other companies, e.g. the customers of other companies. As a result, a member can decide to deliver commodities to own customers as well as the customers of other members. In other words, resources sharing is taken place when a member is making daily decisions. Under this circumstance, one member can charge the other member when this member delivers commodities for the other company, and vice versa.

As each member can make own decisions in this stage, one model is built for a member by satisfying the following resources:

- One depot with sufficient supply
- One fleet of vehicles
- Customers not only from own company but also from other companies

In this way, a mathematical model for each company can be designed to figure out the daily service routes to deliver commodities to customers. Compared to the model of non-collaborative city logistics, each company deals with own depot and own fleet of vehicles. The only difference between these two models is the customers, where the customer information is shared among all the members in the logistics alliance. Due to the capacity limit of the vehicles, each member in the alliance may not have enough resources to satisfy all the customer. Moreover, a customer far away from the depot can lead to more travelling costs. If adding this customer to the service routes may lead to less profits, a member in the alliance may not wish to satisfy this customer. As a result, a member in the alliance can make decisions on whether a demand of a customer they wish to satisfy or not. Under this circumstance, not all the customers need to be satisfied by a single member.

As stated above, information of customers are shared among members in the alliance. It is important to figure out how to charge each other when they share resources. Then, capacity exchange costs are taken into consideration in this model, when one member choose to deliver commodities for own and other companies.

In this study, two ways are designed to measure the capacity exchange costs: 1) according to the travel distances; and 2) according to the actual weight of each commodity.

In the first way, the amount of capacity exchange costs are calculated through travel distances. As stated above, capacity exchange costs are calculated when one member in the alliance choose to deliver commodities for another company, and vice versa. It is assumed that the travelling distance are calculated as the total distance directly from the depot to the customer and then back to the depot. In other words, it is assumed that one member use one vehicle to deliver commodities for one customer of other members. Besides, there is also a rate (per kilometre) identified by each member in the alliance. Thus, the amount one company can charge from another company is calculated as follows:

- Capacity exchange cost (received) = rate (this company) * travel distance (from own depot to other customer and back to own depot)

Analogously, the total amount one company pays to the other company is calculated as follows:

- Capacity exchange cost (paid) = rate (other company) * travel distance (from other depot to own customer and back to other depot)

In the second way, the capacity exchange costs are measured according to the weight of each commodity. Another rates (per kilogram) are proposed by each member in the alliance. Thus, the total amount one company can charge from the other company is calculated as below:

- Capacity exchange cost (received) = rate (this company) * weight of commodity (demand of other company)

Similarly, the total amount one company pays to the other company is calculated as below:

- Capacity exchange cost (paid) = rate (other company) * weight of commodity (own customer demand).

After identifying capacity exchange costs, these costs are then introduced to the model to measure the total profits. For each member in the alliance, the total profits achieved is formulated as follows:

- Total profits = total revenue – travelling costs + capacity exchange costs (received from others) – capacity exchange costs (paid to others)

Analogous to non-collaborative situation, each member in the alliance aims at maximizing individual total profits by following relevant constraints. However, the logistics alliance is regarded as a decentralized collaboration, where each member in the alliance cannot get access to all information of the alliance. In other words, the above model of each member only consists of part of all information. As a result, a combined model with all information available is taken into consideration. In this way, this combined model is formulated by linking the models of individual members together.

As stated above, the central decision maker makes decisions for the ideal collaboration on the service network. It is clear that the optimal solution to the ideal collaboration is the best result of the grand alliance. When companies form a logistics alliance, the maximum overall profits of the grand alliance is also the maximum attainable profits which the logistics alliance aims at achieving. For the purpose of achieving the maximum profits and then allocate all the profits to all the members in the alliance, inverse programming and cutting plane methods are applied to the combined model. In other words, the combined model can guarantee the global allocation plan proposed by the ideal collaboration. By applying these two methods, the optimal routing plan then becomes parameters rather than variables, and the rates become variables rather than parameters. The next step is to identify the value of capacity exchange costs of each company. The value of total profit of each member can be identified as well, where the total profit of each member is regarded as the profits allocated to each member in the alliance.

The process to obtain the above profit allocation plan forms a contract, where profits earned by grand alliance can be allocated to each member in the alliance in a fair way. As the logistics alliance is a decentralized collaboration, each member in the alliance can make own decision according to this contract. This guarantee that individual decisions are in accordance with the decisions made by the central decision maker.

*RQ4: quantify and compare non-collaborative situation and collaborative situations*

Compared with the above three research questions which focuses on building mathematical models, this research question deals with quantifying and analysing the results of the previous models. As stated above, models of non-collaborative situation, ideal collaboration and logistics alliance are built to answer the first three research questions. This research question aims at solving these three models first. Then, the best routing plan of individual company, the optimal routing plan of the ideal collaboration, and the profit allocation plan of the logistics alliance can be obtained. After quantifying the models, comparisons among the results can be made according to the following aspects: 1) the sum of profits earned by companies under non-collaboration and the total profits obtained by the ideal collaboration; and 2) the profits earned by individual company under non-collaboration and the profits allocated to each member in the logistics alliance.

It is expected that collaboration is better than non-collaboration. It is also expected that the profits allocated to each member in the alliance is more than the profits individual member can earn when making decisions individually.

After briefly introducing how to answer each research question, a research framework is then proposed to clearly explain the research design according to model building and result analysing.

**Stage 1: City Logistics without Collaboration**

Problem definition:
- Each company only deliver commodities to own customers
- Each company makes decisions individually

Model purpose:
- To determine the optimal service network and the vehicle allocation plan simultaneously with the maximum profit

Data sources:
- Published benchmarks
- Assumed dataset

Research Question:
- answer research question one

**Stage 2: City Logistics with Ideal and Complete Collaboration**

**(Game Theory)**

Problem definition:
- Different companies work together as a single company where there is a virtual central planner making decisions
- Information is shared and transparent, including vehicle information and customer information
- Capacity exchange cost is not taken into account

Model purpose:
- To determine the optimal vehicle routing plans as well as the vehicle allocation plans with the maximum ideal profits

Data sources:
- Published benchmarks
- Assumed data

Research Question:
- Answer research question two

**Stage 3: Collaborative City Logistics by Forming a Logistics Alliance**

**(Game Theory)**

Problem definition:
- Different companies sign and obey a binding agreement which provides the allocation plan
- There is no central decision maker and each member can make decisions individually
- Each member in the alliance can only use their own fleet of vehicle to deliver customer orders to customers

| | |
|---|---|
| | - Customer information is shared and each member can deliver commodities to not only own customers but also customers from other companies<br>- Capacity exchange cost is taken into account |
| Model purpose: | - To calculate the value of capacity exchange costs and to identify the profit allocation plan according to the optimal vehicle routing plan |
| Contract design: | - Rates measured by travelling distances<br>- Rates measured by the actual weight of each commodity |
| Solution algorithms: | - Inverse programming<br>- Cutting plan method |
| Data sources: | - Published benchmarks<br>- Assumed data |
| Research Question: | - Answer research question three |

**Stage 4: Computational Results**

| | |
|---|---|
| Tasks: | - Quantify profits earned by non-collaborative city logistics with relevant optimal vehicle routing plan<br>- Quantify total profits obtained by ideal collaboration with relevant optimal service network<br>- Quantify profits allocated to each member in the alliance<br>- Compare total profits between non-collaboration and ideal collaboration<br>- Compare individual profits between non-collaborative situation and the logistics alliance<br>- Analyse the results under different circumstances |
| Research Question: | - Answer research question four |

*Figure 3.1 A brief illustration of the research framework*

After illustrating the research framework based on model building, solving and analysing in a clear way, basic assumptions are then proposed as following before setting up mathematical models.

- Assumption 1: there are altogether $n$ companies and each company has a depot and a fleet of vehicles.
- Assumption 2: each company makes decision individually on servicing its own customers daily before forming an alliance. Each company needs to determine the optimal routing plan every day for the next day’s deliveries.

- Assumption 3: resources will be shared after the formation of the logistics alliance, including the vehicles, depots and customer orders. Cost and profit will be split between member companies.
- Assumption 4: each customer has a demand, and all the demands must be satisfied.
- Assumption 5: there is sufficient stock at each depot to meet all the demands of the customers.
- Assumption 6: the vehicle routing schedules should be realized within a single day.
- Assumption 7: the weight of cargo will be considered in the process of allocating it to vehicles. However, the other requirements will not be considered, such as the temperature for food products and the dimensions for light cargo.
- Assumption 8: travelling time and travelling distances between each pair of nodes (including customers as well as depots) is fixed, where traffic on the road will not be considered.
- Assumption 9: road network will be modelled as a directed or complete network. The dynamic feature of the road network will not be considered, such as the traffic signals and temporary road closures.

The above assumptions are commonly adopted in the existing models of vehicle routing problem (Kuyzu, 1985; Toth and Vigo, 2002; Daneshzand, 2011; Montoya-Torres et al., 2015).

After making the above assumptions clearly, models can then be built according to different situations in the above three different stages. A mathematical model of vehicle routing problem has the following features:

- Decision variables
- Constraints
- An objective function

More specifically, decision variables are defined to find available service routes and available vehicle allocation plans in both stage one and stage two. The objective function is defined to minimize the total costs or maximize the total profits, where the available routing plans become optimal. Constraints are various under different circumstances, e.g. vehicle capacity and time window. In this study, vehicle capacities are considered identical with truckload shipping, and all the demands delivered by a vehicle must be no more than the capacity of the vehicle. The time window clarify the time range within which a customer must be satisfied.

Analogous to the first two stages, decision variables are set to find available routing plans, the objective function is defined to measure the maximum profits with relevant constraints. However, as the optimal routing plan with the maximum attainable profits are already figured out by the grand alliance, the third stage focuses on calculating the value of rates as well as the individual profits allocated to each member in the alliance. Then, inverse programming and cutting plane methods are applied to the combined model, where decision variables becomes parameters in the objective function, and vice versa. In this way, the optimal service routes and the total profits are known in advance, while the capacity exchange costs become decision variables in this stage. Moreover, the objective function minimize the differences between current capacity exchange costs and optimal capacity exchange costs rather than maximize the total profits. Profits allocated to each member in the alliance can then be calculated by solving the model which applies inverse programming and cutting plan method. In the final stage, all models can be quantified, and results between non-collaborative and collaborative situations are compared and analysed.

As stated above, this study focuses on designing a contract providing motivation and allocation mechanisms on the tactical level, where these mechanisms can motivate companies to form a sustainable and stable logistics alliance. In this way, companies can agree to sign and obey the binding agreement in order to make a logistics alliance stable.

## 3.3 Data Collection & Data Analysis

### *3.3.1 Data Sources*

In traditional vehicle routing problems and collaborative models, benchmark dataset and assumed datasets are two commonly applied datasets (Baldacci, Toth and Vigo, 2007; Baldacci, Toth and Vigo, 2010; Fukasawa et al., 2006; Alba and Dorronsoro, 2006; Contardo and Marinelli, 2014; Azi, Gendreau and Potvin, 2007; Solomon, 1987; Baldacci, Mingozzi and Roerti, 2012; Danna and Le Pape, 2015; Dell'Amico, Rinhini and Salani, 2006; Cruijssen and Salomon, 2004; Berger and Bierwirth, 2007; Berger and Bierwirth, 2010; Perez-Bernabeu et al, 2015; Buijs et al. 2016; Frisk et al., 2010; Audy, D'Amours and Rousseau, 2011). These datasets were applied to test whether a model works as expected. The below table summarizes the common dataset applied when solving relevant vehicle routing problems.

| Dataset | Author (year) | Relevant Model |
|---|---|---|
| **Instances Classes A, B, E, M & P** | Baldacci, Toth and Vigo (2007) | CVRP |
| | Baldacci, Toth and Vigo (2010) | CVRP |
| | Fukasawa et al. (2006) | CVRP |

| | | |
|---|---|---|
| | Contardo and Martinelli (2014) | MDCVRP |
| **Instances Class F** | Baldacci, Toth and Vigo (2010) | CVRP |
| | Fukasawa et al. (2006) | CVRP |
| | Contardo and Martinelli (2014) | MDCVRP |
| **Instances Classes 1, 2S, 2C, 3S & 3C** | Dell'Amico, Rinhini and Salani (2006) | VRPPD |
| **Randomly generated dataset** | Solomon (1987) | VRPTW |
| | Azi, Gendreau and Potvin (2007) | VRPTW |
| **Instances proposed by Solomon** | Baldacci, Mingozzi and Roerti (2012) | VRPTW |
| | Berger and Bierwirth (2010) | Collaboration |
| **Instances proposed by Cordeau, Gendreau and Laporte** | Contardo and Marinelli (2014) | MDVRP |
| **Instances proposed by Golden et al.** | Alba and Dorronsoro (2006) | CVRP |
| **Instances proposed by Tailard** | Alba and Dorronsoro (2006) | CVRP |
| **Instances proposed by Van Breedam** | Alba and Dorronsoro (2006) | CVRP |
| **Instances derived from the TSP benchmark** | Berger and Bierwirth (2007) | Collaboration |
| **Benchmark instances** | Perez-Bernabeu et al. (2015) | Collaboration |
| **Assumed dataset** | Danna and Le Pape (2015) | MDVRP |
| | Cruijssen And Salamon (2004) | Collaboration |
| **Data collected from companies** | Buijs et al. (2016) | Collaboration |
| | Frisk et al. (2010) | Collaboration |
| | Audy, D'Amours and Rousseau (2011) | Collaboration |

*Table 3.1 A brief introduction of commonly applied datasets*

As described above, there are a large number of datasets available which has already been proposed and tested for different models under different circumstances. These existing datasets are commonly applied datasets to test whether a modified model works or not. Besides, the existing benchmark datasets are plenty enough to test one single model. In this way, there is no need to collect data from companies in practice for the purpose of testing a model.

In this research, datasets are used in the following stages: 1) city logistics without collaboration; 2) city logistics with ideal collaboration; and 3) city logistics alliances.

In the first stage, published benchmarks data for vehicle routing problem with time window models are applied, which are available on https://neo.lcc.uma.es/vrp/vrp-instances/. Each dataset consists of the following data: 1) coordination of nodes (including depot and customers); 2) demand of customers; 3) beginning of time window; 4) end of time window; 5) service time; 6) number of vehicle; and 7) capacity of vehicle. Except for the above data, travelling costs can be measured by travelling distances, which can be easily calculated through coordination of two nodes. Due to the fact that the above datasets can be applied to models to measure the minimum total costs rather than calculate the maximum total profits, assumed data is also taken into consideration. More specifically, the assumed data is applied to generate revenue, as the total profit is calculated by revenue minus total costs. After introducing the content of data, these data are then applied to non-collaborative model and to test the model. The aim of this stage is to figure out the optimal service routes with the maximum profits.

In the second stage, published benchmarks data for multi-depot vehicle routing problem with time window models are used. These benchmarks are available on https://neo.lcc.uma.es/vrp/vrp-instances/. Each dataset consists of the following information: 1) coordination of depot as well as customers; 2) customer demand; 3) start of time range; 4) end of time range; 5) service time; 6) vehicle number; and 7) vehicle capacity. Analogously, travelling costs can be measured by travelling distances, and revenue is generated to calculate the total profits. The aim of this stage is to figure out the optimal service network with the maximum attainable profits of grand alliance.

In the third stage, the optimal solution of the ideal collaboration is applied as the dataset, including the optimal service routes and the optimal overall profits of the grand alliance. The aim of this stage is to figure out the value of capacity exchange costs, and then come up with the profit allocated to each member in the alliance.

### *3.3.2 Data Analysis*

<u>*Model building*</u>

In this research, models are built for non-collaborative city logistics, ideal collaboration and city logistics alliance. As discussed earlier in 3.2 research design, models are then displayed in the table below.

| **Stages** | **Model** |
|---|---|
| Stage 1: non-collaboration | • Vehicle routing problem with time window |
| Stage 2: ideal collaboration | • Multi-depot vehicle routing problem with time window |
| Stage 3: logistics alliances | • Model for each member in the alliance with resources sharing<br>• A combined model |

| | |
|---|---|
| | • An inverse model of the combined model |

Table 3.2 Models built in each stages

*Model Solving and Relevant Software*

After building mathematical models, datasets are then applied to test a model. The solution to a model can be achieved if there is no error. For vehicle routing problem and collaborative models, CPLEX is the most commonly used software to solve the mixed-integer programming models (Table 3.3). CPLEX Optimizer can solve a linear programming problem and a mixed integer programming problem with high-performance (http://www.ibm.com/analytics/cplex-optimizer). Except for using the language of CPLEX to solve a mathematical model, other languages can also be used when CPLEX software is combined with other software, such as C++ and Java. In this way, C++ language is allowed to compile a project. As stated above, this combination is widely used to solve vehicle routing problems.

| | **Author (year)** | **software** |
|---|---|---|
| **CVRP** | Baldacci, Toth and Vigo (2007) | CPLEX |
| | Baldacci, Toth and Vigo (2010) | CPLEX |
| | Fukasawa et al. (2006) | CPLEX 7.1 |
| | Alba and Dorronsoro (2006) | JCELL2oli has been implemented in Java |
| **MDVRP** | Contardo and Martinelli (2014) | CPLEX and C++ |
| **Collaborative Model** | Audy, D'Amours and Rousseau (2011) | ILOG CPLEX |

Table 3.3 Examples of commonly used software

According to the fact that CPLEX together with C++ can provide a powerful tool to solve linear programming problems and mixed-integer programming problems, this combination of these two software is applied to solve all the models in the three stages. More specifically, the model of non-collaborative city logistics, the model of ideal collaboration, the model of single member in the alliance, and the combined model of logistics alliance are mixed-integer programming problems. While the relaxed model of the combined model and the inverse model in stage three are linear programming models. In a word, CPLEX and C++ software are applied to solve models in different stages in this research.

*Result Evaluation*

As discussed earlier in 3.2 research design, results are first quantified as follows:

- Stage 1: optimal routing plans and maximum profits of non-collaboration
- Stage 2: optimal service network and maximum overall profits of ideal collaboration
- Stage 3: the value of capacity exchange costs and profit allocation plan

The results are then compared as follows:

- Comparison between non-collaboration and ideal collaboration (total profits)
- Comparison between non-collaborative city logistics and the logistics alliance (individual profit)

It is expected that collaboration is better than non-collaboration, and the final profit allocation plan is effective and efficient.

## 3.4 Research Methods

### *3.4.1 Cooperative Game Theory*

Cooperative game theory is applied in both stage two (ideal collaboration) and stage three (logistics alliances), where there are more than two companies choose to form a collaboration in a centralized way and in the decentralized way respectively. More specifically, a cooperative coalitional game with transferrable utilities (a branch of cooperative game theory) is applied in this study, which focuses on benefit allocation.

In a cooperative game theory, there is a set of players $N = \{1, 2, 3, \dots, n\}$ and a characteristic function $V(N)$. The players are regarded as the members in the alliance, and the characteristic function measures the total benefits obtained by the grand alliance. There is also an allocation vector $x = \{x_1, x_2, \dots, x_n\}$ in cooperative game theory, where $x_i$ stands for the profits received from the alliance. Each allocation vector stands for one available allocation plan, and allocate benefits to each member in the alliance.

For the purpose of forming a stable logistics alliance, an allocation in the core is then taken into consideration. This concept is a significant solution concept in cooperative theory with two important properties: efficiency property and group rationality property. More specifically, efficiency property makes sure that the payoff of the grand coalition is the maximum payoff available, where the total payoff can be allocated to each member in the alliance. While group rationality property makes sure that no players can form a sub-coalition for the purpose of achieving more benefits, as the total payoff allocated by the grand alliance to the members who wish to form a sub-coalition is more than or equal to the total benefit the sub-coalition can obtain (Kubo and Kasugai, 1992; Chalkiadakis, Elkind and Wooldridge, 2012). These two properties guarantee that the grand coalition is the only stable collaboration which can be formed by the members.

For the purpose of allocating total benefits to each member in a fair way, a coalitional cooperative game can provide reasonable motivation mechanism and allocation mechanism. The logistics alliance aims at achieving the global optimality of the grand coalition, while each member in the alliance aims at individual maximum payoff. Then, capacity exchange costs is taken into consideration to provide incentives. These incentives can provide players with acceptable profits and can also encourage players to share their resources as expected. More importantly, no matter which solution each member selects, the global optimality can be satisfied. That is, optimal solutions can be achieved as planned.

### *3.4.2 Inverse Programming & Cutting Plane Methods*

As discussed earlier, the optimal solution of stage two will be applied in stage three to figure out the value of capacity exchange costs. Under this circumstance, the decision variables in stage two are no longer decision variables in stage three. They become the information known in advance. Then, inverse programming is considered to form an inverse model.

Inverse programming can be directly applied to linear programming problems. There are altogether two models, a primal model and an inverse model. There is also a set of feasible solution known in advance to the primal model. New value of cost vector can be achieved by applying inverse programming, where the set of feasible solution becomes optimal. However, the model of vehicle routing problems and its variants are mixed-integer programming problems rather than pure linear programming problems, as the decision variables are binary variables. Under this circumstance, inverse linear programming solution method cannot be directly applied to the problems discussed in this study.

A cutting plane method based on inverse programming is then taken into consideration. The cutting plane method proposed by Wang (2009) can be applied to solve the inverse integer programming problems. It first requires an original optimization model, which is the combined model in this study. The decision variables in this problem are binary variables. Then, the content of the algorithm is briefly described in vector-matrix notations as follows.

(Original Model) $\max \quad c^T x$

$$s.t. \quad Ax \leq b$$

$$x \in \{0,1\}$$

The above model is an optimization model, where decision variables are binary variables. The model consists of a set of decision variables $x$, a group of constraints, and an objective function. The cost vector $c$ is the parameter in the objective function. The objective function is to maximize the total profits.

$$\text{(Inverse Model)} \qquad \begin{aligned} & \mathit{minimize} && e + f \\ & \mathit{subject\ to} && A^T\pi \geq c - e + f \\ & && \pi \geq 0, e \geq 0, f \geq 0 \end{aligned}$$

The above inverse model derives from the dual model of the relaxed original model, where $c - d = e - f, \|c - d\| = e + f$.

The cutting plane method based on inverse programming algorithm aims at finding a new cost vector $d = c - e + f$ of the inverse model, which can make the feasible solution $x'$ becoming the optimal solution to the original model.

More specifically, when the cost vector is $c$ in the original model, $x'$ is a set of feasible solution. While the cost vector is changed to $d$ instead of $c$ in the original model, $x'$ is then the optimal solution. The steps to obtain the new cost vector $d = c - e + f$ are described as follows.

- Step 1: solve the inverse model to obtain optimal solutions $\pi^*, e^*$ and $f^*$. Thus, the new cost vector $d$ can be obtained, as $d = c - \ e^* + f^*$.
- Step 2: apply new cost vector $d$ instead of $c$ in the original model, then solve the original model to obtain the current optimal solution $x^*$.
- Step 3: test the inequality $(c - e^* + f^*)x' \geq (c - e^* + f^*)x^*$. If this inequality is satisfied, then stop. The current cost vector $d = c - \ e^* + f^*$ is the optimal cost vector. If the above inequality is not satisfied, a set of constraints $(c - e + f)x' \geq (c - e + f)x^*$ is then added to the inverse model. After that, go back to step 1, and repeat this procedure until stop.

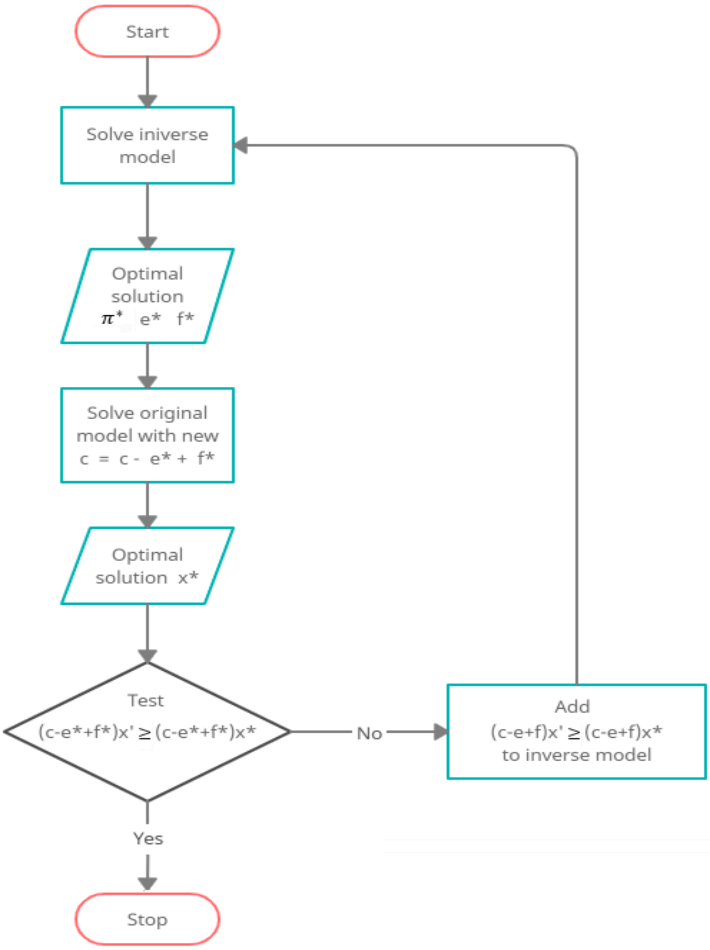

*Figure 3.2 Steps to use cutting plane method*

The above steps and figure clearly describe the procedure to obtain the new cost vector $d$. The inequality in step three guarantee the feasible solution becomes optimal with the new cost vector $d$. The left term represents the value of objective function of the original model with the new cost vector $d$ and the feasible solution known in advance. While the right term is the other value of the objective function of the original model with the new cost vector $d$ and the current optimal solution obtained in step two. In this way, this inequality ensures that the feasible solution with the new cost vector $d$ maximize the total profits.

In this research, the optimal service network of ideal collaboration and the maximum overall profits can be obtained by solving the model in stage two, which is regarded as the feasible solution to the model of logistics alliance. The combined model in stage three is regarded as the original model, where the capacity exchange costs act as the parameter. Then, cutting plane methods can be applied to the combined model in order to form the inverse model. Meanwhile, the capacity exchange costs act as the variables in the inverse model. By following the above steps, new values of capacity exchange costs can be obtained where the feasible solution becomes the optimal solution to the original model. After that, profits allocated to each member in the alliance can be calculated with the optimal capacity exchange costs. In this way, the optimal allocation plan can be achieved.

## 3.5 Research Ethics

Research ethics is a criterion to judge individual participation, for the sake of making certain researchers doing their research and achieving their goals in an ethical way (Denscombe, 2010). In other words, research ethics deals with the condition, where human actions are involved (Saunders, Lewis and Thornhill, 2012). Researchers need to obey the research ethics, as it can lead researcher to do the right thing without any harmful actions (Denscombe, 2007).

In this research, a quantitative study is conducted with four stages. In the first stage, the objective is to build a mathematical model for a single company making decisions individually. In the second stage, the objective is to build a model for the ideal collaboration when all the companies work as a large single company. In the third stage, the objective is to build models for the logistics alliance with resources sharing. The data sources of the above three stages are benchmark datasets and assumed datasets. In the last stage, the result of each model is quantified and then compared to ensure the effectiveness of the model. Besides, motivation and allocation mechanisms are also put forward to answer the research questions. It is obvious that there is no human participation in this research. More specifically, data are not gathered either by conducting interviews or through questionnaires. As a result, there is no ethical issue involved in this research.

## 3.6 Summary

This chapter focuses on designing a research, discussing issues on data collection and data analysis, discussing research methods as well as research ethics. Meanwhile, the research aims can be achieved and the research questions can be answered.

In section 3.1, there is a brief introduction about this chapter and the structure of the following sections.

In section 3.2, the research design is discussed. A quantitative research is conducted to achieve the research aims, and what to do to answer each research question is discussed in detail. In addition, a research framework is displayed to show the research design according to model building, model solving and result analysis in a clear way. The relevant assumptions of model and the features of model are later introduced for both non-collaborative situation and collaborative situation.

In section 3.3, data collection and data analysis are discussed. In data collection, the sources of data and the content of data in each stage are presented. In data analysis, model building, model solving (including relevant software) and model evaluating are discussed. Apart from model solving, the other two parts are discussed in a brief way, as they are previously discussed in section 3.2 research design.

In section 3.4, research methods are discussed, including cooperative game theory, inverse programming and cutting plane methods. Cooperative game theory is applied in ideal collaboration (stage two) and the logistics alliance (stage three), where a centralized collaboration and a decentralized collaboration are formed respectively. Inverse programming is discussed briefly, as it can only be applied to linear programming problems. Then, cutting plane methods based on inverse programming is discussed in detail, including the steps to apply this method, as it can be applied to mixed-integer programming problems. Moreover, the value of capacity exchange costs can be achieved by applying cutting plane method based on inverse programming.

In section 3.5, research ethics are discussed. In this study, a quantitative research is conducted through model building, model solving and result analysis. The sources of dataset are benchmark dataset and assumed dataset, without human participation. As a result, there is no ethical issues in this research.

# Chapter 4 Travel Distance based Mechanism Design

## 4.1 Introduction

In this chapter, it aims at how to motivate logistics companies to form a stable logistics alliance and how to allocate total profits obtained by the ideal collaboration to each member in the logistics alliance. The research aim is achieved and research questions are answered by designing a reasonable contract for the members in the alliance. This contract is designed to provide incentives to encourage companies to form an alliance and to provide reasonable profit allocation plan each member in the alliance can be satisfied with. Meanwhile, this contract is also designed to guarantee the profit allocation plan can be achieved before forming an alliance. It is expected that the profits allocated among alliance members are more than the profits they can earn when they are making decisions individually. Analogously, it is expected that the sum of profits allocated to a group of members is more than the profits this group can earn when they choose to form a sub-coalition. Under this circumstance, each member in the alliance is satisfied with the contract and is also willing to sign and obey the contract. In this way, the profit allocation plan can be implemented and guaranteed by the contract.

In section 4.2, a problem definition is first offered, including a brief introduction of the problem, the models to be built at the first three stages (non-collaboration, ideal collaboration and logistics alliance), and the basic assumptions of different models in different stages.

In section 4.3, details of non-collaborative situation is presented. This section focuses on building a mathematical model for non-collaborative city logistics. This includes how each company makes individual decisions on the best service routes with the maximum profits. In this study, a mathematical model of vehicle routing problem with time window is applied and then explained.

In section 4.4, details of ideal collaboration is introduced. This section focuses on setting up a mathematical model for complete collaboration, where there is a central decision planner makes the global decision for the entire alliance. This includes how the central decision maker figure out the best service routes with the maximum overall profits. In this study, a mathematical model of multi-depot vehicle routing problem with time window is built and explained.

In section 4.5, how to form a logistics alliance and how to allocate profits among members in the alliance are discussed. This section devotes to the case of logistics alliance, which including how a member in the alliance makes individual decisions according to resources not only from their own, but also resources shared by others. In this logistics alliance, capacity exchange costs are taken into consideration to measure the costs when members choose to share their resources. After that, how to calculate the capacity exchange costs is introduced.

In section 4.6, a brief summary of this chapter is offered.

### 4.2 Problem Description

As discussed in 1.3 research aims and research questions, this research extends the existing vehicle routing problems to the context of logistics alliance. In order to answer the research questions, the following three situations are proposed in 3.2 research design (including research framework):

- Stage 1: city logistics without collaboration
- Stage 2: city logistics with ideal collaboration
- Stage 3: collaborative city logistics by forming a logistics alliance

Stage 1: before forming an alliance, one company need to identify the total benefits it can earn when making decisions individually. As discussed earlier, vehicle routing problem with time window model is applied in this research. The total profits can then be quantified by each company when they do not form an alliance. A comparison can be made between the profits earned by non-collaborative city logistics and the profits allocated by the logistics alliance. In this way, one company can choose to take part in an alliance if it is satisfied with the allocation plan. Otherwise, one company can choose to quit an alliance. In order to make an alliance stable, it is important to come up with proper incentives to encourage potential members to build an alliance.

Stage 2: analogous to the non-collaborative situation, a collaboration also aims at the optimal routing plan with the maximum profits when forming an alliance. The problem to this stage is that how can the collaboration achieve the maximum attainable profits. It is then assumed that there is a central decision maker who can make the overall routing plans for the entire alliance. The virtual central decision maker can get access to all information and resources. Without considering resources sharing, this decision maker can make the most of all the resources to service all the customers. As discussed earlier, multi-depot vehicle routing problem with time window model is applied to quantify the total profits. An ideal collaboration, or complete collaboration, is then formed where all the companies work as a single company. One company do not need to deliver commodities to a customer if the customer is too far away from the depot. The central decision maker can allocate the customer to other company in order to reduce costs. Compared the solution to the ideal collaboration with the sum of profits obtained by individual companies (non-collaboration), it is expected that the collaboration can achieve better results. Compared to the collaboration with resources sharing, it is obvious that the decision made by the virtual central planner is the best decision. In order to form a logistics alliance, the remaining problem is that how the logistics alliance can achieve the total profits earned by ideal collaboration.

Stage 3: compare to ideal collaboration, there is no central decision maker when companies choose to form a logistics alliance. Analogous to non-collaborative city logistics, each member in the alliance can make decisions individually. When taking resources sharing into consideration, each member can make decisions on optimal rouging plan with the maximum profits by considering own resources and resources from other members. A contract is required before forming a logistics alliance. This contract focuses on the following issues: 1) what resources can be shared; 2) how to charge each other when sharing resources; and 3) how to allocate profits to each member in a fair way. Meanwhile, a contract also deals with the following problems: 1) how can this decentralized collaboration guarantee members to obtain the same profits under perfect collaboration; and 2) how can the individual decisions made by each member in accordance with the global collaboration. More specifically, a contract need to ensure that the decision made by the virtual central planner under perfect collaboration is still followed by logistics alliances. Besides, no matter what decisions each member in the alliance made, the optimal solution to the ideal collaboration can still be achieved. In order to solve these problems, capacity exchange costs are introduced to measure the total costs when members are sharing their resources. The amount of capacity exchange costs receiving from others determine the profits arising from resources sharing, while the amount of capacity exchange costs paying to others determine the costs arising from resources sharing.

In the contract, it allows members to share customer information, including customer demand and time window. In other words, each member can only get access to partial information in this decentralized collaboration. A mathematical model is built for each member in the alliance when they make decisions individually. This model is an extended form of vehicle routing problem with time window. The total profits (including revenue, travelling costs, and capacity exchange costs) can be obtained by quantifying this model.

As stated earlier, the model built for each member in the alliance only have access to partial information, while the model for ideal collaboration have access to all information. These two models are not in accordance with each other. For this reason, a model with full information is then proposed by combing the models of each member in the alliance. This combined model can guarantee all the profits earned by ideal collaboration can be allocated to each member in a fair way.

After clearly introducing what to do in the first three stages, this problem will be mathematically formulated. Let $L = \{1, 2, \dots, l\}$ be a set of companies, and each company $l$ can choose to form an alliance. Each company has a depot $n + 1$, and a set of customers $N = \{1, 2, \dots, n\}$. Each customer has a non-negative demand $d_i$, and a non-negative time window $[a_i, b_i]$, where customer $i$ needs to be visited between this time ranges. Early arrival to customer $i$ is allowed, but the company has to wait until the beginning time $a_i$. However, late arrival to customer $i$ is not allowed, i.e., customer $i$ is not available to be serviced.

In order to achieve the research aim and answer the research questions, a research framework is designed and basic assumptions are proposed as follows.

In the first stage, logistics companies make their own decisions. Each company can apply vehicle routing problem with time window model to calculate the total profits they could earn. In this stage, each company only services their own customers using their own vehicles. After solving the model, they can determine the optimal routes and vehicle allocation plan. There are basic assumptions that must be obeyed in the vehicle routing problems in this stage. For the purpose of easy and clear understanding, the basic assumptions used for developing the non-collaborative model in the first stage are given as follows.

- Assumption 1: there are $l$ logistics companies.
- Assumption 2: each company has $n$ customers with different demands and time windows.
- Assumption 3: each company owns a depot with sufficient stock to service all the customers on a daily basis.
- Assumption 4: each company owns a fleet of vehicles with identical capacity.

- Assumption 5: travelling time and costs between each pair of nodes (including depot and customers) are fixed.
- Assumption 6: service network is modelled as a directed complete network, and dynamic features of road network and urban traffic are not considered.

In the second stage, the case of perfect collaboration is considered. In this case, logistics companies make decisions like a single company. A virtual central planner has access to all the information, and makes all the decisions for all the companies, where the ownership of vehicles and customer orders are not considered by the virtual central planner. In other words, vehicle of one company can be allocated to service customer order of another company. As such, a multi-depot vehicle routing problem with time window model can be applied to obtain the optimal routing plan for each vehicle with the maximum profits of the entire system. The assumptions followed by this perfect collaboration model are similar to those followed by non-collaboration.

- Assumption 1: there are altogether $l$ logistics companies.
- Assumption 2: there are altogether $n * l$ customers with different demands and time windows.
- Assumption 3: there are $l$ depots with sufficient stock to service all the customers on a daily basis.
- Assumption 4: each company owns a fleet of vehicles with homogenous capacity.
- Assumption 5: travelling time and costs are fixed.
- Assumption 6: service network is modelled as a directed complete network, without considering dynamic features.

In the third stage, the case of logistics alliance is considered. In this case, logistics companies have decided to form a logistics alliance by following some form of contract. In this stage, models for conventional vehicle routing problems cannot be directly applied. New models need to be developed whilst satisfying the following new assumptions. These new assumptions for logistics alliance model are displayed as follows.

- Assumption 1: each company owns a depot with sufficient stock to service all the customers (not only own customers but also other company's customers) on a daily basis.
- Assumption 2: each company makes its own decision on how to share the resources.

- Assumption 3: capacity exchange costs is taken into consideration to measure the costs when sharing resources.

### 4.3 Network Design for Non-Collaborative Situation

In this part, a routing service network is designed for a single company when each company makes own decisions to maximise their own profits. In the first stage, each company make decisions separately. The aim of this stage is to simultaneously design vehicle routing plan and vehicle allocation plan for each company respectively. As time window is taken into consideration, the model built in this stage also considers the time range each customer is visited by a particular vehicle. Each company aims at achieving their maximum profits, and each customer must be visited within the corresponding time window. According to the assumption that each company owns only one depot, this is a single-company VRP problem. Before presenting models for this scenario, the following notations are shown first.

**Indexes**
$\boldsymbol{i}, \boldsymbol{j}$: stand for nodes ($\boldsymbol{n+1}$ for depot, $\boldsymbol{1, 2, \ldots, n}$ for customers)
$\boldsymbol{k}$: stands for vehicles

**Parameters**
$\boldsymbol{R_i}$: unit revenue received when satisfying customer $\boldsymbol{i}$
$\boldsymbol{d_i}$: demand of customer $\boldsymbol{i}$
$\boldsymbol{c_{ij}}$: travelling cost between node $\boldsymbol{i}$ and node $\boldsymbol{j}$
$\boldsymbol{q_k}$: capacity of vehicle $\boldsymbol{k}$
$\boldsymbol{s_i}$: service time of customer $\boldsymbol{i}$
$\boldsymbol{T_{ij}}$: travelling time from node $\boldsymbol{i}$ to node $\boldsymbol{j}$
$\boldsymbol{M}$: a large number
$\boldsymbol{a_i}$: the lower bound of time window
$\boldsymbol{b_i}$: the upper bound of time window

**Decision Variables**
$\boldsymbol{x_{ijk}}$: whether customer $\boldsymbol{i}$ and $\boldsymbol{j}$ are serviced by vehicle $\boldsymbol{k}$ one after another
$\boldsymbol{y_{ik}}$: whether customer $\boldsymbol{i}$ is visited by vehicle $\boldsymbol{k}$
$\boldsymbol{t_{ik}}$: the time when vehicle $\boldsymbol{k}$ arrives at customer $\boldsymbol{i}$

*Table 4.1 Notations of Indexes, Parameters and Variables*

Let $G = (V, E)$ be a directed graph with a vertex set $V = \{1, 2, \ldots, n+1\}$ and an edge set $E$, where there is a set of customers $\{1, 2, \ldots n\}$ and a depot $n+1$. Each customer has a nonnegative demand $d_i$, and a range of time window $[a_i, b_i]$. Besides, there is also a nonnegative service time $s_i$ for each customer, and a nonnegative revenue $R_i$ to obtain if customer $i$ is visited. Between each pair of nodes, there is a positive travelling cost $c_{ij}$ and travelling time $T_{ij}$.

This company owns a fleet of $K$ vehicles, and each vehicle $k$ has a capacity $q_k$.

In this model, there are three sets of decision variables described as follows.

1) There is a set of binary variables $x_{ijk}$, and each variable only takes either of two values, 0 or 1. If $x_{ijk} = 1$, it means that edge <$i,j$> is visited by vehicle $k$. If this edge is not visited, then $x_{ijk} = 0$.

2) There is another set of binary variables $y_{ik}$. If $y_{ik} = 1$, it menas that customer $i$ is visited by vehicle $k$. If customer $i$ is not visited by vehicle $k$, then $y_{ik} = 0$.

3) There is a set of non-negative continuous variables $t_{ik}$, which stands for the beginning time customer $i$ is visited by vehicle $k$.

The aim of this stage is to design a service network and a vehicle allocation plan for each single company to obtain the maximum profits, such that

- Each route starts and ends at the depot
- Each customer can be visited only once within the time window by exactly one vehicle
- Each vehicle should satisfy the capacity constraint and time window constraint
- Each company should not use more vehicles than available

The mathematical formulation is displayed as follows:

(Model 1)

$$Maximize \quad \sum_{i=1}^{n+1}\sum_{k=1}^{K} R_i d_i y_{ik} - \sum_{i=1}^{n+1}\sum_{j=1}^{n+1}\sum_{k=1}^{K} c_{ij} x_{ijk} \tag{9}$$

$$subject\ to \quad \sum_{i=1}^{n+1} x_{ijk} = y_{jk} \quad j \in N', k \in K \tag{10}$$

$$\sum_{j=1}^{n+1} x_{ijk} = y_{ik} \quad i \in N', k \in K \tag{11}$$

$$\sum_{i=1}^{n} x_{i,n+1,k} \leq 1 \quad k \in K \tag{12}$$

$$\sum_{j=1}^{n} x_{n+1,jk} \leq 1 \quad k \in K \tag{13}$$

$$\sum_{i=1}^{n+1} x_{ihk} - \sum_{j=1}^{n+1} x_{hjk} = 0 \quad h \in N', k \in K \tag{14}$$

$$\sum_{k=1}^{K} y_{ik} = 1 \quad i \in N \tag{15}$$

$$\sum_{i=1}^{n+1} d_i y_{ik} \leq q_k \quad k \in K \tag{16}$$

$$t_{ik} + s_i + T_{ij} - M\big(1 - x_{ijk}\big) \leq t_{jk}, i \in N, j \in N, k \in K \tag{17}$$

$$a_i y_{ik} \leq t_{ik} \leq b_i y_{ik}, \qquad i \in N', \;\; k \in K \tag{18}$$

$$x_{ijk} \in \{0, 1\} \,\forall i, j, k; \quad y_{ik} \in \{0,1\} \,\forall i, k; \quad t_{ik} \geq 0, \forall i, k \tag{19}$$

In the above formulation, objective function (9) aims to maximize total profits for each company. Constraints (10) and (11) show the relationship between two sets of binary decision variables. Constraints (12) and (13) make sure that each route start and end at the depot. Constraint (14) makes sure that the amount of incoming arcs is equal to the amount of outgoing arcs. Constraint (15) makes sure that each customer is visited by exactly one vehicle. Constraint (16) is a capacity constraint, it makes sure that the total capacity vehicle used must be no more than its physical capacity. Constraint (17) calculates the beginning time to service each customer. Constraint (18) makes sure the beginning time to service each customer is within the time window. Constraint (19) lists the three decision variables in this stage.

After solving the above model, the optimal routing plans and the maximum overall profits could then be obtained by each member.

## 4.4 Network Design for Ideal Collaboration

In this part, a network is designed for the ideal collaboration. In the second stage, companies choose to form an ideal collaboration. It is assumed that there is a virtual central decision maker who can make routing plans for the entire alliance. This collaboration guarantee all the companies together can achieve the largest overall profits as they work as a single company.

The virtual central planner makes decisions on the following aspects: 1) the central decision maker makes a decision on the optimal service network, i.e., the optimal service routes to deliver commodities to the customers; 2) the central decision maker makes a decision on the optimal vehicle allocation plan, i.e., which vehicles are used on the optimal service routes; and 3) the central planner makes a decision on the time each customer is visited, which is between the time windows of each customer.

In this stage, all the information and resources are available for the central decision maker. These information and resources are displayed as follows.

- there are altogether $L$ depots from $L$ different companies, as each company owns one depot
- there are altogether $n * L$ customers, and all the demands of the customer, the location of the customer and the time window of the customer are known in advance by the central decision maker
- there are altogether $k * L$ vehicles from $L$ companies

The aim of ideal collaboration is to design a vehicle routing plan that can lead to the maximum system profits. Compared with the previous problem, this problem is a multi-depot vehicle routing problem with time window. Before building mathematical models for the ideal collaboration case, the following notations are defined.

Let $G = (V, E)$ be a directed graph with a vertex set $V = \{1, 2, \dots, n + m\}$ and an edge set $E$, where $\{n + 1, n + 2, \dots, n + m\}$ stand for depots and $\{1, 2, \dots, n\}$ stand for customers. Each customer has a nonnegative demand $d_i$ , service time $s_i$, revenue $R_i$, an open window $a_i$, and close window $b_i$. Analogously, each depot has a zero demand ($d_{n+1} = d_{n+2} = \cdots = d_{n+m} = 0$), a zero service time ($s_{n+1} = s_{n+2} = \cdots = s_{n+m} = 0$), a zero open window ($a_{n+1} = a_{n+2} = \cdots = a_{n+m} = 0$), and a positive close window ($b_{n+1} = b_{n+2} = \cdots, = b_{n+m} > 0$). For each edge, there is a positive travelling cost $c_{ij}$ and a travelling time $T_{ij}$.

The whole company owns $K' = \sum_L K$ vehicles, and each vehicle $k$ has a positive capacity $q_k$.

In this model, three sets of decision variables are displayed as follow

1) There is a set of binary variables $x_{ijk}$. If edge $<i, j>$ is visited by vehicle $k$, $x_{ijk} = 1$; otherwise, $x_{ijk} = 0$.

2) There is another set of binary variables $y_{ik}$. If customer $i$ is visited by vehicle $k$, $y_{ik} = 1$; otherwise, $y_{ik} = 0$.

3) There is a set of nonnegative continuous variables $t_{ik}$, which stands for the start time to service customer $i$ by vehicle $k$.

The purpose of this stage is to work out optimal vehicle routing plan for this whole company with the maximum profits, such that

- Each route starts and ends at the depot,
- Each customer can be serviced exactly once by one vehicle,
- Time window constraint is satisfied,
- Capacity constraint of each vehicle is satisfied,
- Vehicle availability constraint of each vehicle is satisfied.

The following model derives from vehicle routing problems with time window (Montoya-Torres et al., 2015). The mathematical formulation is displayed as follows.

(Model 2)

$$Maximize \sum_{i=1}^{n+m}\sum_{k=1}^{K} R_i d_i y_{ik} - \sum_{i=1}^{n+m}\sum_{j=1}^{n+m}\sum_{k=1}^{K} c_{ij} x_{ijk} \tag{20}$$

$$subject\ to \sum_{i=1}^{n+m} x_{ijk} = y_{jk} \quad j \in N', k \in K \tag{21}$$

$$\sum_{j=1}^{n+m} x_{ijk} = y_{ik} \quad i \in N', k \in K \tag{22}$$

$$\sum_{i=n+1}^{n+m}\sum_{j=1}^{n} x_{ijk} \le 1 \quad k \in K \tag{23}$$

$$\sum_{j=n+1}^{n+m}\sum_{i=1}^{n} x_{ijk} \le 1 \quad k \in K \tag{24}$$

$$\sum_{i=1}^{n+m} x_{ihk} - \sum_{j=1}^{n+m} x_{hjk} = 0 \quad h \in N', k \in K \tag{25}$$

$$\sum_{k=1}^{K} y_{ik} = 1 \quad i \in N \tag{26}$$

$$\sum_{i=1}^{n+m} d_i y_{ik} \le q_k \quad k \in K \tag{27}$$

$$t_{ik} + s_i + T_{ij} - M\left(1 - x_{ijk}\right) \le t_{jk}, i \in N, j \in N, k \in K \tag{28}$$

$$a_i y_{ik} \le t_{ik} \le b_i y_{ik}, \qquad i \in N', \;\; k \in K \tag{29}$$

$$x_{ijk} \in \{0, 1\}\, \forall i, j, k; \qquad y_{ik} \in \{0,1\}\, \forall i, k; \qquad t_{ik} \ge 0, \forall i, k \tag{30}$$

In the above formulation, objective function (20) maximize overall total profits. Constraints (21) and (22) calculate the value of $y_{ik}$ and $y_{jk}$. Constraints (23) and (24) shows whether vehicle $k$ is used or not. Constraint (25) makes sure that the amount of incoming arcs and outgoing arcs is equal. Constraint (26) makes sure that each customer is visited by one vehicle. Constraint (27) is a capacity constraint. Constraint (28) defines the beginning time to service each customer. Constraint (29) makes sure the beginning time to service each customer is within the time window. Constraint (30) displays the three decision variables in this stage.

After solving the above model, the optimal routing plans and the maximum overall profits for the entire alliance could then be received. It is clear to see that the outcome of the model is what the logistics alliance wishes to receive. However, it is not a realistic assumption that there is a central decision maker making decisions for the whole alliance, as individual companies usually make their own decisions.

### 4.5 Network Design for a Logistics Alliance

In this part, a decentralised decision making system is considered. The decentralised decision making reflects how the logistics companies make decision in reality. The challenging task under decentralised decision making is to obtain the same profits as that under the ideal collaboration.

To fulfil the task, capacity exchange cost between different logistics companies is considered to coordinate the decentralised decision making system. As discussed in the previous part, the optimal result of the grand alliance can be obtained by the central decision maker. However, this result is not enough to encourage the companies to form an alliance as there is no incentive to encourage each member to share their resources, and each member is selfish and aims at maximising their own maximum profits. As such, capacity exchange cost is introduced in this part to quantify the value one company could earn when this company delivers items for other companies. Analogously, capacity exchange cost also measures the value one company have to pay when the customer demands are delivered by other companies. In the following part, a contract is designed based on capacity exchange costs. The steps to calculate the capacity exchange costs will be given, i.e., how to allocate the total profits to each member in the alliance to ensure that all the members are satisfied with the allocation.

### *4.5.1 Content of the Contract*

As in a decentralized collaboration, each member in the alliance can make private decisions. Information of customers is shared among all the member in the alliance. However, compared to the ideal collaboration, individual company can only get access to partial information and resources of the grand alliance. More specifically, each member can deliver commodities from its own depot to all the customers (own customers and customers from others) by using its own vehicles. Under this circumstance, an individual member does not need to visit all the customers, which is different from the classic vehicle routing problems. In this way, each member in the alliance can choose some of the customers they wish to service, where the individual maximum profits can be obtained.

Capacity exchange cost is then applied to provide incentives for each member in the alliance, which represents the extra value earned by providing services for other customers, and also represents the extra cost paid to others when own customers are visited by others. The contract consists of the following aspects:

- A specific method to charge the capacity exchange cost
- The reasonable allocation plan can be implemented where the overall profits can be allocated to each member in a fair way to keep the alliance stable

In this way, members in the alliance can sign and obey this contract, and can be allocated more profits than working independently.

In the first contract, capacity exchange cost is applied when one company delivers customer orders for other companies, and vice versa. More specifically, company A can receive a capacity exchange cost from company B if company A delivers a company B's customer order. In return, company B needs to pay that capacity exchange cost to company A.

In this contract, capacity exchange cost is measured according to the travelling distances between depot and the customers. More specifically, if one company wish to deliver commodities for another company, this company then delivers the commodity directly from the depot to the customer. Then, the travelling costs between the depot and the customer can be calculated, and the relevant capacity exchange cost is measured proportional to this travelling costs. An exchange rate $r^l$ is introduced as the unit rate (per kilometre) of company $l$. If one company $l$ chooses to deliver commodities to customer $i$, and customer $i$ belongs to other companies, then $y_{ik} = 1$. Vehicle $k$ is used by company $l$ to deliver products to customer $i$. The total amount company $l$ can charge the other company is $r^l * d_{n+1,i} * y_{ik}$, where $d_{n+1,i}$ stands for the travel distance between depot $n + 1$ and customer $i$. Analogously, company $l$ need to pay the relevant amount to other companies if own customer demand is delivered by other companies.

### *4.5.2 Model of the Logistics Alliance*

In this stage, logistics companies aim at forming a stable logistics alliance. The goal of this alliance is to obtain the maximum attainable overall profits and a proper plan to allocate overall profits. In the previous stage, a central decision maker has already made decisions for the alliance on how to design a service network and how to allocate vehicles to each routes simultaneously. Then in this stage, each member in the alliance can make their own decisions on how to share their resources and calculate relevant costs. More specifically, capacity exchange cost is taken into consideration when sharing resources, such as the demand of customers. Each member in the alliance can receive capacity exchange costs from other members if this member delivers customer orders for other companies. Similarly, each member in the alliance need to pay capacity exchange costs to other members if customer orders from this member are delivered by other members. The aim of this stage is to design a service network for each member in the alliance, and calculate the value of capacity exchange costs, then the profit allocation plan can be achieved. In mathematical optimization, capacity exchange costs are the parameters in the objective function. In order to obtain the optimal value of capacity exchange costs, cutting plane method is applied. It is expected that the optimal routing plan made by central decision maker is also the optimal routing plan for individual company with the optimal capacity exchange costs. All of the above is the content of the contract, which all the members in the alliance must sign and obey before forming an alliance.

In this part, a model is built for each member in the logistics alliances. The model derives from vehicle routing problems with a time window (Sanchez et al., 2016).

Let $G = (V, E)$ be a directed graph with a vertex set and an edge set. For company $A, N^A = \{1, 2, \dots, m + n, m + n + 1\}$ is a set of nodes where $m + n + 1$ stands for the depot, $\{1, \dots, m\}$ stands for customers of company $A$, and $\{m + 1, \dots, m + n\}$ stands for customers of other companies. Each customer has a demand $d_i$, service time $s_i$, a time window $[a_i, b_i]$, and a revenue $R_i$. In this model, not all the customer orders have to be satisfied. If a customer is visited, it must be within the time window. In addition, $c_{ij}$ and $T_{ij}$ stand for travelling costs and travelling time respectively, $K^A$ and $q_k$ stand for the total vehicle amount and the capacity of the vehicles respectively.

It is of vital importance to put forward a way for members to share their resources and their profits. In this model, $r_A$ and $\overline{r_A}$ are proposed to measure the capacity exchange costs, where $r_A$ stand for the unit rate per kilometre of company $A$ for delivering orders for others, and $\overline{r_A}$ stands for the rate of other companies. More specifically, if company $A$ delivers products for company B' customers, it will receive the amount of money $r_A d_{0i}$ (rate * distances between depot and customer $i$). On the other hand, it needs to pay the amount of money $r_B d_{0i}$ (rate * distances between depot and customer), if its customer is serviced by company B.

(Model 3)

$$\text{maximize} \quad \sum_{i \in A} \sum_{k \in V^A} R_i d_i y_{ik} - \sum_{i \in A} \sum_{j \in N^A} \sum_{k \in V^A} c_{ij} x_{ijk}$$

$$+ \sum_{i \notin A} \sum_{k \in V^A} r_A d_{0i} y_{ik} - \sum_{L \notin A} \sum_{i \in A} \sum_{k \in V^A} r_L d_{0i} (1 - y_{ik}) \tag{31}$$

$$\text{subject to} \quad \sum_{i=1}^{m+n+1} x_{ijk} = y_{jk} \quad j \in N^A, k \in V^A \tag{32}$$

$$\sum_{j=1}^{m+n+1} x_{ijk} = y_{ik} \quad i \in N^A, k \in V^A \tag{33}$$

$$\sum_{k \in V^A} y_{ik} \le K^A \qquad i = m + n + 1 \tag{34}$$

$$\sum_{k \in V^A} y_{ik} \le 1 \qquad i = 1, \dots, m + n \tag{35}$$

$$\sum_{i=1}^{m+n+1} d_i y_{ik} \le q_k \; k \in V^A \tag{36}$$

$$\sum_{j=1}^{m+n} x_{0jk} \le 1 \;\; k \in V^A \tag{37}$$

$$\sum_{i=1}^{m+n} x_{i0k} \le 1 \;\; k \in V^A \tag{38}$$

$$\sum_{i=1}^{m+n+1} x_{ihk} - \sum_{j=1}^{m+n+1} x_{hjk} = 0 \;\; k \in V^A, h \in N^A \tag{39}$$

$$t_{ik} + s_i + T_{ij} - M\left(1 - x_{ijk}\right) \le t_{jk} \;\; i \in N^A \; j = 1, \dots, m + n, k \in K^A \tag{40}$$

$$a_i y_{ik} \le t_{ik} \le b_i y_{ik} \; i \in N^A, k \in V^A \tag{41}$$

Where

$$x_{ijk} = \begin{cases} 1, & if\ (i,j)\ is\ serviced\ by\ vehicle\ k \\ 0, & otherwise \end{cases}$$

$$y_{ik} = \begin{cases} 1, & if\ customer\ i\ is\ serviced\ by\ vehicle\ k \\ 0, & otherwise \end{cases}$$

$t_{ik}$ *is the beginning time to service customer i by vehicle k*

In the above formulation, the objective function consists of four terms to maximize the profits. The first term calculates the revenue if one company satisfies its own customers. The second term calculates the travel costs if one company delivers its own customer orders. The third term calculates the capacity exchange costs received from others if one company delivers customer orders for other companies. The fourth term calculates the capacity exchange costs paid to others if one company choose not to satisfy these orders using own vehicle. Constraints (32) and (33) show the relationship between two sets of binary variables.

Constraint (34) ensures that the number of routes is no more than the amount of vehicles. Constraint (35) ensures that each customer is visited no more than once. Constraint (36) is a capacity constraints, that is, the total customer order each vehicle delivers cannot exceed the vehicle capacity. Constraints (37) and (38) make sure that each vehicle should start and end at the depot. Constraint (39) makes sure that the number of incoming arcs and outgoing arcs are the same for each node. Constraint (40) defines the beginning time when customer $j$ is serviced according to the following three aspects, the beginning time when customer $i$ is serviced, service time and travelling time between customer $i$ and customer $j$, if customer $j$ is visited after customer $i$ through edge $< i, j >$. Constraint (41) ensures that if customer $i$ is visited, it should be within the time window.

### *4.5.3 Capacity Exchange Costs*

In this stage, each member in the logistics alliance can get access to own resources, including own depot, own fleet of vehicles and own customers. Besides, each member can also get access to customer information of other members, as resources are shared within the logistics alliance. Individual company is only interested in maximising its own profits (including capacity exchange costs), and they make individual decisions selfishly. It is obvious that the above information are only partial information compared with all the information held by the central decision maker. As such, inverse programming could not be directly applied to the above model (model 3), because the information of model 2 is not in accordance with the information in model 3. More specifically, if inverse programming is applied directly to model 3 for each member in the alliance, however, the total overall profits calculated together is not the overall maximum profits logistics alliance wish to obtain. What's worse, directly applying inverse programming to model 3 will result in the following two types of conflicts, which against the basic assumptions.

- Type 1 conflict: it is possible that a set of customers are not visited by any company.
- Type 2 conflict: it is also possible that a set of customers are visited more than once.

Both these two situations are not allowed in vehicle routing problems, as each customer must be visited exactly once by exactly one vehicle. In order to solve this problem, a new model need to be proposed to contain whole information of the alliance and ensure that all the customers are visited only once. Then, cutting plane method could be applied to solve the problem.

The way to be employed is to combine the model of each member together by adding additional constraints. In this way, this combined model can gain access to all the information, and ensure that all the customers could be visited once.

Let $G = (V, E)$ be a directed graph, where $N^A = \{1, 2, \dots, m + n, m + n + 1\}$, $N^B = \{1,2, \dots, m + n, m + n + 2\}, \dots, N^L = \{1,2, \dots, m + n, m + n + l\}$ are sets of nodes for company $A, B$ and $L$ respectively. For these nodes, $\{1, 2, \dots, m + n\}$ stand for all the customers of $A, B, \dots, L$, and $m + n + 1, m + n + 2$, and $m + n + l$ are the depot for company $A$, $B$ and $L$ respectively. Customer demand $d_i$, service time $s_i$, and revenue $R_i$ are all positive for customers and all zero for depots. Time window $[a_i, b_i]$ is the time range within which a customer $i$ can be visited. In addition, $c_{ij}$, $T_{ij}$, $K^A$, and $q_k$ stand for travelling costs, travelling time, vehicle amount, and vehicle capacity respectively.

In this model, three sets of decision variables are displayed as follows. A set of binary variables $x_{ijk}$, another set of binary variables $y_{ik}$, and a set of nonnegative continuous variables $t_{ik}$. In this model, a set of linking constraints is proposed to combine models for each member in the alliance together.

In this model, it requires a set of linking constraints to combine $L$ individual models (the model for $L$ companies) together. As a matter of fact, customer information is shared, and all $L$ companies can get access to the location and demand information of each customer. As discussed earlier, an individual company does not need to visit all the customers. On the contrary, the alliance needs to satisfy all the customers. This could result in a conflict on the total service times of each customer. As a result, each customer only being visited once by exactly one vehicle are the reasonable linking constraints for these $L$ individual systems.

(MODEL 4)

$$\text{maximize} \quad \sum_{l\in L}\Big[\sum_{i\in l}\sum_{k\in V^l} R_i d_i y_{ik} - \sum_{i\in l}\sum_{j\in N^l}\sum_{k\in V^l} c_{ij} x_{ijk}$$

$$+\sum_{i\notin l}\sum_{k\in V^l} r_l d_{0i} y_{ik} - \sum_{a\notin l}\sum_{i\in l}\sum_{k\in V^l} r_a d_{0i}(1 - y_{ik})\Big] \tag{42}$$

$$\text{subject to} \quad \sum_{l\in L}\sum_{k\in V^l} y_{ik} = 1 \qquad i = 1, \dots, m + n \tag{43}$$

$$\sum_{i=1}^{m+n} x_{ijk} + x_{m+n+l,jk} = y_{jk} \;\; j \in \; N^l \;\; k \in V^l \tag{44}$$

$$\sum_{j=1}^{m+n} x_{ijk} + x_{i,m+n+l,k} = y_{ik} \;\; i \in \; N^l \;\; k \in V^l \tag{45}$$

$$\sum_{k \in V^l} y_{ik} \leq K^l \qquad i = m + n + l \tag{46}$$

$$\sum_{i=0}^{m+n} d_i y_{ik} \leq q_k \quad k \in V^l \tag{47}$$

$$\sum_{j=1}^{m+n} x_{m+n+l,jk} \leq 1 \quad k \in V^l \tag{48}$$

$$\sum_{i=1}^{m+n} x_{i,m+n+l,k} \leq 1 \quad k \in V^l \tag{49}$$

$$\sum_{i=1}^{m+n} x_{ihk} + x_{m+n+l,hk} - \sum_{j=1}^{m+n} x_{hjk} - x_{h,m+n+l,k} = 0 \;\; k \in V^l, h \in N^l \tag{50}$$

$$t_{ik} + s_i + T_{ij} - M\left(1 - x_{ijk}\right) \leq t_{jk} \;\; i \in N^l \, j = 1, \dots, m+n, k \in K^l \tag{51}$$

$$a_i y_{ik} \leq t_{ik} \leq b_i y_{ik} \; i \in N^l k \in V^l \tag{52}$$

Where

$$x_{ijk} = \begin{cases} 1, & if < i,j > is\ serviced\ by\ vehicle\ k \\ 0, & otherwise \end{cases}$$

$$y_{ik} = \begin{cases} 1, & if\ customer\ i\ is\ serviced\ by\ vehicle\ k \\ 0, & otherwise \end{cases}$$

$t_{ik}$ $is\ the\ beginning\ time\ for\ servicing\ customer\ i\ by\ vehicle\ k$

In the above formulation, the objective function consists of four terms in order to maximize total profits. Term one calculates the total revenue $L$ companies can obtain. Term two calculates the travel costs for $L$ companies. Term three calculates the capacity exchange costs received from other companies. Term four calculates the capacity exchange costs paid to other companies. Constraints (43) are the linking constraints. These constraints make sure that each customer could be visited exactly once by one vehicle. Constraints (44) and (45) show the relationships between two sets of binary variables. Constraints (46) ensure that the total number of routes is no more than the total number of vehicles. Constraints (47) are capacity constraints. Constraints (48) and (49) make sure that each vehicle should start and end at the depot. Constraints (50) make sure that the number of incoming arcs and outgoing arcs are the same for each node. Constraints (51) define the beginning time for servicing customer $j$ directly after customer $i$. Constraints (52) are time window constraints.

*Relaxed Model*

After adding a set of linking constraints, model 4 contains all the information which is the same as the information from the central decision maker. Then, the model need to be relaxed for the purpose of applying inverse programming.

(MODEL 5)

$$\text{maximize} \quad \sum_{l\in L}[\sum_{i\in l}\sum_{k\in V^l} R_i d_i y_{ik} - \sum_{i\in l}\sum_{j\in N^l}\sum_{k\in V^l} c_{ij}x_{ijk}$$

$$+\sum_{i\notin l}\sum_{k\in V^l} r_l d_{0i} y_{ik} - \sum_{a\notin l}\sum_{i\in l}\sum_{k\in V^l} r_a d_{0i}(1-y_{ik})] \tag{53}$$

$$\text{subject to} \quad \sum_{l\in L}\sum_{k\in V^l} y_{ik} = 1 \qquad i = 1,\ldots,m+n \tag{54}$$

$$\sum_{i=1}^{m+n} x_{ijk} + x_{m+n+l,jk} = y_{jk} \;\; j \in\ N^l \;\; k \in V^l \tag{55}$$

$$\sum_{j=1}^{m+n} x_{ijk} + x_{i,m+n+l,k} = y_{ik} \;\; i \in\ N^l \;\; k \in V^l \tag{56}$$

$$\sum_{k\in V^l} y_{ik} \le K^l \qquad i = m+n+l \tag{57}$$

$$\sum_{i=0}^{m+n} d_i y_{ik} \le q_k \quad k \in V^l \tag{58}$$

$$\sum_{j=1}^{m+n} x_{m+n+l,jk} \leq 1 \quad k \in V^l \tag{59}$$

$$\sum_{i=1}^{m+n} x_{i,m+n+l,k} \leq 1 \quad k \in V^l \tag{60}$$

$$\sum_{i=1}^{m+n} x_{ihk} + x_{m+n+l,hk} - \sum_{j=1}^{m+n} x_{hjk} - x_{h,m+n+l,k} = 0 \quad k \in V^l, h \in N^l \tag{61}$$

$$t_{ik} + s_i + T_{ij} - M\left(1 - x_{ijk}\right) \leq t_{jk} \quad i \in N^l \; j = 1, \dots, m+n, k \in K^l \tag{62}$$

$$a_i y_{ik} \leq t_{ik} \leq b_i y_{ik} \; i \in N^l k \in V^l \tag{63}$$

$$0 \leq x_{ijk} \leq 1, 0 \leq y_{ik} \leq 1, t_{ik} \geq 0 \tag{64}$$

Compared to model 4, the only difference between the above model and model 4 is that all the decision variables in the above model are relaxed to continuous variables rather than binary variables.

After that, it is then possible to apply cutting plane method to the above model. Before applying the cutting plane method, the dual model should first be proposed. Capacity exchange costs (measured by rates) could then be a variable in the model instead of parameters in the objective function. The value of rates could be received after solving the problem. Let $u_i, \alpha_{jk}, \beta_{ik}, v_0, \omega_k, \lambda_k, \gamma_k, \pi_{ik}, \theta_{ijk}, \mu_{ik}, \eta_{ik}$ be the dual variables relevant to constraints (54) – (63) respectively, where $v_0 \geq 0, \lambda_k \geq 0, \omega_k \geq 0, \gamma_k \geq 0, \theta_{ijk} \geq 0, \mu_{ik} \geq 0, \eta_{ik} \geq 0$, and other variables are not restricted in sign. Then dual model of model 4 is as follows.

(MODEL 6)

$$minimize \quad -\sum_{a \notin L} \sum_{i \in L} \sum_{k \in V^l} r_a d_{0i} + \sum_{i \in C} u_i + \sum_{l \in L} \sum_{k \in V^l} (\omega_k q_k + \gamma_k + \lambda_k)$$

$$+ \sum_{l \in L} \sum_{i \in C} \sum_{j \in C} \sum_{k \in V^l} \theta_{ijk} \left(M - s_i - T_{ij}\right) + v_0 K^l \tag{65}$$

$$\text{subject to} \quad \alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + M\theta_{ijk} \geq -c_{ij} \quad i \in L, j \in C, k \in V \tag{66}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + M\theta_{ijk} + \gamma_k \geq -c_{ij} \quad i \in L, j = depot, k \in V \tag{67}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + M\theta_{ijk} \geq 0 \qquad i \notin L, j \in C, k \in V \tag{68}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + \gamma_k \geq 0 \qquad i \notin L, j = depot, k \in V \tag{69}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + \lambda_k \geq 0 \qquad i = depot, j \in C, k \in V \tag{70}$$

$$u_i - \alpha_{ik} - \beta_{ik} + d_i w_k + a_i \mu_{ik} - b_i \eta_{ik} \geq R_i d_i + \sum_{a \notin l} r_a d_{0i} \quad i \in L, k \in L \tag{71}$$

$$u_i - \alpha_{ik} - \beta_{ik} + d_i w_k + a_i \mu_{ik} - b_i \eta_{ik} \geq r_l d_{0i} \quad i \notin L, k \in L \tag{72}$$

$$v_0 - \alpha_{ik} - \beta_{ik} + d_i w_k + a_i \mu_{ik} - b_i \eta_{ik} \geq 0 \quad i = depot, k \in L \tag{73}$$

$$\sum_{h \in C} \theta_{ihk} - \sum_{h \in C} \theta_{hjk} - \mu_{ik} + \eta_{ik} \geq 0 \quad i \in L, k \in V \tag{74}$$

$$-\mu_{ik} + \eta_{ik} \geq 0 \quad i = depot, k \in V \tag{75}$$

After that, cutting plane method could be applied to the above model. In the cutting plane method, a set of feasible solutions to the original optimization model is known in advance, together with the value of relevant cost vector c. It is expected that this feasible solution to the origin model could turn out to be an optimal solution to the inverse model with a new cost vector $d$, where the difference between cost vector $c$ and $d$ ($||c - d||$) is the smallest.

In this study, capacity exchange costs are proposed as the cost vector. Let $r_l'$ be the optimal cost vector. This problem tries to find out the value of $r_l'$, where the global optimal outcome ($y_{ik}'$ and $x_{ijk}'$) could be optimal in individual systems.

Let $e \geq 0, f \geq 0$, such that $r_l' - r_l = e - f, |r_l' - r_l| = e + f, l \in L.$

The inverse programming model is then displayed as follows.

(MODEL 7)

$$\text{minimize} \qquad e + f \tag{76}$$

$$\text{subject to} \qquad \alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + M\theta_{ijk} \geq -c_{ij} \quad i \in L, j \in C, k \in V \tag{77}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + M\theta_{ijk} + r_k \geq -c_{ij} \quad i \in L, j = depot, k \in V \tag{78}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + M\theta_{ijk} \geq 0 \qquad i \notin L, j \in C, k \in V \tag{79}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + r_k \geq 0 \qquad i \notin L, j = depot, k \in V \tag{80}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + \lambda_k \geq 0 \qquad i = depot, j \in C, k \in V \tag{81}$$

$$u_i - \alpha_{ik} - \beta_{ik} + d_i w_k + a_i \mu_{ik} - b_i \eta_{ik} \geq R_i d_i + \sum_{a \notin L} (r_a - e + f) d_{0i} \qquad i \in L, k \in L \tag{82}$$

$$u_i - \alpha_{ik} - \beta_{ik} + d_i w_k + a_i \mu_{ik} - b_i \eta_{ik} \geq (r_l - e + f) d_{0i} \quad i \notin L, k \in L \tag{83}$$

$$v_0 - \alpha_{ik} - \beta_{ik} + d_i w_k + a_i \mu_{ik} - b_i \eta_{ik} \geq 0 \quad i = depot, k \in L \tag{84}$$

$$\sum_{h \in C} \theta_{ihk} - \sum_{h \in C} \theta_{hjk} - \mu_{ik} + \eta_{ik} \geq 0 \quad i \in L, k \in V \tag{85}$$

$$-\mu_{ik} + \eta_{ik} \geq 0 \quad i = depot, k \in V \tag{86}$$

In the above formulation, the objective function is to minimise the difference between cost vectors. All the constraints derive from the constraints (54) – (63) of the dual system. The only difference in the constraints is that $r_l' (= r_l - e + f)\ is$ used instead of $r_l$ in the inverse model.

Then, the value of $r_l'$ could be obtained according to the following steps:

- Step 1: solve the inverse programming model (model 7), and come up with the optimal value of each variable, including $e, f$, and $r_l'$.
- Step 2: calculate the new values $r_l' = r_l - e + f$. Use $r_l'$ instead of $r_l$ in the original optimization model (model 4), and come up with the current optimal value of decision variables $y_{ik}^*$ and $x_{ijk}^*$.
- Step 3: compare the following two values of objective function of the original optimization model: 1) use new rate $r_l'$ and feasible solution ($y_{ik}'$ & $x_{ijk}'$) to calculate one value of the objective function; and 2) use new rate $r_l'$ and current optimal solution ($y_{ik}^*$ & $x_{ijk}^*$) to calculate the other value of the objective funtion.

  If $obj(r_l', y_{ik}', x_{ijk}') \geq obj(r_l', y_{ik}^*, x_{ijk}^*)$, then stop. The left term is the value of objective function of model 4, where the value of parameter is the new rate obtained in step 2 and the value of decision variables are optimal service routes of ideal collaboration. The right term is the other value of objective function of model 4, where the value of parameter is also the new rate and the value of decision variables are the optimal solutions obtained in step 2. This inequality guarantee that the service routes of ideal collaboration with new rate is now the optimal solution of the logistics alliance.

- Step 4: otherwise, if the above inequality is not satisfied, a set of constraints (87) need to be added to the inverse model (model 7).

$$\begin{aligned}
&\sum_{l\in L}[\sum_{i\in l}\sum_{k\in V^l} R_i d_i y'_{ik} - \sum_{i\in l}\sum_{j\in N^l}\sum_{k\in V^l} c_{ij}x'_{ijk} \\
&+\sum_{i\notin l}\sum_{k\in V^l}(r_l - e + f)d_{0i}y'_{ik} \\
&-\sum_{a\notin l}\sum_{i\in l}\sum_{k\in V^l}(r_a - e + f)d_{0i}(1-y'_{ik})] \\
&\geq \sum_{l\in L}[\sum_{i\in l}\sum_{k\in V^l} R_i d_i y^*_{ik} - \sum_{i\in l}\sum_{j\in N^l}\sum_{k\in V^l} c_{ij}x^*_{ijk} \\
&+\sum_{i\notin l}\sum_{k\in V^l}(r_l - e + f)d_{0i}y^*_{ik} \\
&-\sum_{a\notin l}\sum_{i\in l}\sum_{k\in V^l}(r_a - e + f)d_{0i}(1-y^*_{ik})] \qquad (87)
\end{aligned}$$

- Step 5: Go back to step 1, and repeat the above steps, until the inequality $obj(r'_l, y'_{ik}, x'_{ijk}) \geq obj(r'_l, y^*_{ik}, x^*_{ijk})$ is satisfied.

After calculating the capacity exchange cost of each company, the total profits each member in the alliance can receive are then identified, that is, the profit allocation plan of the logistics alliance is obtained.

## 4.6 Summary

In this chapter, the first contract is designed to form an alliance and then allocate total profits of the grand alliance to each member in the alliance in a fair way. This contract not only provides incentives to encourage each member to form a stable alliance, but also guarantee the allocation plan can be implemented.

In section 4.1, a brief introduction is offered, and followed by the structure of this section.

In section 4.2, the problems are described in accordance with the research design and research framework, including problems and basic assumptions for non-collaboration, ideal collaboration and logistics alliance.

In section 4.3, a model of vehicle routing problem with time window is applied to design service networks for individual companies when they make decisions individually.

In section 4.4, a model of multi-depot vehicle routing problem with time window is applied to design networks for an ideal collaboration. The optimal routing plan and the optimal total profits for the complete collaboration are then obtained.

In section 4.5, a modified model for a single member in the logistics alliance is proposed with partial information. Then, a combined model for all the members in the logistics alliance is proposed with full information. Capacity exchange cost is considered when sharing resources. Cutting plane method is applied to calculate the value of capacity exchange costs. The profits allocated to each member can be achieved after capacity exchange costs are obtained.

# Chapter 5 Commodity Weight based Mechanism Design

## 5.1 Introduction

In this chapter, another contract is designed to realize the research aim and answer the research questions. Analogously, this contract is also designed to motivate alliance members to take part in a collaboration. Meanwhile, total profits obtained by ideal alliance can be allocated to each member in the alliance in a fair way. In other words, this contract also guarantee the allocation plan can be implemented.

In section 5.2, a problem description is first proposed, including a brief introduction of each problem, what models are built in each stages and the basic assumptions of different models.

In section 5.3, details of forming an alliances is presented. A non-collaborative model is first built to identify how a single company makes decisions before forming an alliance. A single company can decide whether to form a logistics alliance or not according to the optimal solution of the non-collaborative model. After that, a centralized collaborative model is then proposed to figure out the maximum attainable profits earned by a collaboration.

In section 5.4, details of allocating total profits to each member in the alliance is presented. A model for each member in the alliance is built to identify how each member can make separate decisions when they share customer information. Capacity exchange costs are proposed to calculate the total costs when resources are shared among the member in the alliance. In order to calculate the capacity exchange costs, a combined model is built which consists of full information. A cutting plane method is applied to come up with the value of capacity exchange costs. In this way, the profit allocation plan can be achieved.

In section 5.5, a summary of this chapter is offered.

## 5.2 Problem Description

This problem is introduced in the context of mathematical modelling. Let $G = (V, E)$ be a complete graph, where $V$ is a vertex set and $E$ is an edge set. For each company, node $n + 1$ is the depot and the rests $\{1, 2, \dots, n\}$ are customers. Each customer $i$ has a demand $d_i$, which must be satisfied by the company. Besides, customer $i$ must be visited between the time range $[a_i, b_i]$.

Basic assumptions to this problem is described as follows, according to different stages of the research framework.

In the first stage, each company choose to make decisions individually. Vehicle routing problem with time window model can be directly applied to find the optimal service routes to obtain the maximum attainable profits. Basic assumptions to this type of problem are listed as follows, which are similar to the assumptions of vehicle routing problems.

- Assumption 1: each company has a depot to store the customer demands
- Assumption 2: each company has a fleet of vehicles
- Assumption 3: the demand of each customer must be satisfied and must be visited within the time window
- Assumption 4: travelling distance, travelling time and travelling costs on each edge are fixed
- Assumption 5: network is designed as a complete network and is also designed on a daily basis

In the second stage, companies choose to form an ideal collaboration. In this centralized collaboration, companies can share the resources without considering capacity exchange costs. Under this circumstance, model of multi-depot vehicle routing problem with time window can then be applied to find optimal service routes with the global maximum profits. Basic assumptions to this problem is described as follows.

- Assumption 1: there are $l$ logistics companies, and each company owns a depot with sufficient supply
- Assumption 2: each company has $n$ customers
- Assumption 3: each customer has a non-negative demand and a time window
- Assumption 4: each company has a fleet of vehicles with the same capacity
- Assumption 5: only the weight of commodity is considered
- Assumption 6: travelling time and costs are fixed

In the third stage, companies choose to form a logistics alliance. In this decentralized collaboration, each company can make own decisions as in practice. Under this circumstance, new assumptions are proposed as follows.

- Assumption 1: each company owns a depot and a fleet of vehicles

- Assumption 2: customer information is shared among all the companies, and each company can choose whether to service a customer or not
- Assumption 3: capacity exchange costs is considered when companies choose to share resources

### 5.3 Forming an Alliance

In this part, the first and second research questions are answered by designing service networks for stage one and stage two. Models are built for non-collaborative and ideal collaborative situations respectively.

#### *5.3.1 Network Design for Non-Collaborative Situation*

In this part, the model is built for the non-collaborative city logistics. In this stage, each company makes decisions individually. Before presenting models, the following notations are shown first.

**Indexes**
$\boldsymbol{i}, \boldsymbol{j}$: stand for nodes ($\boldsymbol{n+1}$ for depot, $\boldsymbol{1, 2, \dots, n}$ for customers)
$\boldsymbol{k}$: stands for vehicles

**Parameters**
$\boldsymbol{R_i}$: unit revenue received when satisfying customer $\boldsymbol{i}$
$\boldsymbol{d_i}$: demand of customer $\boldsymbol{i}$
$\boldsymbol{c_{ij}}$: travelling cost between node $\boldsymbol{i}$ and node $\boldsymbol{j}$
$\boldsymbol{q_k}$: capacity of vehicle $\boldsymbol{k}$
$\boldsymbol{s_i}$: service time of customer $\boldsymbol{i}$
$\boldsymbol{T_{ij}}$: travelling time from node $\boldsymbol{i}$ to node $\boldsymbol{j}$
$\boldsymbol{M}$: a large number
$\boldsymbol{a_i}$: the lower bound of time window
$\boldsymbol{b_i}$: the upper bound of time window

**Variables**
$\boldsymbol{x_{ijk}}$: whether customer $\boldsymbol{i}$ and $\boldsymbol{j}$ are serviced by vehicle $\boldsymbol{k}$ one after another
$\boldsymbol{t_{ik}}$: the time when vechicle $\boldsymbol{k}$ arrives at customer $\boldsymbol{i}$

*Table 5.1 Notations of Indexes, Parameters and Variables*

Let $G = (V, E)$ be a directed graph with a vertex set $V = \{1, 2, \dots, n+1\}$ and an edge set $E$. The node $n+1$ is the depot with sufficient supply, and the other $n$ nodes represent altogether $n$ customers. Customer demand $d_i$ must be satisfied within the time window $[a_i, b_i]$, thus, the company can obtain a revenue $R_i$. On each edge, there is a travelling cost $c_{ij}(\geq 0)$, a travelling time $T_{ij}(\geq 0)$, and a travelling distance $d_{ij}(\geq 0)$.

There are altogether $K$ vehicles, and the capacity of each vehicle is $q_k(\geq 0)$.

In this model, there are two sets of decision variables. One is a set of binary variables $x_{ijk}$, which represents whether node $j$ is visited directly after node $i$ by vehicle $k$. There are two possible values, zero or one. If it equals one, arc $< i,j >$ is visited by vehicle $k$; if it equals zero, then arc $< i,j >$ is not visited by vehicle $k$. The other set of decision variables are continuous variables $t_{ik} \geq 0$, which stands for the time to start service customer $i$.

The aim of this stage is to find the optimal routing plan for individual company, such that

- Depot should be the start point and the end point of each route;
- Each customer must be visited exactly once within the time range;
- Capacity constraint must be satisfied by each vehicle.

Then the mathematical formulation is displayed as follows:

(Model 8)

$$Maximize \quad \sum_{i=1}^{n+1}\sum_{k=1}^{K} R_i d_i \sum_{j=1}^{n+1} x_{ijk} - \sum_{i=1}^{n+1}\sum_{j=1}^{n+1}\sum_{k=1}^{K} c_{ij} x_{ijk} \tag{88}$$

$$subject\ to \quad \sum_{k=1}^{K}\sum_{j=1}^{n+1} x_{ijk} = 1 \qquad i \in N \tag{89}$$

$$\sum_{k=1}^{K}\sum_{i=1}^{n+1} x_{ijk} = 1 \qquad j \in N \tag{90}$$

$$\sum_{i=1}^{n} x_{i,n+1,k} \leq 1 \quad k \in K \tag{91}$$

$$\sum_{j=1}^{n} x_{n+1,jk} \leq 1 \quad k \in K \tag{92}$$

$$\sum_{i=1}^{n+1} x_{ihk} - \sum_{j=1}^{n+1} x_{hjk} = 0 \quad h \in N', k \in K \tag{93}$$

$$\sum_{i=1}^{n+1} d_i \sum_{j=1}^{n+1} x_{ijk} \leq q_k \quad k \in K \tag{94}$$

$$t_{ik} + s_i + T_{ij} - M(1 - x_{ijk}) \le t_{jk}, i \in N, j \in N, k \in K \tag{95}$$

$$a_i \sum_{j=1}^{n+1} x_{ijk} \le t_{ik} \le b_i \sum_{j=1}^{n+1} x_{ijk}, \qquad i \in N', \ k \in K \tag{96}$$

$$x_{ijk} \in \{0, 1\} \,\forall i, j, k; \qquad t_{ik} \ge 0, \forall i, k \tag{97}$$

In the above formulation, objective function maximize the total profits. Constraint (89) and (90) ensure that each customer is serviced once by one vehicle. Constraint (91) ensures that each depot has an incoming arc on each route. Analogously, constraint (92) ensures that each depot has an outgoing arc on each route. Constraint (93) ensures that the number of incoming arc and outgoing arc on each node is identical. Constraint (94) is the capacity constraint. Constraint (95) shows the start time to service customers. Constraint (96) is the time window constraint. Constraint (97) shows the two decisions variables.

A single company can apply this model to make the most of its resources in order to obtain the maximum profits. Meanwhile, which vehicles are used to deliver commodities on each route are obtained, together with the optimal service routes. This is the best result each company can achieve when they choose to work on their own.

### *5.3.2 Network Design for Ideal Collaboration*

In the next stage, companies choose to form an ideal alliance in order to improve their service levels. In this centralized collaboration, it is assumed that there is a central decision maker to make decisions on service network with the maximum profits for the entire alliance. Information is shared among all the members, where capacity exchange costs are not taken into consideration. It is obvious that the ideal collaboration can create the global maximum attainable profits. By solving the centralised decision making problem, the optimal service routing plan is obtained, and the vehicle allocation plan is also achieved.

As stated earlier, all information in this stage are shared by all the companies. As a result, there are altogether $l$ companies and $l$ depots, and each depot has sufficient stock to satisfy the customers. Each company owns a fleet of vehicle $k$, and the capacity of each vehicle is $q_k$. Besides, there are $n$ customers for each company, the demand $d_i$ of each customer, the time window $[a_i, b_i]$ of each customer, and the location of each customer are all shared among the members in the alliance. Due to the fact that the location of each customer and each depot is fixed, then, the relevant travel distances, the relevant travel time, and the relevant travel costs between them are all fixed and known in advance. Compared to the previous problem, there are more than one depot in this problem, as such, this problem is a multi-depot vehicle routing problem with time window. Before building mathematical models for this stage, the following notations are defined.

Let $G = (V, E)$ be a directed graph with a vertex set and an edge set. For the vertex set $V = \{1, 2, \ldots, n + m\}$, the first $n$ nodes stand for the customers, and the last $m$ nodes stand for the depots. There is a demand $d_i$ on each node, and a service time $s_i$ to service each customer. What's more, the customer $i$ must be serviced within the time window $[a_i, b_i]$. After the demand is satisfied, then a revenue $R_i$ can be obtained. For each customer, the value of the demand, service time, and time window are all non-negative; while for each depot, the value of demand and service time are both zero. For each edge, there are travelling costs $c_{ij}$, travelling time $T_{ij}$ and travelling distances $d_{ij}$, all the value of the above parameters are positive.

There are altogether $K' = \sum_L K$ vehicles, and the capacity of each vehicle is $q_k (> 0)$.

In this model, there are two sets of decision variables, which are listed as follows. One is a set of binary variables $x_{ijk}$, which stands for whether edge $< i, j >$ is visited by vehicle $k$. There are two possible values, one or zero. If $x_{ijk} = 1$, customer $j$ is visited directly after customer $i$ by vehicle $k$; if $x_{ijk} = 0$, customer $j$ is not visited after customer $i$ by vehicle $k$. The other one is a set of continuous variables $t_{ik} \geq 0$, which is the beginning time to service customer $i$ by vehicle $k$.

In this stage, model is built to find optimal service routes by satisfying the following assumptions:

- Depot is the start point and end point of each service route;
- Each customer must be visited once only within the time window;
- Each vehicle must obey the capacity constraint;
- The total amount of service routes (the vehicles used) must be no more than the vehicles available.

Then, the mathematical formulation is displayed as follows.

(Model 9)

$$Maximize \quad \sum_{i=1}^{n+m}\sum_{k=1}^{K'} R_i d_i \sum_{j=1}^{n+m} x_{ijk} - \sum_{i=1}^{n+m}\sum_{j=1}^{n+m}\sum_{k=1}^{K} c_{ij}x_{ijk} \tag{98}$$

$$subject\ to \quad \sum_{k=1}^{K'}\sum_{j=1}^{n+m} x_{ijk} = 1 \quad i \in N \tag{99}$$

$$\sum_{k=1}^{K'}\sum_{i=1}^{n+m} x_{ijk} = 1 \quad j \in N \tag{100}$$

$$\sum_{i=n+1}^{n+m}\sum_{j=1}^{n} x_{ijk} \le 1 \quad k \in K \tag{101}$$

$$\sum_{j=n+1}^{n+m}\sum_{i=1}^{n} x_{ijk} \le 1 \quad k \in K \tag{102}$$

$$\sum_{i=1}^{n+m} x_{ihk} - \sum_{j=1}^{n+m} x_{hjk} = 0 \quad h \in N', k \in K \tag{103}$$

$$\sum_{i=1}^{n+m} d_i \sum_{j=1}^{n+m} x_{ijk} \le q_k \quad k \in K \tag{104}$$

$$t_{ik} + s_i + T_{ij} - M\left(1 - x_{ijk}\right) \le t_{jk}, i \in N, j \in N, k \in K \tag{105}$$

$$a_i \sum_{j=1}^{n+m} x_{ijk} \le t_{ik} \le b_i \sum_{j=1}^{n+m} x_{ijk}, \quad i \in N', \ k \in K \tag{106}$$

$$x_{ijk} \in \{0,1\}\ \forall i,j,k; \quad t_{ik} \ge 0, \forall i,k \tag{107}$$

In the above formulation, objective function (98) maximize the global profits. Constraint (99) and (100) ensure that each customer is visited by one vehicle. Constraint (101) ensures that each route ends at the depot. Constraint (102) ensures that each route starts from the depot. Constraint (103) ensures that the incoming arcs and outgoing arcs on each depot is equal. Constraint (104) is the capacity constraint. Constraint (105) defined the start time to service node $j$ directly after servicing node $i$. Constraint (106) is the time window constraint. Constraint (107) listed the two sets of decision variables.

Once the above model is solved, the service routes with the highest profits can be obtained. Under this circumstance, the central decision maker is able to implement the ideal collaboration, and obtain the optimal overall profits. However, it is not realistic that there is only a central decision maker to make decisions for the entire alliance. As stated earlier, each member in the alliance also aims at maximising personal maximum attainable profits. The remaining problem is how to realize the global maximum profits when companies choose to form a logistics alliance. In this decentralized collaboration, each member can make own decisions on delivering commodities for itself and for other companies as well. The idea is to set up a contract for these companies, and give them incentives to achieve the global optimality.

## 5.4 Profit Allocation

As discussed in the previous section, a central decision maker has already made decisions on the optimal service network and vehicle allocation plan with the maximum profits for the centralized collaboration. In this section, the aim is to realize the optimal solution of the grand alliance and allocate the maximum profits to each member in a fair way. When all the members in the alliance are allocated more profits than the profit they can earn individually, this alliance is a stable alliance that each member is satisfied with the profit allocation plan.

In this section, another contract is designed for logistics companies when they choose to form a logistics alliance. Capacity exchange costs can provide incentives, which measures the extra fee obtained by sharing resources. Then, the profit allocation plan can be achieved after calculating the capacity exchange costs of each member in the alliance.

### *5.4.1 Content of the Contract*

This contract is also designed for a decentralized collaboration, where each company can make individual decisions with own resources and shared resources. Customer location and customer demand are shared among members in the alliance. Each member can choose to service own customers as well as other customers, and there is no need to service all the customers.

Capacity exchange cost is proposed to measure the extra value obtained when resources are shared. Each company can receive the capacity exchange cost when delivering commodities for other members, and pay the capacity exchange cost to others when other companies provide services for own customers. The contract is designed with the following aspects:

- How to charge the capacity exchange cost
- A reasonable allocation plan
- The above allocation plan can be implemented

Thus, alliance members can sign and obey this contract to receive more profits and keep this logistics alliance stable.

As discussed earlier, each company can only get access to its own depot and its own vehicles. As a result, the model built for individual member consists of partial information. Therefore, a combined model with whole information is needed to calculate capacity exchange costs.

In this contract, capacity exchange cost is measured according to the actual weight of each commodity. An exchange rate $t^l$ is introduced as the unit rate (per kilogram) of commodity $i$, and the unit rate is the same for commodities from the same member in the alliance. If customer $i$ from another company is satisfied by company $l$, this company can charge $t^l * weight_i$; if customer demands from company $l$ are delivered by other companies, then this company need to pay $\sum_{a \notin l} t^a * weight_i$ to the other companies.

### *5.4.2 Logistics Alliance*

The aim of this stage is to design service networks for each member in the alliance where capacity exchange cost is taken into consideration. The value of capacity exchange costs need to be identified, then the profit allocation plan can be achieved.

Let $G = (V, E)$ be a directed graph with a vertex set $V = \{1, 2, \ldots, m + n, m + n + 1\}$ and an edge set $E$. For each node $i$, there is a demand $d_i$ and weight $w_i$. If the demand is satisfied within the time window $[a_i, b_i]$, a revenue $R_i$ is then obtained by the company. For the depot $m + n + 1$, the value of demand and revenue are both zero; while for the $m + n$ customers, the value of demand and revenue are positive. In addition, the first $n$ customers are the customers of company $l$, and the rest $m$ customers are the customers of other companies. Each edge represents a segment line, and two nodes are connected by this segment line. On each edge, there are non-negative travelling costs $c_{ij}$, non-negative travelling distances $d_{ij}$, and non-negative travelling time $T_{ij}$.

Each company $l$ owns a fleet of vehicle $K^l$, and the capacity of each vehicle is $q_k$.

It is important to propose a way for the members to share their resources. In this contract, $t^l$ is proposed to measure the unit rate, where $t^l$ stands for the unit rate for delivering orders for other members per kilogram. More specifically, if one company $l$ delivers products for another company, company $l$ can receive $t^l * weight_i$ from the other company, and vice versa.

(Model 10)

$$\text{maximize} \quad \sum_{i \in l} \sum_{k \in V^l} R_i d_i y_{ik} - \sum_{i \in l} \sum_{j \in N^l} \sum_{k \in V^l} c_{ij} x_{ijk}$$

$$+ \sum_{i \notin l} \sum_{k \in V^l} t^l w_i y_{ik} - \sum_{a \notin l} \sum_{i \in l} \sum_{k \in V^l} t^a w_i (1 - y_{ik}) \tag{108}$$

$$\text{subject to} \quad \sum_{i=1}^{m+n+1} x_{ijk} = y_{jk} \quad j \in N^l, k \in V^l \tag{109}$$

$$\sum_{j=1}^{m+n+1} x_{ijk} = y_{ik} \quad i \in N^l, k \in V^l \tag{110}$$

$$\sum_{k \in V^l} y_{ik} \leq K^l \quad i = m + n + 1 \tag{111}$$

$$\sum_{k \in V^l} y_{ik} \leq 1 \quad i = 1, \dots, m + n \tag{112}$$

$$\sum_{i=1}^{m+n+1} d_i y_{ik} \leq q_k \; k \in V^l \tag{113}$$

$$\sum_{j=1}^{m+n} x_{n+1,jk} \leq 1 \quad k \in V^l \tag{114}$$

$$\sum_{i=1}^{m+n} x_{i,n+1,k} \leq 1 \quad k \in V^l \tag{115}$$

$$\sum_{i=1}^{m+n+1} x_{ihk} - \sum_{j=1}^{m+n+1} x_{hjk} = 0 \;\; k \in V^l, h \in N^l \tag{116}$$

$$t_{ik} + s_i + T_{ij} - M\left(1 - x_{ijk}\right) \le t_{jk} \;\; i \in N^l \; j = 1, \dots, m+n, k \in K^l \tag{117}$$

$$a_i y_{ik} \le t_{ik} \le b_i y_{ik} \; i \in N^l, k \in V^l \tag{118}$$

Where

$$x_{ijk} = \begin{cases} 1, & if\,(i,j) is\ serviced\ by\ vehicle\ k \\ 0, & otherwise \end{cases}$$

$$y_{ik} = \begin{cases} 1, & if\ customer\ i\ is\ serviced\ by\ vehicle\ k \\ 0, & otherwise \end{cases}$$

$t_{ik}$ *is the beginning time to service customer i by vehicle k*

In the above formulation, there are four terms in the objective function to maximize the total profits. The first term is the total revenue if own customer demands are satisfied. The second term is the total travelling costs if one company satisfies own customers. The third term is the capacity exchange costs received from other members if one member choose to deliver commodities for other members. The fourth term is the capacity exchange costs paid to other members if the other company deliver commodities for the member. Constraints (109) and (110) describes the relationships between two sets of binary variables. Constraint (111) is a vehicle availability constraint, which ensures that the total number of routes is less than or equal to the total number of vehicles. Constraint (112) ensures that each customer is visited only once or not visited. Constraint (113) is a capacity constraint, where each vehicle cannot deliver more commodities than the capacity of the vehicle. Constraints (114) and (115) make sure that the depot is the start and end point of each route. Constraint (116) makes sure that each node is connected by incoming arcs and outgoing arcs, and the total number of incoming arcs and outgoing arcs are equal. Constraint (117) defines the start time to service customer *j* directly after servicing customer $i$. Constraint (118) is a time window constraint, which defines the time window on each node.

### *5.4.3 Capacity Exchange Costs*

As stated earlier, each member in the alliance only get access to partial information, its own fleet of vehicles, its own depot, its own customers and customers from all the other companies. When each member in the alliance makes own decisions, there might be two circumstances as follows. 1) It is possible that a customer is serviced more than once. According to the assumption that, each member in the alliance can make own decisions on whether or not to deliver commodities for one customer. Meanwhile, each member in the alliance wish to obtain the maximum profits they can earn. It is possible that more than one members choose the same customer to service if the profits earned from delivering this customer or the capacity exchange costs obtained from other companies are high enough. 2) It is also possible that a customer is not serviced by any company. For example, if a customer is far away from the depot and the weight of the demand is also low, one company is not willing to deliver this order as the profits earned from delivering this customer is very low. Analogously, other companies do not wish to deliver this commodity as the capacity exchange costs obtained from this company is low. Apparently, both the above two situations are not allowed when forming an alliance, where all the customers must be visited exactly once by the alliance members. The reason why the above two circumstances exist is that each member in the alliance can only get access to partial information. If applying the cutting plane method directly to the above model, the relevant optimal solution may not be the optimal solution which the alliance wish to achieve. As such, it requires a model with all the information from all the companies, where the capacity exchange costs are also considered.

In order to combine all the models for each member in the alliance, a set of linking constraints is added to the combined model. In this way, the information in combined model is in accordance with that in ideal collaboration. In addition, the linking constraints can guarantee that each customer is only visited once by one vehicle.

Let $G = (V, E)$ be a directed graph with a vertex set $V$ and an edge set $E$. The vertex set $V = \{1, 2, \dots, m+n, m+n+1, \dots, m+n+L\}$ consist of $m+n$ customers and $L$ depots. On each node, there is a customer demand $d_i$, a service time $s_i$, a revenue $R_i$, and a time window $[a_i, b_i]$. The edge set $E$ consists of all the edges, where each pair of nodes is connected by these edges in the graph. On each edge, there is a fixed travelling time $T_{ij}$, a fixed travelling cost $c_{ij}$, and a fixed travelling distance $d_{ij}$.

In this model, there are three set of decision variables. A set of binary variables $x_{ijk}$ represents whether vehicle $k$ travels from node $i$ to node $j$ or not. Another set of binary variables $y_{ik}$ represents whether vehicle $k$ service customer $i$ or not. A set of continuous variables $t_{ik}$ represents the start time to service customer $i$. In this model, a set of linking constraints is proposed to combine the separate models (models for each member in the alliance) together, as such, all the information and resources are shared among all the members in the alliance.

(MODEL 11)

$$\text{maximize} \quad \sum_{l\in L}[\sum_{i\in l}\sum_{k\in V^l} R_i d_i y_{ik} - \sum_{i\in l}\sum_{j\in N^l}\sum_{k\in V^l} c_{ij}x_{ijk}$$

$$+\sum_{i\notin l}\sum_{k\in V^l} t^l w_i y_{ik} - \sum_{a\notin l}\sum_{i\in l}\sum_{k\in V^l} t^a w_i(1-y_{ik}) \tag{119}$$

$$\text{subject to} \quad \sum_{l\in L}\sum_{k\in V^l} y_{ik} = 1 \qquad i = 1,\dots,m+n \tag{120}$$

$$\sum_{i=1}^{m+n} x_{ijk} + x_{m+n+l,jk} = y_{jk} \;\; j\in\ N^l \;\; k\in V^l \tag{121}$$

$$\sum_{j=1}^{m+n} x_{ijk} + x_{i,m+n+l,k} = y_{ik} \;\; i\in\ N^l \;\; k\in V^l \tag{122}$$

$$\sum_{k\in V^l} y_{ik} \le K^l \qquad i = m+n+l \tag{123}$$

$$\sum_{i=0}^{m+n} d_i y_{ik} \le q_k \quad k\in V^l \tag{124}$$

$$\sum_{j=1}^{m+n} x_{m+n+l,jk} \le 1 \;\; k\in V^l \tag{125}$$

$$\sum_{i=1}^{m+n} x_{i,m+n+l,k} \le 1 \;\; k\in V^l \tag{126}$$

$$\sum_{i=1}^{m+n} x_{ihk} + x_{m+n+l,hk} - \sum_{j=1}^{m+n} x_{hjk} - x_{h,m+n+l,k} = 0 \;\; k\in V^l, h\in N^l \tag{127}$$

$$t_{ik} + s_i + T_{ij} - M(1-x_{ijk}) \le t_{jk} \;\; i\in N^l \; j = 1,\dots,m+n, k\in K^l \tag{128}$$

$$a_i y_{ik} \le t_{ik} \le b_i y_{ik} \; i\in N^l k\in V^l \tag{129}$$

Where

$$x_{ijk} = \begin{cases} 1, & if < i,j > is\ serviced\ by\ vehicle\ k \\ 0, & otherwise \end{cases}$$

$$y_{ik} = \begin{cases} 1, & if\ customer\ i\ is\ serviced\ by\ vehicle\ k \\ 0, & otherwise \end{cases}$$

$t_{ik}\ is\ the\ beginning\ time\ for\ servicing\ customer\ i\ by\ vehicle\ k$

In the above formulation, there are four terms in the objective function to maximize the total profits. The first term is the total revenue obtained by all the companies. The second term is the total travel costs spent by all the companies. The third term is the total capacity exchange costs received from the other members, while the fourth term is the total capacity exchange costs paid to the other members. Constraints (120) are the linking constraints. These constraints define that each customer can only be visited once by one vehicle. Constraints (121) and constraints (122) show the relationships between two sets of binary variables. Constraints (123) is the vehicle availability constraint, where the vehicles used to deliver the customer orders cannot exceed the total number of vehicles available. Constraints (124) are the capacity constraints, where the total customer orders delivered by each vehicle should not exceed the capacity of each vehicle. Constraints (125) and constraint (126) ensures the depot is the start and end point of each route. Constraints (127) ensures each node is connected by incoming arcs and outgoing arcs, and the total number of incoming and outgoing arcs are equal. Constraints (128) calculate the start time to service customer $j$ after visiting customer $i$ by vehicle $k$. Constraint (129) is a time window constraint, which defines the time window on each node.

After adding the linking constraints, the above model then consist of all the information not only from own company, but also from other companies. These information are in accordance with the information from the ideal collaboration.

For the purpose of applying the cutting plane method, the following notations are proposed. Let $u_i, \alpha_{jk}, \beta_{ik}, v_0, \xi_k, \lambda_k, \gamma_k, \pi_{ik}, \theta_{ijk}, \mu_{ik}, \eta_{ik}$ be the dual variables relevant to constraints (120) – (129) respectively, where $v_0 \geq 0, \lambda_k \geq 0, \xi_k \geq 0, \gamma_k \geq 0, \theta_{ijk} \geq 0, \mu_{ik} \geq 0, \eta_{ik} \geq 0$, and other variables are not restricted in sign.

Let $e \geq 0, f \geq 0$, such that $t^{l'} - t^l = e - f, \left|t^{l'} - t^l\right| = e + f, l \in L$.

Then the inverse model is displayed as follows.

(MODEL 12)

$$\text{minimize} \quad e + f \tag{130}$$

$$\text{subject to} \quad \alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + M\theta_{ijk} \geq -c_{ij} \quad i \in L, j \in C, k \in V \tag{131}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + M\theta_{ijk} + \gamma_k \geq -c_{ij} \quad i \in L, j = depot, k \in V \tag{132}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + M\theta_{ijk} \geq 0 \qquad i \notin L, j \in C, k \in V \tag{133}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + \gamma_k \geq 0 \qquad i \notin L, j = depot, k \in V \tag{134}$$

$$\alpha_{jk} + \beta_{ik} - \pi_{ik} + \pi_{jk} + \lambda_k \geq 0 \qquad i = depot, j \in C, k \in V \tag{135}$$

$$u_i - \alpha_{ik} - \beta_{ik} + d_i\xi_k + a_i\mu_{ik} - b_i\eta_{ik} \geq R_i d_i + \sum_{a \notin l} (t^a - e + f) w_i \qquad i \in L, k \in L \tag{136}$$

$$u_i - \alpha_{ik} - \beta_{ik} + d_i\xi_k + a_i\mu_{ik} - b_i\eta_{ik} \geq (t^l - e + f) w_i \quad i \notin L, k \in L \tag{137}$$

$$v_0 - \alpha_{ik} - \beta_{ik} + d_i\xi_k + a_i\mu_{ik} - b_i\eta_{ik} \geq 0 \quad i = depot, k \in L \tag{138}$$

$$\sum_{h \in C} \theta_{ihk} - \sum_{h \in C} \theta_{hjk} - \mu_{ik} + \eta_{ik} \geq 0 \quad i \in L, k \in V \tag{139}$$

$$-\mu_{ik} + \eta_{ik} \geq 0 \quad i = depot, k \in V \tag{140}$$

In the above formulation, the objective function minimize the difference between cost vectors.

Let $x'_{ijk}$ and $y'_{ik}$ be the optimal solution of the grand alliance.

Then, the value of $t^l$ can be calculated following the below steps:

- Step 1: solve the inverse programming model (model 12), and obtain the optimal value of each variable $e$ and $f$, thus new values of $t^l$ can be obtained, where $t^l = t^l - e + f$.

- Step 2: use the new values $t^l = t^l - e + f$ obtained in step one in the original model (model 11). Then the optimal solution to the original model is obtained, where $x_{ijk} = x_{ijk}^*$ and $y_{ik} = y_{ik}^*$.
- Step 3: calculate and compare two values. The first value is the value of the objective function with new values $t^l$ and optimal solutions of grand alliance. The second value is the other value of the objective function with new values $t^l$ and current optimal solution obtained in step 2. If the first value $obj(t^l, x'_{ijk}, y'_{ik})$ is no less than the second value $obj(t^l, x_{ijk}^*, y_{ik}^*)$, then stop.
- Step 4: otherwise, if $obj\left(t^l, x'_{ijk}, y'_{ik}\right) < obj(t^l, x_{ijk}^*, y_{ik}^*)$, add the following set of constraints (141) to the inverse model.

$$\begin{aligned}
&\sum_{l\in L}[\sum_{i\in l}\sum_{k\in V^l} R_i d_i y'_{ik} - \sum_{i\in l}\sum_{j\in N^l}\sum_{k\in V^l} c_{ij} x'_{ijk} \\
&+\sum_{i\notin l}\sum_{k\in V^l}(t^l - e + f) w_i y'_{ik} \\
&-\sum_{a\notin l}\sum_{i\in l}\sum_{k\in V^l}(t^a - e + f) w_i (1 - y'_{ik})] \\
&\geq \sum_{l\in L}[\sum_{i\in l}\sum_{k\in V^l} R_i d_i y_{ik}^* - \sum_{i\in l}\sum_{j\in N^l}\sum_{k\in V^l} c_{ij} x_{ijk}^* \\
&+\sum_{i\notin l}\sum_{k\in V^l}(t^l - e + f) w_i y_{ik}^* \\
&-\sum_{a\notin l}\sum_{i\in l}\sum_{k\in V^l}(t^a - e + f) w_i (1 - y_{ik}^*)] \qquad (141)
\end{aligned}$$

- Step 5: Go back to step 1, and repeat the above steps, until the inequality $obj\left(t^l, x'_{ijk}, y'_{ik}\right) \geq obj(t^l, x_{ijk}^*, y_{ik}^*)$ is satisfied.

After calculating the capacity exchange costs, profits allocated to each member in the alliance can then be calculated.

### 5.5 Summary

In this chapter, the second contract is designed to build an alliance and to allocate total profits to each member. This contract also guarantee the implementation of the allocation plan, where capacity exchange costs are charged according to the actual weight of each commodity.

In section 5.1, there is a brief introduction about this chapter, and the structure of the following sections are also offered.

In section 5.2, a brief problem description is presented, including the content of each stages, relevant models and basic assumptions.

In section 5.3, how to form an alliance is discussed. Companies first choose to work individually in order to identify the optimal profits they can earn on their own. Then, they choose to form a complete collaboration in order to achieve the highest profits a collaboration can obtain. Models are built for these two situations, and optimal routing plans with the maximum profits for non-collaboration and collaboration can be achieved by solving these two models respectively.

In section 5.4, it focuses on distributing profits to each member in the alliance, and models are built for each member as they can make decisions separately. Capacity exchange costs are included when calculating the total profits. A combined model with full information and relevant inverse model are proposed to calculate the value of capacity exchange costs by applying cutting plane methods. In this way, the profits each member can receive from the logistics alliance can be obtained after the value of capacity exchange costs are achieved.

# Chapter 6 Computational Analysis

## 6.1 Introduction

In this chapter, the last research question can be answered. It aims at quantifying the advantages of collaboration over non-collaboration. As stated in the previous chapter, the model of non-collaborative city logistics, the model of ideal collaboration, and the model of logistics alliance are all built and explained. It is then required to solve all the above models, before comparing the results between collaboration and non-collaboration. Therefore, benchmark datasets of vehicle routing problem with time window and assumed data are applied to quantify the models in stage one (non-collaboration), stage two (centralized collaboration) and stage three (decentralized collaboration). Then, the optimal solutions of each stages can be achieved. After that, optimal solutions are compared between non-collaboration and centralized collaboration. It is expected that the result of collaboration is better than the result of non-collaboration. In addition, the optimal solutions are also compared between non-collaboration and decentralized collaboration. It is expected that the profit allocation plan proposed by the contracts can allocated total profits to each member in the alliance in a fair way.

In section 6.2, a simple case study is conducted to quantify the models in three stages. It is assumed that there are in total five companies who wish to form a logistics alliance, and each company has a depot and five customers. Company data and customer data derives from benchmark dataset. C++ together with CPLEX are applied to solve all the models in three stages. The optimal profits of each stage can be achieved and then displayed in the tables, and comparisons are made according to the following two aspects: 1) the sum of optimal profits earned by individual company and the total profits obtained by ideal collaboration; and 2) the value of optimal profits earned by individual company and the profits distributed to each member in the alliance.

In section 6.3, feasibility analysis is conducted according to the first comparison in the case study, which focuses on comparison between collaborative and non-collaborative situations. In this section, this research concludes that collaboration performs better than non-collaboration. The reason why collaboration is better is discussed. In addition, limitations of this research and research in the future are also offered.

In section 6.4, quality of results is discussed according to the second comparison in the case study, which focuses on comparison between profits earned individually and profits allocated by logistics alliance. In this section, this research concludes that profit allocation plan provided by contracts can allocate profits among each member in the alliance in a reasonable way, which allows members to sign and obey the contract in order to form a stable logistics alliance. Besides, limitations of this research and future research are also presented.

In section 6.5, a brief summary is offered.

### 6.2 A Case Study

In this section, a simple case study is conducted to answer research question four in a clear way, where optimal solutions of non-collaboration and collaboration are listed and compared using tables.

As discussed earlier in 3.3.1 data collection, published benchmarks dataset and assumed data are used as two datasets in this research. The published benchmarks data is Solomon's 25 problems instances, which is available on http://neo.lcc.uma.es/vrp/vrp-instances/capacitated-vrp-with-time-windows-instances/. Due to the fact that traditional vehicle routing problem with time window focuses on the optimal service network with the minimum travelling costs rather than maximizing total profits. It is assumed that there is a unit rate of revenue one company can receive when relevant customer is satisfied, and the value of this rate is assumed to be 2.

According to the limitation of memory, a small-scale problem is taken into consideration. In this case study, there are five companies, and each company has a depot and five customers. The data of company and customers derives from Solomon's 25 problems instance (C101), where 25 customers are allocated to five companies. As there is only one depot in this instance, the depot of other companies are randomly selected from other Solomon's instances. The data of these five companies are listed in the table below.

| **Company A** | **Coordination** | **Demand** | **Time Window** | **Service Time** |
|---|---|---|---|---|
| **Depot** | [40, 50] | 0 | [0, 1236] | 0 |
| **Customer 1** | [45, 68] | 10 | [912, 967] | 90 |
| **Customer 2** | [45, 70] | 30 | [825, 870] | 90 |
| **Customer 3** | [42, 66] | 10 | [65, 146] | 90 |
| **Customer 4** | [42, 68] | 10 | [727, 782] | 90 |
| **Customer 5** | [42, 65] | 10 | [15, 67] | 90 |

*Table 6.1 Dataset of Company A*

| Company B | Coordination | Demand | Time Window | Service Time |
|---|---|---|---|---|
| **Depot** | [35, 35] | 0 | [0, 1236] | 0 |
| **Customer 1** | [40, 69] | 20 | [621, 702] | 90 |
| **Customer 2** | [40, 66] | 20 | [170, 225] | 90 |
| **Customer 3** | [38, 68] | 20 | [255, 324] | 90 |
| **Customer 4** | [38, 70] | 10 | [534, 605] | 90 |
| **Customer 5** | [35, 66] | 10 | [357, 410] | 90 |

*Table 6.2 Dataset of Company B*

| Company C | Coordination | Demand | Time Window | Service Time |
|---|---|---|---|---|
| **Depot** | [25, 80] | 0 | [0, 1236] | 0 |
| **Customer 1** | [35, 69] | 10 | [448, 505] | 90 |
| **Customer 2** | [25, 85] | 20 | [652, 721] | 90 |
| **Customer 3** | [22, 75] | 30 | [30, 92] | 90 |
| **Customer 4** | [22, 85] | 10 | [567, 620] | 90 |
| **Customer 5** | [20, 80] | 40 | [384, 429] | 90 |

*Table 6.3 Dataset of Company C*

| Company D | Coordination | Demand | Time Window | Service Time |
|---|---|---|---|---|
| **Depot** | [31, 67] | 0 | [0, 1236] | 0 |
| **Customer 1** | [20, 85] | 40 | [475, 528] | 90 |
| **Customer 2** | [18, 75] | 20 | [99, 148] | 90 |
| **Customer 3** | [15, 75] | 20 | [179, 254] | 90 |
| **Customer 4** | [15, 80] | 10 | [278, 345] | 90 |
| **Customer 5** | [30, 50] | 10 | [10, 73] | 90 |

*Table 6.4 Dataset of Company D*

| Company E | Coordination | Demand | Time Window | Service Time |
|---|---|---|---|---|
| **Depot** | [85, 69] | 0 | [0, 1236] | 0 |
| **Customer 1** | [30, 52] | 20 | [914, 965] | 90 |
| **Customer 2** | [28, 52] | 20 | [812, 883] | 90 |
| **Customer 3** | [28, 55] | 10 | [732, 777] | 90 |
| **Customer 4** | [25, 50] | 10 | [65, 144] | 90 |
| **Customer 5** | [25, 52] | 40 | [169, 224] | 90 |

*Table 6.5 Dataset of Company E*

The above datasets are first used to solve models in stage one and stage two. C++ (Visual Studio 2013) and CPLEX (12.6.3) are applied to solve non-collaborative models and collaborative models.

As there are five companies in this case study, each company can choose different companies to form different collaborations. They can form a two-member collaboration, a three-member collaboration, a four-member collaboration and a grand alliance (five members).

Results (total profits) of stage one (city logistics without collaboration) and stage two (city logistics with ideal collaboration) are quantified and then listed in the tables below, according to the number of participants in the collaborations.

| **2 members** | **Non-collaboration (sum of profits)** | **Collaboration (profits)** | **Improved (%)** |
|---|---|---|---|
| **AB** | 178.14 | 241.67 | 35.66% |
| **AC** | 264.18 | 280.29 | 6.10% |
| **AD** | 216.65 | 234.75 | 8.35% |
| **AE** | 165.83 | 261.14 | 57.47% |
| **BC** | 247.16 | 302.23 | 22.28% |
| **BD** | 199.64 | 249.78 | 25.12% |
| **BE** | 148.81 | 234.02 | 57.25% |
| **CD** | 285.67 | 341.02 | 19.37% |
| **CE** | 234.85 | 296.91 | 26.43% |
| **DE** | 187.33 | 300.26 | 60.29% |

*Table 6.6 Comparison between Non-collaboration and Collaboration (2 members)*

In the above table, two-member situations are taken into consideration. Each company can choose a member to form an alliance. The first column shows the two members, who make decisions individually first, and then choose form an ideal collaboration. The second column shows the sum of profits these two members can earn when they are making decisions individually. The third column shows the total profits obtained by centralized collaboration. The last column shows the improvement between collaboration and non-collaboration.

According to the above table, there are three circumstances with improvements below 20%. Most of the collaborations are effective with improvements between 20% and 40%. There are three collaborations which are significantly effective, and the improvements are around 60%.

| **3 members** | **Non-collaboration (sum of profits)** | **Collaboration (profits)** | **Improved (%)** |
|---|---|---|---|
| **ABC** | 344.74 | 435.91 | 26.44% |
| **ABD** | 297.21 | 378.84 | 27.46% |
| **ABE** | 246.39 | 405.23 | 64.46% |
| **ACD** | 383.25 | 459.40 | 19.87% |
| **ACE** | 332.43 | 443.85 | 33.52% |
| **ADE** | 284.91 | 418.31 | 46.82% |
| **BCD** | 366.24 | 482.22 | 31.67% |
| **BCE** | 315.41 | 455.24 | 44.33% |
| **BDE** | 267.89 | 428.32 | 59.89% |
| **CDE** | 353.93 | 524.92 | 48.31% |

*Table 6.7 Comparison between Non-collaboration and Collaboration (3 members)*

In the above table, three-member situations are taken into account. The members in the collaboration are listed in the first column. The value in the second column is the sum of profits three members obtained when they choose to work independently. The value in the third column is the overall profits earned by the ideal collaboration. The value in the last column is the difference between collaboration and non-collaboration.

According to the above table, there is only one circumstance with improvements below 20%. Most of the collaborations are effective with improvements between 20% and 50%. There are two collaboration with the highest improvement around 60%.

| 4 members | Non-collaboration (sum of profits) | Collaboration (profits) | Improved (%) |
|---|---|---|---|
| **ABCD** | 463.82 | 611.28 | 31.79% |
| **ABCE** | 412.99 | 599.47 | 45.15% |
| **ABDE** | 365.47 | 562.40 | 53.88% |
| **BCDE** | 434.49 | 660.76 | 52.08% |

*Table 6.8 Comparison between Non-collaboration and Collaboration (4 members)*

In the above table, four-member situations are considered. In the first column, the members in the alliance are listed. In the second column, the sum of individually earned profits are displayed. In the third column, the overall profits received by the central decision maker is shown. In the last column, the compared results are listed to show that collaboration can provide a better performance.

According to the above table, all the collaborations are effective and efficient with improvements between 30% and 55%.

| 5 members | Non-collaboration (sum of profits) | Collaboration (profits) | Improved (%) |
|---|---|---|---|
| **ABCDE** | 532.07 | 794.84 | 49.39% |

*Table 6.9 Comparison between Non-collaboration and Collaboration (5 members)*

In the above table, the grand alliance is taken into consideration. This is the only one collaboration where there are five members who wish to form an alliance. The first column shows the members of the grand alliance. The second column shows the sum of optimal profits when companies make decisions separately. The third column shows the overall profits of the grand alliance. The last column shows the improvement between non-collaboration and collaboration. It is obvious that the grand alliance is an effective collaboration with an improvement around 50%.

In the next stage, the datasets of five companies and their customers are then applied to solve models in stage one and stage three. Analogously, C++ (Visual Studio 2013) and CPLEX 12.6.3 are applied to solve the models of non-collaboration and decentralized collaboration.

| | Contract 1 Improved (%) | Contract 2 Improved (%) |
|---|---|---|
| **Company A** | 31.5% | 33.7% |
| **Company B** | 40.1% | 38.1% |

*Table 6.10 Performance of Contracts (2 members)*

According to the above table, company A and company B choose to form a logistics alliance, and then profits can be allocated to them according to the contracts. Analogus to the previous tables, the data in this table show the profit improvement (in percentage) between non-collaborative situation and the decentralized collaboration. The second column shows the improvement between non-colalboration and the first contract, while the third column shows the improvement between non-collaborative situation and the second contract. As displayed in the above table, it is obvious that more profits can be allocated according to both these two contracts than the profits they can earn individually.

| | Contract 1 Improved (%) | Contract 2 Improved (%) |
|---|---|---|
| **Company A** | 17.6% | 17.5% |
| **Company B** | 12.7% | 18.5% |
| **Company C** | 38.2% | 35.5% |

*Table 6.11 Performance of Contracts (3 members)*

According to the above table, company A, B and C choose to form a decentralized collaboration according to these two contracts. In the second column, it shows the value (in percentage) that more profits each company can be allocated according to contract one. In the third column, it shows the other value (in percentage) that more profits can be allocated to each member according to contract two. Compared with non-collaborative situation, it is obvious that these two allocation plans are effective, and all the members in the alliance are satisfied with these allocation plans.

| | Contract 1 Improved (%) | Contract 2 Improved (%) |
|---|---|---|
| **Company A** | 22.7% | 28.6% |
| **Company B** | 42.7% | 35.2% |
| **Company C** | 41.67% | 25.8% |
| **Company D** | 18.1% | 26.5% |

*Table 6.12 Performance of Contracts (4 members)*

According to the above table, company A, B, C and D are members of a logistics alliance. The more profits (in percentage) allocated to each member in the alliance according to contract one and contract two are displayed in column two and column three respectively. Analogously, both these two contracts can provide proper incentives for members to form an alliance, as each member in the alliance can receive more profits according to the contracts.

| | **Contract 1 Improved (%)** | **Contract 2 Improved (%)** |
|---|---|---|
| **Company A** | 31.7% | 46.8% |
| **Company B** | 35.9% | 44.1% |
| **Company C** | 56.1% | 50.9% |
| **Company D** | 57.6% | 51.5% |
| **Company E** | 59.7% | 52.1% |

*Table 6.13 Performance of Contracts (5 members)*

According to the above table, all five companies wish to form a grand alliance. The data in the second column shows the improvement according to contract one, while the data in the third column shows the improvement according to contract two. As shown in the above table, it is obvious that each member in the alliance can obtain more profits from the logistics alliances, and the grand alliance is a stable alliance.

### 6.3 Feasibility Analysis

In this section, research question four is answered by quantifying models of non-collaborative city logistics and ideal collaboration, and comparing the optimal solution between these two models.

According to the tables in 6.2, when two members, three members, four members and five members choose to form a logistics alliance, the total profits earned by ideal collaboration is better than the sum of profits obtained when working separately. It is obvious that no matter how many members wish to form a logistics alliance, the collaboration always performs better. In conclusion, collaboration is better than non-collaboration according to the data shown in the tables. Most of the improvements are between 20% and 50%, and there are even significant effective collaboration with improvements around 60%. Although there are few cases with low improvements under 20%, which indicates that the profits obtained by collaboration is a little higher than the sum of total profits earned by individual company. It is still possible that each member can be allocated more profits after they form a collaboration.

The reason why collaboration is better than non-collaboration is as follows: 1) there is a central decision maker in the centralized collaboration. Companies are willing to share all the information and all their resources under this circumstance, therefore this central planner can get access to all the information. Then the decision maker can make global decisions for the entire collaboration and make full use of all resources; and 2) there is no fee considered in this centralized collaboration. Companies do not charge each other when they share all their resources, due to the fact that members in the collaboration work as a single company. The above two reasons make the collaboration better than non-collaboration.

After comparing the data of different stages and analysing the reason why collaboration performs better, this study then focuses on the limitations of the research, and how to improve it in the future.

When forming models for traditional vehicle routing problem with time windows, the following constraints are usually taken into consideration: 1) capacity constraints: the total demand a vehicle delivers in a route cannot exceed the capacity of a vehicle; and 2) time window constraints: the total time a customer is serviced should be in the time window. Besides, the objective function is usually used to minimize total travelling costs. In accordance with the assumptions of traditional vehicle routing problems, this research follows the same assumptions, while maximizing the total profits. However, when a vehicle is used to deliver commodities to the customers, the cost of using a vehicle is not taken into consideration. This can result in a situation that more vehicles are used to deliver products when the maximum profits can be achieved. In the future, the cost of using a vehicle will be taken into consideration in order to reduce number of vehicles used and also decrease the empty return.

As stated earlier in this research, only small-scale problems are conducted according to the following reasons: 1) solving a model with large-scale datasets are time consuming. When trying to solve a problem with fifty customer or more, it usually takes more than half an hour to solve a single model; and 2) solving a model with large-scale datasets can result in error. Due to the memory limit of the computer, an error (out of memory) often occurs after waiting for a long time. According to the aim of this research, datasets are applied to test and evaluate a model. Therefore, small-scale datasets are used to test whether the models works as expected or not. In the future, large-scale problem will be taken into consideration when heuristic solution algorithms are applied to solve a model.

## 6.4 Quality of Results

In this part, research question four is answered by quantifying models of non-collaboration and models of logistics alliance. Comparisons are made between the best solutions of these two situations.

According to the tables in 6.2, both these two contracts can provide reasonable profit allocation plans to allocate profits to each member in the allaince. According to the data shown in the table, each member can receive more profits from the collaboration. In this way, each member can be satisfied with the allocation plan. This indicates that both these two contracts can provide proper incentives to encourage members to form a stable alliance.

Comparing these two contracts, both of them focuses on allocating profits to each members in the alliance. In other words, these two contracts distributes the overall profits to each member in the alliance. As shown in the previous tables, there is no contract performs better (or worse) than the other one, as the profit allocated to each member according to one contract are not all higher than (or all lower) than the profit distributed to each member according to the other contract. In addition, it is possible that the same profit allocation plan can be offered by these two contracts, according to the similar structure of these two contracts. It is obvious that both these two contracts can provide proper incentives to encourage members to form an alliance, as profits allocated to each member is more than the profits they can earn when they work individually. In conclusion, decentralized collaboration is better than non-collaboration, and these two contracts can be applied when companies choose to form a logistics alliance.

After analysing the results of the two contracts, the limitations and improvement in the future is then proposed.

In this research, two simple contracts are provided to allocate optimal profits to each member in the alliance. Capacity exchange costs are introduced to charge other companies when delivering products for others, and vice versa. Capacity exchange costs are defined according to the following aspects: 1) according to the travelling distances between depot and customer; and 2) according to the actual weight of commodities. These two criteria are commonly used criteria in delivery. However, these two methods are simple methods, which provide similar structures. In the future, more criteria will be taken into consideration when designing a contract, for example, both these two criteria are considered simultaneously in a single contract.

When building models for traditional vehicle routing problems, it is usually assumed that there is a depot with sufficient supply. In accordance with the traditional vehicle routing problems, it is also assumed that all depot have sufficient stock to fulfil the demand of own customers and other customers in this research. However, inventory exchange cost is not taken into consideration. More specifically, inventory exchange cost is not charged when one company delivers products from own depot to customers of other companies. Only customer information are shared among members in the alliance, and capacity exchange costs are charged when delivering commodities for other customers in this research. As a result, inventory exchange costs as well as the stock level will be taken into account.

## 6.5 Summary

In this research, the last research question is answered by quantifying models of non-collaborative city logistics, models of centralized collaboration, and models of decentralized collaboration. A case study is conducted and results are analysed according to the following comparisons: 1) the sum of profits earned by individual companies and the total profits obtained by centralized collaboration; and 2) the optimal profits earned when making decisions individually and the profits allocated to each member in the alliance. After analysing the result, two conclusions are made as follows: 1) collaboration is better than non-collaboration; and 2) both these two profit allocation plans can allocate more profits to each member in the alliance than the profits each company can achieve when making decisions individually. This indicates that all members are satisfied with the profit allocation plans, and then a stable logistics alliance can be formed.

In section 6.1, a brief introduction is offered as well as the structure of this chapter.

In section 6.2, a simple case study is conducted, where there are altogether five companies and each company has a depot, a fleet of vehicles, and five customers. In addition, the relevant best results of the three stages are quantified and presented in tables. There are also comparisons between results of non-collaboration and collaboration.

In section 6.3, a feasibility analysis is conducted according to the comparison between non-collaboration and ideal collaboration. A conclusion is made that collaboration performs better. The reason why collaboration is better than non-collaboration is discussed, followed by the limitations of this study and future research.

In section 6.4, quality of results is conducted according to the comparison between non-collaboration and logistics alliance. A conclusion is made that both these two contracts can allocate overall profits to each member in the alliance in a fair way, and each alliance member can receive more profits from the logistics alliance. Limitations and future research are also discussed in this section.

# Chapter 7 Discussion

## 7.1 Introduction

This chapter focuses on discussing the similarities and differences within this research. Moreover, it also focuses on discussing the similarities and differences between this research and previous researches. More specifically, two contracts proposed in this research are discussed first, and followed by similarities and differences. Then, there is a comparison between previous research and this research is discussed according to the following three aspects: 1) how to form a collaboration; 2) how to allocate benefits to each member in the alliance; and 3) the performance of collaboration.

In section 7.2, two profit allocation plans proposed in this research are discussed with similarities and differences.

In section 7.3, collaboration forming, profit allocation plan, and the performance of collaboration are compared and contrasted between this research and previous researches.

In section 7.4, a brief summary if offered.

## 7.2 Comparison between Two Contracts

In this section, comparisons between contract one and contract two are discussed according to the following aspects:

- The content of two contracts
- The results of profit allocation

Both these two contracts focuses on allocating overall profits to each member in the alliance in a fair way, where capacity exchange costs are taken into consideration. These capacity exchange costs aim at providing incentives for each member in the alliance, when a member delivers commodities for other companies. In this way, member in the alliance can be allocated more profits than working independently. As long as the final profits received are more than the individual profits, members in the alliance can be satisfied with the profit allocation plan. Both these two contracts can be applied to decentralized collaborations, where stable logistics alliances can be formed.

These two contracts provide two different ways to measure the capacity exchange costs. In these two contracts, information of customers is shared among members in the alliance. The first contract calculated the capacity exchange costs according to the travel distances between the depot and customers. While the second contract calculated the capacity exchange costs according to the weight of commodity. In other words, different charging criteria are used in different contracts.

According to the tables in 6.2, both these two contracts can allocate overall profits to each member in the alliance in a fair way. Proper incentives can be provided by both two contracts that each member can receive more profits from the collaboration. However, there is no contract that provides more profits to all the members than the other one, and it is possible that these two contracts can provide the same profits allocation plan to allocate profits to each member in the alliance.

## 7.3 Comparison to the Previous Researches

This section focuses on comparing and contrasting the similarities and differences between previous researches and this research. How to form a collaboration in this research and previous researches are first discussed and compared. How to allocate benefits among members are then discussed, including profit allocation methods. At last, performance of collaboration in this research and previous researches are discussed and compared, and followed by improvements.

### *7.3.1 Forming a Collaboration*

Cooperative game theory provides a vital important role when there are two or more members choose to form a collaboration. As discussed earlier in chapter 2 literature review, cooperative coalitional game with transferrable utilities focuses on the distribution of payoffs. In this research, cooperative coalition game is also applied as profits need to be achieved and allocated to each member in the alliance.

| Collaboration | Articles |
|---|---|
| **Centralized Collaboration** | Montoya-Torres et al. (2016), Quintero-Araujo et al. (2016), Sanchez et al. (2016), Soyasal et al. (2018), Perez-Bernabeu et al. (2015), Buijs et al. (2016), Dai and Chen (2012), Hernandez and Peeta (2011), Nadarajah and Bookbinder (2013), Weng and Xu (2014), Wang et al. (2014) |
| **Decentralized Collaboration** | Berger and Bierwirth (2007), Wang and Kopfer (2014), Cuervo et al. (2016), Wang et al. (2014), Hernandez and Peeta (2014), Fernandez, Fontana and Speranza (2016) |

*Table 7.1 Researches based on centralized collaboration and decentralized collaboration*

From the perspective of centralized collaboration and decentralized collaboration, most researches focus on only one type of collaboration (Table 7.1). While in this research, both centralized collaboration and decentralized collaboration are taken into consideration. Centralized collaboration is applied in ideal collaboration, where there is a central decision maker who makes decisions for the entire alliance. While decentralized collaboration is applied in logistics alliance, where each member in the alliance can make decisions individually. There is also a link between these two collaborations in this research. The optimal allocation plan achieved by centralized collaboration is regarded as the optimal soluiton a logistics alliance can achieve, and then this allocation plan can be achieved by decentralized collaboration according to inverse programming and cutting plane method.

Moreover, capacity exchange costs is taken into consideration in decentralized collaboration. Proper incentives are provided and members in the alliance can received more profits than working independently. This fills the research gap 1, motivation mechanisms are designed for logistics alliance, and incentives are provided when sharing resources.

### *7.3.2 Benefit Allocation*

As reviewed in section 2.4 benefit allocation, previous researches allocated costs to each member by applying existing allocation algorithms based on game theory. The below table shows the commonly used cost allocation methods.

| **Cost allocation methods** | **Article (Cost/profit allocation)** |
|---|---|
| **Proportional Allocation** | Liu et al. (2010), Ozener (2014) |
| **Core** | Kimms and Kozeletskyi (2016) |
| **Shapley Value** | Vanovermeire and Sorensen (2014b), Zakharov and Shehegryaev (2015), Dahlberg, et al. (2018) |
| **Nucleolus** | Liu et al. (2010), Frisk et al. (2010), Dahlberg, et al. (2018) |
| **Equal Profit Method** | Dahlberg, et al. (2018) |

*Table 7.2 Cost Allocation Methods*

Compared with the above allocation methods, this research also focuses on allocating benefits to each member in a fair way according to efficiency property and group rationality property. In addition, members in the alliance are satisfied with the allocation plan, as members in the alliance can receive more profits from the logistics alliance.

However, the above allocation methods only allocate benefits to each member. What's worse, it is possible that there is no allocation plan by applying the above cost allocation methods, when the core is empty (Agarwal & Ergun, 2010; Kimms and Kozeletskyi, 2016). In addition, the implementation of the allocation plan is not considered according to the above allocation methods. In other words, this research designs contracts to allocate profits to each member in the alliance, and also guarantee the allocation plan can be implemented as expected. That is, no matter what decisions each member in the logistics alliance make, the allocation plan can be achieved.

Compared to the cost allocation methods, small-scale datasets are applied to test and evaluate the models, while the existing cost allocation methods can be applied to large-scale problems. This is also discussed in the previous chapters that large-scale datasets will be applied in the future study.

Compared to the cost allocation methods, members can charge each other when sharing resources in this research, rather than simply allocating benefits to each member according to existing mechanisms. Capacity exchange costs are introduced to measure the total profits allocated to each member. Once the capacity exchange costs are calculated, the profit allocation plan can then be achieved.

The above comparisons are made between this research and existing benefit allocation methods. Another comparison can be made between comparing contracts. In the contract proposed by Chu et al. (2020), there is a common agency and several express companies. While in this research, a decentralized collaboration is formed when allocating all profits to the members, where each member in the alliance make individual decisions without a central decision maker. This fills the research gap 2, contracts are designed for logistics to allocate profits to each member in a fair way.

### *7.3.3 Performance of Collaboration*

| Articles | Reduction in cost / distances |
|---|---|
| Montoya-Torres et al. (2016) | Travel distance 25.6% |
| Quintero-Araujo et al. (2016) | Cost 4% |
| Sanchez et al. (2016) | Cost 55% |
| Cruijissen and Salomon (2004) | Cost 5% - 15%, average 7% |
| Soyasal et al. (2018) | Cost 4% - 24% |

*Table 7.3 Reduction in costs or distances of Collaboration*

In traditional vehicle routing problem and its variants, the objective function usually minimize the total travelling costs or total travelling distances. According to the above table, most of the improvements are between 5% and 25%, where there is also an effective collaboration with improvement of 55%.

As discussed earlier in 6.2 case study, the improvements of collaborations are displayed according to different number of companies in the collaboration. The improvements of these collaborations are shown in the figures below: when two members form an alliance, when three members form an alliance, when four members form a collaboration, and a grand alliance with five members.

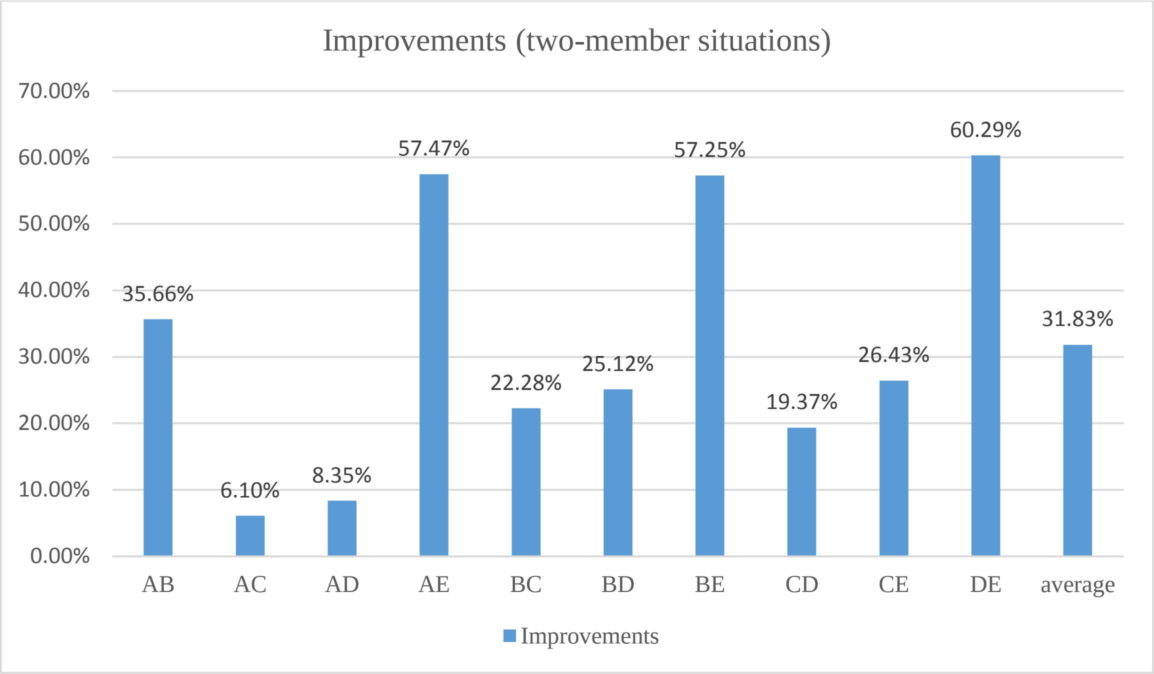

*Figure 7.1 Improvements of Collaboration (two-member situations)*

In the above figure, two companies choose to form an alliance to improve their profits and service. According to the data, there are two low improvements with a value below 10%. Most of the improvements are between 20% and 40%, while three significant improvements are between 55% and 65%. The average of improvements is 31.83%.

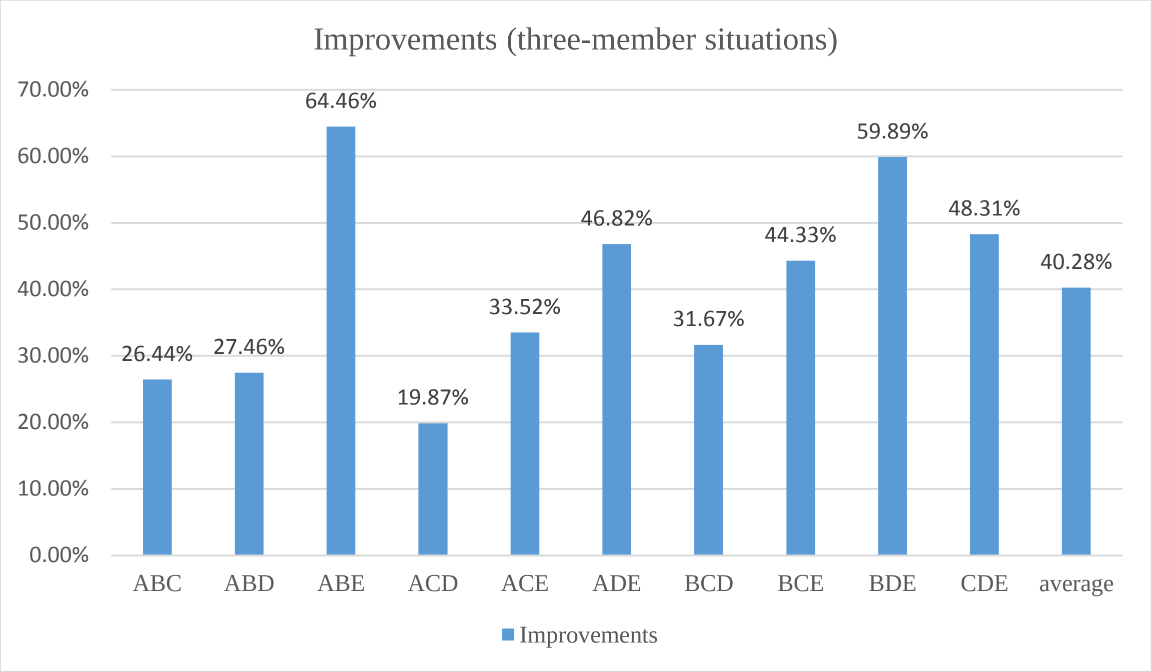

*Figure 7.2 Improvements of Collaboration (three-member situations)*

In the above figure, a collaboration consists of three members. The majority of improvements are between 20% to 50%, while there is one just below 20% and two significant improvements above 55%. The average of improvements is 40.28%

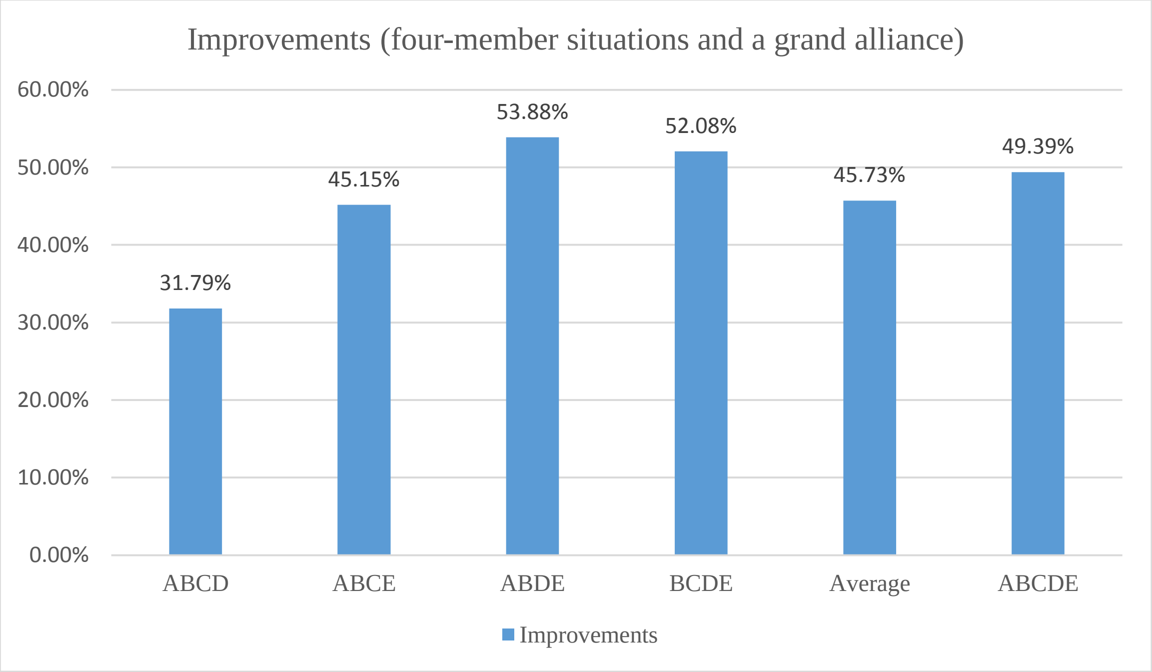

*Figure 7.3 Improvements of Collaboration (four-member situations and a grand alliance)*

The above figure shows the improvement of collaboration where there are four members in the alliance (column 1-4). It also shows the improvement of grand alliance (column 5). All these improvements are between 30% and 55%.

Compared to the previous researches, the profits earned by the grand alliance are improved from 5% - 25% to 20% – 50%. The best improvements between 55% - 65% can meet the level of 55%. The average improvements of this research are 31.83%, 40.28%, 45.73% and 49.39% respectively. This improvement is much higher than the improvements of previous studies (between 4% - 24%). However, there are still few collaboration with improvements below 10%.

The reason to the improvements is that a centralized collaboration is formed. All information is shared, and a central decision maker can get access to all the information. Besides, this central decision maker can make decisions for the entire collaboration and make the most of all resources, which can significantly improve non-collaboration.

## 7.4 Summary

In this chapter, a discussion is first made to discuss the similarities and differences within this research. Two contracts in this research are compared and contrasted. Then, there is another discussion on this research and previous researches. Collaboration formation, benefits allocation and result analysis are then compared.

In section 7.1, a brief introduction is offered followed by the structure of this chapter.

In section 7.2, similarities and differences between contract one (capacity exchange costs charged according to travel distances) and contract two (capacity exchange costs charged according to the weight of commodities) are discussed.

In section 7.3, a comparison is made between previous researches and this research. Especially from the following aspects: 1) how to form a collaboration; 2) how to allocate benefits to each member; and 3) the performance of collaboration.

# Chapter 8 Conclusion

## 8.1 Introduction

In this chapter, a conclusion is made to summarize this research according to the following aspects: main findings, main contributions, limitations and future research.

In section 8.2, main findings are offered to show how the research aims have been achieved and how the research questions have been answered.

In section 8.3, main contributions are offered according to the following aspects: 1) contribution to the theory; and 2) contribution to the practice.

In section 8.4, limitations are offered.

In section 8.5, future research is offered.

In section 8.6, a summary is offered.

## 8.2 Main Findings

In this research, the aim is to investigate motivation and allocation mechanisms for logistics alliance by extending existing vehicle routing problem models. Thus, a quantitative study is conducted, and the following research questions are answered in a clear way.

*Research Question 1: design the optimal service network for non-collaborative city logistics where a single company makes own decision*

In this stage, company choose to make decisions individually. According to mathematical models building, traditional vehicle routing problem with time window can be employed to the problem at this stage. As in traditional vehicle routing problems, one company aims at the optimal service network with the minimum costs or minimum travel distances. In this research, this model is then modified to find optimal routing plan with the maximum profits by following basic assumptions of vehicle routing problems with time window. With the help of the modified model, each company can design optimal service routes with the most profits.

*Research Question 2: design optimal service network for the grand alliance with maximum profits under ideal collaboration*

In this stage, company choose to form an ideal collaboration, where there is a virtual central decision planner who makes decisions for the entire collaboration. All information are shared among members in the alliance, and the central decision maker can get access to all the information. Besides, no fees are taken into consideration in this alliance, as all companies are working as a single company. As a result, the multi-depot vehicle routing problem with time window model can then be used in this centralized collaboration. Analogously, this multi-depot model is also modified to maximize total profits instead of minimizing travel costs. With the help of this modified model, the central decision maker can obtain the optimal service routing plan with the maximum overall profits.

*Research Question 3: design motivation mechanisms and allocation mechanisms to provide incentives to encourage members to form a stable alliance; and to allocate overall profits to each member in a fair way.*

In this stage, company choose to form a logistics alliance, which is a decentralized collaboration. Members share their customer information (including customer order and customer location) with each other. Then, capacity exchange costs are introduced to charge the other companies when one company delivers commodities for others.

In this decentralized collaboration, there is no central decision maker who makes global decisions. Thus, each company can make own decisions on choosing which customers to service. A modified vehicle routing problem with time window model is proposed. The objective function of this model is to maximize total profits earned by individual member, and the profits are calculated by revenue minus travelling costs plus capacity exchange costs received from others minus capacity exchange costs paid to others. The constraints to this model is also modified as there is no need for one company to service all the customers.

For the purpose of measuring the capacity exchange costs, two contracts are designed as follows: 1) capacity exchange costs charged according to the travel distances from customer to depot; 2) capacity exchange costs charged according to the weight of commodities.

It is clear that each company in the decentralized collaboration only get access to partial information, then a model with full information is proposed with a linking constraint. This combined model is used as the original model, and an inverse model is then obtained according to the dual theory. Cutting plane method based on inverse programming is then applied to both the original model and the inverse model to find the value of capacity exchange costs. After that, profit allocation plan can be obtained.

Capacity exchange costs in the contracts can provide incentives to encourage members to form an alliance, as the profits allocated to each member in the alliance is more than the profits earned individually. In this way, members are satisfied with the allocation plan, and this alliance is then stable.

*Research Question 4: quantify and compare optimal solutions of non-collaboration and collaboration*

In order to answer research question 4, models in stage one, stage two and stage three are quantified first. As a result, optimal solutions of non-collaboration, centralized collaboration and decentralized collaboration are all obtained.

Optimal solutions of non-collaboration and centralized collaboration are compared to show that the performance of collaboration is better than non-collaboration.

Optimal solution of non-collaboration and decentralized collaboration are then compared to show that the contracts can provide reasonable allocation mechanism to distribute the profits to each member in a fair way.

## 8.3 Main Contributions

From the perspective of theory, this research fill the research gaps in the literature. In this research, both motivation mechanisms and allocation mechanisms are designed for logistics alliances on tactical level. More importantly, contracts are designed in this research to allocate total profits and guarantee the implementation of the allocation plan.

In this research, both centralized collaboration and decentralized collaboration are considered. Centralized collaboration focuses on figuring out the maximum profits a collaboration can achieve. While decentralized collaboration focuses on allocating the maximum profits to each member in the alliance in a fair way. As described in the contracts, capacity exchange costs can provide right incentives to encourage members to form an alliance. This fill the research gap one, as motivation mechanism is provided in this research.

In previous researches, benefit allocation methods are directly applied to figure out the profit allocation plan. An existing contract design focuses on central collaboration where there is a common agency. In this research, contracts are designed for decentralized collaboration, where each member in the alliance can make decisions individually. This research provides a reasonable allocation plan to keep the alliance stable, where all the members in the alliance are satisfied with the profit allocation plan. These contracts also guarantee that the optimal allocation plan can be achieved as planned. This fill the research gap two, as two contracts are designed for logistics alliances.

From the perspective of practice, this research encourages potential members to form an alliance by providing proper incentives. A single company in practice can apply data to the models of three stages, and then compare the results between collaboration and non-collaboration. The comparison between non-collaboration and collaboration indicates that collaboration is better than non-collaboration. The comparison between non-collaboration and logistics alliance indicate that these contracts can provide enough incentives for companies to form an alliance. According to these two conclusions, it is suggested that logistics companies in practice can choose to form a logistics alliance by following the contracts.

## 8.4 Limitations

In this section, limitations of this research is discussed.

Firstly, following the basic assumptions of traditional vehicle routing problem with time window, vehicle capacity constraints and time window constraints are taken into consideration. The objective function maximize the total profits (revenue minus costs) instead of minimizing the total travelling costs. However, there is no cost to use one vehicle. As a result, it is possible that more vehicles are used to deliver commodities if the profits can be maximized. This may result in low usage of capacity as well as empty return.

Secondly, customer order and customer location are shared among members in the alliance. Capacity exchange costs are provided for one company to charge another company when this company delivers commodities for other companies. According to the traditional vehicle routing problems, it is assumed that a depot has sufficient stock to satisfy all the customers. However, inventory sharing is not taken into consideration. More specifically, when a company deliver commodities from own depot to other customers using own fleet of vehicles, capacity exchange costs are only charged according to the travelling distances or weight of commodities, without considering inventory sharing.

Lastly, small-scale datasets are applied in this research to test models. A quantitative study is conducted in this research to build models in three stages. Besides, models in the three stages need to be quantified and compared to evaluate models. Small-scale datasets can be used to test models. The time used to solve one problem is usually very short and the optimal results can be quantified and compared. However, other studies tend to use large-scale datasets to test models and evaluate solution algorithms. According to the limitation of memory, an error usually occurs (out of memory) when large-scale dataset is used to test models.

## 8.5 Future Research

As discussed in the limitations, the following future research areas are taken into consideration.

Firstly, cost of using one vehicle will be taken into consideration. In order to achieve maximum profits, it is possible to use more vehicles than expected to deliver products to meet the demand of customers, which can cause lower capacity used and more empty return. As a result, a proper vehicle using cost will be considered in order to reduce usage of vehicles.

Secondly, inventory exchange will be taken into consideration. This also requires a more complex contract to calculate capacity exchange costs. In this research, capacity exchange costs are charged according to travelling distances or according to weight of commodities. There is a need to consider inventory exchange as it can provide incentives to encourage members to form an alliance.

Lastly, large-scale dataset will be used to test and evaluate models. Apart from memory limitation, solution algorithms will be learnt and applied to solve models with large-scale datasets.

# Appendix

## A code example (C++ & CPLEX) to solve vehicle routing problems with time window

```
#include <ilcplex/ilocplex.h>
ILOSTLBEGIN

typedef IloArray<IloBoolVarArray> BoolVarArray2;
typedef IloArray<IloArray<IloBoolVarArray>> BoolVarArray3;
typedef IloArray<IloNumVarArray> NumVarArray2;
typedef IloArray<IloNumArray> NumArray2;

#define M 10000
#define renevue 2

int main(int argc, char** argv)
{
        IloEnv env;

        try {

                // READ DATA FROM FILE

                const char* filename = "D:/data/C101.txt";
                if (argc > 1) filename = argv[1];
                ifstream file(filename);
                if (!file) {
                        cerr << "No such file: " << filename << endl;
                        throw (-1);
                }

                IloNumArray xCoor(env), yCoor(env), demand(env), openWindow(env),
closeWindow(env), serviceTime(env), capacity(env);
                file >> xCoor >> yCoor >> demand >> openWindow >> closeWindow >> serviceTime >>
capacity;

                IloInt i, j, k;
                IloInt nbNodes = demand.getSize();
                IloInt nbVehicles = capacity.getSize();

                NumArray2 travelDistance(env, nbNodes);
                for (i = 0; i < nbNodes; i++) {
                        travelDistance[i] = IloNumArray(env, nbNodes);
                        for (j = 0; j < nbNodes; j++) {
                                travelDistance[i][j] = sqrt((xCoor[j] - xCoor[i])*(xCoor[j] -
xCoor[i]) + (yCoor[j] - yCoor[i])*(yCoor[j] - yCoor[i]));
                        }
                }


                // MODEL

                IloModel model(env);

                // decision variables

                BoolVarArray3 x(env, nbNodes);
```

```
for (i = 0; i < nbNodes; i++) {
        x[i] = BoolVarArray2(env, nbNodes);
        for (j = 0; j < nbNodes; j++) {
                x[i][j] = IloBoolVarArray(env, nbVehicles);
        }
}

BoolVarArray2 y(env, nbNodes);
for (i = 0; i < nbNodes; i++) {
        y[i] = IloBoolVarArray(env, nbVehicles);
}

NumVarArray2 t(env, nbNodes);
for (i = 0; i < nbNodes; i++) {
        t[i] = IloNumVarArray(env, nbVehicles, 0.0, IloInfinity);
}

// constraint 1

for (k = 0; k < nbVehicles; k++) {
        for (j = 0; j < nbNodes; j++) {
                IloExpr expr1(env);
                for (i = 0; i < nbNodes; i++) {
                        expr1 += x[i][j][k];
                }
                model.add(expr1 == y[j][k]);
                expr1.end();
        }
}

// constraint 2

for (k = 0; k < nbVehicles; k++) {
        for (i = 0; i < nbNodes; i++) {
                IloExpr expr2(env);
                for (j = 0; j < nbNodes; j++) {
                        expr2 += x[i][j][k];
                }
                model.add(expr2 == y[i][k]);
                expr2.end();
        }
}

// constraint 3

for (k = 0; k < nbVehicles; k++) {
        IloExpr expr3(env);
        IloExpr expr4(env);
        for (j = 0; j < nbNodes - 1; j++) {
                expr3 += x[nbNodes - 1][j][k];
                expr4 += x[j][nbNodes - 1][k];
        }
        model.add(expr3 <= 1);
        model.add(expr4 <= 1);
        expr3.end();
        expr4.end();
}
```

```
		// constraint 4

		for (k = 0; k < nbVehicles; k++) {
			for (j = 0; j < nbNodes; j++) {
				IloExpr expr5(env);
				IloExpr expr6(env);
				for (i = 0; i < nbNodes; i++) {
					expr5 += x[i][j][k];
					expr6 += x[j][i][k];
				}
				model.add(expr5 - expr6 == 0);
				expr5.end();
				expr6.end();
			}
		}

		// constraint 5

		for (i = 0; i < nbNodes - 1; i++) {
			IloExpr expr7(env);
			for (k = 0; k < nbVehicles; k++) {
				expr7 += y[i][k];
			}
			model.add(expr7 == 1);
			expr7.end();
		}

		// constraint 6

		for (k = 0; k < nbVehicles; k++) {
			IloExpr expr8(env);
			for (i = 0; i < nbNodes; i++) {
				expr8 += demand[i] * y[i][k];
			}
			model.add(expr8 <= capacity[k]);
			expr8.end();
		}

		// constraint 7

		for (k = 0; k < nbVehicles; k++) {
			for (j = 0; j < nbNodes - 1; j++) {
				for (i = 0; i < nbNodes - 1; i++) {
					model.add(t[i][k] + serviceTime[i] + travelDistance[i][j]
- M * (1 - x[i][j][k]) <= t[j][k]);
				}
			}
		}

		// constraint 8

		for (k = 0; k < nbVehicles; k++) {
			for (i = 0; i < nbNodes; i++) {
				model.add(t[i][k] >= openWindow[i] * y[i][k] && t[i][k] <=
closeWindow[i] * y[i][k]);
			}
		}
```

```
        // objective function
        IloExpr obj(env);
        IloExpr obj1(env), obj2(env);
        for (i = 0; i < nbNodes; i++) {
            obj1 += revenue * demand[i] * y[i][k];
        }
        for (k = 0; k < nbVehicles; k++) {
            for (j = 0; j < nbNodes; j++) {
                for (i = 0; i < nbNodes; i++) {
                    obj2 += travelDistance[i][j] * x[i][j][k];
                }
            }
        }
        obj = obj1 - obj2;
        IloObjective fn = IloMaximize(env, obj);
        model.add(fn);
        obj.end();


        // SOLUTION

        IloCplex cplex(model);
        cplex.solve();

        env.out() << "solution status = " << cplex.getStatus() << endl;
        env.out() << "optimal value = " << cplex.getObjValue() << endl;

        for (k = 0; k < nbVehicles; k++) {
            for (j = 0; j < nbNodes; j++) {
                for (i = 0; i < nbNodes; i++) {
                    if (cplex.getValue(x[i][j][k]))
                        env.out() << "x[" << i + 1 << "][" << j + 1 <<
"][" << k + 1 << "] = " << cplex.getValue(x[i][j][k]) << endl;
                }
            }
        }

        for (k = 0; k < nbVehicles; k++) {
            for (i = 0; i < nbNodes; i++) {
                if (cplex.getValue(y[i][k]))
                    env.out() << "y[" << i + 1 << "][" << k + 1 << "] = " <<
cplex.getValue(y[i][k]) << endl;
            }
        }


        IloNumArray capValue(env, nbVehicles);
        for (k = 0; k < nbVehicles; k++) {
            for (i = 0; i < nbNodes; i++) {
                capValue[k] += demand[i] * cplex.getValue(y[i][k]);
            }
            if (capValue[k]) {
                env.out() << "used capacity aof vehicle " << k + 1 << " = " <<
capValue[k] << endl;
            }
        }

    }
```

```
        catch (IloException& ex) {
                cerr << "ERROR: " << ex << endl;
        }

        catch (...) {
                cerr << "ERROR: unknown exception caught!" << endl;
        }

        env.end();
        return 0;

}
```

# References

Adenso-Diaz, B., Lozano, S., Garcia-Carbajal, S. and Smith-Miles, K. (2014) 'Assessing partnership savings in horizontal cooperation by planning linked deliveries'. *Transportation Research Part A*, 66 (2014) pp. 268 – 279.

Agarwal, R. and Ergun, O. (2010) 'Network Design and Allocation Mechanisms for Carrier Alliances in Liner Shipping', *Operations Research*, 58 (6), pp. 1726 – 1742.

Ahuja, R. K. and Orlin, J. B. (2001) 'Inverse Optimization'. *Operations Research*, 49 (5), pp. 771 – 783.

Alba, E. and Dorronsoro, B. (2006) 'Computing nine new best-so-far solutions for Capacitated VRP with a cellular Genetic Algorithm' Information Processing Letters, 98 (2006), pp. 225 – 230.

Algaba, E., Fragnelli, V., Llorca, N., and Sanchez-Soriano, J. (2019) 'Horizontal cooperation in a multimodal public transport system: The profit allocation problem'. *European Journal of Operational Research*, 275 (2019), pp. 659 – 665.

Angelelli, E., and Speranza, M. G. (2002). 'The periodic vehicle routing problem with intermediate facilities'. European journal of Operational research, 137(2), pp. 233-247.

Audy, J. F., D’Amours, S. and Rousseau, L. M. (2011) 'Cost Allocation in the Establishment of a Collaborative Transportation Agreement – An application in the furniture industry'. *Journal of the Operational Research Society*, 62 (6), pp. 960 – 970.

Azi, N., Gendreau, M. and Potvin, J. Y. (2007) 'An exact algorithm for a single-vehicle routing problem with time windows and multiple routes'. *European Journal of Operational Research,* 178, pp. 755 – 766.

Bahinipati, B. K., Kanda, A. and Deshmukh, S. G. (2009) 'Horizontal collaboration in semiconductor manufacturing industry supply chain: An evaluation of collaboration intensity index', *Computers & Industrial Engineering*, 57, pp. 880 – 895.

Baldacci, R. Mingozzi, A. and Roerti, R. (2012) 'Recent exact algorithms for solving the vehicle routing problem under capacity and time window constraints'. *European Journal of Operational Research*, 218, pp. 1 – 6.

Baldacci, R., Toth, P., and Vigo, D. (2007) 'Recent advances in vehicle routing exact algorithms'. *4OR: A Quarterly Journal of Operations Research*, 5 (4), pp. 269 – 298.

Baldacci, R., Toth, P. and Vigo, D. (2010) 'Exact algorithms for routing problems under vehicle capacity constraints', *Annuals of Operations Research*, 175 (1), pp. 213 – 245.

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

Berger, S. and Bierwirth, C. (2007) 'The Collaborative Carrier Vehicle Routing Problem for Capacitated Travelling Salesman Tours'. *Working Paper Series of the MUL Halle*, 63, pp. 75 – 78.

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

Bloos, M. and Kopfer, H. (2011) 'On the Formation of Operational Transport Collaboration Systems', in Kreowski, H. J., Scholz-Reiter, B. and Thoben, K. D. (eds.) *Dynamics in Logistics*. Berlin Heidelberg: Springer-Verlag, pp. 191 – 201.

Bulut, A. and Ralphs, T. K. (2015) 'On the Complexity of Inverse Mixed Integer Linear Optimization'. *Industrial and Systems Engineering*, pp. 1 – 17.

Buijs, P., Alvarez, J. A. L., Veenstra, M. and Roodbergen, K. J (2016) 'Improved Collaborative Transport Planning at Dutch Logistics Service Provider Fritom'. *Interfaces*, 46 (2), pp. 119 – 132.

Chabot, T., Bouchard, F., Legault-Michaud, A., Renaud, J. and Coelho, L. C. (2018) 'Service level, cost and environmental optimization of collaborative transportation'. *Transportation Research Part E*. 110 (2018) pp. 1 – 14.

Chalkiadakis, G. Elkind, E. and Wooldridge, M. (2012) 'Computational Aspects of Cooperative Game Theory'. *Artificial Intelligence and Machine Learning*, 5 (6), pp. 1 – 168.

Chen, H. (2016) 'Combinatorial clock-proxy exchange for carrier collaboration in less than truck load transportation'. *Transportation Research Part E*, 91, pp. 152 – 172.

Chu, X., Liu, J., Ren, L. and Gong, D. (2020) 'Optimal contract design with a common agency in last-mile logistics' Transportation Research Part E: Logistics and Transportation Review, 139 (2020).

Contardo, C., and Martinelli, R. (2014) 'A new exact algorithm for the multi-depot vehicle routing problem under capacity and route length constraints', *Discrete Optimization*. 12, pp.129 – 146.

Cook, W.J., Cunningham, W.H., Pulleyblank, W.R. and Schrijver, A. (1997) *Combinatorial Optimization*. New York:  John Wiley & Sons.

Cordeau, J.F., Gendreau, M. and Laporte, G. (1997) 'A tabu search heuristic for periodic and multi-depot vehicle routing problem', *Networks*, 30, pp.105 – 119.

Cordeau, J.-F., Laporte, G., Savelsbergh, M.W.P. and Vigo, D. (2007) 'Vehicle Routing', in Barnhart, C. and Laporte, G. (eds.) *Handbook in Operations Research & Management Science*.  pp.367 – 428.

Crainic, T.G. (2008) 'City Logistics'. *CIRRELT-2008*, pp.1 – 46.

Crainic, T.G., Errico, F., Rei, W. and Ricciardi, N. (2012) 'Integrating c2e and c2c traffic into city logistics planning', *Procedia – Social and Behavioural Sciences*, 39, pp.47 – 60.

Crainic, T.G., Ricciardi, N. and Storchi, G. (2009) 'Models for Evaluating and Planning City Logistics Systems', *Transportation Science*, 43 (4), pp.407 – 548. (p.408)

Cruijssen, F., Borm, P., Fleuren, H., and Hamers, H. (2010) 'Supplier-initiated outsourcing: a methodology to exploit synergy in transportation' *European Journal of Operational Research*, 207 (2), pp. 763 – 774.

Cruijssen, F., Braysy, O., Dullaert, W., Fleuren, H. & Salomon (2007) 'Joint route planning under varying market conditions'. *International Journal of Physical Distribution & Logistics Management.* 37 (4) pp. 287 – 304.

Cruijssen, F., Dullaert, W. and Fleuren, H. (2007) 'Horizontal Cooperation in Transport and Logistics: A Literature Review', *Transportation Journal*, 46(3), pp.22 – 39.

Cruijssen, F. and Salomon, M. (2004) 'Empirical Study: Order Sharing between Transportation Companies May Result in Cost Reductions Between 5 to 15 Percent', *CentER Discussion Paper, 2004-80,* pp.1 – 22.

Cuervo, D. P., Vanovermeire, C., and Sorensen, K. (2016) 'Determining collaborative profits in coalitions formed by two partners with varying characteristics' *Transportation Research Part C: Emerging Technologies*, 70, pp. 171 – 184.

Dahl, S., and Derigs, U. (2011) 'Cooperative planning in express carrier networks – an empirical study on the effectiveness of a real-time decision support system' *Decision Support Systems*, 51 (3), pp. 620 – 626.

Dahlberg, J. Engevall, S. Gothe-Lundgren, M., Jornsten, K. and Ronnqvist, M. (2018) 'Incitements for transportation collaboration by cost allocation' *Central European Journal of Operations Research*, 27, pp. 1009 – 1032.

Dai, B. & Chen, H. (2009) 'Mathematical model and solution approach for collaborative logistics in less than truckload transportation', *IEEE*, pp. 767 - 772.

Daneshzand, F. (2011) 'The Vehicle-Routing Problem', in Farahani, R. Z., Rezapour, S. and Kardar, L. (eds.) *Logistics Operations and Management: Concepts and Models*, pp. 127 – 153.

Danna, E. and Le Pape, C. (2005) 'Branch-and-Price Heuristics: A case study on the vehicle routing problem with time window', in Desaulniers, G., Desrosiers, J. and Solomon, M.M. (eds.) *Column Generation*. pp. 99 -130.

Dantzig, G.B. and Ramser, J.H. (1959) 'The Truck Dispatching Problem', *Management Science*, 6(1), pp.80 – 91.

De Souza, R., Goh, M., Lau, H.C., Ng, W.S. and Tan, P.S. (2014) 'Collaborative Urban Logistics - Synchronizing the Last Mile'. *Procedia – Social and Behavioural Sciences*, 125, pp.422 – 431.

Dell'Amico, M., Righini, G. and Salani, M. (2006) 'A branch-and-price approach to the vehicle routing problem with simultaneous distribution and allocation', *Transportation Science*. 40 (2), pp.235 – 247.

Denscombe, M. (2007) *The good research guide for small-scale social research projects*. 3rd edition. Maidenhead: Open University Press.

Denscombe, M. (2010) *Ground rules for social research guidelines for good practice*. 2nd edition. Maidenhead: Open University Press.

Ehmke, J.F. (2012) *Integration of Information and Optimization Models for Routing in City Logistics,* New York: Springer.

Engevall, S., Gothe-Lundgren, M., and Varbrand, P., 2004. The heterogeneous vehicle-routing game. *Transportation Science*, 38 (1), pp. 71 – 85.

Fernandez, E., Fontana, D. and Speranza, M.G. (2016) 'On the Collaboration Uncapacitated Arc Routing Problem', *Computers & Operations Research*. 67, pp.120 – 131.

Fernandez, E., Roca-Riu, M. & Speranza, M.G. (2018) 'The Shared Customer Collaboration Vehicle Routing Problem'. *European Journal of Operational Research,* 265 (2018), pp. 1078 - 1093.

Fischetti, M., Toth, P. and Vigo, D. (1994) 'A branch and bound algorithm for the capacitated vehicle routing problem on directed graphs', *Operations Research*. 42, pp.846 – 859.

Fisher, M.L. and Jaikumar, R. (1981) 'A generalized assignment heuristic for vehicle routing', *Networks*. 14, pp.545 – 565.

Flood, M. M. (1956) 'The Travelling Salesman Problem'. Operations Research, 4 (1), pp. 61 – 75.

Francois, J., Moad, K. Bourrieres, F. P. and Lebel, L. 'A tactical planning model for collaborative timber transport', *IFAC PapersOnLine,* 50-1 (2017) pp. 11713 – 11718.

Frisk, M., Gothe-Lundgren, M., Jornsten, K. and Ronnqvist, M. (2010) 'Cost allocation in collaborative forest transportation', *European Journal of Operational Research,* 205, pp.448 – 458.

Fukasawa, R., Longo, H., Lysgaard, J., deAragao, M.P. Reis, M., Uchoa, E. and Werneck, R.F. (2006) 'Rubust Branch-and-Cut-and-Price for the Capacitated Vehicle Routing Problem', *Mathematical Programming*, 106(3), pp.491 – 511.

Gilles, R.P. (2010) *The Cooperative Game Theory of Networks and hierarchies*. Heidelkerg: Springer.

Golden, B., Raghavan, S. and Wasil, E. (2008) *The Vehicle Routing Problem: Latest Advances and New Challenges*. New York: Springer.

Gonzalez-Feliu, J. and Salanova, J.M. (2012) 'Defining and evaluating collaborative urban freight transportation systems', *Procedia – Social and Behavioural Sciences,* 39, pp.172 – 183.

Gonzalez-Feliu, J. and Morana, J. (2011) 'Collaborative transportation sharing: from theory to practice via a case study from France', in Yearwood, J. and Stranieri, A. (eds.) *Technologies for Supporting Reasoning Communities and Collaborative Decision Making: Cooperative Approaches.* pp.252 – 271.

Gonzalez-Feliu, J., Morana, J., Grau, J.M.S. and Ma, T.Y. (2013) 'Design and scenario assessment for collaborative logistics and freight transport systems', *International Journal of Transport Economics,* 40(2), pp.207 – 240.

Gothe-Lundgren, M., Jornsten, K., Varbrand., P. (1996) 'On the nucleolus of the basic vehicle routing game' *Mathematical Programming,* 72 (1), pp. 83 – 100.

Granot, D., Hamers, H., Kuipers, J., Maschler, M., 2011. On Chinese postman games where residents of each road pay the cost of their road. *Games and Economic Behavior,* 72 (2), pp. 427 – 438.

Guajardo, M., Jornsten, K., and Ronnqvist, M. (2015). Constructive and blocking power in collaborative transportation. *OR Spectrum,* 38 (1), pp. 25 – 50.

Guajardo, M. and Ronnqvist, M. (2016) 'A review on cost allocation methods in collaborative transportation', *International Transactions in Operational Research,* 23, pp.371 – 392.

Hernandez, S., and Peeta, S. (2014) 'Centralized time-dependent multiple-carrier collaboration problem for less-than-truckload carriers' *Transportation Research Record: Journal of the Transportation Research Board,* 2263, pp. 26 – 34.

Hezarkhani, B., Slikker, M., and van Woensel, T. (2015) A competitive solution for cooperative truckload delivery. *OR Spectrum,* 38 (1), pp. 51 – 80.

Kallehauge, B., Larsen, J., Madsen, O.B.G. and Solomon, M.M. (2005) 'Vehicle Routing Problem with Time Windows', in Dwsaulniers, G., Desrosiers, j. and Solomon, M.M., *Column Generation.* New York: Springer, pp.3 – 14.

Khooban, Z. (2001) 'Transportation', in Farahani, R., Rezapour, S. and Kardar, L. (eds.) *Logistics Operations and Management Concepts and Models*. pp.109 – 126.

Kilby, P. and Shaw, P. (2006) 'Vehicle Routing', in Rossi, F., van Beek, P. and Walsh, T. (eds.) *Handbook of Constraint Programming*. pp.801 – 836.

Kimms, A. and Kozeletskyi, I. (2016) 'Core-based cost allocation in the cooperative traveling salesman problem', *European Journal of Operational Research*, 248, pp.910 – 916.

Kirsch, A. (2010) *An Introduction to the Mathematical Theory of Inverse Problems (2nd edition)*. Springer: New York.

Krajewska, M. A., and Kopfer, H. (2006) 'Collaborating freight forwarding enterprises – request allocation and profit sharing' *OR Spectrum*, 28 (3), pp. 301 – 317.

Krajewska, M.A., Kopfer, H. Laporte, G. Rupke, S. and Zaccour, G. (2008) 'Horizontal cooperation among freight carriers: request allocation and profit sharing', *Journal of the Operational Research Society*, 59(11), pp.1483 – 1491.

Kubo, M. and Kasugai, H. (1992) 'On the core of the network design game', *Journal of the Operations Research*, 35(3), pp.250 – 255.

Kulkarni, R.V. and Bhave, P.R. (1985) 'Integer programming formulations of vehicle routing problems', *European Journal of Operational Research*, 20(1), pp.58 – 67.

Lambert, D.M. (2008) *Supply Chain Management: processes, partnerships*, performance 3rd edition. Sarasota, Florida: Supply Chain Management Institute.

Laporte, G. (1992) 'The Vehicle Routing Problem: An overview of exact and approximate algorithms', *European Journal of Operational Research*, 59(3), pp.345 –358.

Li, J. (2013) 'Model and Simulation for Collaborative VRPSPD', *Journal of Networks*, 8(2), pp.331 – 338.

Liong, C.Y., Wan Rosmanira, I., Khairuddin, O. and Zirour, M. (2008) 'Vehicle Routing Problem: Models and Solutions', *Journal of Quality Measurement and Analysis*, 4(1), pp.205 – 218.

Liu, R., Jiang, Z., Fung, R.Y.K., Chen, F. & Liu, X. (2010) 'Two-phase heuristic algorithms for full truckloads multi-depot capacitated vehicle routing problem in carrier collaboration'. *Computers & Operations Research*, 37(2010), pp. 950 – 959.

Liu, R., Jiang, Z., Liu, X. and Chen, F. (2010) 'Task selection and routing problems in collaborative truckload transportation', *Transportation Research Part E*, 46, pp.1071 – 1085.

Liu, P., Wu, Y. and Xu, N. (2010) 'Allocating Collaborative Profit in Less-than-Truckload Carrier Alliance', *J. Service Science & Management*, 3, pp.143 – 149.

Lozano, S., Moreno, P., Adenso-Diax, B. and Algaba, E. (2013) Cooperative game theory approach to allocating benefits of horizontal cooperation. *European Journal of Operational Research*, 229 (2), pp. 444 – 452.

Mason, R., Lalwani, C. and Boughton, R. (2007) 'Combining vertical and horizontal collaboration for transport optimization', *Supply Chain Management: An International Journal*, 12(3), pp.187 – 199.

Massol, S. and Tchung-Ming, S. (2010) 'Cooperation among liquefied natural gas suppliers: Is rationalization the sole objective? '. *Energy Economics*, 32 (4), pp. 933 – 947.

Montoya-Torres, J.R., Lopez Franco, J., Nieto Isaza, S., Felizzola Jimenez, H. and Herazo-Padilla, N. (2015) 'A literature review on the vehicle routing problem with multiple depots', *Computers & Industrial Engineering*, 79, pp.115 – 129.

Montoya-Torres, J. R., Munoz-Villamizar, A. & Vega-Mejia, C. A. (2016) 'On the impact of collaborative strategies for goods delivery in city logistics', *Production Planning & Control*, 27 (6), pp. 443 – 455.

Munoz-Villamizar, A., Montoya-Torres, J. R. and Javier. F., (2017) 'Impact of the use of electric vehicles in collaborative urban transport networks: a case study' *Transportation Research Part D*, 50 (2017) pp. 40 – 54.

Myerson, R. B. (1991) *Game theory: analysis of conflict*. Harvard University Press: Cambridge, Mass.

Nadarajah, S., and Bookbinder, J. H. (2013) 'Less-than-truckload carrier collaboration problem: Modelling framework and solution approach' *Journal of Heuristics*, 19, pp. 917 – 942.

Ozener, O.O. (2014) 'Developing a Collaborative Planning Framework for Sustainable Transportation', *Mathematical Problems in Engineering*, 2014, pp.1 – 15.

Ozener, O.O. and Ergun, O. (2008) 'Allocating costs in a collaborative transportation procurement network'. *Transportation Science,* 42 (2), pp. 146-165.

Pateman, H., Cahoon, S. and Chen, S.L. (2016) 'The Role and Value of Collaboration in the Logistics Industry: An Empirical Study in Australia' *The Asian Journal of Shipping and Logistics*, 32 (1), pp. 33 – 40.

Perez-Bernabeu, E., Juan, A.A., Faulin, J. and Barrios, B.B. (2015) 'Horizontal cooperation in road transportation: a case illustrating savings in distances and greenhouse gas emissions', *International Transactions in Operations Research,* 22, pp.585 – 606.

Quintero-Araujo, C.L., Gruler, A. & Juan, A.A. (2016) 'Quantifying potential benefits of horizontal cooperation in urban transportation under uncertainty: a simheuristic approach', in Luaces, O., Gamez, J.A., Barrenechea, E., Troncoso, A., Galar, M., Quintina, H. & Corchado, E. (Eds.) 2016 *Advances in Artificial Intelligence.* Springer, pp. 280 - 289.

Rushton, A., Croucher, P. and Baker, P. (2014) *The Handbook of Logistics and Distribution Management* 5th edition. London: Kogan Page.

Sanchez, M., Pradenas, L., Deschamps, J.C. & Parada, V. (2016) 'Reducing the carbon footprint in a vehicle routing problem by pooling resources from different companies'. *Netnomics*, 17 (2016), pp. 29 - 45.

Saunders, M., Lewis, P. and Thornhill, A. (2012) *Research Methods for Business Students* 6th edition. Harlow: Pearson.

Simchi-Levi, D., Chen, X. and Bramel, J. (2014) *The Logic of Logistics: Theory, Algorithms, and Applications for Logistics Management* 3rd edition. New York: Springer.

Solomon, M.M. (1987) 'Algorithms for the vehicle routing and scheduling problems with time window constraints', *Operations Research,* 35(2), pp.254 – 265.

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

Sun, L., Rangarajan, A., Karwan, M.H., Pinto, J.M. (2015). 'Transportation cost allocation on a fixed route'. *Computers & Industrial Engineering*, 83, pp. 61 – 73.

Taniguchi, E. and Thompson, R.G. (2001) *City Logistics: Network Modelling and Intelligent Transport Systems*. Bingley: Emerald.

Taranotola, A. (2005) *Inverse Problem Theory and Methods for Model Parameter Estimation*. Society for Industrial and Applied Mathematics Philadelphia.

Thompson, R.G. and Hassall, K.P. (2012) 'A collaborative urban distribution network', *Procedia – Social and Behavioural Sciences*, 39, pp.230 – 240.

Toth, P., & Vigo, D. (1997). 'An exact algorithm for the vehicle routing problem with backhauls'. Transportation science, 31(4), pp. 372-385.

Toth, P. and Vigo, D. (2002) 'Models, relaxations and exact approaches for the capacitated vehicle routing problem', *Discrete Applied Mathematics*, 123(1-3), pp.487 – 512.

Vanovermeire, C. and Sorensen, K. (2014b) 'Measuring and rewarding flexibility in collaborative distribution, including two-partner coalitions' *European Journal of Operational Research*, 239 (1), pp. 157 – 165.

Verstrepen, Cools, Cruijssen and Dullaert (2009) collaborative system

Vornhusen, B. Wang, X. and Kopfer, H. (2014) 'Vehicle routing under consideration of transhipment in horizontal coalitions of freight carriers', *Procedia CIRP*, 19, pp.117 – 122.

Wang, L. (2009) 'Cutting plane algorithms for the inverse mixed integer linear programming problem'. *Operations Research Letters*, 37 (2009) pp. 114 – 116.

Wang, X. and Kopfer, H. (2014) 'Collaborative transportation planning of less-than-truckload freight', *OR Spectrum*, 36, pp.357 – 380.

Wang,X., Kopfer, H. and Gendreau, M. (2014) 'Operational transportation planning of freight forwarding companies in horizontal coalitions', *European Journal of Operational Research*, 237, pp.1133 – 1141.

Weise, T., Podlich, A. and Gorldt, C. (2009) 'Solving Real-World Vehicle Routing Problems with Evolutionary Algorithms', in Chiong, R. and Dhakal, S. (eds.) *Natural Intelligence for Scheduling, Planning and Packing Problems*. Berlin Heidelbery: Springer, pp.29 – 53.

Weng, K., and Xu, Z. H. (2014) 'Flow merging and hub route optimization in collaborative transportation' *Journal of Applied Mathematics*, 2014.

Zakharov, V. and Shchegryaev, A. (2015) 'Stable cooperation in dynamic vehicle routing problems' *Automation and Remote Control*, 76 (5), pp. 935 – 943.