

Polyhedral Study of Baldacci's Model for the Capacitated  
Vehicle Routing Problem and Its Extension to the Resource  
Constrained Shortest Path Problem

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January 1, 2024

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# Chapter 1

## Introduction

The Resource Constrained Shortest Path Problem (RCSPP) is a fundamental problem in discrete optimization. RCSPP is aimed for finding a cost-optimal path, with additional resource constraints. For instance, under the transportation background, consider a vehicle from a factory to some markets for delivery and satisfies the demand of visited markets. The cost could be the fuel cost, time penalty and the resource constraint could be the capacity of fuel tank of a vehicle. The constraint make sense, since the gas stations are separated in the whole region. RCSPP is a  $\mathcal{NP}$ -hard problem [Hartmanis(1982)] even if the costs are all non-negative.  $\mathcal{NP}$  versus  $\mathcal{P}$  is still an open question yet, that means when the problem has a large size, all algorithms researchers have yet are not polynomial. However, since RCSPP has some applications in the transportation and management area, indeed, this problem is a sub-problem of many famous problems in transportation. Therefore, researching the RCSPP is meaningful, particularly, for the real-world transportation companies.

The classic linear programming model directly from the description of RCSPP is quiet simple and natural, just follow the model of shortest path problem and add the resource constraints. Therefore, researcher are focus on developing algorithms to solve RCSPP. Aneja et al. proposed a network reduction algorithm [Aneja et al.(1983)Aneja, Aggarwal, and Nair]. The algorithm deletes and remove the nodes or arcs can't appear in feasible solutions, meanwhile record the current cost-least solution. After 6 years, Beasley and Christofides use the same rule as Aneja et al, but they also considered reduce the cost to solve a dual lagrangean problem [Beasley and Christofides(1989)]. Indeed, using lagrangean relaxation is a most common technique in solving RCSPP. Mehlhorn and Ziegelmann use ellipsoid method to solve the dual problem [Mehlhorn and Ziegelmann(2000)], and they computed the complexity of their alogrithm for RCSPP with a single resource constraint. It's also possible to use Path ranking based approach, dynamic programming and Branch&Backtracking algorithm to close the gap of prime problem and dual problem. The main idea of path ranking based approach is finding a feasible path with highest

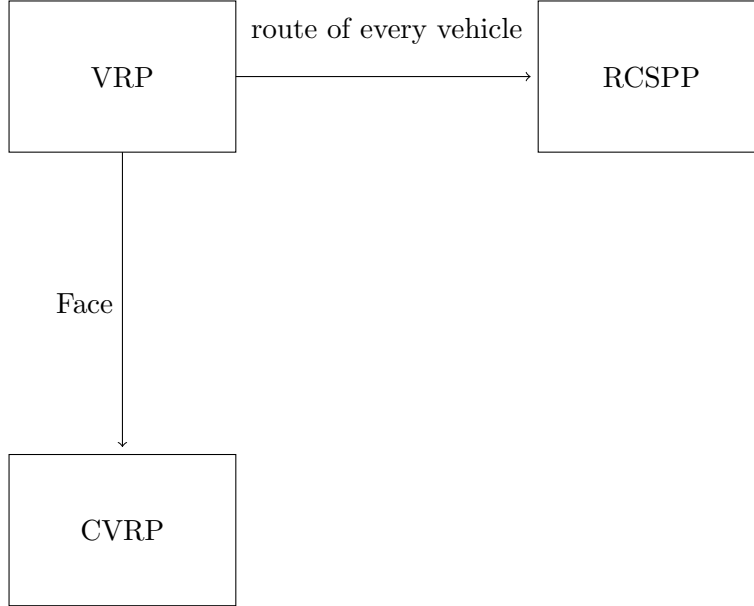
rank with respect to cost. The path ranking approach was first used by Handler and Zang [Handler and Zang(1980)], they reduced the cost of arcs in lagrangean problem to make the algorithm efficient. Apart of this trick, convexity and Chebyshev-like norm are common technique to make the path ranking based approach efficient, these ideas can be found in [Santos et al.(2007)Santos, Coutinho-Rodrigues, and Current] and [Pugliese and Guerriero(2013)]. While trying use dynamic programming to solve RCSPP, every state is a sub-path, then the algorithm glue two sub-paths with the resource restriction. Dynamic programming is a common trick, for instances, Mehlhorn and Ziegelmann use the dynamic programming while solving the prime problem [Mehlhorn and Ziegelmann(2000)]. The Branching&Backtracking algorithm is based on the rules to search the feasible solutions. The oldest paper use this idea was written by Beasley and Christofides in 1989 [Beasley and Christofides(1989)]. And a recent work with Branching&Backtracking scheme was did by Muhandirange and Boland [Muhandirange and Boland(2009)]. The tableau shows our literature research.

In particularly, RCSPP is usually used to help solving the Vehicle Routing Problem

	Network Reduction	Dual Problem	Path Ranking	Dynamic Programming	B&B scheme
Handler and Zang [1980]		×	×		
Aneja et al. [1983]	×			×	
Beasley and Christofides [1989]	×	×			×
Mehlhorn and Ziegelmann [2000]	×	×		×	
Santos et al [2007]			×		
DPuglia Pugliese and Guerriero [2013]			×		
Muhandirange and Boland [2009]	×	×			×

Table 1.1: RCSPP Algorithms

(VRP). The VRP is aimed for finding a cost-optimal schedule for  $M$  many vehicles, such that all vehicles depart from a factory for delivery, and satisfy the demands of all markets. After delivery, all vehicle will return to the factory. A special case of VRP is the Capacitated Vehicle Problem (CVRP) where all markets are visited exactly once. And since in VRP, all markets should be satisfied and vehicles can only visit a market with integer times, so in VRP, all markets are visited at least once. Therefore, the solution set of CVRP is a face of solution set of VRP. After adding one artificial point, a trip, which means the destination is the place of departure, can be transferred to a path by replacing the destination with the artificial point. After the transformation, the route of a vehicle in VRP is a resource constrained path. The following diagram shows the relationship



VRP and CVRP are usually considered as fundamental problems in discrete optimization. Actually, CVRP is more popular, because it has the degree constraints, which make it make sense in reality background. Researchers came up several different models to describe CVRP. In 1959, George Dantzig and John Ramser asked the world about VRP [Dantzig and Ramser(1959)]. In 5 years, Balinski and Quand proposed a set partition model for VRP. They regarded all possible route as variables, and the degree constraints force that every node appears once in some routes. Let  $R$  be the set of all possible routes,  $d_r$  be the cost of route  $r$  and  $a_{i,r}$  be a binary variable indicate that if the consumer  $i$  is visited in route  $r$ , the mathematical formula is

$$\begin{aligned}
 & \min \sum_{r \in R} d_r y_r \\
 & \text{subject to:} \\
 & \sum_{\text{consumer } i} a_{i,r} = 1 \\
 & \sum_{r \in R} y_r = m \\
 & a_{i,r}, y_r \in \{0, 1\}
 \end{aligned}$$

Later researchers tried use column generation algorithm and dynamic programming to solve Balinski and Quand's model. But the results are not positive, only Agarwal, Mathur, and Salkin using column generation algorithm successful solve instances with 15–25 many consumers [Agarwal et al.(1989)Agarwal, Mathur, and Salkin]. In 2008, Baldacci, Christofides,

and Mingozi adding some inequalities and equalities constraints into this classical set partition model. Their method is able to solve the instances with 37 to 127 many vertices [Baldacci et al.(2008)Baldacci, Christofides, and Mingozi].

Apart from regarding the possible routes as variables, it's natural to directly use edges as variables. This idea derives the vehicle flow model, which is first modeled by Laporte and Nobert [Laporte and Nobert(1983)]. They describe the problem as

$$\begin{aligned}
& \sum_{\{i,j\} \in E} c_{ij} x_{ij} \\
& \text{subject to:} \\
& \sum_{j=1}^n x_{\{0,j\}} = 2M \\
& \sum_{i \neq j} x_{\{i,j\}} = 2 \quad \forall i \in [n] \\
& \sum_{i \in S} \sum_{j \in S^c} x_{\{i,j\}} \geq 2m(S) \quad \forall S \subseteq [n] \\
& x_{\{0,j\}} \in \{0, 1, 2\} \quad \forall j \in [n] \\
& x_{\{i,j\}} \in \{0, 1\} \quad \forall i, j \in [n], i \neq j
\end{aligned}$$

Here  $m(S)$  represent the minimal number of vehicles such that the demand of all consumer in  $S$  can be met. Branch and Cut algorithm is common used in solving this model.

In the vehicle flow model,  $m(S)$  cost a lot of computation. One idea to deal with the resource constraints is constructing a flow, every time, flow meet a consumer, the flow value will decrease by the demand of this consumer. Therefore, the resource constraints are equivalent to all flow values are non-negative. The commodity flow model follows this idea. Gavish and Graves [Gavish and Graves(1978)] extended Garvin's idea in an oil delivery problem [Garvin et al.(1957)Garvin, Crandall, John, and Spellman], gave their commodity flow model. For every consumer, they set variables indicate the flow from every edge in order to satisfies this consumer. In 2004, Baldacci raise his two commodity flow [Baldacci et al.(2004)Baldacci, Hadjiconstantinou, and Mingozi], his computation result shows a progress.

Baldacci's model has advantages compared to other models. The variables and constraints are increase polynomially while other two models, the vehicle flow model and set partition model, increase exponentially. This make the model is solvable by current linear programming solver. For examples, Baldacci's model can solve a problem with 104 vertices size, which is not solved until Baldacci did it, and for some test benchmark, this model is optimal.

The main topic of this thesis, is studying the Baldacci's model and follow his idea to propose a new mixed integer programming model for RCSPP. We claim this new model is

better than the classic RCSPP model.

In section 3, we study the Baldacci's model. We first find some implicit equations, then we develop a method to read the redundancy of the equation system and find redundant equation. We also use this method to exclude some inequality from facet defining inequality. In with an extra condition that every consumer has the same demand, we prove the dimension of the polytopes from linear relaxation and Baldacci's model. Since the dimension is proved, we find some facet defining inequalities.

In section 4, we propose a new model for RCSPP followed Baldacci's idea. We use an example to show that this model is better, that is the polytope project onto the edge variable space is a proper subset of classic model. Then similar to the section 3, we first find the redundant equation and by constructing the affinely independent points, we claim the dimension of the polytope after linear relaxation. With the assumption that every consumer has the same demand, we can find the dimension of the polytope from the new model. Moreover, we find some simple cuts, but when the capacity is exactly twice of the demand, the cuts can provide a complete description of polytope from mixed integer programming.

## Chapter 2

# Notations and Preliminaries

The preliminaries are basic knowledge about polytopes and optimization.

I am using the same notations as Prof. Ralf Borndörfer used. I emphasize some uncommon notation here. Let  $ij$  be abbreviation of the tuple  $(i, j)$  if the context is clear, and in an undirected graph  $G = (V, E)$   $\gamma(u) := \{v : \{u, v\} \in E\}$ , and in a directed graph  $D = (V, A)$ ,  $\gamma^+(u) := \{v : (u, v) \in A\}$  and  $\gamma^-(u) := \{v : (v, u) \in A\}$ . And in a simple graph, we use a sequence of vertices  $(u_1, u_2, \dots, u_n)$  to represent a path.



## Chapter 3

# Capacitated Vehicle Routing Problem

This section introduces Baldacci's approach to the capacitated vehicle routing problem. Subsection 3.1 gives a formal statement of the problem. Subsection 3.2 states the integer program that was suggested by Baldacci [year]. Subsection 3.3 shows some polyhedral result on Baldacci's model. Subsection 3.4 shows more polyhedral result under a special case.

### 3.1 Problem Description

Baldacci proposed an integer programming model for the CVRP, that is based on the idea of a resource flow. Informal description of the idea.

**Definition 3.1.1 (Capacitated Vehicle Routing Problem (CVRP))** *Given:* Undirected simple graph  $G = (V, E)$ , two special vertices, the sink  $s \in V$  and the target  $t \in V$ , non-negative integer edge costs  $c \in \mathbb{N}_{\geq 0}^E$ , natural numbers  $M, Q \in \mathbb{N}$  and node demands  $q \in \mathbb{N}_{\geq 0}^N$ , where  $N = V \setminus \{s, t\}$ . A route  $f$  consists of  $M$  simple  $st$ -path in  $G$ , its cost and demand are  $c(f)$  and  $q(f)$ , respectively, and it is feasible if  $q(f) \leq Q$  holds. A schedule is a set of feasible routes that visits every nodes except  $s, t$  exactly once. **Sought:** A schedule of minimal total cost.

### 3.2 Baldacci's Model

Consider a undirected graph  $G = (V, E)$ , where  $E = \{\{u, v\} : u, v \in N\} \cup \{\{s, u\} : u \in N\} \cup \{\{v, t\} : v \in N\}$ , and a directed graph  $D(G) = (V, A(E))$  such that  $A(E) = \{uv : \{u, v\} \in E\} \cup \{vu : \{u, v\} \in E\}$ . For all edge  $\{u, v\} \in E$ , assign an edge variable  $\xi_{\{u, v\}}$ ,

and for all arc  $uv \in A(E)$ , assign a flow variable  $x_{uv}$ . Then the Baldacci's model [Baldacci et al.(2004)Baldacci, Hadjiconstantinou, and Mingozzi] is the following

$$\min \sum_{\{u,v\} \in E} c_{\{u,v\}} \xi_{\{u,v\}}$$

subject to:

$$\sum_{v \in \gamma(u)} (x_{vu} - x_{uv}) = 2q_u \quad \forall u \in N \quad (3.1)$$

$$\sum_{v \in N} x_{sv} = q(N) \quad (3.2)$$

$$\sum_{v \in N} x_{vs} = MQ - q(N) \quad (3.3)$$

$$\sum_{v \in N} x_{tv} = MQ \quad (3.4)$$

$$x_{uv} + x_{vu} = Q\xi_{\{u,v\}} \quad \forall \{u,v\} \in E \quad (3.5)$$

$$\sum_{v \in \gamma(u)} \xi_{\{u,v\}} = 2 \quad \forall u \in N \quad (3.6)$$

$$x_{uv} \geq 0, x_{vu} \geq 0, \xi_{\{u,v\}} \in \{0,1\} \quad \forall \{u,v\} \in E$$

In this model, (3.6) is for the degree constraint. (3.1) is for satisfying the demands of all consumers. In the solution, here is a flow and a residual flow represent the load and empty space of vehicle respectively. (3.5) implies the capacity of each vehicle and connects variables  $\xi_{\{u,v\}}$ ,  $x_{uv}$  and  $x_{vu}$ . The rest of equations are for the initial condition.

### 3.3 Polyhedral Study of Baldacci's Model

#### 3.3.1 Complete the equation system

Let  $B_{IP}$  be the polytope of Baldacci's model and  $B_{LP}$  be the polytope of Baldacci's model after relaxing variable  $\xi_{\{u,v\}} \in \{0,1\}$  to  $\xi_{\{u,v\}} \in [0,1]$  for all  $\{u,v\} \in E$ . It's clear that  $B_{IP} \subseteq B_{LP}$ . Our first step is finding some implicit valid equations for  $B_{LP}$ , these inequalities can help us to approach the dimension.

**Observation 1**  $x_{ut} = 0$  for all  $u \in N$

*Proof:*

$$\begin{aligned}
0 &= \sum_{uv \in A(E)} (x_{uv} - x_{vu}) = \sum_{u \in V} \sum_{v \in \gamma(u)} (x_{uv} - x_{vu}) \\
&= \sum_{v \in N} (x_{sv} - x_{vs}) + \sum_{v \in N} (x_{tv} - x_{vt}) + \sum_{u \in N} \sum_{v \in \gamma(u)} (x_{uv} - x_{vu}) \\
&= \sum_{u \in N} q_u - (MQ - \sum_{u \in N} q_u) + MQ - \sum_{u \in N} x_{ut} + \sum_{u \in N} (-2q_u) \\
&= - \sum_{u \in N} x_{ut}
\end{aligned}$$

Since  $x_{ut} \geq 0$  for all  $u \in N$ , therefore  $x_{ut} = 0$  for all  $u \in N$ , and these equations are valid for  $B_{LP}$ . Now we do some operations to draw equations that are independent to others. Plug (3.5) into (3.6), yields

$$\sum_{v \in \gamma(u)} x_{uv} + x_{vu} = 2Q$$

Combined with (3.1),

$$\begin{cases} \sum_{v \in \gamma(u)} x_{vu} - x_{uv} = 2q_u \\ \sum_{v \in \gamma(u)} x_{vu} + x_{uv} = 2Q \end{cases} \Rightarrow \begin{cases} \sum_{v \in \gamma(u)} x_{vu} = Q + q_i \\ \sum_{v \in \gamma(u)} x_{uv} = Q - q_i \end{cases}$$

The Baldacci's model is equivalent to

$$\min \sum_{\{u,v\} \in E} c_{\{u,v\}} \xi_{\{u,v\}}$$

subject to:

$$\sum_{v \in \gamma(u)} x_{vu} = Q + q_u \quad \forall u \in N \quad (3.7)$$

$$\sum_{v \in \gamma(u)} x_{uv} = Q - q_u \quad \forall u \in N \quad (3.8)$$

$$\sum_{u \in N} x_{su} = \sum_{u \in N} q_u \quad (3.9)$$

$$\sum_{u \in N} x_{us} = MQ - \sum_{u \in N} q_u \quad (3.10)$$

$$\sum_{u \in N} x_{tu} = MQ \quad (3.11)$$

$$x_{ut} = 0 \quad \forall u \in N \quad (3.12)$$

$$x_{uv} + x_{vu} = Q \xi_{\{u,v\}} \quad \forall \{u,v\} \in E \quad (3.13)$$

$$x_{uv} \geq 0, x_{vu} \geq 0, \xi_{\{u,v\}} \in \{0,1\} \quad \forall \{u,v\} \in E$$

We eliminate some equation constraints involve the variables  $\xi_{ij}$ , such that the variable  $\xi_{ij}$  only appears exactly once in (3.13), so these equations from (3.13) are independent to equation system in (3.7)-(3.12). Therefore, after the operation, equations from (3.13) can't be redundant.

Recall that

$$0 = \sum_{uv \in A(E)} (x_{uv} - x_{vu}) = \sum_{v \in N} (x_{sv} - x_{vs}) + \sum_{v \in N} (x_{tv} - x_{vt}) + \sum_{u \in N} \sum_{v \in \gamma(u)} (x_{uv} - x_{vu})$$

The equation above tells the equation system from (3.7)-(3.12) is redundant. Therefore, we need to find the how many redundant equations in this model. In the next section, we will explain how to find it.

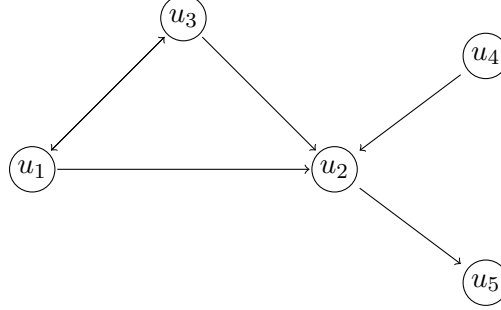
### 3.3.2 A method for reading the irredundancy

Consider a directed connected graph  $D_1(G) = (U, \bar{A})$ . For every arc  $(u, v)$  in  $\bar{A}$ , assign a variable  $x_{uv}$ . Since  $D_1(G)$  is connected, at least one of  $\gamma^+(u)$ ,  $\gamma^-(u)$  is non-empty for an arbitrary  $u \in U$ . Then for every non-empty set  $\gamma^+(u)$  and  $\gamma^-(u)$ , we assign the following equations with proper value  $\beta_u, \bar{\beta}_u$

$$\sum_{v \in \gamma^+(u)} x_{uv} = \beta_u \quad \text{or} \quad \sum_{v \in \gamma^-(u)} x_{vu} = \bar{\beta}_u \quad (3.14)$$

Here is an example about how to this process works.

**Example 3.3.1** *Let the directed graph be*



*This graph will give the following equation system with proper choice of  $\beta$  and  $\bar{\beta}$*

$$\begin{aligned}
x_{u_1,u_2} + x_{u_1,u_3} &= \beta_{u_1} \\
x_{u_3,u_1} &= \bar{\beta}_{u_1} \\
x_{u_2,u_5} &= \beta_{u_2} \\
x_{u_1,u_2} + x_{u_3,u_2} + x_{u_4,u_2} &= \bar{\beta}_{u_2} \\
x_{u_3,u_1} + x_{u_3,u_2} &= \beta_{u_3} \\
x_{u_1,u_3} &= \bar{\beta}_{u_3} \\
x_{u_4,u_2} &= \beta_{u_4} \\
x_{u_2,u_5} &= \bar{\beta}_{u_5}
\end{aligned}$$

Now write the whole equation system as a matrix form  $Cx = d$ . Here is a bijection such that we can find the corresponding node and the arc direction of every row of  $C$ . Therefore, the rows in  $C$  can be represent as  $c_{\gamma^+(u)}$  and  $c_{\gamma^-(u)}$  with respect to  $\gamma^+(u)$  and  $\gamma^-(u)$ . Now, we are going to discuss about a vector  $\mathbf{a}$  such that  $\mathbf{a}^T C = \mathbf{0}^T$ , since  $\dim\{\mathbf{a} : \mathbf{a}^T C = \mathbf{0}^T\}$  will give us the  $\text{rank}(C)$ . Let  $\alpha^+(u), \alpha^-(u)$  be entries of  $\mathbf{a}$ , such that

$$\mathbf{a}^T C = \sum_{\substack{u \in V \\ \gamma^+(u) \neq \emptyset}} \alpha^+(u) c_{\gamma^+(u)} + \sum_{\substack{u \in V \\ \gamma^-(u) \neq \emptyset}} \alpha^-(u) c_{\gamma^-(u)}$$

At the beginning, here are two observations.

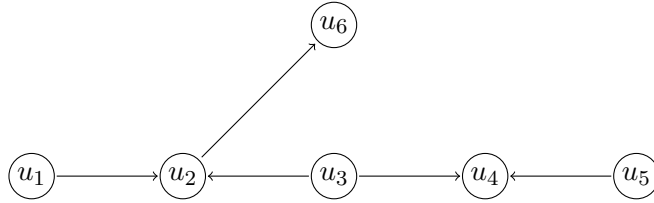
**Observation 2** *Only in  $c_{\gamma^+(u)}$  and  $c_{\gamma^-(v)}$ , the column respects to variable  $x_{uv}$  is non-zero.*

**Observation 3** *An arc  $(u, v) \in D_1(G)$  implies a relationship that  $\alpha^+(u) = -\alpha^-(v)$  since this is the only way to eliminate variable  $x_{uv}$*

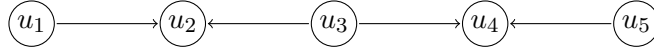
Since the graph  $G(U, \bar{A})$  is connected, we could and we want to extend our observations to all vertices, that is finding a series of equations involving all the vertices of  $G(U, \bar{A})$ . Therefore, we need a special “path” to transfer this property.

**Definition 3.3.1 (Alternating Path)** *Let  $(u_1, \dots, u_n)$  be a sequence of distinct vertices in  $G(U, \bar{A})$ . If here is a sequence of arcs  $(a_1, \dots, a_{n-1})$ , such that for all  $k \in [n-1]$ ,  $a_{2k+1} = (u_{2k+1}, u_{2k+2})$ ,  $a_{2k} = (u_{2k+1}, u_{2k})$  or  $a_{2k+1} = (u_{2k+2}, u_{2k+1})$ ,  $a_{2i} = (u_{2k}, u_{2k})$ , then we call this sequence  $(u_1, a_1, u_2, \dots, a_{n-1}, u_n)$  alternating path, and the number of arcs contained in an alternating path is called the length of this alternating path.*

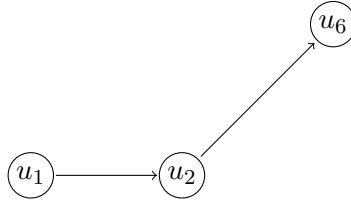
**Example 3.3.2** *Here is an example for the alternating path I defined*



*The sequence  $(u_1, e_{u_1,u_2}, u_2, e_{u_3,u_2}, u_3, e_{u_3,u_4}, u_4, e_{u_5,u_4}, u_5)$  is an alternating path.*



*And the sequence  $(u_1, e_{u_1,u_2}, u_2, e_{u_2,u_6}, u_6)$  is not an alternating path.*



**Lemma 1** *If here is an alternating path  $(u_1, a_1, \dots, a_{n-1}, u_n) = P$  in the graph  $G(U, \bar{A})$ . Then for all  $k \in [n]$ , we have*

- when  $a_1 = (u_1, u_2)$ :

$$\alpha^+(u_1) = (-1)^{k-1} \alpha^{\text{sign}((-1)^{k-1})}(u_k)$$

- when  $a_1 = (u_2, u_1)$ :

$$\alpha^-(u_1) = (-1)^{k-1} \alpha^{\text{sign}((-1)^{k-1})}(u_k)$$

*Proof:* Induction on the length of alternating path.

For these alternating paths have length 1, it's just the observation 3.

Suppose the statement is true for all alternating paths with length  $k - 1$ .

Assume  $a_1 = (u_1, u_2)$ , then  $a_k = (a_k, a_{k+1})$  if  $k \equiv 1 \pmod{2}$  and  $a_k = (a_{k+1}, a_k)$  if  $k \equiv 0 \pmod{2}$ . In the first case ( $k \equiv 1 \pmod{2}$ ), we have

$$\begin{aligned}\alpha^+(u_1) &= \alpha^+(u_k) \\ \alpha^+(u_k) &= -\alpha^-(u_{k+1})\end{aligned}$$

Therefore  $\alpha^+(u_1) = \alpha^-(u_{k+1})$ . In all other cases, the proofs are similar.

One alternating path derives equations with respect to arcs, and in the graph  $D(G)$ , every arc has an arc with opposite direction associated with. So, we actually have two parallel alternating paths. And we want to connect the equations derived from the parallel alternating paths.

**Theorem 3.3.2** *Let  $P = (u_1, a_1, \dots, a_{2k}, u_{2k+1}) \subseteq G(U, \bar{A})$  be an alternating path with length  $2k$ . If  $-P := (u_{2k+1}, -a_{2k}, u_{2k}, \dots, -a_1, u_1)$  exists in  $G(U, \bar{A})$ , and here is an arc  $(u_1, u_{2k+1}) \in \bar{A}$ . Then,*

$$\forall u \in V(P), \alpha^+(u) = -\alpha^-(u) \text{ and } \forall u, v \in V(P), |a^+(u)| = |a^+(v)|$$

Moreover, let  $N$  be the set of vertices are in  $P$  or adjacent to  $P$ . If  $\mathbf{a}^T C = \mathbf{0}^T$ , then  $|\alpha^{\text{sign}_1}(u)| = |\alpha^{\text{sign}_2}(v)|$  for all  $u, v \in N$ , where  $\text{sign}_1, \text{sign}_2 \in \{-, +\}$

*Proof:*

Since  $k \geq 1$ , then here exist a point  $u_l$ , such that both  $l - 1, 2k + 1 - l$  are odd. Therefore, from the Lemma 1, we have

$$\begin{aligned}\alpha^+(u_1) &= -\alpha^-(u_l) & \alpha^-(u_1) &= -\alpha^+(u_l) \\ \alpha^+(u_{2k+1}) &= -\alpha^-(u_l) & \alpha^-(u_{2k+1}) &= -\alpha^+(u_l)\end{aligned}$$

Since here is an arc  $(u_1, u_{2k+1})$ , so  $\alpha^+(u_1) = -\alpha^-(u_{2k+1})$ . This means  $\alpha^+(u_l) = -\alpha^-(u_l)$ . Then Lemma 1 can extend the relation to all vertices.

In this section, given a directed graph, for any vertices in this graph, we associate it with equations of the form (3.14). Then we can just read the graph and use the Theorem 3.3.2 to know if here exists redundant equations.

### 3.3.3 Dimension and Facets Results for $B_{LP}$

Now, we return to (3.7) – (3.12) in Baldacci's model. In this model, every vertices has two equations of the form (3.14), and the graph has many edges, so we can always find a large even alternating path  $P$  with vertex ordered as  $(u_1, \dots, u_{2k+1})$ , such that  $u_1, u_{2k+1}$  are adjacent,  $-P$  exist in the induced graph  $D(G) = (V, A(E))$  and all vertices in  $V$  are

either contained in  $P$  or adjacent to some vertices in  $P$ . So, exactly one equation in the equation system is redundant. Assume  $|N| = n \geq 3$ , then

$$\dim B_{LP} \leq 3\left(\binom{n+2}{2} - 1\right) - \left(\binom{n+2}{2} - 1\right) - (3n+3) + 1 = n^2 - 2$$

Although we only know the upper bound of dimension yet. But we can decide some inequalities aren't facets by count how many inequalities will be tight

**Observation 4**  $\xi_{\{u,v\}} \geq 0$ , where  $u, v \in N$ , isn't a facet defining inequality when  $|N| \geq 5$ .

*proof:*

$$\begin{cases} \xi_{\{u,v\}} = 0 \\ x_{uv} + x_{vu} = Q\xi_{\{u,v\}} \Rightarrow x_{uv} = x_{vu} = \xi_{\{u,v\}} = 0 \\ x_{uv}, x_{vu} \geq 0 \end{cases}$$

It's sufficient to check that  $x_{uv} = 0$  isn't a linear combination of equations in (3.7)-(3.13) and  $\xi_{\{u,v\}} = 0$ . At the beginning, apply then Theorem 3.3.2 for a subgraph induced by  $V \setminus \{u, v\}$ , and then check the whole system.

**Observation 5** If  $M = 1$ , then  $\xi_{\{s,u\}} \leq 1$ ,  $\xi_{\{u,t\}} \leq 1$  is not a facet defining inequality.

*Proof:*

Note we have

$$\begin{aligned} \sum_{u \in N} x_{tu} &= Q \\ x_{ut} &= 0 \quad \forall u \in N \\ x_{uv} + x_{vu} &= Q\xi_{\{u,v\}} \quad \forall \{u, v\} \in E \end{aligned}$$

Therefore, we have

$$\begin{aligned} \sum_{u \in N} Q\xi_{\{t,u\}} &= \sum_{u \in N} (x_{tu} + x_{ut}) = \sum_{u \in N} x_{tu} = Q \\ \Rightarrow \sum_{u \in N} \xi_{\{t,u\}} &= 1 \end{aligned}$$

If for one  $u_1$  such that  $\xi_{\{u_0,t\}} = 1$ , then it implies that  $\xi_{\{u,t\}} = 0$  for all  $u \neq u_0$ . Similarly, from

$$\begin{aligned} \sum_{u \in N} x_{us} &= Q - \sum_{u \in N} q_u \\ \sum_{u \in N} x_{su} &= \sum_{u \in N} q_u \end{aligned}$$



We get

$$\sum_{u \in N} \xi_{\{s,u\}} = 1$$

So, we have the observation.

### 3.4 Dimension and Facets Result for Unit Demand Case

If  $q_u = 1$  for all  $u \in V$ , we can this is the unit demand case. Therefore, in this case all vertices in  $N$  are "equivalent", in the sense we can get another feasible by exchange vertices. Recall Baldacci's model under this special case is

$$\min \sum_{\{u,v\} \in E} c_{\{u,v\}} \xi_{\{u,v\}}$$

subject to:

$$\sum_{v \in \gamma(u)} x_{vu} = Q + q_u \quad \forall u \in N \quad (3.15)$$

$$\sum_{v \in \gamma(u)} x_{uv} = Q - q_u \quad \forall u \in N \quad (3.16)$$

$$\sum_{u \in N} x_{su} = \sum_{u \in N} q_u \quad (3.17)$$

$$\sum_{u \in N} x_{us} = MQ - \sum_{u \in N} q_u \quad (3.18)$$

$$\sum_{u \in N} x_{tu} = MQ \quad (3.19)$$

$$x_{ut} = 0 \quad \forall j \in N \quad (3.20)$$

$$x_{uv} + x_{vu} = Q \xi_{\{u,v\}} \quad \forall \{u,v\} \in E \quad (3.21)$$

$$x_{uv} \geq 0, x_{vu} \geq 0, \xi_{\{u,v\}} \in \{0,1\} \quad \forall \{u,v\} \in E$$

In previous section, we have obtain a upper bound of the dimension of  $B_{LP}$ . In this section, we will show in this special case, we can find a lower bound of dimension. Precisely, that is the following theorem

**Theorem 3.4.1** *Under the unit demand case, If  $Q \geq 5$ ,  $M \geq 2$  and  $MQ > n = |N| > (M-1) + Q$ , the polytopes from Baldacci's model are denoted by  $B_{IP}^{u+}, B_{LP}^{u+}$  respectively. A result is  $B_{IP}^{u+}, B_{LP}^{u+}$  are  $(n^2 - 2)$ -dimensional polytopes.*

It's sufficient to show  $n^2 - 2 = \dim B_{LP}$ . We will use a similar idea as [Campos et al.(1991)Campos, Corberan, and Mota] by showing every valid equation for  $B_{LP}$  has to be a linear combination of equations in (3.15)-(3.21).

Let  $\mathbf{c}^T \begin{pmatrix} \mathbf{x} \\ \boldsymbol{\xi} \end{pmatrix} = \beta$  be an arbitrary valid equation for  $B_{IP}$ . Let  $T \begin{pmatrix} \mathbf{x} \\ \boldsymbol{\xi} \end{pmatrix} = \mathbf{t}$  be the matrix of equations in (3.15)-(3.21). Since  $\mathbf{c}^T \begin{pmatrix} \mathbf{x} \\ \boldsymbol{\xi} \end{pmatrix} = \beta$  is a valid equation, it's enough to show  $\mathbf{c}^T \in \text{row}(T)$ . We know the every column of  $\mathbf{c}^T$  and  $T$  corresponding to one unique variable. So, we use  $\mathbf{c}^T|_{\{x_{uv}\}}$  and  $T|_{\{x_{uv}\}}$  to denote the column corresponding to  $x_{uv}$ , same for other variables. We will take the following steps to prove Theorem 3.4.1.

*Step 1:*

Finding a full-rank square submatrix  $M$  of  $T$ . Fix two vertices  $v_1, v_2$  in  $V$ , let

$$\begin{aligned} I &= \{x_{su}\}_{u \in N} \cup \{x_{us}\}_{u \in N} \cup \{x_{ut}\}_{u \in N} \cup \{x_{v_1 v_2}, x_{tv_1}\} \cup \{\xi_{\{u,v\}}\}_{uv \in E} \\ I_x &= \{x_{su}\}_{u \in N} \cup \{x_{us}\}_{u \in N} \cup \{x_{ut}\}_{u \in N} \cup \{x_{v_1 v_2}, x_{tv_1}\} \end{aligned}$$

Then  $M := T|_I$  is a full-rank square matrix.

*Proof:*

It's clear that every row of  $T|_I$  from (3.21) is independent to all other rows, since the variable  $\xi_{\{uv\}}$  only appears in (3.21). Therefore, it's enough to show that the matrix  $T'|_I$  which consists of the rows from (3.15)-(3.20) in  $T|_I$  is full rank.

Construct a directed graph  $D_2(G) = (V, A')$  such that  $A' = \{(u, v) : x_{uv} \in I_x\}$ . Then the equations system  $T'_I$  represents is of the form (3.14) in  $D_2(G)$ . Therefore, using the similar analysis in previous section shows  $T'|_I$  is row full rank matrix.

*Step 2:*

Since  $M$  is full rank,  $\boldsymbol{\nu}^T(T|_I) = (\mathbf{c}^T|_I)$  has a unique solution. Let  $\mathbf{r}^T = \mathbf{c}^T - \boldsymbol{\nu}^T T$ , it sufficient to show  $\mathbf{r}^T = \mathbf{0}^T$ . Since  $\mathbf{c}^T$  is a valid equality. So, let  $s_1, s_2$  be two different schedule and  $\mathbf{z}(s_1), \mathbf{z}(s_2)$  be the embedded points in vector space, we have

$$\langle \mathbf{r}, (\mathbf{z}(s_1) - \mathbf{z}(s_2)) \rangle = 0 \quad (3.22)$$

*Step 3:*

First we pick two arbitrary vertices  $u_1, u_2$ , then take two schedule  $s_1, s_2$ , such that  $p_1 \subseteq s_1, p_2 \subseteq s_2$  and  $s_1 \setminus p_1 = s_2 \setminus p_2$

$$\begin{aligned} p_1 &= (s, u_{i_1}, u_1, u_2, u_{i_3}, \dots, u_{i_m}, t) \\ p_2 &= (s, u_{i_1}, u_2, u_1, u_{i_3}, \dots, u_{i_m}, t) \end{aligned}$$

Use the equation (3.22), we have a equation. For convenience, in this proof,  $\mathbf{r}_{u_i u_j}^T$  are abbreviate as  $\mathbf{r}_{ij}^T$

$$\begin{aligned} &(m-1)(\mathbf{r}_{i_1 1}^T - \mathbf{r}_{i_1 2}^T) + (m-2)(\mathbf{r}_{12}^T - \mathbf{r}_{21}^T) + (m-3)(\mathbf{r}_{2i_3}^T - \mathbf{r}_{1i_3}^T) + \\ &(Q - (m-1))(\mathbf{r}_{1i_1}^T - \mathbf{r}_{2i_1}^T) + (Q - (m-2))(\mathbf{r}_{21}^T - \mathbf{r}_{12}^T) + (Q - (m-3))(\mathbf{r}_{i_3 2}^T - \mathbf{r}_{i_3 1}^T) = 0 \end{aligned} \quad (3.23)$$

*Step 4:*

Similarly, take two schedule with different paths

$$\begin{aligned} p_1 &= (s, u_{i_m}, u_{i_1}, u_1, u_2, u_{i_3}, \dots, u_{i_{m-1}}, t) \\ p_2 &= (s, u_{i_m}, u_{i_1}, u_2, u_1, u_{i_3}, \dots, u_{i_{m-1}}, t) \end{aligned}$$

And drive an equation

$$\begin{aligned} (m-2)(\mathbf{r}_{i_1 1}^T - \mathbf{r}_{i_1 2}^T) + (m-3)(\mathbf{r}_{12}^T - \mathbf{r}_{21}^T) + (m-4)(\mathbf{r}_{2i_3}^T - \mathbf{r}_{1i_3}^T) \\ + (Q - (m-2))(\mathbf{r}_{1i_1}^T - \mathbf{r}_{2i_1}^T) + (Q - (m-3))(\mathbf{r}_{21}^T - \mathbf{r}_{12}^T) + (Q - (m-4))(\mathbf{r}_{i_3 2}^T - \mathbf{r}_{i_3 1}^T) = 0 \end{aligned} \quad (3.24)$$

Subtract (3.24) from (3.23)

$$(\mathbf{r}_{i_1 1}^T - \mathbf{r}_{i_1 2}^T) + (\mathbf{r}_{12}^T - \mathbf{r}_{21}^T) + (\mathbf{r}_{2i_3}^T - \mathbf{r}_{1i_3}^T) = (\mathbf{r}_{1i_1}^T - \mathbf{r}_{2i_1}^T) + (\mathbf{r}_{21}^T - \mathbf{r}_{12}^T) + (\mathbf{r}_{i_3 2}^T - \mathbf{r}_{i_3 1}^T) \quad (3.25)$$

After that take

$$\begin{aligned} p_1 &= (s, u_1, u_2, u_{i_3}, \dots, u_{i_m}, u_{i_1}, t) \\ p_2 &= (s, u_2, u_1, u_{i_3}, \dots, u_{i_m}, u_{i_1}, t) \end{aligned}$$

drive

$$\begin{aligned} (m-1)(\mathbf{r}_{12}^T - \mathbf{r}_{21}^T) + (m-2)(\mathbf{r}_{2i_3}^T - \mathbf{r}_{1i_3}^T) \\ + (Q - (m-1))(\mathbf{r}_{21}^T - \mathbf{r}_{12}^T) + (Q - (m-2))(\mathbf{r}_{i_3 2}^T - \mathbf{r}_{i_3 1}^T) = 0 \end{aligned} \quad (3.26)$$

From the equations above, we can drive

$$m(\mathbf{r}_{i_1 1}^T - \mathbf{r}_{i_1 2}^T) = (m-Q)(\mathbf{r}_{1i_1}^T - \mathbf{r}_{2i_1}^T) \quad (3.27)$$

If here is a  $st$ -path with length  $Q+1$  in the solution set, then  $\mathbf{r}_{i_1 1}^T = \mathbf{r}_{i_1 2}^T$ . Since the choice of  $u_{i_1}, u_1, u_2$  are arbitrary, therefore, indeed we have  $\mathbf{r}_{ij}^T = \mathbf{r}_{ik}^T$  for any  $u_i, u_j, u_k \in N$ . Similarly, If here is a  $st$ -path with length at most  $Q$  in the solution set, then  $\mathbf{r}_{ji}^T = \mathbf{r}_{ki}^T$  for any  $u_i, u_j, u_k \in N$ . So,  $\mathbf{r}_{ij}^T = \mathbf{r}_{kl}^T$  for any  $u_i, u_j, u_k, u_l \in N$ .

*Step 5:* Let

$$\begin{aligned} p_1 &= (s, u_{i_1}, u_{i_2}, \dots, u_{i_m}, u_1, u_2, t) \\ p_2 &= (s, u_{i_1}, u_{i_2}, \dots, u_{i_m}, u_2, u_1, t) \end{aligned}$$

With the result in Step 4, we get

$$\mathbf{r}_{ti}^T = \mathbf{r}_{tj}^T \quad \forall u_i, u_j \in N$$

Since by the construction of  $\boldsymbol{\nu}$ ,  $\mathbf{r}^T|_I = \mathbf{0}^T$ , therefore  $\mathbf{r}^T = \mathbf{0}^T$ .

The requirement on the length of a path needs the extra assumption about  $M, Q$

Now, since we know the dimension of polytope, we can go to decide the facets defining inequality of  $B_{LP}^{u+}, B_{IP}^{u+}$

**Observation 6**  $\xi_{\{u,t\}} \geq 0$  and  $x_{tu} \geq 0$  defines facet of  $B_{LP}^u$  and  $B_{IP}^u$

*Proof :*

Similar to the dimension proof and take

$$I = \{\{x_{su}\}_{u \in N}, \{x_{us}\}_{u \in N}, \{x_{ut}\}_{u \in N}, x_{u_1, u_2}, x_{tu_j}, x_{tu_k}, \{\xi_{u,v}\}_{\{u,v\} \in E}\}$$

**Observation 7** The polytope  $B_{LP}$  is invariant under relabel the vertices in  $N$ .

This observation is based on the graph is very "complete", relabel the vertices doesn't change the equation system of  $B_{LP}$ , and therefore, the polytope  $B_{LP}$  is also symmetric.

**Theorem 3.4.2**  $x_{uv} \geq 0$  defines a facet of  $B_{LP}^{u+}$  for all  $u, v \in N$ , if  $|N| \geq 16$

*Proof :* Let  $n = |N|$ , we know  $\dim B_{LP}^{u+} = n^2 - 2$ , so the number of facet defining inequalities is at least  $n^2 - 1$ . Since  $B_{LP}^{u+}$  is a special case of  $B_{LP}$  and  $N \geq Q \geq 5$ , we know that  $\xi_{\{u,v\}} \geq 0$  isn't a facet. Here are totally  $2(n^2 + 3n) - \binom{n}{2}$  many potential facet defining inequalities and  $n^2 - n$  many inequalities of the form  $x_{uv} \geq 0$  for  $u, v \in N$ . Therefore, if  $n \geq 16$ , then by pigeonhole principle,  $x_{uv} \geq 0$  is a facet for some  $u, v \in N$ . However, because of Observation 7,  $x_{uv} \geq 0$  is a facet for all  $u, v \in N$

## Chapter 4

# Resource Constrained Shortest Path Problem

In section 4.1, we state the RSCPP and the basic classical model. In section 4.2, we follow the idea of Baldacci and give a new model for RCSP, and show this model is better than the basic model. In section 4.3, we discuss the dimension of the LP-relaxation. In section 4.4, we discuss the dimension of the lattice polytope while all demand are units. In section 4.5, we give a series of cuts, these cuts are facets under the unit demand case and works well when capacity  $Q = 2$ .

### 4.1 Problem Description and Classical Model

**Definition 4.1.1 (Resource Constrained Shortest Path Problem (RCSP))** *Given:* directed simple graph  $G = (V, A)$ , two special vertices, the sink  $s \in V$  and the target  $t \in V$ , non-negative integer edge costs  $c \in \mathbb{N}_{\geq 0}^E$ , natural numbers  $Q \in \mathbb{N}$  and node demands  $q \in \mathbb{N}_{\geq 0}^N$ , where  $N = V \setminus \{s, t\}$ . A route is simple  $st$ -path  $p$  in  $G$ , its cost and demand are  $c(p)$  and  $q(p)$ , respectively, and it is feasible if  $q(p) \leq Q$  holds. **Sought:** A route of minimal total cost.

And a natural model for RCSPP is adding resource constraints to the shortest path problem.

$$\min \sum_{uv \in A} c_{uv} x_{uv}$$

subject to:

$$\sum_{u \in N} x_{su} = 1 \tag{4.1}$$

$$\sum_{u \in N} x_{ut} = 1 \tag{4.2}$$

$$x_{us} = x_{tu} = 0 \quad \forall u \in N \tag{4.3}$$

$$\sum_{v \in \gamma^-(u)} x_{vu} - \sum_{v \in \gamma^+(u)} x_{uv} = 0 \quad \forall u \in N \tag{4.4}$$

$$\sum_{u \in N} q_u \left( \sum_{v \in \gamma^+(u)} x_{uv} \right) \leq Q \tag{4.5}$$

$$x_{uv} \in \{0, 1\} \quad \forall uv \in A \tag{4.6}$$

## 4.2 A New Model

Transfer a given undirected graph  $G = (V, E)$  into a directed graph  $D(G) = (V, A(E))$  with  $c_{\{u,v\}} = c_{uv} = c_{vu}$ . Assign an arc variable  $x_{uv}$  and a flow variable  $y_{uv}$  for all  $uv \in A(E)$ .

$$\min \sum_{uv \in A(E)} c_{uv} x_{uv}$$

subject to:

$$\sum_{u \in N} x_{su} = 1 \quad (4.7)$$

$$x_{us} = x_{tu} = 0 \quad \forall u \in N \quad (4.8)$$

$$\sum_{u \in N} x_{ut} = 1 \quad (4.9)$$

$$y_{us} = 0 \quad \forall u \in N \quad (4.10)$$

$$\sum_{v \in \gamma(u)} x_{vu} - \sum_{v \in \gamma(u)} x_{uv} = 0 \quad \forall u \in N \quad (4.11)$$

$$y_{uv} + y_{vu} = Q(x_{uv} + x_{vu}) \quad \forall \{u, v\} \in E \quad (4.12)$$

$$\sum_{v \in \gamma(u)} (y_{vu} - y_{uv}) = q_u \sum_{v \in \gamma(u)} (x_{vu} + x_{uv}) \quad \forall u \in N \quad (4.13)$$

$$x_{uv}, x_{vu} \in \{0, 1\}, y_{uv} \geq 0, y_{vu} \geq 0 \quad \forall \{u, v\} \in E \quad (4.14)$$

This model is also based on the flow conservation formula, replace the resource constraints by (4.12) and (4.13), which follow the idea of Baldacci's model.

Since we have a new model, the first thing is that we should compare this new model with the classical model.

**Observation 8** *The set of feasible solutions of the new model project onto the arc variables space is a subset of the set of feasible solutions of the basic model. Moreover, it can be a proper subset.*

*Proof :* It's sufficient to check the feasible solutions of the new model satisfy (4.5):

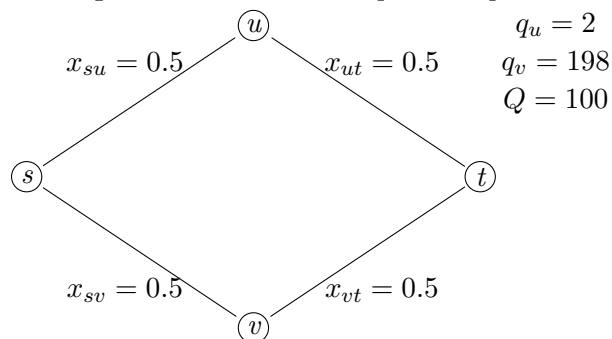
$$\begin{aligned} \sum_{u \in N} \sum_{v \in \gamma(u)} q_u (x_{uv} + x_{vu}) &= \sum_{u \in N} \sum_{v \in \gamma(u)} (y_{vu} - y_{uv}) \\ &= \sum_{u \in N} \sum_{\substack{v \in \gamma(u) \\ v \in N}} (y_{vu} - y_{uv}) + \sum_{u \in N} (y_{su} - y_{us} + y_{tu} - y_{ut}) \\ &\leq \sum_{u \in N} (y_{su} + y_{us} + y_{tu} + y_{ut}) \\ &= \sum_{u \in N} Q(x_{su} + x_{us}) + \sum_{u \in N} Q(x_{tu} + x_{ut}) = 2Q \end{aligned}$$

Then the flow conservation constraint says:

$$\sum_{u \in N} q_u \sum_{v \in \gamma(u)} x_{uv} = \sum_{u \in N} q_u \sum_{v \in \gamma(u)} x_{vu}$$

So, the solutions of new model satisfy (4.5).

**Example 4.2.1** Here is simple example to show the new model is better.



This is a solution of the basic model. However, this can't be a solution of the new model. Consider the equation on  $v$

$$y_{sv} + y_{tv} - y_{vs} - y_{vt} = q_v(x_{sv} + x_{tv} + x_{vs} + x_{vt}) = 198$$

$$y_{sv} + y_{vs} = Q(x_{sv} + x_{vs}) = 50$$

$$y_{vt} + y_{tv} = Q(x_{tv} + x_{vt}) = 50$$

Since all variables are non-negative, the following inequality is impossible, which means this new model is better than the classical model.

$$198 = y_{sv} + y_{tv} - y_{vs} - y_{vt} > y_{sv} + y_{tv} + y_{vs} + y_{vt} = 100$$

Actually, here is a stronger result. Let  $f$  be a flow with respect to the arcs such that  $f = \sum_{i=1}^m \mu_i p_i$  for some paths  $p_i$  with  $\sum_{i=1}^m \mu_i = 1$ . If  $\forall i, j \in [m], V(p_i) \cap V(p_j) = \{s, t\}$ , then a necessary condition such that  $f$  can be the projection of a solution of the new model is

$$q(p_i) := \sum_{u \in V(p_i)} q_u \leq Q \quad \forall i \in [m]$$

The advantage in this case is that we don't need to consider the weights. Checking the demands of paths are enough to see if the solution is feasible.

**Observation 9** Let path  $p$  be  $(s = u_0, u_1, \dots, u_m, u_{m+1} = t)$ , here are trivial value for flow variables that  $y_{u_i u_{i+1}} = Q - \sum_{j=1}^i q_{u_j}$  and  $y_{u_{i+1} u_i} = \sum_{j=1}^i q_{u_j}$  can associate to this path to get a solution for the new model. Moreover, if the vertices in  $p$  are distinct, then the value of flow variables are unique, ie the trivial value for flow variables are the only way to associate  $p$  to a solution of the new model.



*Proof:*

This construction gives a solution  $f$ . Suppose here is another flow solution  $f'$  for  $p$ , then  $f - f'$  is a solution for the homogeneous equation system with all arc variables equal to 0. Then, plug  $x_{uv} = x_{vu} = 0$  for all  $\{u, v\} \in E$  into the equation (4.12) and (4.13), we get

$$\begin{aligned} y_{uv} + y_{vu} &= 0 \quad \forall \{u, v\} \in E \\ \sum_{v \in \gamma(u)} (y_{vu} - y_{uv}) &= 0 \quad \forall u \in N \end{aligned}$$

Therefore we conclude that  $f - f' = \mathbf{0}$ . That means the solution associates to a  $s - t$  path is unique.

### 4.3 Dimension of a Polytope from the Model

Now consider  $E = \{\{u, v\} : u, v \in N\} \cup \{\{s, u\} : u \in N\} \cup \{\{v, t\} : v \in N\}$ , where  $|N| = n$ . In this case for all  $u \in V$ ,  $\gamma(u) = \gamma^+(u) = \gamma^-(u)$ . Let  $P_{LP}$  be the polytope of the LP-relaxation of model in this graph. Use the similar idea in previous section, the equations can be transferred to

$$\sum_{u \in N} x_{su} = 1 \tag{4.15}$$

$$\sum_{u \in N} x_{ut} = 1 \tag{4.16}$$

$$\sum_{v \in \gamma(u)} x_{uv} - \frac{1}{2} \sum_{v \in \gamma(u)} (y_{vu} - y_{uv}) = 0 \quad \forall u \in N \tag{4.17}$$

$$\sum_{v \in \gamma(u)} x_{vu} - \frac{1}{2} \sum_{v \in \gamma(u)} (y_{vu} - y_{uv}) = 0 \quad \forall u \in N \tag{4.18}$$

$$x_{us} = 0 \quad \forall u \in N \tag{4.19}$$

$$x_{tu} = 0 \quad \forall u \in N \tag{4.20}$$

$$y_{us} = 0 \quad \forall u \in N \tag{4.21}$$

$$y_{uv} + y_{vu} = Q(x_{uv} + x_{vu}) \quad \forall \{u, v\} \in E \tag{4.22}$$

Write the model as  $\begin{pmatrix} C \\ X \\ Y \\ G \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} c \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{pmatrix}$ , where  $C$  represents the equations from (4.15)-

(4.18),  $X$  represents equations from (4.19)-(4.20),  $Y$  represents (4.21) and  $G$  represents equations from (4.22). Actually, from these equations, we can conclude that  $y_{us} = Qx_{us} \forall u \in N$ , but These equations are already in the row space of this matrix.

**Lemma 2** Only one equation in  $\begin{pmatrix} C \\ X \\ Y \\ G \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} c \\ 0 \\ 0 \\ 0 \end{pmatrix}$  is redundant. That means the rank

of matrix  $\begin{pmatrix} C \\ X \\ Y \\ G \end{pmatrix}$  is  $\frac{1}{2}n^2 + \frac{13}{2}n + 1$ .

*Proof:* We use the same idea as previous section. Consider  $(\mathbf{a}^T, \boldsymbol{\mu}^T, \lambda, \mathbf{b}^T)$  such that

$$(\mathbf{a}^T, \boldsymbol{\mu}^T, \boldsymbol{\omega}^T, \mathbf{b}^T) \begin{pmatrix} C \\ X \\ Y \\ G \end{pmatrix} = \mathbf{0}^T$$

Let

- $\alpha^+(u)$  be the entry in  $\mathbf{a}^T$  corresponding to

$$\sum_{v \in \gamma^+(u)} x_{uv} = \begin{cases} 1 & \text{if } u = s \\ \frac{1}{2} \sum_{v \in \gamma(u)} (y_{vu} - y_{uv}) & \text{if } u \in N \end{cases}$$

- $\alpha^-(u)$  be the entry in  $\mathbf{a}^T$  corresponding to

$$\sum_{v \in \gamma^-(u)} x_{vu} = \begin{cases} 1 & \text{if } u = t \\ \frac{1}{2} \sum_{v \in \gamma(u)} (y_{vu} - y_{uv}) & \text{if } u \in N \end{cases}$$

- $\mu^+(u)$  be the entry in  $\boldsymbol{\mu}^T$  corresponding to

$$x_{us} = 0$$

- $\mu^-(u)$  be the entry in  $\boldsymbol{\mu}^T$  corresponding to

$$x_{tu} = 0$$

- $\omega(u)$  be the entry in  $\boldsymbol{\omega}^T$  corresponding to

$$y_{us} = 0$$

- $\beta_{\{u,v\}}$  be the entry in  $\mathbf{b}^T$  corresponding to

$$y_{uv} + y_{vu} - Q(x_{uv} + x_{vu}) = 0$$

Firstly, we arbitrary choose  $u, v \in N$ , these variables only appears in (4.17),(4.18) and (4.22), in order to cancel the variables  $x_{uv}$  and  $x_{vu}$ , we have

$$\alpha^+(u) + \alpha^-(v) + Q\beta_{\{u,v\}} = 0 \text{ and } \alpha^-(u) + \alpha^+(v) + Q\beta_{\{u,v\}} = 0$$

Then consider variables  $y_{uv}$  and  $y_{vu}$  which also only appears in (4.17),(4.18) and (4.22), yields

$$\begin{aligned} -2\beta_{\{u,v\}} + \alpha^+(u) + \alpha^-(u) - \alpha^-(v) - \alpha^+(v) &= 0 \\ -2\beta_{\{u,v\}} - \alpha^+(u) - \alpha^-(u) + \alpha^-(v) + \alpha^+(v) &= 0 \end{aligned}$$

Since  $u, v$  are arbitrary, for any  $u, v \in N$ ,  $\beta_{\{u,v\}} = 0$ ,  $\alpha^+(u) = -\alpha^-(v)$ . Then we start to cancel the variable  $y_{ut}$ :

$$\alpha^+(u) + \alpha^-(u) - \beta_{\{u,t\}} = 0 \text{ and } \alpha^+(u) + \alpha^-(u) + \beta_{\{u,t\}} = 0$$

This implies  $\beta_{\{u,t\}} = 0$  and  $\alpha^+(u) = \alpha^-(u)$  for all  $u \in N$ . Now we cancel the variables  $x_{ut}, x_{tu}$

$$\mu^-(u) = -\alpha^-(u) \text{ and } \alpha^-(t) = -\alpha^+(u)$$

After this, we cancel the variables  $y_{us}$  and  $y_{su}$

$$-2\beta_{\{u,s\}} + \alpha^+(u) + \alpha^-(u) + 2\omega_u = 0 \text{ and } -2\beta_{\{u,s\}} + \alpha^+(u) + \alpha^-(u) = 0$$

And we get  $\beta_{\{u,s\}} = 0, \omega(u) = 0$  for all  $u \in \omega$ . Finally, we can cancel the  $x_{us}$  and  $x_{su}$

$$\alpha^+(s) = -\alpha^-(u) \text{ and } \mu^+(u) = -\alpha^+(u)$$

We have canceled all variables, and these relationships tell

$$\dim\{(\mathbf{a}^T, \boldsymbol{\mu}^T, \boldsymbol{\omega}^T, \mathbf{b}^T) : (\mathbf{a}^T, \boldsymbol{\mu}^T, \boldsymbol{\omega}^T, \mathbf{b}^T) \begin{pmatrix} C \\ X \\ Y \\ G \end{pmatrix} = \mathbf{0}^T\} = 1$$

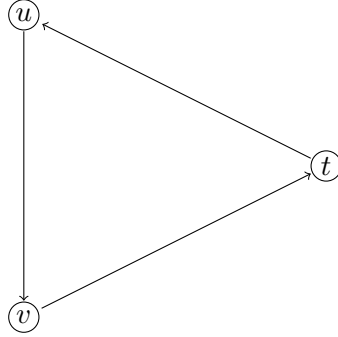
The rank of matrix follows immediately. Now, this lemma provides a upper bound of dimension, the next task is constructing affinely independent points.

**Theorem 4.3.1** *If  $3Q > 5 \max_{u \in N} q_u$ , then  $\dim P_{LP} = 3\binom{n}{2} + n - 1$*

*Proof :*

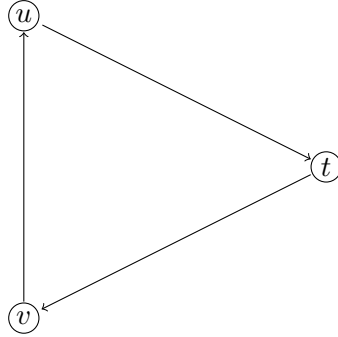
$\dim P_{LP} \leq 3\binom{n}{2} + n - 1$  is immediately from Lemma 2. So, it's sufficient to find  $3\binom{n}{2} + n$  many affinely independent points. It's clear that path  $p_u := (s, u, t)$  with associated flow variables are affinely independent. Let  $f = \frac{1}{n} \sum_{u \in N} p_u$ . Then for every two  $u, v \in N$ , we construct three different solution.

$c_{uv}^1$ :



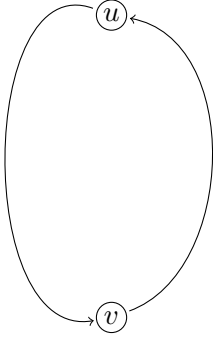
$$\begin{aligned}
 x_{vu} &= x_{tu} = x_{tv} = 0 \\
 x_{uv} &= 0.5 \\
 x_{ut} &= -0.5 \\
 x_{vt} &= 0.5 \\
 y_{uv} &= 0.5Q \\
 y_{vu} &= 0 \\
 y_{ut} &= -0.25Q - 0.25q_u \\
 y_{tu} &= 0.25Q + 0.25q_u \\
 y_{vt} &= 0.25Q - 0.25q_v \\
 y_{tv} &= -0.25Q + 0.25q_v
 \end{aligned}$$

$c_{uv}^2$ :



$$\begin{aligned}
 x_{uv} &= x_{tu} = x_{vt} = 0 \\
 x_{vu} &= 0.5 \\
 x_{ut} &= 0.5 \\
 x_{vt} &= -0.5 \\
 y_{vu} &= 0.5Q \\
 y_{uv} &= 0 \\
 y_{ut} &= 0.25Q - 0.25q_u \\
 y_{tu} &= -0.25Q + 0.25q_u \\
 y_{vt} &= -0.25Q - 0.25q_v \\
 y_{tv} &= 0.25Q + 0.25q_v
 \end{aligned}$$

Take a small enough positive parameter  $\epsilon$ , then  $c_{uv}^3$  is constructed as:



(t)

$$\begin{aligned}
x_{ut} &= x_{tu} = x_{vt} = x_{tv} = 0 \\
x_{vu} &= 0.25 \\
x_{uv} &= 0.25 \\
y_{uv} &= 0.25Q + \epsilon \\
y_{vu} &= 0.25Q - \epsilon \\
y_{ut} &= -\epsilon - 0.25q_u \\
y_{tu} &= \epsilon + 0.25q_u \\
y_{vt} &= \epsilon - 0.25q_v \\
y_{tv} &= -\epsilon + 0.25q_v
\end{aligned}$$

It's easy to check that  $f + \frac{1}{n}c_{uv}^i$  is a solution for arbitrary  $u, v \in N$  and  $i \in [3]$ . Also, we can check  $\{f + \frac{1}{n}c_{uv}^i\}_{u,v \in N, i \in [3]} \cup \{p_u\}_{u \in N}$  are affinely independent. Therefore,

$$\dim P_{LP} = 3 \binom{n}{2} + n - 1$$

#### 4.4 Integer Solution Polytope for Unit Demand Case

Now we consider the case that  $q_u = 1$  for all  $u \in N$ , and in this case we can compute the dimension of the convex hull of integer solution  $P_{IP}^u$ . Assume  $|N| = n$

**Observation 10** *Let  $|N| \geq Q$ . If  $Q=1$ , then  $\dim P_{IP}^u = n-1$ , and if  $Q=2$ , then  $\dim P_{IP}^u = 2 \binom{n}{2} + n - 1$*

*Proof :*

Recall the constraints (4.13)

$$\sum_{v \in \gamma(u)} (y_{vu} - y_{uv}) = q_u \sum_{v \in \gamma(u)} (x_{vu} + x_{uv}) \quad \forall u \in N$$

I sum them over all  $u \in N$ , and since the unit case

$$\begin{aligned}
\sum_{u \in N} \left( \sum_{v \in \gamma(u)} (x_{uv} + x_{vu}) \right) &= \sum_{u \in N} \sum_{v \in \gamma(u)} (y_{vu} - y_{uv}) \\
&= \sum_{u \in N} (y_{su} + y_{tu} - y_{us} - y_{ut}) = Q + \sum_{u \in N} (y_{tu} - y_{ut}) \leq 2Q
\end{aligned}$$

Since

$$\sum_{u \in N} x_{su} = \sum_{u \in N} x_{ut} = 1 \text{ and } \forall u \in N, x_{us} = x_{tu} = 0$$

If  $Q = 1$ , then  $\sum_{u,v \in N} (x_{uv} + x_{vu}) = 0$ , so all integer solutions project onto the arc variables

are of the form  $(s, u, t)$

If  $Q = 2$ , then  $2 \sum_{v \in \gamma(u) \setminus \{s,t\}} \sum_{u \in N} x_{uv} = \sum_{u,v \in N} (x_{uv} + x_{vu}) \leq 2$ , that means we can at most take one arc with head or tail in  $N$ . So, all integer solution w.r.t arcs are either of the form  $(s, u, t)$  or  $(s, u, v, t)$ .

In Observation 9, we know that the way to associate flow is unique, and all solutions are affinely independent. So, we have the dimension.

We have observed the dimension in two simple and specific case, Now, we are going to prove the dimension for  $Q \geq 3$ .

**Theorem 4.4.1** *Let  $|N| \geq Q$ . If  $Q \geq 3$ , then  $\dim P_{IP}^u = 3\binom{n}{2} + n - 1$*

*Proof:*

Since  $3Q \geq 9 > 5$ ,  $\dim P_{IP}^u \leq \dim P_{LP} = 3\binom{n}{2} + n - 1$ , then we will construct affinely independent points. Label the vertices in  $N$  such that  $N = \{u_1, u_2, \dots, u_n\}$ . Take path  $(s, u_i, t)$  and  $(s, u_i, u_j, t)$  for all  $i, j \in [n]$ . And we take paths  $(s, u_i, u_j, u_k, t)$  such that  $k > j$  and  $i \equiv j - 1 \pmod{n}$ . We have  $\binom{3}{n}2 + n - 1$  many different paths, now we add one more paths  $(s, u_{n-1}, u_1, u_n, t)$ . Let  $\mathcal{P}_3$  be the set of all paths with length 3, and  $S := \{(i, j) : (s, u_i, u_j, u_k, t) \in \mathcal{P}_3\}$ . Indeed  $S = \{(n, 1), (n - 1, 1)\} \cup \{(1, 2), (2, 3), \dots, (n - 2, n - 1)\}$

- Let  $z(i)$  be the corresponding solution of the model w.r.t  $(s, u_i, t)$
- Let  $z(i, j)$  be the corresponding solution of the model w.r.t  $(s, u_i, u_j, t)$
- Let  $z(i, j, k)$  be the corresponding solution of the model w.r.t  $(s, u_i, u_j, u_k, t)$

The following is show our construction gives  $3\binom{n}{2} + n$  many affinely independent points. Let  $\alpha(i), \alpha(i, j), \alpha(i, j, k)$  be the coefficient of solutions  $z(i), z(i, j), z(i, j, k)$  respectively. Consider

$$\sum_{i \in [n]} \alpha(i)z(i) + \sum_{\substack{i, j \in [n] \\ i \neq j}} \alpha(i, j)z(i, j) + \sum_{(s, u_i, u_j, u_k, t) \in \mathcal{P}_3} \alpha(i, j, k)z(i, j, k) = 0$$

where  $\sum_{i \in [n]} \alpha(i) + \sum_{i, j \in [n]} \alpha(i, j) + \sum_{(s, u_i, u_j, u_k, t) \in \mathcal{P}_3} \alpha(i, j, k)z(i, j, k) = 0$

Firstly, note that for all  $(u_i, u_j)$  with  $i > j$  and  $(u_i, u_j) \notin S$ , then only in the  $z(i, j)$  this coordinate is non-zero. So  $\alpha(i, j) = 0$  for all  $i > j$  with  $(i, j) \notin S$ . Then we look at  $(u_j, u_k)$  such that  $(j, k) \notin S$ , then the coordinate corresponding to the arc is non-zero only in  $z(j, k)$  and  $z(i, j, k)$ . Therefore, for these  $(j, k)$ ,  $\alpha(j, k) = -\alpha(i, j, k)$ . Then we check the flow value on  $(u_j, u_k)$ , we get  $\alpha(j, k) = \alpha(i, j, k) = 0$ .

The coefficients may be non-zero yet are  $\{\alpha(i)\}_{i \in [n]} \cup \{\alpha(i, j) : (i, j) \in S\} \cup \{\alpha(i, j, k) : (s, u_i, u_j, u_k, t) \in \mathcal{P}_3, j < k, (j, k) \in S\}$ . Note the only way that  $(i, j) = (n - 2, n - 1)$  in

$(s, u_i, u_j, u_k, t)$  is  $(s, u_{n-2}, u_{n-1}, u_n, t)$ . Since  $\alpha(n-2, n-1, n) = -\alpha(n-2, n-1) = 0$ , therefore by the same discuss  $\alpha(n-3, n-2, n-1) = -\alpha(n-3, n-2) = 0$ , and then  $\alpha(i, j, k)$  where  $i = n-3, j = n-2$  are all zero. So  $\alpha(n-4, n-3, n-2) = -\alpha(n-4, n-3) = 0$ . Repeat this process, then this means we know that the coefficients  $\{\alpha(i, j) : (i, j) \in S, 1 < i < j\} \cup \{\alpha(i, j, k) : (s, u_i, u_j, u_k, t) \in P_3, 1 < j < k, (j, k) \in S\}$  are all zero. Also, we can remove  $\{\alpha(i) : i \in [n-2], i \neq 1\}$ . Therefore, only  $\alpha(1), \alpha(n), \alpha(n-1), \alpha(n-1, 1), \alpha(1, n-1), \alpha(1, n), \alpha(n, 1), \alpha(n-1, 1, n), \alpha(n, 1, n-1)$  are not known yet. However, by computation, we know all them are 0. Therefore, we find  $3\binom{n}{2} + n$  many affinely independent points.

## 4.5 Cuts

We consider the undirected graph  $G = (V, E)$  and its induced graph  $G = (V, A(E))$  as section 4.3. Let  $p = (s, \dots, u, t)$  be a path. If all vertices of  $p$  are distinct, then before the vehicle entering the last vertex  $u$ , it should carry at least  $q_u$  many flow. However, if we have a cycle, when a vertex  $u \in N$  are visited more then once. Here is a freedom to manage how to satisfies the demand of  $u$ . For example in the path  $p = (s, \dots, w, u, v, u, t)$ , assume  $u$  is visited exactly twice. Then I can take

$$\begin{aligned} y_{wu} + y_{vu} - y_{uw} - y_{uv} &= 2q_u \\ y_{vu} + y_{tu} - y_{uv} - y_{ut} &= 0 \end{aligned}$$

However, since the objective function only cares about arc variable, then we can cut these solutions. Note, in this model we have two flows, one is a  $st$ -flow and another is the residual  $ts$ -flow. So, what we discussed can be directly applied to the residual flow. Here is a cut

$$y_{vu} \geq \min_{w \in N} q_w(x_{uw} + x_{vu}) \quad \forall u \in N, v \in \gamma(u) \quad (4.23)$$

These cuts work very well in unit demand case.

**Theorem 4.5.1** *Let  $|N| \geq Q$ . If  $q_u = 1$  for all  $u \in N$  and  $Q \geq 3$ , then the inequality in (4.23) define a facet for the polytope of LP-relaxation and convex hull of integer solution  $P_{LP}^u, P_{IP}^u$*

*Proof :* We firstly show that  $y_{vu} = \min_{w \in N} q_w(x_{uw} + x_{vu})$  is independent to the original equation system. From Section 4.3, we know that all equations from (4.22) are independent. And since  $u, v \in N$ , so here are only one equation in (4.22) is relevant to  $y_{uv}$ . That means  $y_{vu} = \min_{w \in N} q_w(x_{uw} + x_{vu})$  is independent for any  $u, v \in N$ .

Then we claim that we can construct  $3\binom{n}{2} + n - 1$  many affinely independent points with the cut is tight. Let  $N = \{u_i\}_{i=1}^n$ . We take paths in the three forms. Based on the symmetry, W.L.O.G, let  $u = u_l, v = u_r$  such that  $l < r - 1, l, r \in \{2, 3, \dots, n-1\}$

- $(s, u_i, t)$  for all  $i \in [n]$

- $(s, u_i, u_j, t)$  for all  $i, j \in [n]$ , but  $(i, j) \neq (l, r)$
- $(s, u_{i-1}, u_i, u_j, t)$  for all  $i, j \in [n]$  with  $i < j$  but  $(i, j) \neq (l, r)$ . Here the  $i - 1$  is also similar to Section 4.4, that is respect to the remainder of modulo  $n$ .
- $(s, u_r, u_l, u_{l+1}, t)$ . The plus is respect to the remainder of modulo  $n$ .

Similar to Section 4.4, they are affinely independent points. Therefore  $y_{vu} \geq \min_{w \in N} q_w(x_{uw} + x_{vu})$  is a facet defining inequality for any  $u, v \in N$ .

**Theorem 4.5.2** *Let  $|N| \geq Q$ . If  $Q = 2$ , then adding these cuts will give a complete description of  $P_{IP}^u$*

*Proof :*

Since  $Q = 2$ , By the cuts

$$\begin{aligned} y_{vu} &\geq (x_{uv} + x_{vu}) \quad \forall u, v \in N \\ y_{uv} &\geq (x_{uv} + x_{vu}) \quad \forall u, v \in N \end{aligned}$$

and

$$y_{uv} + y_{vu} = 2(x_{uv} + x_{vu}) \tag{4.24}$$

Therefore, indeed, we get  $y_{uv} = y_{vu}$  for all  $u, v \in N$ . And all possible paths  $(s, u, t)$  or  $(s, u, v, t)$  are satisfy (4.24).

Let  $f$  be a solution satisfies the model include the cuts (4.23). We first look at the arc variables. By flow decomposition theorem,  $f = \sum_{i=1}^m \mu_i p_i + \sum_{i=1}^l \lambda_i c_i$ , where  $p_i$  are paths with distinct vertices,  $c_i$  are cycles and  $\sum_{i=1}^m \mu_i = 1$ . Since the flow variable associated with a path with distinct vertices have unique value. So, it sufficient to show that  $\lambda_i = 0$  for all  $i$ . Let  $f' = \sum_{i=1}^m \mu_i p_i$ , and  $z(f), z(f')$  be the solutions of the model with flow  $f, f'$  respectively. Then  $z(f) - z(f')$  is a solution of the homogeneous equations. Our cycle can't include vertices  $s, t$ , so  $x_{su}, x_{us}, x_{tu}, x_{ut} = 0$ , therefore  $y_{su}, y_{us}, y_{tu}, y_{ut} = 0$ . The use (4.13),

$$0 = \sum_{u, v \in N} (y_{vu} - y_{uv}) = (x_{uv} + x_{vu}) \Rightarrow x_{uv} + x_{vu} = 0$$

Therefore  $\lambda_i = 0$ , that is here is no cycles in  $f$ . So every solution is a convex combination of integer solutions, this implies that all vertices are integral.

## 4.6 Computational Results

All instance are generated by the Delaunay Triangulation on random points on a plane, and they can be found in my github



# Chapter 5

## Summary

### Summary

We studied the Baldacci's two commodity flows model for vehicle routing problem, deriving implicit equations from the original equation system. Then, we discuss the redundant equations from all equation constraints. Therefore, we obtain a upper bound for the dimension of the polytope after relaxation. We identified certain inequalities that cannot be facet defining inequalities. Additional, We study a special case where all consumers have the same demands. In this special case, we find the dimension of the polyotpe for Baldacci's model and the facet defining inequalities.

Continuing with Baldacci's approach, we proposed a new model for the resource constrained shortest path problem. Using a simple example, we show the projection of the feasible solution set can be a proper subset of the classical feasible solution set, which shows the advantages of our new model. We also discuss the redundancy of the equation system, and prove the dimension of the polytope of relaxation. Similar to the previous discussion, we consider the special case where all consumers have the same demands, and obtain the dimension of the polytope and the facet defining inequalities. Additional, We find simple cuts preserving the optimal solution. Moreover, in a very simple case, the cuts can give a complete description for the polytope.

In the end, we compare the performance of our new model and the classical model on graphs based on Delaunay triangulation.

## Zusammenfassung

Wir haben Baldaccis Zwei-Güterströme-Modell für das Fahrzeugroutenproblem studiert und dabei implizite Gleichungen aus dem ursprünglichen Gleichungssystem abgeleitet. Anschließend haben wir die redundanten Gleichungen aller Gleichheitsbedingungen diskutiert. Daher erhalten wir eine Obergrenze für die Dimension des Polytops nach der Relaxation. Wir haben bestimmte Ungleichungen identifiziert, die keine facettenbildenden Ungleichungen sein können. Zusätzlich haben wir einen speziellen Fall untersucht, in dem alle Verbraucher die gleichen Anforderungen haben. In diesem speziellen Fall haben wir die Dimension des Polytops für Baldaccis Modell und die facettenbildenden Ungleichungen herausgefunden.

Im Einklang mit Baldaccis Ansatz haben wir ein neues Modell für das Problem des ressourcenbeschränkten kürzesten Pfades vorgeschlagen. Anhand eines einfachen Beispiels zeigen wir, dass die Projektion der Menge der zulässigen Lösungen eine echte Teilmenge der klassischen Menge der zulässigen Lösungen sein kann, was die Vorteile unseres neuen Modells zeigt. Wir diskutieren auch die Redundanz des Gleichungssystems und beweisen die Dimension des Polytops nach der Relaxation. Ähnlich wie bei der vorherigen Diskussion betrachten wir den speziellen Fall, in dem alle Verbraucher die gleichen Anforderungen haben, und erhalten die Dimension des Polytops und die facettenbildenden Ungleichungen.

Zusätzlich finden wir einfache Schnitte, die die optimale Lösung erhalten. Darüber hinaus können diese Schnitte in einem sehr einfachen Fall eine vollständige Beschreibung für das Polytop liefern.

Abschließend vergleichen wir die Leistung unseres neuen Modells und des klassischen Modells auf Graphen, die auf der Delaunay-Triangulation basieren.

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