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On the Integrality of the Uncapacitated Facility Location Polytope

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ON THE INTEGRALITY OF THE UNCAPACITATED FACILITY LOCATION POLYTOPE

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Abstract. We study a system of linear inequalities associated with the uncapacitated facility location problem. We show that this system defines a polytope with integer extreme points if and only if the graph does not contain a certain type of odd cycles. We also derive odd cycle inequalities and give a separation algorithm.

1. Introduction

Let $G = (V, A)$ be a directed graph, not necessarily connected, where each arc and each node has a cost (or a profit) associated with it. We study the following version of the *uncapacitated facility location problem* (UFLP), a set of nodes is selected, usually called *centers*, and then each non-selected node can be assigned to a center. The goal is to minimize the sum of the costs of the selected nodes plus the sum of the costs yielded by the assignment. The linear system below defines a linear programming relaxation.

$$\sum_{(u,v)\in A} x(u,v) + y(u) \le 1 \quad \forall u \in V, \tag{1}$$

$$x(u,v) \le y(v) \quad \forall (u,v) \in A, \tag{2}$$

$$0 \le y(v) \le 1 \quad \forall v \in V, \tag{3}$$

$$x(u,v) \ge 0 \quad \forall (u,v) \in A. \tag{4}$$

For each node u, the variable $y(u)$ takes the value 1 if the node u is selected and 0 otherwise. For each arc (u, v) the variable $x(u, v)$ takes the value 1 if u is assigned to v and 0 otherwise. Inequalities (1) express the fact that either node u can be selected or it can be assigned to another node. Inequalities (2) indicate that if a node u is assigned to a node v then this last node should be selected. A variation of the UFLP that is common in the literature is when V is partitioned into V_1 and V_2, and the nodes in V_1 cannot be selected but they should be assigned to a node in V_2. This is obtained by fixing to zero some of the variables y and setting into equation some of the inequalities (1).

Let $P(G)$ be the polytope defined by (1)-(4), and let $UFLP(G)$ be the convex hull of $P(G) \cap \{0, 1\}^{|V|+|A|}$. Clearly

$$UFLP(G) \subseteq P(G).$$

In this paper we characterize the graphs G for which $UFLP(G) = P(G)$. More precisely, we show that $UFLP(G) = P(G)$ if and only if G does not contain certain type of "odd" cycles. We also give a polynomial algorithm to recognize the graphs in this class.

In [10] a slightly different model for the UFLP was transformed into a vertex packing problem in an undirected graph, then necessary and sufficient conditions for this new graph to be perfect were given. The facets of the uncapacitated facility location polytope

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have been studied in [11], [9], [4], [5], [3]. In [1, 2] we gave a description of $UFLP(G)$ for two special classes of graphs. The UFLP has also been studied from the point of view of approximation algorithms in [6] [13] and others. Other references on this problem are [8] and [12].

For a directed graph $G = (V, A)$ and a set $W \subset V$, we denote by $\delta^+(W)$ the set of arcs $(u, v) \in A$, with $u \in W$ and $v \in V \setminus W$. Also we denote by $\delta^-(W)$ the set of arcs (u, v), with $v \in W$ and $u \in V \setminus W$. We write $\delta^+(v)$ and $\delta^-(v)$ instead of $\delta^+(\{v\})$ and $\delta^-(\{v\})$, respectively. If there is a risk of confusion we use δ^+_G and δ^-_G. A node u with $\delta^+(u) = \emptyset$ is called a *pendent* node.

A simple cycle C is an ordered sequence

$$v_0, a_0, v_1, a_1, \dots, a_{p-1}, v_p,$$

where

- v_i, $0 \le i \le p-1$, are distinct nodes,
- a_i, $0 \le i \le p-1$, are distinct arcs,
- either v_i is the tail of a_i and v_{i+1} is the head of a_i, or v_i is the head of a_i and v_{i+1} is the tail of a_i, for $0 \le i \le p-1$, and
- $v_0 = v_p$.

By setting $a_p = a_0$, we associate with C three more sets as below.

- We denote by $\hat{C}$ the set of nodes v_i, such that v_i is the head of a_{i-1} and also the head of a_i, $1 \le i \le p$.
- We denote by $\dot{C}$ the set of nodes v_i, such that v_i is the tail of a_{i-1} and also the tail of a_i, $1 \le i \le p$.
- We denote by $\tilde{C}$ the set of nodes v_i, such that either v_i is the head of a_{i-1} and also the tail of a_i, or v_i is the tail of a_{i-1} and also the head of a_i, $1 \le i \le p$.

Notice that $|\hat{C}| = |\dot{C}|$. A cycle will be called *odd* if $p + |\dot{C}|$ (or $|\tilde{C}| + |\dot{C}|$) is odd, otherwise it will be called *even*. A cycle C with $\dot{C} = \emptyset$ is a *directed* cycle. The set of arcs in C is denoted by $A(C)$. We plan to prove that $UFLP(G) = P(G)$ if and only if G has no odd cycle.

If we do not require $v_0 = v_p$ we have a *path* P. In a similar way we define $\dot{P}$, $\hat{P}$ and $\tilde{P}$, excluding v_0 and v_p. We say that P is *odd* if $p + |\dot{P}|$ is odd, otherwise it is *even*. For the path P, the nodes $v_1, \dots, v_{p-1}$ are called *internal*.

If G is a connected graph and there is a node u such that its removal disconnects G, we say that u is an *articulation point*. A graph is said to be *two-connected* if at least two nodes should be removed to disconnect it. For simplicity, sometimes we use z to denote the vector (x, y), i. e. $z(u) = y(u)$ and $z(u, v) = x(u, v)$. Also for $S \subseteq V \cup A$ we use $z(S)$ to denote $z(S) = \sum_{a \in S} z(a)$.

A *polyhedron* P is defined by a set of linear inequalities. i. e., $P = \{x \mid Ax \le b\}$. A *face* of P is obtained by setting into equation some of these inequalities. An *extreme point* of P is given by a face that contains a unique element. In other words, some inequalities are set to equation so that this system has a unique solution.

This paper is organized as follows. In Section 2 we give a decomposition theorem that shows that one has to concentrate on two-connected graphs. In Section 3 we describe some transformations of the graph that are needed in the following section. Section 4 is devoted to two-connected graphs. In Section 5 we study graphs with odd cycles. The separation problem for the so-called odd cycle inequalities is studied in Section 6. In Section 7 we show how to test the existence of an odd cycle.

2. Decomposition

In this section we consider a graph $G = (V, A)$ that decomposes into two graphs $G_1 = (V_1, A_1)$ and $G_2 = (V_2, A_2)$, with $V = V_1 \cup V_2$, $V_1 \cap V_2 = \{u\}$, $A = A_1 \cup A_2$, $A_1 \cap A_2 = \emptyset$. We define G'_1 that is obtained from G_1 after replacing u by u'. We also define G'_2, obtained from G_2 after replacing u by u''. See Figure 1. The theorem below shows that we have to concentrate on two-connected graphs.

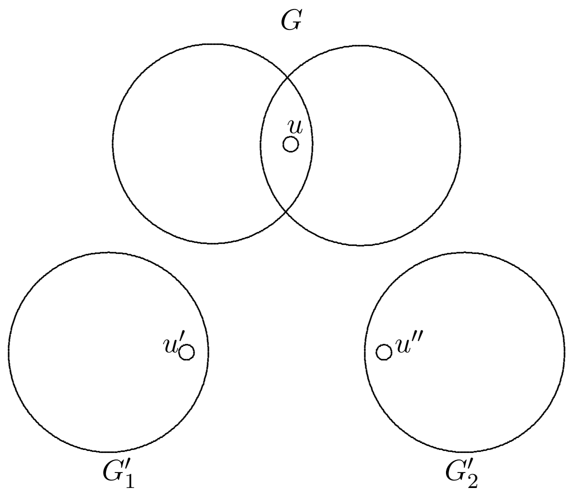

Figure 1

Theorem 1. *Suppose that the system*

$$Az' \leq b \tag{5}$$

$$z'\left(\delta^+_{G'_1}(u')\right) + z'(u') \leq 1 \tag{6}$$

describes $UFLP(G'_1)$. *Suppose that* (5) *contains the inequalities* (1)-(4) *except for* (6). *Similarly suppose that*

$$Cz'' \leq d \tag{7}$$

$$z''\left(\delta^+_{G'_2}(u'')\right) + z''(u'') \leq 1 \tag{8}$$

describes $UFLP(G'_2)$. *Also* (7) *contains the inequalities* (1)-(4) *except for* (8). *Then the system below describes an integral polyhedron.*

$$Az' \leq b \tag{9}$$

$$Cz'' \leq d \tag{10}$$

$$z'\left(\delta^+_{G'_1}(u')\right) + z''\left(\delta^+_{G'_2}(u'')\right) + z'(u') \leq 1 \tag{11}$$

$$z'(u') = z''(u'') \tag{12}$$

Proof. Let $(\bar{z}', \bar{z}'')$ be an extreme point of the polytope defined by the above system. We study two cases.

Case 1: $\bar{z}'(u') = 0$.

We have that $\bar z' \in UFLP(G_1')$ and $\bar z'' \in UFLP(G_2')$. If $\bar z'$ is an extreme point of $UFLP(G_1')$, we have to consider two sub-cases:

- $\bar z'\Big(\delta^+_{G_1'}(u')\Big) = 0.$

  If $\bar z''$ is not an extreme point of $UFLP(G_2')$, $\bar z'' = 1/2\lambda_1 + 1/2\lambda_2$, with λ_1, λ_2 in $UFLP(G_2')$, $\lambda_1 \neq \lambda_2$. Since $\lambda_1\Big(\delta^+_{G_2'}(u'')\Big) \leq 1$, $\lambda_2\Big(\delta^+_{G_2'}(u'')\Big) \leq 1$, we have that $(\bar z', \bar z'') = 1/2(\bar z', \lambda_1) + 1/2(\bar z', \lambda_2)$, with $(\bar z', \lambda_1)$ and $(\bar z', \lambda_2)$ satisfying (9)-(12), a contradiction. Thus $\bar z''$ is an extreme point and $(\bar z', \bar z'')$ is an integral vector.
- $\bar z'\Big(\delta^+_{G_1'}(u')\Big) = 1.$

  This implies $\bar z''\Big(\delta^+_{G_2'}(u'')\Big) = 0$. If $\bar z''$ is not an extreme point, $\bar z'' = 1/2\lambda_1 + 1/2\lambda_2$, with λ_1, λ_2 in $UFLP(G_2')$, $\lambda_1 \neq \lambda_2$. Since $\lambda_1\Big(\delta^+_{G_2'}(u'')\Big) = 0 = \lambda_2\Big(\delta^+_{G_2'}(u'')\Big)$, we have that $(\bar z', \bar z'') = 1/2(\bar z', \lambda_1) + 1/2(\bar z', \lambda_2)$, with $(\bar z', \lambda_1)$ and $(\bar z', \lambda_2)$ satisfying (9)-(12), a contradiction. Thus $\bar z''$ is an extreme point and $(\bar z', \bar z'')$ is an integral vector.

Now we should study the situation in which $\bar z'$ and $\bar z''$ are not extreme points.

We should have $\bar z' = 1/2\omega_1 + 1/2\omega_2$, with ω_1, ω_2 in $UFLP(G_1')$, $\omega_1 \neq \omega_2$. If $\omega_1\Big(\delta^+_{G_1'}(u')\Big) = \omega_2\Big(\delta^+_{G_1'}(u')\Big) = \bar z'\Big(\delta^+_{G_1'}(u')\Big)$, we have $(\bar z', \bar z'') = 1/2(\omega_1, \bar z'') + 1/2(\omega_2, \bar z'')$, with $(\omega_1, \bar z'')$ and $(\omega_2, \bar z'')$ satisfying (9)-(12). A contradiction.

Now we assume that

$$\omega_1\Big(\delta^+_{G_1'}(u')\Big) = \bar z'\Big(\delta^+_{G_1'}(u')\Big) - \epsilon$$
$$\omega_2\Big(\delta^+_{G_1'}(u')\Big) = \bar z'\Big(\delta^+_{G_1'}(u')\Big) + \epsilon,$$

with $\epsilon > 0$.

We also have $\bar z'' = 1/2\lambda_1 + 1/2\lambda_2$, with λ_1, λ_2 in $UFLP(G_2')$, $\lambda_1 \neq \lambda_2$. If $\lambda_1\Big(\delta^+_{G_2'}(u'')\Big) = \lambda_2\Big(\delta^+_{G_2'}(u'')\Big) = \bar z''\Big(\delta^+_{G_2'}(u'')\Big)$, we obtain a contradiction as above. Therefore we can suppose that

$$\lambda_1\Big(\delta^+_{G_2'}(u'')\Big) = \bar z''\Big(\delta^+_{G_2'}(u'')\Big) + \rho$$
$$\lambda_2\Big(\delta^+_{G_2'}(u'')\Big) = \bar z''\Big(\delta^+_{G_2'}(u'')\Big) - \rho,$$

with $\rho > 0$.

We can assume that $\epsilon = \rho$, so we have $(\bar z', \bar z'') = 1/2(\omega_1, \lambda_1) + 1/2(\omega_2, \lambda_2)$, with (ω_1, λ_1) and (ω_2, λ_2) satisfying (9)-(12). A contradiction.

Case 2: $0 < \bar z'(u')$.

We have that $\bar z' \in UFLP(G_1')$ and $\bar z'' \in UFLP(G_2')$. Thus $\bar z'$ is a convex combination of extreme points μ_i of $UFLP(G_1')$ that satisfy with equality every constraint that is satisfied with equality by $\bar z'$. Also $\bar z''$ is a convex combination of extreme points ϕ_j of $UFLP(G_2')$ that satisfy with equality every constraint satisfied with equality by $\bar z''$.

We can assume that $\mu_1(u') = 1 = \phi_1(u'')$. After putting together these two vectors we obtain a 0-1 vector that satisfies with equality every constraint that is satisfied with equality by the original vector $(\bar z', \bar z'')$, a contradiction. □

We have the following corollary.

Corollary 2. *The polytope $UFLP(G)$ is defined by the system* (9)- (12) *after identifying the variables $z'(u')$ and $z''(u'')$.*

3. Graph Transformations

First we plan to prove that if G has no odd cycle then $UFLP(G) = P(G)$. The proof consists of assuming that $\bar{z}$ is a fractional extreme point of $P(G)$ and arriving to a contradiction. Below we give several assumptions that can be made about $\bar{z}$ and G, they will be used in the next section.

Lemma 3. *We can assume that $\bar{z}(u, v) > 0$ for all $(u, v) \in A$.*

Proof. Let G' be the graph obtained after removing all arcs (u, v) with $\bar{z}(u, v) = 0$, and let z' be the vector obtained after removing all components $\bar{z}(u, v) = 0$. Then z' is a fractional extreme point of $P(G')$. □

Lemma 4. *If $0 < \bar{z}(u, v) < \bar{z}(v)$, we can assume that v is a pendent node with $|\delta^-(v)| = 1$ and $\bar{z}(v) = 1$.*

Proof. If v is not pendent or $|\delta^-(v)| > 1$, we can remove (u, v) and add a new node v' and the arc (u, v'). Then we can define $z'(u, v') = \bar{z}(u, v)$, $z'(v') = 1$, and $z'(s, t) = \bar{z}(s, t)$, $z'(r) = z(r)$ for all other nodes and arcs. Let G' be this new graph. We have that the constraints that are tight for $\bar{z}$ are also tight for z', so z' is an extreme point of $P(G')$. □

Lemma 5. *We can assume that G consists of only one connected component.*

Proof. Let G_1 be a connected component of G. Let z_1 be the projection of $\bar{z}$ onto the space associated with G_1. Then z_1 is an extreme point of $P(G_1)$. □

Lemma 6. *We can assume that $0 < \bar{z}(u, v) < 1$ for all $(u, v) \in A$.*

Proof. If $\bar{z}(u, v) = 1$ it follows from Lemma 3 that $\delta^-(u) = \emptyset$ and $\delta^+(u) = \{(u, v)\}$. Since $\bar{z}(v) = 1$ Lemma 3 implies that v is pendent, it follows from Lemma 4 that $\bar{z}(r, v) = 1$ for all $(r, v) \in \delta^-(v)$. Therefore $\delta^-(v)$ is a connected component of G. All variables associated with this connected component take integer values. □

Lemma 7. *We can assume that G is either two-connected or it consists of a single arc.*

Proof. If G has an articulation point we can apply Theorem 1 to decompose G into G_1 and G_2. If inequalities (1)-(4) define $UFLP(G_1)$ and $UFLP(G_2)$, then a similar system should define $UFLP(G)$. One can keep decomposing as long as the graph has an articulation point. □

If the graph G consists of a single arc it is fairly easy to see that $UFLP(G) = P(G)$, so now we have to deal with the two-connected components. This is treated in the next section.

4. Treating two-connected graphs

In this section we assume that the graph G is two-connected and it has no odd cycle. Let $\bar{z}$ be a fractional extreme point of $P(G)$, we are going to assign labels l to the nodes and arcs and define $z'(u,v) = \bar{z}(u,v) + l(u,v)\epsilon$, $z'(u) = \bar{z}(u) + l(u)\epsilon$, $\epsilon > 0$, for each arc (u,v) and each node u. We shall see that every constraint that is satisfied with equality by $\bar{z}$ is also satisfied with equality by z'. This is the required contradiction.

Given a path $P = v_0, a_0, \ldots, a_{p-1}, v_p$. Assume that the label of a_0, $l(a_0)$ has the value 1 or -1. We define the *labeling procedure* as follows.

For $i = 1$ to $p-1$ do

- If v_i is the head of a_{i-1} and it is the tail of a_i then $l(v_i) = l(a_{i-1})$, $l(a_i) = -l(v_i)$.
- If v_i is the head of a_{i-1} and it is the head of a_i then $l(v_i) = l(a_{i-1})$, $l(a_i) = l(v_i)$.
- If v_i is the tail of a_{i-1} and it is the head of a_i then $l(v_i) = -l(a_{i-1})$, $l(a_i) = l(v_i)$.
- If v_i is the tail of a_{i-1} and it is the tail of a_i then $l(v_i) = 0$, $l(a_i) = -l(a_{i-1})$.

Notice that the labels of v_0 and v_p were not defined.

We have to study several cases as follows.

Case 1. G contains a directed cycle $C = v_0, a_0, \ldots, a_{p-1}, v_p$. Assume that the head of a_0 is v_1, set $l(v_0) = -1$, $l(a_0) = 1$ and extend the labels as above.

Case 2. G contains a cycle $C = v_0, a_0, \ldots, a_{p-1}, v_p$ and $\dot{C} \neq \emptyset$. Assume $v_0 \in \dot{C}$. Set $l(v_0) = 0$, $l(a_0) = 1$ and extend the labels.

The lemma below is needed to show that for v_0, the constraints that were satisfied with equality by $\bar{z}$ remain satisfied with equality.

Lemma 8. *After labeling as in cases 1 and 2 we have $l(a_{p-1}) = -l(a_0)$.*

Proof. Case 1 should be clear, so we have to study Case 2. Let $v_{j(0)}, v_{j(1)}, \ldots, v_{j(k)}$ be the ordered sequence of nodes in $\dot{C}$, with $v_{j(0)} = v_{j(k)}$. A path in C

$$v_{j(i)}, a_{j(i)}, \ldots, a_{j(i+1)-1}, v_{j(i+1)}$$

from $v_{j(i)}$ to $v_{j(i+1)}$ will be called a *segment* and denoted by S_i. A segment is *odd* (resp. *even*) if it contains and *odd* (resp. *even*) number of arcs. Let n_e be the number of even segments and n_o the number of odd segments. We have that $n_e + n_o = |\dot{C}|$. We also have that the parity of p is equal to the parity of n_o. Therefore $n_o + |\dot{C}|$ should be even.

The labeling has the following properties:

a) If the segment is odd then $l(a_{j(i)}) = -l(a_{j(i+1)-1})$.
b) If the segment is even then $l(a_{j(i)}) = l(a_{j(i+1)-1})$.

Now we build an undirected cycle as follows. For every node $v_{j(i)}$ we have a two nodes u_i^1 and u_i^2, we add an edge between them marked "blue". For every segment from $v_{j(i)}$ to $v_{j(i+1)}$ we have an edge from u_i^2 to u_{i+1}^1. If the segment is odd we mark the edge "blue", otherwise we mark it "green". Start by giving the label $l(u_0^2) = 1$ to u_0^2. Continue labeling so that if st is a blue edge then $l(t) = -l(s)$ and if the edge is green then $l(t) = l(s)$. The label of u_i^2 corresponds to the label of $a_{j(i)}$ and the label of u_{i+1}^1 corresponds to the label of $a_{j(i+1)-1}$. There is an even number of blue edges in the cycle, therefore $l(u_0^1) = -l(u_0^2)$. Thus

$$l(a_{p-1}) = -l(a_0).$$

□

Notice that after the first cycle has been labeled as in cases 1 or 2, the properties below hold, we shall see that these properties hold throughout the entire labeling procedure.

Property 1. If a node has a nonzero label, then it is the tail of at most one labeled arc.

Property 2. If a node has a zero label, then it is the tail of exactly two labeled arcs.

The lemma below shows that for labeling purposes, any path can be represented by a path with one, two or three arcs.

Lemma 9. *Let $P = v_0, a_0, v_1, a_1, \dots, a_{p-1}, v_p$ be a path. Suppose that we set $l(a_0)$ and we extend the labels, then the label of a_{p-1} is determined by*

- *the orientation of a_0,*
- *the orientation of a_{p-1}, and*
- *the parity of P.*

Proof. Add a node t and the arcs $\bar{a} = (t, v_0)$ and $\tilde{a} = (t, v_p)$ to create a cycle. If the cycle is odd subdivide $\tilde{a}$ to make it even. Set $l(t) = 0$, $l(\bar{a}) = 1$ and extend the labels as in Case 2. It follows from Lemma 8 that the label of the arc before $\bar{a}$ is $-l(\bar{a})$, this determines the label of the previous arc and so on. □

Once a cycle C has been labeled as in cases 1 or 2, we have to extend the labeling as follows.

Case 3. Suppose that $l(v_0) \neq 0$ for $v_0 \in C$, (v_0 is the head of a labeled arc), and there is a path $P = v_0, a_0, v_1, a_1, \dots, a_{p-1}, v_p$ in G such that:

- v_0 is the head of a_0,
- $v_p \in C$,
- $\{v_1, \dots, v_{p-1}\}$ is disjoint from C.

We set $l(a_0) = l(v_0)$ and extend the labels. Case 3 is needed so that any inequality (2) associated with v_0 that is satisfied with equality, remains satisfied with equality.

We have to see that the label $l(a_{p-1})$ is such that constraints associated with v_p that were satisfied with equality remain satisfied with equality. This is discussed in the next lemma.

Lemma 10. *If v_p is the head of a_{p-1} then $l(a_{p-1}) = l(v_p)$. If v_p is the tail of a_{p-1} then $l(a_{p-1}) = -l(v_p)$.*

Proof. Notice that $v_0 \notin \dot{C}$, in Figure 2 we represent the possible configurations for the paths in C between v_0 and v_p. In this figure we show whether v_0 and v_p are the head or the tail of the arcs in C incident to them. These two paths are denoted by P_1 and P_2. Lemma 9 shows that we can assume that these paths have at most three arcs.

Consider configuration (1), these two paths should have different parity. When adding the path P, an odd cycle is created with either P_1 or P_2. So configuration (1) will not occur. The same happens with configuration (2).

Now we discuss configuration (3). These two paths should have the same parity. If v_p is the tail of a_{p-1} then P would create an odd cycle with either P_1 or P_2. If v_p is the head of a_{p-1} then P should have the same parity as P_1 and P_2. Then $l(a_{p-1}) = l(v_p)$.

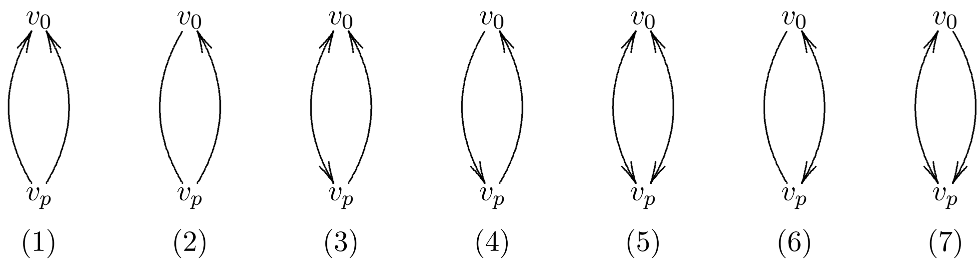

FIGURE 2. Possible paths in C between v_0 and v_p. It is shown whether v_0 and v_p are the head or the tail of the arcs in C incident to them.

The study of configuration (4) is similar. The two paths should have the same parity. If v_p is the tail of a_{p-1} then P would create an odd cycle with either P_1 or P_2. If v_p is the head of a_{p-1} then P should have the same parity as P_1 and P_2, and $l(a_{p-1}) = l(v_p)$.

For configuration (5) again the two paths should have the same parity. If v_p is the head of a_{p-1} then P should have the same parity as P_1 and P_2, and $l(a_{p-1}) = l(v_p)$. If v_p is the tail of a_{p-1} then P should have the same parity as P_1 and P_2, and $l(a_{p-1}) = -l(v_p)$.

Also in configuration (6) the paths P_1 and P_2 should have the same parity. If v_p is the tail of a_{p-1} then P would form an odd cycle with either P_1 or P_2. If v_p is the head of a_{p-1} then P should have the same parity as P_1 and P_2, and $l(a_{p-1}) = l(v_p)$.

In configuration (7) also the two paths should have the same parity. If v_p is the head of a_{p-1} then P should have the same parity as P_1 and P_2, and $l(a_{p-1}) = l(v_p)$. If v_p is the tail of a_{p-1} then P should have the same parity as P_1 and P_2, and $l(a_{p-1}) = -l(v_p)$. □

Based on this the labels are extended recursively. Denote by G_l the subgraph defined by the labeled arcs. This is a two-connected graph, so for any two nodes v_0 and v_p it contains a cycle going through these two nodes. Thus we can check if Case 3 applies and extend the labels adding each time a path to the graph G_l. The two lemmas below shows that properties 1 and 2 remain satisfied.

Lemma 11. *Let v_p be a node with $l(v_p) \neq 0$. If v_p is the tail of an arc in G_l, then in Case 3 it cannot be the tail of a_{p-1}. Thus Property 1 remains satisfied.*

Proof. There is a cycle C in G_l containing v_0 and v_p. Property 1 implies that v_0 is the head of at least one arc in C. We can assume that v_p is the tail of an arc in C. Suppose not, let a be an arc in G_l whose tail is v_p. Let u be the head of a. Since G_l is two-connected, there is a path Q from u to a node v in C with $v \neq v_p$. The path Q only intersects C at the node v. We can add a and Q to C and remove the path in C from v_p to v that does not contain v_0 as an internal node.

The cycle C can contain configurations (3), (4) and (6) of Figure 2. In these three cases, the head of a_{p-1} is v_p. □

Lemma 12. *Let v_p be a node with $l(v_p) = 0$, thus v_p is the tail of exactly two arcs in G_l. Then in Case 3 it cannot be the tail of a_{p-1}. Therefore Property 2 remains satisfied.*

Proof. Let a_1, a_2 be the two arcs in G_l having v_p as their tail. Since $l(v_p) = 0$, the cycle C in Case 3 must contain both arcs a_1 and a_2. But configuration (1) cannot occur. □

Once Case 3 has been exhausted we might have some nodes in G_l that are not pendent in G and that are only the head of labeled arcs. For such nodes we have to ensure that inequalities (1) that were satisfied as equality remain satisfied as equality. This is treated in the following.

Case 4. Suppose that v_0 is only the head of labeled arcs, ($l(v_0) \neq 0$), v_0 is not pendent. We have that $\delta^+(v_0) \neq \emptyset$ thus there is a cycle C in G_l and there is a path $P = v_0, a_0, v_1, a_1, \dots, a_{p-1}, v_p$ in G such that:

- $v_0 \in C$ is the tail of a_0,
- $v_p \in C$,
- $\{v_1, \dots, v_{p-1}\}$ is disjoint from G_l.

We set $l(a_0) = -l(v_0)$ and extend the labels. We have to see that the label $l(a_{p-1})$ is such that constraints associated with v_p, that were satisfied with equality, remain satisfied with equality. This is discussed below.

Lemma 13. *In Case 4 we have that v_p is the tail of a_{p-1} and $l(a_{p-1}) = -l(v_p)$. Also properties 1 and 2 continue to hold.*

Proof. The cycle C can correspond to configurations (1), (3) or (5) of Figure 2.

For configuration (1), the paths P_1 and P_2 have different parities, therefore adding the path P would create an odd cycle.

Consider now configuration (3). The paths P_1 and P_2 have the same parity. If v_p is the tail of a_{p-1} then adding P to C would create an odd cycle. If v_p is the head of a_{p-1} we would have a situation treated in Case 3 and configuration (7).

Finally consider configuration (5). If v_p is the head of a_{p-1} we would have a situation treated in Case 3 and configuration (5). If v_p is the tail of a_{p-1}, then P should have the same parity as P_1 and P_2, thus $l(a_{p-1}) = -l(v_p)$. If v_p was the tail of an arc in G_l we would have a cycle like in configuration (3). Adding P to this cycle would create an odd cycle. Therefore v_p was not the tail of an arc in G_l and properties 1 and 2 continue to hold. □

To summarize, the labeling algorithm consists of the following steps.

- Step 1. Identify a cycle C in G and treat it as in cases 1 or 2. Set $G_l = C$.
- Step 2. For as long as needed label as in Case 3. Each time add to G_l the new set of labeled nodes and arcs.
- Step 3. If needed, label as in Case 4. Each time add to G_l the new set of labeled nodes and arcs. If some new labels have been assigned in this step go to Step 2, otherwise stop.

At this point we can discuss the properties of the labeling procedure. The labels are such that any inequality (2) that was satisfied with equality by $\bar{z}$ is also satisfied with equality by z'. To see that inequalities (1) that were tight remain tight, we need two observations about G_l:

- Any node that has a nonzero label is the tail of exactly one labeled arc having the opposite label.
- If u is a node with $l(u) = 0$, then there are exactly two labeled arcs having opposite labels and whose tail is u.

Finally we give the label "0" to all nodes and arcs that are unlabeled, this completes the definition of z'. Lemma 6 shows that inequalities (4) will not be violated. The fact that nodes v with $\bar{z}(v) = 0$ or $\bar{z}(v) = 1$ receive a zero label, shows that inequalities (3) will not be violated. Any constraint that is satisfied with equality by $\bar{z}$ is also satisfied with equality by z', this contradicts the assumption that $\bar{z}$ is an extreme point. We can state the main result of this section.

Theorem 14. *If the graph G is two-connected and has no odd cycle then $UFLP(G) = P(G)$.*

This implies the following.

Theorem 15. *If G is a graph with no odd cycle, then $UFLP(G) = P(G)$.*

Theorem 16. *For graphs with no odd cycle, the uncapacitated facility location problem is polynomially solvable.*

5. Odd cycles

In this section we study the effect of odd cycles in $P(G)$. Let C be an odd cycle. We can define a fractional vector $(\bar{x}, \bar{y}) \in P(G)$ as follows:

(13) $$\bar{y}(u) = 0 \quad \text{for all nodes } u \in \dot{C},$$

(14) $$\bar{y}(u) = 1/2 \quad \text{for all nodes } u \in C \setminus \dot{C},$$

(15) $$\bar{x}(a) = 1/2 \quad \text{for } a \in A(C),$$

(16) $$\bar{y}(v) = 0 \quad \text{for all other nodes } v \notin C,$$

(17) $$\bar{x}(a) = 0 \quad \text{for all other arcs.}$$

In Figure 3 we show two examples. The numbers close to the nodes correspond to the y variables, and the numbers close to the arcs correspond to the x variables.

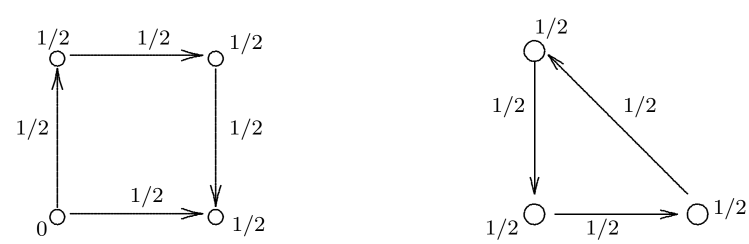

Figure 3

Below we show a family of inequalities that separate the vectors defined above from $UFLP(G)$. We call them *odd cycle* inequalities.

Lemma 17. *The following inequalities are valid for $UFLP(G)$.*

(18) $$\sum_{a \in A(C)} x(a) - \sum_{v \in \hat{C}} y(v) \le \frac{|\tilde{C}| + |\hat{C}| - 1}{2}$$

for every odd cycle C.

Proof. From inequalities (1)-(4) we obtain

$$\begin{aligned}
&x(u,v)+x(\delta^+(v))\le 1, \text{ for every arc } (u,v)\in C,\ v\notin \hat{C},\\
&x(u,v)-y(v)\le 0, \text{ for every arc } (u,v)\in C,\ v\in \hat{C},\\
&x(\delta^+(v))\le 1, \text{ for } v\in \dot{C}.
\end{aligned}$$

Their sum gives

$$2\sum_{a\in A(C)} x(a)-2\sum_{v\in\hat{C}} y(v)+\sum_{v\in\dot{C}} x(\delta^+(v)\setminus A(C))+\sum_{v\in\tilde{C}} x(\delta^+(v)\setminus A(C))\le |A(C)|-2|\hat{C}|+|\dot{C}|.$$

which implies

$$2\sum_{a\in A(C)} x(a)-2\sum_{v\in\hat{C}} y(v)\le |\tilde{C}|+|\dot{C}|.$$

dividing by 2 and rounding down the right hand side we obtain

$$\sum_{a\in A(C)} x(a)-\sum_{v\in\hat{C}} y(v)\le \frac{|\tilde{C}|+|\dot{C}|-1}{2}$$

□

Now we can present our main result.

Theorem 18. *Let G be a directed graph, then $UFLP(G)=P(G)$ if and only if G does not contain an odd cycle.*

Proof. If G contains and odd cycle C, then we can define a vector $(\bar{x},\bar{y})\in P(G)$ as in (13)-(17). We have

$$\sum_{a\in A(C)} \bar{x}(a)-\sum_{v\in\hat{C}} \bar{y}(v)=\frac{|\tilde{C}|+|\hat{C}|}{2}.$$

Lemma 17 shows that $\bar{z}\notin UFLP(G)$.

Then the theorem follows from Theorem 15. □

6. Separation of odd cycle inequalities

Now we study the separation problem: Given a vector $(\bar{x},\bar{y})\in P(G)$, find an odd cycle inequality (18), if there is any, that separates $(\bar{x},\bar{y})$ from $UFLP(G)$.

To solve the separation problem we write the inequalities as

$$2\sum_{a\in A(C)} x(a)+\sum_{v\in\hat{C}}(1-2y(v))\le |A(C)|-1,$$

or

$$\sum_{a\in A(C)}(1-2x(a))+\sum_{v\in\hat{C}}(2y(v)-1)\ge 1.$$

In order to reduce this to a shortest path problem several graph transformation are required.

6.1. **First Transformation.** We build an auxiliary undirected graph $H = (N, F)$. For every arc $a = (u, v) \in A$ we create the nodes (u, a) and (v, a) in H. The first node is called a *tail* node and the second one is called a *head* node. The tail node is associated with u and the head node is associated with v. We also create and edge between these two nodes with the weight $(1 - 2\bar{x}(u, v))$ and give the label *blue* to this edge, also this type of edge will be called *old*. See Figure 4.

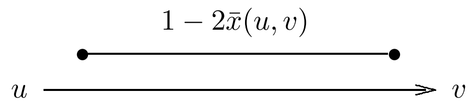

Figure 4. Edge associated with the arc (u, v). It has the label blue and is called old.

Now for every node $v \in V$ and every pair of nodes in H associated with v we create an edge in H as follows. This type of edges will be called *new*. Let n_1 and n_2 be two nodes in H associated with v, we distinguish two cases:

- At least one of them is a tail node. In this case we add and edge between them with weight zero and label *black*.
- Both n_1 and n_2 are head nodes. In this case we add an edge between them with weight $2\bar{y}(v) - 1$ and we label this edge blue. See Figure 5.

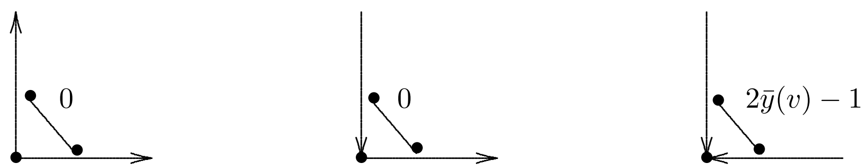

Figure 5. New edges. In the first two cases they have the label black, in the last case it has the label blue. Beside each new edge we show their weight.

A cycle in H consisting of an alternating sequence of old and new edges is called an *alternating* cycle. The separation problem reduces to finding an alternating cycle in H with an odd number of blue edges and total weight less than one.

6.2. **Second transformation.** To find an alternating cycle in H with an odd number of blue edges, we create a new graph H' as follows. For every node $n \in H$ we make two copies n' and n''. Let $n_1 n_2$ be an edge in H, we have two cases:

- If $n_1 n_2$ is blue, we create the edges $n'_1 n''_2$ and $n''_1 n'_2$ with the same weight as $n_1 n_2$, and the same name (old or new).
- If $n_1 n_2$ is black we create the edges $n'_1 n'_2$ and $n''_1 n''_2$ with the same weight as $n_1 n_2$, and the same name (new).

Then for every node $n \in H$ we find a shortest alternating path P from n' to n'' in H'. The first edge in the path should be new, and the last edge should be old. Suppose that the weight of P is less than one, then for each node $p \in H$ such that p' and p'' are in P we identify them. This gives a (non-necessarily simple) cycle that is alternating, has an odd number of blue edges and has weight less than one. Notice that the derivation of inequalities (18) does not depend upon the cycle being simple.

Since the edge-weights could be negative, to find a shortest alternating path we have to modify Bellman-Ford algorithm for shortest paths as follows. Let s be a source node. Let $f_o^k(v)$ be the length of a shortest alternating path from s to v having at most k arcs, whose first arc is new and whose last arc is old. Let $f_n^k(v)$ be the length of a shortest alternating path from s to v having at most k arcs, whose first arc is new and whose last arc is new. These values are computed with the following formulas:

$$\begin{aligned}
&f_o^k(v) = \min\left\{f_o^{k-1}(v), \min\{f_n^{k-1}(u) + d_{uv} \mid uv \text{ is old}\}\right\},\\
&f_n^k(v) = \min\left\{f_n^{k-1}(v), \min\{f_o^{k-1}(u) + d_{uv} \mid uv \text{ is new}\}\right\},\\
&f_o^0(s) = 0, \quad f_n^0(s) = \infty,\\
&f_o^0(v) = f_n^0(v) = \infty, \text{ for } v \neq s.
\end{aligned}$$

This algorithm requires that the graph has no alternating cycle of negative weight, this is shown below.

Lemma 19. *The edge weights cannot create a cycle of negative weight.*

Proof. Suppose that

$$\sum_{a\in A(C)} (1 - 2\bar{x}(a)) + \sum_{v\in\hat{C}} \big(2\bar{y}(v) - 1\big) < 0,$$

for some cycle C. This implies

$$2\sum_{a\in A(C)} \bar{x}(a) - 2\sum_{v\in\hat{C}} \bar{y}(v) > |C| - |\hat{C}|,$$

but when deriving inequalities (18) we had

$$2\sum_{a\in A(C)} \bar{x}(a) - 2\sum_{v\in\hat{C}} \bar{y}(v) \leq |C| - |\hat{C}|.$$

□

We can state the following.

Theorem 20. *The separation problem for inequalities* (18) *can be solved in* $O(|V|^2|A|)$ *time.*

7. Detecting odd cycles

Now we study how to recognize the graphs G for which $UFLP(G) = P(G)$. We start with a graph G and several transformations are needed.

The first transformation consists of building an undirected graph $H = (N, E)$. For every node $u \in G$ we have the nodes u' and u'' in N, and the edge $u'u'' \in E$. For every arc $(u, v) \in G$ we have an edge $u'v'' \in E$. See Figure 6.

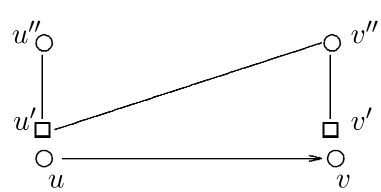

Figure 6

Consider a cycle C in G, we build a cycle C_H in H as follows.

- If (u,v) and (u,w) are in C, then the edges $u'v''$ and $u'w''$ are taken.
- If (u,v) and (w,v) are in C, then the edges $u'v''$ and $v''w'$ are taken.
- If (u,v) and (v,w) are in C, then the edges $u'v''$, $v''v'$, and $v'w''$ are taken.

On the other hand, a cycle in H corresponds to a cycle in G. Thus there is a one to one correspondence among cycles of G and cycles of H. Moreover, if the cycle in H has cardinality $2q$, then $q = |\dot{C}| + \tilde{C}|$, where C is the corresponding cycle in G. Therefore an odd cycle in G corresponds to a cycle in H of cardinality $2(2p+1)$ for some positive integer p. See Figure 7.

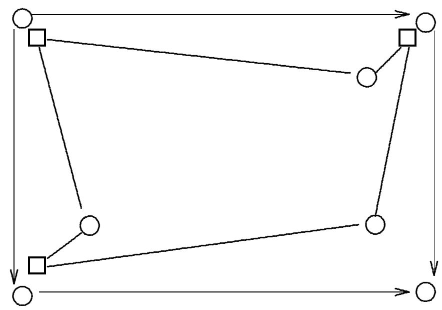

FIGURE 7. An odd cycle in G and the corresponding cycle in H. The nodes of H close to a node $u \in G$ correspond to u' or u''.

In other words, finding an odd cycle in G reduces to finding a cycle of cardinality $2(2p+1)$, for some positive integer p, in the bipartite graph H.

For this question, a linear time algorithm was given in [14], a simple $O(|V||A|^2)$ has been given in [7], we describe it below.

First we should find a cycle basis of H and test if the cardinality of every cycle in this basis is 0 mod 4. If there is one whose cardinality is 2 mod 4 we are done. Otherwise consider the symmetric difference of two cycles whose cardinality is 0 mod 4. If the cardinality of their intersection is even then the cardinality of their symmetric difference is 0 mod 4, otherwise it is 2 mod 4. Since any cycle C can be obtained as symmetric difference of some cycles in the basis, if the cardinality of C is 2 mod 4, then there are at least two cycles in the basis whose symmetric difference has cardinality 2 mod 4. Therefore one just has to test all elements of a cycle basis and the symmetric difference of all pairs.

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