Traveling Salesman Path Problems

by

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Abstract

In the Traveling Salesman Path Problem, we are given a set of cities, traveling costs between city pairs and fixed source and destination cities. The objective is to find a minimum cost path from the source to destination visiting all cities exactly once. The problem is a generalization of the Traveling Salesman Problem with many important applications.

In this thesis, we study polyhedral and combinatorial properties of a variant we call the Traveling Salesman Walk Problem, in which the minimum cost walk from the source to destination visits all cities *at least* once. Using the approach of linear programming, we study properties of the polyhedron corresponding to a linear programming relaxation of the traveling salesman walk problem. Our results relate the structure of the underlying graph of the problem instance with polyhedral properties of the corresponding fractional walk polyhedron.

We first characterize traveling salesman walk perfect graphs, graphs for which the convex hull of incidence vectors of traveling salesman walks can be described by linear inequalities. We show these graphs have a description by way of forbidden minors and also characterize them constructively. We extend these results to relate the underlying graph structure to the integrality gap of the corresponding fractional walk polyhedron. We present several graph operations which preserve integrality gap; these operations allow us to find the integrality gap of graphs built from smaller bricks, whose integrality gaps can be found by computational or other methods.

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Chapter 1

Introduction

In this thesis, we study properties of the polyhedron corresponding to a linear programming relaxation of the traveling salesman walk problem. Our results relate the structure of the underlying graph of the problem instance with polyhedral properties of the corresponding fractional walk polyhedron. We first characterize the set of graphs for which the extreme points of the fractional walk polyhedron correspond to traveling salesman walks. For these graphs, the convex hull of solutions to the traveling salesman walk problem has a known complete description by linear inequalities. We extend these results to relate the structure of the underlying graph to the *integrality gap* of the corresponding fractional walk polyhedron. We present graph operations which preserve integrality gap; these operations allow us to find the integrality gap of graphs built from smaller *bricks*, whose integrality gaps can be found by computational or other methods.

The Traveling Salesman Problem (TSP) and its variants have occupied a central role in the field of combinatorial optimization. For a graph G, a *simple cycle* is a cycle with no repeated vertices and a *Hamiltonian cycle* is a simple cycle visiting all vertices of G. Given a cost function c on the edges of G, the traveling salesman problem is to find a Hamiltonian cycle in G of minimum cost. A great deal of research has been devoted to developing improved algorithms for solving large instances to optimality, designing heuristics, analyzing algorithms for random and online instances, and proving approximation guarantees. The books [23] and [29] provide a compendium of results and history on the problem.

An approach that has been extremely successful for this and many other combinatorial optimization problems is the method of *linear programming.* In the general linear programming (LP) problem, the objective is to minimize a linear function subject to a system of linear constraints. The feasible solutions of a linear programming problem form a polyhedron and if the objective function minimum is attained, it must include an extreme point of this polyhedron. Linear programming techniques such as the ellipsoid method and interior point methods apply if the polyhedron is given by linear inequalities ([22]). To cast the TSP in the framework of linear programming, we associate a polytope, called the *traveling salesman polytope*, to the set of TSP solutions by considering the convex hull of Hamiltonian cycles in G. The problem of minimizing a cost function over the traveling salesman polytope is equivalent to finding the minimal cost Hamiltonian circuit and hence, is NP-complete ([15]). Therefore, it is unlikely that a description of the traveling salesman polytope by linear inequalities exists for general graphs. This was formalized by Papadimitriou and Yannakakis in [34], who showed that if the problem of determining whether a given inequality is a facet of the traveling salesman polytope is in NP, then NP=co-NP.

Dantzig, Fulkerson, and Johnson developed methods to prove optimality of solutions by starting from the optimal solution to a relaxation of the problem and repeatedly adding inequalities or *cuts* ([10]). Since their foundational work on these *branch-and-cut* algorithms, there has been a significant increase in the size instances of the traveling salesman problem which can be solved exactly (see [10], [23], [30], [32]). In 1991, Gerhard Reinelt collected the TSP library (TSPLIB) of instances for benchmarking of TSP algorithms, with instances ranging from 17 to 85,900 cities. At the time, thirty TSPLIB instances were unsolved; in 1995, David Applegate, Bob Bixby, Bill Cook, and Vasek Chvatal gave solutions to all but ten of the instances. On the TSPLIB website, Reinelt writes

> I had not expected when publishing this library (that) due to enormous algorithmic progress, all problems except for pla85900 are now solved to optimality!

Motivation for some problems in the library come from drilling holes in printed circuit boards and X-ray crystallography, where the cities are desired positions of holes and snapshot angles and the salesman tours are routes of the drill and diffractometer. Other applications include problems in routing, machine scheduling, clustering, computer wiring, and curve reconstruction.

Since the decision version of the traveling salesman problem is NP-complete, it is unlikely that a polynomial-time algorithm for the problem exists. Therefore, there has been increased focus on designing good *approximation algorithms* for the problem. An α-approximation algorithm for a minimization problem is a polynomial time algorithm which outputs a solution of value at most α times the optimal solution. The value α is the *approximation ratio* or *approximation factor* for the problem. In the case of general costs, there is no constant factor approximation algorithm for the TSP unless P = NP ([35]). Therefore, we focus our attention on *metric* instances, with costs satisfying the triangle inequality.

While the metric case remains NP-hard, in 1976, Christofides showed a constant factor approximation algorithm exists, with approximation ratio $\frac{3}{2}$ ([8]). Despite many attempts to find a better approximation guarantee, improving this factor has remained an open problem for almost thirty years.

For the lower bound on approximability, Papadimitriou and Vempala have shown that unless P = NP, there is no polynomial time algorithm that finds a tour of length at most $220/219 - \epsilon$ times optimal for any $\epsilon > 0$ ([33]).

1.1 Traveling Salesman Variants and Generalizations

Much study has been devoted to variants of the traveling salesman problem, often obtained by modifying the objective function or underlying graph for the problem. Variants include the Asymmetric Traveling Salesman Problem (ATSP), Prize Collecting TSP, Maximum TSP and the Traveling Salesman Repairman Problem. Other variants which introduce constraints on the order in which cities can be visited include the TSP with precedence constraints ([2], [4]) and online TSP ([3], [27], [28]).

From the algorithmic perspective, there are special cases of the problem which are either polynomial time solvable ([5], [23]) or for which there are approximation algorithms with guarantees better than the factor $\frac{3}{2}$ of Christofides' algorithm. In the *Euclidean Traveling Salesman Problem*, we are given n vertices in $\mathbb{R}^d$ and the edge cost between any two vertices is their Euclidean distance. In [1], Arora shows a polynomial time approximation scheme for the Euclidean TSP for fixed dimension d. For the class of 3-connected cubic graphs, Gamarnik, Lewenstein, and Sviridenko show that the approximation guarantee is strictly better than $\frac{3}{2}$ by designing a $\frac{3}{2} - \frac{5}{389}$ algorithm for this set of graphs ([14]).

1.2 Linear Programming Formulation

Let $G = (V, E)$ be a graph on $n = |V|$ vertices. For any subset $S \subseteq V$, $G(S)$ will denote the induced subgraph on S. Let $\delta(S)$ denote the set of edges with exactly one endpoint in S and for subsets $S_1, S_2 \subseteq V$ let (S_1, S_2) denote the set of edges with one endpoint in S_1 and the other endpoint in S_2. Given a Hamiltonian cycle, let x_e denote an indicator variable which takes value 1 for edges e in the Hamiltonian cycle and 0 for all other edges and for a subset $F \subseteq E$, let $x(F) = \sum_{e \in F} x_e$. Then the traveling salesman problem with symmetric costs can be captured by the following integer program formulation.

$$
\begin{aligned}
\min \quad & \textstyle\sum_{e \in E} c_e x_e & & (1.1)\\
\text{subject to} \quad & x(\delta(S)) \geq 2 & \text{for all } \emptyset \neq S \subset V, \quad & (1.2)\\
& x(\delta(v)) = 2 & \text{for all } v \in V \quad & (1.3)\\
& x_e \in \{0, 1\} & \text{for all } e \in E \quad & (1.4)
\end{aligned}
$$

By relaxing the integrality constraints, we obtain the following linear program.

$$
\begin{aligned}
\min \quad & \textstyle\sum_{e \in E} c_e x_e & & (1.5)\\
\text{subject to} \quad & x(\delta(S)) \geq 2 & \text{for all } \emptyset \neq S \subset V, \quad & (1.6)\\
& x(\delta(v)) = 2 & \text{for all } v \in V \quad & (1.7)\\
& x_e \geq 0 & \text{for all } e \in E \quad & (1.8)
\end{aligned}
$$

Constraints (1.6) are *cut constraints*, (1.7) are *degree constraints*, and (1.8) are *nonnegativity constraints*. The polytope defined by (1.6), (1.7), and (1.8) is the well-studied *subtour elimination polytope*. In [24] and [25], Held and Karp applied the method of Lagrangean relaxation to the TSP to show that the optimal linear program value over the subtour polytope is the value of the Lagrangean dual corresponding to the 1-tree relaxation (also called Held-Karp bound). This value can be obtained by subgradient optimization and is the most efficient method known to solve the linear program. This heuristic also performs very well in practice, delivering solutions of near-optimal value for most instances of the symmetric TSP with triangle inequality. The best known bound on the ratio between the optimal tour and the Held-Karp lower bound is $\frac{3}{2}$, a result first proved by Wolsey ([41]). An independent proof is given by Shmoys and Williamson ([37], [40]), who also analyze the structure of the Held-Karp solutions.

One problem that arises from restricting the traveling salesman route to Hamiltonian cycles is that the shortest way to visit all the vertices of G may not be a simple cycle, i.e., may visit some vertices or edges multiple times. Another problem, arising from the linear programming relaxation for this formulation, is that the subtour elimination polytope is not full dimensional. We resolve these problems by considering the *Graphical Traveling Salesman Problem*. In this problem, given edge costs on a graph G, a *graphical traveling salesman tour* on G, or *tour* for short, is a cycle visiting all vertices at least once, with multiple visits to edges and vertices allowed. The Graphical TSP asks for a minimum cost tour of G. This is equivalent to the TSP on the *metric completion* of G, where the cost between any pair of cities is the cost of the shortest path connecting the cities.

Let $X_{TSP}(G)$ denote the set of tours of G. The *graphical traveling salesman polyhedron of* G is the convex hull of tours $conv(X_{TSP}(G))$. If T is a tour of G, then so is $T + (2e)$ for any edge e and therefore, the graphical TSP polyhedron is an unbounded polyhedron if G is connected. The *fractional traveling salesman polyhedron of* G, denoted $P(G)$, is defined by the cut constraints and nonnegativity constraints (1.6) and (1.8):

$$P(G) = \left\{ \begin{array}{ll} x \in \mathbb{R}^{|E|}: & x(\delta(S)) \geq 2 \quad \text{for } S \subsetneq V, S \neq \emptyset \\ & x \geq 0 \end{array} \right\}.$$

Note that the face of $P(G)$ defined by the inequality $x(E) = n$ is precisely the subtour elimination polytope. In [20] and [31], it is shown that for cost functions satisfying the triangle inequality, minimizing the objective function (1.5) over the subtour elimination polytope is equivalent to minimizing the objective function over the fractional traveling salesman polyhedron.

Given polyhedra P and Q, P is a *relaxation* of Q if $P \supseteq Q$. For many combinatorial optimization problems, Q is an integral polyhedron obtained by taking the convex hull of solutions to the problem and P is a relaxation obtained by a set of valid inequalities for this solution set. In this case, the *integrality gap* of relaxation P is the smallest r such that for any cost function c,

$$\min\{cx : x \in P\} \leq r \min\{cx : x \in Q\}.$$

For a polyhedron Q of blocking type, we need only consider nonnegative cost functions c. For the traveling salesman problem on a graph G, we consider the integrality gap between polytope $Q = conv(X_{TSP}(G))$ and its relaxation the fractional TSP polyhedron $P = P(G)$. We call the integrality gap of this relaxation the *TSP integrality gap.*

1.3 Traveling Salesman Paths

In this thesis, we study a generalization of the traveling salesman problem which has not received much attention, the *Traveling Salesman Path (TSPATH) Problem.* In this problem, we are given initial and final cities s and t as additional input; the goal is to find a Hamiltonian path from s to t visiting all cities exactly once. The problem arises naturally in many applications of the traveling salesman problem.

The integer program describing the problem is

$$\begin{aligned}
\min \quad & \textstyle\sum_{e\in E} c_e x_e & & (1.9)\\
\text{subject to} \quad & x(\delta(S)) \geq 1 & \text{if } |\{s,t\} \cap S| = 1 \text{ for } S \subsetneq V, S \neq \emptyset & \quad (1.10)\\
& x(\delta(S)) \geq 2 & \text{if } |\{s,t\} \cap S| = 0 \text{ or } 2 \text{ for } S \subsetneq V, S \neq \emptyset & \quad (1.11)\\
& x(\delta(v)) = 2 & \text{for all } v \in V\backslash\{s,t\} & \quad (1.12)\\
& x(\delta(s)) = x(\delta(t)) = 1 & \text{if } s \neq t & \quad (1.13)\\
& x(\delta(s)) = x(\delta(t)) = 2 & \text{if } s = t & \quad (1.14)\\
& x_e \in \{0,1\} & \text{for all } e \in E. & \quad (1.15)
\end{aligned}$$

Relaxing the integrality constraints, we obtain the linear program

$$\begin{array}{llll}
\min & \sum_{e\in E} c_e x_e & & (1.16)\\
\text{subject to} & x(\delta(S)) \geq 1 & \text{if } |\{s,t\}\cap S| = 1 \text{ for } S \subsetneq V, S \neq \emptyset & (1.17)\\
& x(\delta(S)) \geq 2 & \text{if } |\{s,t\}\cap S| = 0 \text{ or } 2 \text{ for } S \subsetneq V, S \neq \emptyset & (1.18)\\
& x(\delta(v)) = 2 & \text{for all } v \in V\backslash\{s,t\} & (1.19)\\
& x(\delta(s)) = x(\delta(t)) = 1 & \text{if } s \neq t & (1.20)\\
& x(\delta(s)) = x(\delta(t)) = 2 & \text{if } s = t & (1.21)\\
& x_e \geq 0 & \text{for all } e \in E. & (1.22)
\end{array}$$

As with the tour problem, we relax the condition of visiting every vertex exactly once and define an *s-t traveling salesman walk* as a walk from s to t visiting all vertices at least once with possibly multiple visits to edges or vertices. Given a graph with edge costs, the *traveling salesman walk (TSW) problem* asks for the minimum cost s-t traveling salesman walk.

The *fractional traveling salesman walk polyhedron* for a graph G with fixed vertices s and t is defined by

$$P(G,s,t) = \left\{ x \in \mathbb{R}^{|E|} : \begin{array}{lll} x(\delta(S)) \geq 1 & \text{if } |\{s,t\}\cap S| = 1 & \text{for } S \subsetneq V, S \neq \emptyset \\ x(\delta(S) \geq 2 & \text{if } |\{s,t\}\cap S| = 0 \text{ or } 2 & \text{for } S \subsetneq V, S \neq \emptyset \\ x \geq 0 & & \end{array} \right\}$$

Let $X(G,s,t)$ denote the set of s-t traveling salesman walks. For the traveling salesman walk problem on a graph G, we consider the integrality gap between polytope $Q = conv(X(G,s,t))$ and its relaxation the fractional TSW polyhedron $P = P(G,s,t)$. We call the integrality gap of this relaxation the *s-t TSW integrality gap.* The maximum over all choices of s and t of the s-t TSW integrality gap is the *TSW integrality gap.* If the graph is disconnected, then the traveling salesman polytope and its fractional relaxation (in both the tour and walk problems) are empty; by convention, these graph will have integrality gap 1. Note that in the case $s = t$, the TSW problem reduces to the traveling salesman tour problem and the TSW relaxation reduces to the TSP relaxation, implying the TSW integrality gap is at least that of the TSP.

In this thesis, we address two aspects of the traveling salesman walk problem. The first is inspired by the work of Fonlupt and Naddef which characterizes the set of graphs for which the extreme points of the fractional traveling salesman polyhedron are traveling salesman tours [12]. This family of graphs is called *TSP-perfect* and is characterized by a list of forbidden minors. For such graphs, the TSP polyhedron and fractional TSP polyhedron have the same extreme points, implying that the TSP polyhedron has a known description by linear inequalities and therefore, the optimal tour can be found in polynomial time.

We consider the analogous problem for the TSW problem and give a complete characterization of graphs for which the extreme points of the traveling salesman walk polyhedron correspond to traveling salesman walks. Our characterization of these *walk-perfect* graphs is also by forbidden minors. In Section 2.1, we give a constructive description for this set of graphs and in section 2.2, we use the description to prove our main theorem. In Section 2.3, we give a second proof of the characterization of these graphs based on the characterization of TSP-perfect graphs from [12].

Next, we address approximation algorithms for the TSW problem. In [26], Hoogeveen gives an approximation algorithm for the TSW problem for graphs with symmetric edge costs satisfying the triangle inequality. For fixed s and t, he gives a 5/3-approximation for the minimum cost s-t traveling salesman walk and for fixed s (and varying endpoint), he gives a 3/2-approximation for the minimum cost traveling salesman walk starting at s. An independent proof for the 5/3 approximation algorithm for two fixed endpoints is due to Vempala ([39]). We address the asymmetric version of the traveling salesman walk problem (ATSW), in which edge costs satisfy the triangle inequality but may be asymmetric (i.e. $c_{ij} \neq c_{ji}$). For the asymmetric traveling salesman tour problem (ATSP), Frieze, Galbiati and Maffioli give a $\log n$-approximation algorithm in [13]. Using similar methods, we give the first non-trivial algorithm for the ATSW problem, with approximation factor $O(\sqrt{n})$.

In Chapter 3, we give an independent proof for the characterization of TSP-perfect graphs using similar techniques to our characterization of walk-perfect graphs. We first use computational methods to show TSP-perfection of a set of 2-connected and 3-connected graphs we call *TSP-perfect bricks.* We then show TSP-perfection is preserved under the two operations used to obtain all graphs without the stated excluded minors for TSP perfectness. This resolves the problem posed at the end of [12].

We extend these results in Chapter 4 to show operations which preserve integrality gap of the linear programming relaxations. The results in this chapter connect the integrality gap of the traveling salesman and traveling salesman walk problems with the excluded minor theory of Robertson, Seymour and Thomas ([21], [38]) and suggest new avenues for proving bounds on integrality gaps for these linear programming relaxations.

Chapter 2 of this thesis is based on joint work with Alantha Newman and Santosh Vempala.

Chapter 2

Walk-Perfection

In this chapter, we introduce the notion of walk-perfection of a graph and give a complete characterization of walk-perfect graphs. We first review previous work on TSP-perfect graphs and introduce notation from the literature. A *tour* of graph G is a connected multigraph with even degree at every vertex. Let $X_{TSP}(G)$ denote the set of traveling salesman tours of G and consider the fractional TSP polyhedron

$$P(G) = \left\{ \begin{array}{ll} x \in \mathbb{R}^{|E|}: & x(\delta(S)) \geq 2 \quad \text{for } S \subsetneq V, S \neq \emptyset \\ & x \geq 0 \end{array} \right\}.$$

Clearly, $conv(X_{TSP}(G)) \subseteq P(G)$; however, there are graphs for which the inclusion is strict. A graph G is *TSP-perfect* if $conv(X_{TSP}(G)) = P(G)$, i.e., the vertices of the fractional traveling salesman polyhedron are traveling salesman tours. Note that the equality always holds for disconnected graphs G, since both the convex hull of tours and the fractional TSP polyhedron are the empty set. Therefore, all disconnected graphs are TSP-perfect.

A *minor* of a graph $G = (V, E)$ is a graph that can be obtained from G by a sequence of edge deletions (denoted $G \backslash \{e\}$) and edge contractions (denoted $G.e$). A family of graphs is *minor closed* if for any graph G in the family, every minor of G is also in the family. A graph G is H *minor free* if G does not contain H as a minor. For fixed graphs $H_1, H_2, \ldots H_k$, let $\mathcal{K}_{[H_1, H_2, \ldots H_k]}$ denote the set of graphs not containing any of $H_1, H_2, \ldots H_k$ as a minor. Let M_1, M_2, M_3 be the three graphs shown in Figure 2.1. Fonlupt and Naddef show that there is a forbidden minor characterization of TSP-perfect graphs using these graphs.

Theorem 2.0.1. *[12] A connected graph G is TSP-perfect if and only if G is $[M_1, M_2, M_3]$ minor free.*

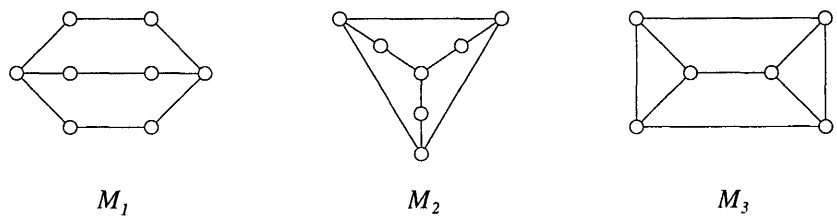


Figure 2.1: Excluded minors for TSP-perfect graphs.

We consider the analogous problem for the traveling salesman walk problem. An *s-t traveling salesman walk* is a connected multigraph with even degree at every vertex if $s = t$ and even degree at every vertex except s and t if $s \neq t$. Let $X(G, s, t)$ denote the set of s-t traveling salesman walks and consider the fractional traveling salesman walk polyhedron

$$P(G,s,t) = \left\{ x \in \mathbb{R}^{|E|} : \begin{array}{lll} x(\delta(S)) \geq 1 & \text{if } |\{s,t\} \cap S| = 1 & \text{for } S \subsetneq V, S \neq \emptyset \\ x(\delta(S) \geq 2 & \text{if } |\{s,t\} \cap S| = 0 \text{ or } 2 & \text{for } S \subsetneq V, S \neq \emptyset \\ x \geq 0 & & \end{array} \right\}.$$

Note that $X(G, s, t)$ is *not* necessarily the set of integral points in $P(G, s, t)$, as shown by the following example.

Example 2.0.2. *Consider the 6-cycle C_6 with s and t at distance 3. The assignment $x_e^* = 1$ for all edges e is an integral solution in $P(G, s, t)$, but does not correspond to an s-t traveling salesman walk.*

As with the traveling salesman problem, there are graphs for which the inclusion $conv(X(G, s, t)) \subseteq P(G, s, t)$ is strict. Our goal is to characterize graphs G for which equality holds for any choice of s and t.

Definition 2.0.3. *A graph G is s-t* walk-perfect *if $P(G, s, t) = conv(X(G, s, t))$ and G is* walk-perfect *if it is s-t walk-perfect for all choices of s and t.*

As in the case of TSP-perfection, any disconnected graph G satisfies $conv(X(G,s,t)) = P(G,s,t)$, since both the convex hull of s-t traveling salesman walks and the fractional TSW polytope are the empty set. Therefore, all disconnected graphs are walk-perfect and we focus our attention on characterizing the set of connected walk-perfect graphs.

In Example 2.0.2, if all edge costs in the six cycle are equal to a fixed positive value, x^* is an optimal solution over $P(G,s,t)$ that does not correspond to an s-t traveling salesman walk. This shows that C_6 with s and t at distance 3 is not s-t walk-perfect and therefore, C_6 is not walk-perfect. In the next two sections, we prove the following theorem.

Theorem 2.0.4. *A connected graph G is walk-perfect if and only if G is C_6 minor free.*

2.1 C_6 Minor Free Graphs

In this section, we give a constructive characterization of the set of C_6 minor free graphs. We will use this characterization to prove our main theorem.

We first show that we can reduce our problem to the characterization of 2-connected walk-perfect graphs. Suppose G_1 and G_2 are connected graphs with specified vertices $s_1, t_1 \in V(G_1)$ and $s_2, t_2 \in V(G_2)$. Let $v_1 \in V(G_1)$ and $v_2 \in V(G_2)$ be chosen so that at least two of s_1, s_2, t_1, t_2 are equal to v_1 or v_2. The operation Φ_1 identifies vertices v_1 and v_2 to obtain graph G (see Figure 2.2) with cut vertex v. If the set $\{s_1, s_2, t_1, t_2\} \backslash \{v_1, v_2\}$ has two vertices, then relabel these vertices by s and t. If it has one vertex, then relabel this vertex by s and let $t = v$; if it has no vertices, then let $s = v$ and $t = v$.

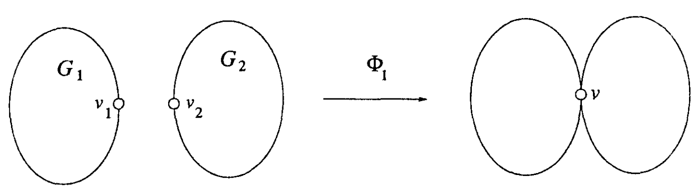


Figure 2.2: Operation Φ_1.

Every 1-connected graph can be built by repeated applications of operation Φ_1 from *blocks* which are either 2-connected graphs or single edges. In Lemma 2.2.6, we will show that walk-perfection of a graph is preserved under operation Φ_1 and therefore, we can focus our attention on the characterization of 2-connected walk-perfect graphs.

An *ear decomposition* $G_1, G_2, \ldots G_m = G$ of a graph G is a sequence of subgraphs starting from a simple graph G_1 (a vertex, edge or cycle) such that for each i, G_{i+1} is obtained from G_i by *adding an ear.* The operation of adding an ear is performed by choosing two vertices u and v (the *endpoints* of the ear) from G_i and adding a path from u to v using new vertices (or no vertices if the path is edge (u, v)). If $u \neq v$, the ear is *proper* and a proper ear decomposition is one in which every ear operation is proper. The following theorem is due to Robbins.

Theorem 2.1.1. *[36] G is 2-connected if and only if G has a proper ear decomposition starting from any cycle of G.*

One particular ear operation is duplication of a degree-2 vertex. In such an operation, for a vertex u of degree 2 in G_i with neighborhood $N(u) = \{a, b\}$, duplication of u results in graph G_{i+1} on vertices and edges

$$\begin{aligned} V(G_{i+1}) &= V(G_i) \cup \{u'\} \\ E(G_{i+1}) &= E(G_i) \cup \{(a, u'), (u', b)\}). \end{aligned}$$

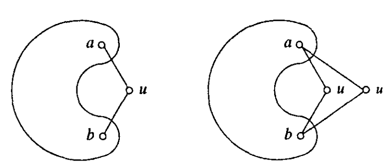


Figure 2.3: Vertex duplication of degree-2 vertex.

Let K_5 denote the complete graph on 5 vertices and consider the class $\mathcal{T}$ of 2-connected graphs obtained from K_5 by repeated applications of the operations edge deletion, edge contraction, and duplication of degree-2 vertices. We show that this set of graphs is exactly the set of 2-connected graphs in $\mathcal{K}_{[C_6]}$.

Theorem 2.1.2. *A 2-connected graph G is C_6 minor free if and only if $G \in \mathcal{T}$.*

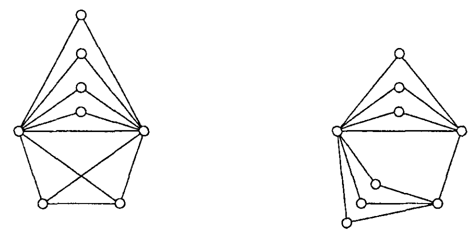


Figure 2.4: Examples of graphs in $\mathcal{T}$.

Proof. Since K_5 does not contain a 6-cycle and the size of the largest cycle cannot increase under edge deletion, contraction, or vertex duplication, no graph in $\mathcal{T}$ contains a C_6 minor.

Conversely, suppose G is 2-connected and C_6 minor free. We will show $G \in \mathcal{T}$ by showing that there is an ear decomposition of G starting with a minor of K_5 such that each ear operation corresponds to edge addition or vertex duplication of a degree-2 vertex. By Theorem 2.1.1, G has a proper ear decomposition $G_1, G_2, \ldots G_m = G$ and we can choose the initial graph G_1 in the decomposition to be the largest cycle $C_k = \{v_1, v_2, \ldots v_k\}$ in G ($k \leq 5$ by assumption). The edges (v_i, v_{i+1}) for $i = 1, 2, \ldots k-1$ and (v_k, v_1) will be called *cycle edges* and the edges (v_i, v_j) with $j \neq i-1, i+1 \pmod{k}$ will be called *chords.* If there are $j-1$ induced chords in G between vertices $v_1, v_2, \ldots v_k$, let G_j denote the cycle $v_1, v_2, \ldots v_k$ together with all induced chords and let $a, b \in \{v_1, \ldots v_k\}$ be the two vertices that are endpoints for the next ear operation. Because we have already included all chords, the next ear cannot be edge (a, b). Also, note that the length of the longest path between a and b in G_j is at least $\lceil \frac{k}{2} \rceil$, so if the next ear is a path of length at least 3, then it would create a cycle of length at least $\lceil \frac{k}{2} \rceil + 3 > k$ (since $k \leq 5$), a contradiction to our choice of k. Therefore, it must be a path of length 2 which consists of an additional vertex u' and edges $(a, u'), (u', b)$. Now, if (a, b) is a cycle edge in C_k, then the longest path from a to b has length $k-1$, so adding an ear of length 2 would create a $k+1$ cycle, a contradiction. Therefore, (a, b) cannot be a cycle edge (but a and b may be connected by a chord). Since $k \leq 5$, a and b have a common neighbor, say u.

Claim: $\deg_{G_j}(u) = 2$, i.e., the neighborhood of u in G_j is $N_{G_j}(u) = \{a, b\}$. Otherwise, let $w \in N_{G_j}(u) \backslash \{a, b\}$. Since $k \leq 5$, w must also be adjacent to either a or b, say a. Then the cycle formed by concatenating the path $(w, u), (u, a), (a, u'), (u', b)$ and the path from b to

w (along G_1, but not through a) has length at least $k+1$, which is a contradiction (see Figure 2.5).

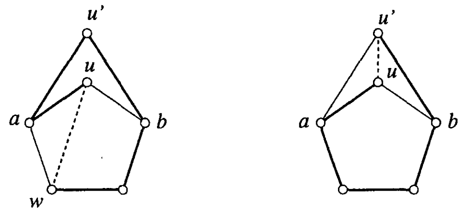


Figure 2.5: Forbidden adjacencies in the ear operation.

Therefore, u has degree 2 in G_j and the operation of adding vertex u' and edges $(a,u'),(u',b)$ corresponds to vertex duplication of u. Note that since $(G_j \backslash \{u\}) \cup \{u'\} = G_j$, the same argument shows we cannot add a path p of any length from either u or u' to any other vertex in $G_j \backslash \{a,b\}$. Similarly, we cannot add a path p of any length between u and u' (denoted $u \xrightarrow{p} u'$), since the cycle formed by concatenating the path $(b,u), u \xrightarrow{p} u', (u',a)$ and the path of $k-2$ cycle edges from a to b has length at least $k+1$ (see Figure 2.5). Therefore, neither u nor u' can be chosen as endpoints of the next ear. This implies we must always use vertices among $\{v_1, v_2, \ldots v_k\}$ as ear endpoints and each ear operation corresponds to duplicating a vertex. Since G_1 is a minor of K_5, it follows that $G \in \mathcal{T}$. $\square$

This theorem gives us a constructive characterization of the set of 2-connected C_6 minor free graphs. Note that the proof of Theorem 2.1.2 also shows the following.

Corollary 2.1.3. *Suppose $G \in \mathcal{T}$ is obtained from K_5 by a sequence of edge deletions, contractions and degree-2 vertex duplications. Then first performing all edge deletions and contractions followed by any permutation of the degree-2 vertex duplications also results in graph G.*

From this corollary, if graph $G \in \mathcal{T}$ has two specified vertices s and t which result from the duplication of a degree-2 vertex u, then we can reorder the vertex duplications so that the duplication of u to obtain s and t comes first in the ordering and all other vertex duplications follow. Otherwise, if s and t do not result from the duplication of a degree-2 vertex, we can assume that s and t are vertices in the initial subgraph of K_5 to which the operations of edge deletion, edge contraction, and degree-2 vertex duplication are performed to obtain G.

2.2 Characterization of Walk-Perfect Graphs

In this section, we will show that C_6 is the only forbidden minor in the set of 2-connected traveling salesman walk-perfect graphs by showing that all graphs in $\mathcal{K}_{[C_6]}$ are walk-perfect. Since graph G has specified vertices s and t, we first define the notion of a *labeled minor* of a graph. The operation of edge deletion remains the same as for unlabeled graphs. For the operation of edge contraction, if an edge e is chosen for edge contraction, the resulting vertex from the contraction receives the labels of both endpoints of e, with possibly both labels s and t. In the case s and t label the same vertex in the resulting graph, an s-t traveling salesman walk is a traveling salesman tour.

We first show that walk-perfection is preserved under the labeled minor operations; the proof is modeled on Fonlupt and Naddef's proof that TSP-perfection is preserved under the minor operations [12].

Lemma 2.2.1. *Any connected labeled minor of a connected walk-perfect graph is walk-perfect.*

Proof. Suppose connected graph G has specified vertices $s, t \in V(G)$ and suppose G is s-t walk-perfect. We show that if deletion of an edge e results in a connected graph, then the minor $G \setminus \{e\}$ is s-t walk-perfect. Since $G \setminus \{e\}$ is connected, $P(G \setminus \{e\}, s, t)$ is nonempty. Then let y be an extreme point of $P(G \setminus \{e\}, s, t)$ and let

$$x_f = \begin{cases} y_f & \text{if } f \in E \setminus \{e\}, \\ 0 & \text{if } f = e. \end{cases}$$

Since y is an extreme point of $P(G \setminus \{e\}, s, t)$ and since x has one more variable and one more linearly independent tight constraint than y, x is an extreme point in $P(G, s, t)$. By s-t walk-perfection of G, x is an s-t traveling salesman walk in G, and since x does not use edge e, y is an s-t traveling salesman walk in $G \setminus \{e\}$. Thus, $G\setminus\{e\}$ is s-t walk-perfect.

Now, for the edge contraction operation, if G is connected, then $G.e$ is connected, so for any vertices s and t, $P(G.e, s, t)$ is nonempty. Let y be an extreme point of $P(G.e, s, t)$ and let

$$\overline{x}_f = \begin{cases} y_f & \text{if } f \in E \setminus \{e\}, \\ 0 & \text{if } f = e. \end{cases}$$

Consider cuts $\delta(W')$ of G containing e such that s and t are on the same side of the cut and let $\alpha = \min \overline{x}(\delta(W'))$. Similarly, consider cuts $\delta(W'')$ of G containing e such that s and t fall on different sides of the cut and let $\beta = \min \overline{x}(\delta(W''))$. Now, let

$$x_f = \begin{cases} y_f & \text{if } f \in E \setminus \{e\}, \\ \max\{0, 2-\alpha, 1-\beta\} & \text{if } f = e. \end{cases} \tag{2.1}$$

Note that $x \in P(G, s, t)$ since any cut $\delta(W')$ containing e that does not separate s and t satisfies $x(\delta(W')) \geq 2$, any cut $\delta(W'')$ containing e that separates s and t satisfies $x(\delta(W'')) \geq 1$, and any cut not containing e is also a cut in $G.e$.

Let $\theta(x)$ and $\theta(y)$ denote the set of tight constraints for x and y. By possibly taking complements, we can assume any tight constraint C in $\theta(y)$ does not contain the vertex resulting from contraction of edge e. Then C is also a tight constraint for x. Since any tight edge constraint for y is also tight for x, it follows that x is defined by $\theta(y)$ and

$$x_e = 0 \text{ if } \alpha \geq 2 \text{ and } \beta \geq 1$$
$$x(\delta(\overline{W}')) = 2 \text{ if } \alpha < 2 \text{ and } 2-\alpha \geq 1-\beta$$
$$x(\delta(\overline{W}'')) = 1 \text{ if } \beta < 1 \text{ and } 1-\beta \geq 2-\alpha,$$

where $\overline{W}' = \arg\min \overline{x}(\delta(W'))$ and $\overline{W}'' = \arg\min \overline{x}(\delta(W''))$. Since x has one more variable and one more linearly independent tight constraint, it is an extreme point of $P(G, s, t)$ and therefore an s-t traveling salesman walk in G (by s-t walk-perfection of $P(G, s, t)$). Therefore, y is an s-t traveling salesman walk in $G.e$, implying $G.f$ is s-t walk-perfect. □

Lemma 2.2.2. *K_5 is walk-perfect.*

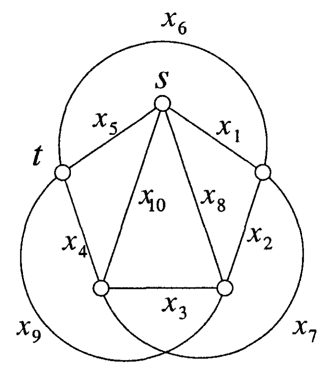


Figure 2.6: Labeling on edges of K_5.

Proof of Lemma 2.2.2. If $s = t$, then s-t walk-perfection is equivalent to TSP-perfection and the lemma follows from the characterization of TSP-perfect graphs (Theorem 2.0.1). For $s \neq t$, we can arbitrarily choose vertices s and t by symmetry. For the edge labeling in Figure 2.6, we input the following inequalities to the program `polymake`. The first 15 inequalities are cut constraints and the final 10 inequalities are nonnegativity constraints (see Appendix for details on the format of inequalities and extreme points in `polymake`).

K_5 INEQUALITIES

```
-1 1 0 0 0 1 0 0 1 0 1    0 1 0 0 0 0 0 0 0 0 0
-2 1 1 0 0 0 1 1 0 0 0    0 0 1 0 0 0 0 0 0 0 0
-2 0 1 1 0 0 0 0 1 1 0    0 0 0 1 0 0 0 0 0 0 0
-2 0 0 1 1 0 0 1 0 0 1    0 0 0 0 1 0 0 0 0 0 0
-1 0 0 0 1 1 1 0 0 1 0    0 0 0 0 0 1 0 0 0 0 0
-1 0 1 0 0 1 1 1 1 0 1    0 0 0 0 0 0 1 0 0 0 0
-2 1 0 1 0 0 1 1 1 1 0    0 0 0 0 0 0 0 1 0 0 0
-2 0 1 0 1 0 0 1 1 1 1    0 0 0 0 0 0 0 0 1 0 0
-1 0 0 1 0 1 1 1 0 1 1    0 0 0 0 0 0 0 0 0 1 0
-2 1 0 0 1 0 1 0 1 1 1    0 0 0 0 0 0 0 0 0 0 1
-1 1 1 1 0 1 0 0 0 1 1
-1 1 0 1 1 1 0 1 1 0 0
-2 1 1 1 1 0 1 0 0 0 1
-1 1 1 0 1 1 0 1 0 1 0
-1 0 1 1 1 1 1 0 1 0 0
```

The output of the program is the following list of extreme points. We check that for each extreme point, the degree of every vertex $v \notin \{s, t\}$ is even and the degrees of s and t are odd. Since these conditions are satisfied, all of the extreme points correspond to s-t traveling salesman walks, proving the lemma. $\square$

We give another proof of this result in Section 2.3. Note that if G is a connected graph, then the fractional s-t walk polyhedron $P(G, s, t)$ is full dimensional (otherwise, $P(G, s, t)$

K_5 EXTREME POINTS

0 0 1 1 0 2 0 1 0 0	0 0 1 0 0 1 1 1 0 0	0 0 0 0 0 1 1 2 0 1	0 0 0 1 0 2 0 2 0 1
0 0 0 0 0 1 1 0 2 1	0 0 0 2 0 2 0 1 1 0	0 0 0 1 0 1 1 1 1 0	0 0 0 0 0 2 0 1 1 2
0 0 0 0 0 2 2 1 1 0	0 0 0 1 0 2 0 0 2 1	0 0 0 2 0 0 2 1 1 0	0 0 2 0 0 1 1 0 0 1
0 0 2 0 0 2 0 1 1 0	0 0 1 0 0 2 0 0 1 1	0 0 1 1 0 0 2 1 0 0	0 0 2 1 0 2 0 0 0 1
0 2 1 0 0 0 0 0 1 1	0 1 2 0 0 1 0 1 0 0	0 1 1 0 0 1 0 0 0 1	0 2 0 1 0 2 0 0 0 1
0 1 0 1 0 1 0 0 1 1	0 2 0 1 0 0 0 0 2 1	0 2 0 0 0 1 1 0 0 1	0 1 0 0 0 1 2 1 0 0
0 1 0 0 0 1 0 1 0 2	0 1 0 1 0 0 1 1 0 0	0 1 0 2 0 1 0 1 0 0	0 1 0 1 1 0 1 0 1 0
0 1 0 0 1 0 1 1 0 1	0 1 0 0 0 0 1 0 1 1	0 0 0 1 0 0 2 0 2 1	0 0 1 0 1 0 2 1 0 1
0 0 1 0 0 0 2 0 1 1	0 0 0 0 0 0 2 1 1 2	0 0 0 0 1 0 2 2 0 2	0 0 0 1 0 0 2 2 0 1
0 0 0 0 1 0 2 0 2 2	0 0 2 0 1 0 2 0 0 2	0 0 2 1 0 0 2 0 0 1	0 0 0 1 1 1 1 0 2 0
0 0 1 0 1 1 1 0 1 0	0 0 0 2 1 2 0 2 0 0	0 0 0 1 1 1 1 2 0 0	0 0 0 0 1 2 0 2 0 2
0 0 0 0 1 2 2 2 0 0	0 0 0 0 1 2 0 0 2 2	0 0 0 0 1 2 2 0 2 0	0 0 0 2 1 2 0 0 2 0
0 0 2 0 1 2 0 2 0 0	0 0 1 0 1 2 0 1 0 1	0 0 2 0 1 2 0 0 0 2	0 0 2 0 1 2 2 0 0 0
0 0 2 0 1 2 0 0 2 0	0 0 2 1 1 1 1 0 0 0	0 0 2 2 1 2 0 0 0 0	0 0 1 1 1 2 0 0 1 0
0 0 2 0 1 0 2 0 2 0	0 0 0 2 1 0 2 0 2 0	0 0 1 1 1 0 2 0 1 0	0 0 0 2 1 0 2 2 0 0
0 0 2 2 1 0 2 0 0 0	0 0 2 0 1 0 2 2 0 0	0 0 2 0 0 0 2 1 1 0	0 2 0 0 0 0 0 1 1 2
0 2 0 0 1 0 0 2 0 2	0 2 0 0 0 0 2 1 1 0	0 2 0 0 1 0 2 2 0 0	0 2 0 2 0 0 0 1 1 0
0 2 0 1 0 0 0 2 0 1	0 2 0 2 1 0 0 2 0 0	0 2 0 0 1 0 2 0 0 2	0 2 0 1 0 0 2 0 0 1
0 1 0 0 1 1 0 0 1 2	0 2 0 0 1 2 0 0 0 2	0 1 0 0 1 1 2 0 1 0	0 2 0 0 1 2 2 0 0 0
0 1 0 2 1 1 0 0 1 0	0 2 0 1 1 1 1 0 0 0	0 2 0 2 1 2 0 0 0 0	0 2 0 0 1 0 0 0 2 2
0 2 0 0 1 0 2 0 2 0	0 2 0 2 1 0 0 0 2 0	0 2 0 2 1 0 2 0 0 0	0 1 1 0 0 0 1 1 1 0
0 1 1 0 1 0 1 2 0 0	0 2 2 0 0 0 0 1 1 0	0 2 1 0 1 0 0 1 0 1	0 2 2 0 1 0 0 2 0 0
0 1 1 0 1 0 1 0 0 2	0 2 2 0 1 0 0 0 0 2	0 1 2 0 1 1 0 0 1 0	0 1 1 0 1 2 1 0 0 0
0 2 2 0 1 2 0 0 0 0	0 1 1 0 1 0 1 0 2 0	0 2 2 0 1 0 0 0 2 0	0 2 1 1 0 0 0 1 0 0
0 1 1 1 0 0 1 0 0 1	0 2 2 1 0 0 0 0 0 1	0 2 2 2 1 0 0 0 0 0	0 2 1 1 1 0 0 0 1 0
0 1 1 2 1 0 1 0 0 0	0 1 1 1 1 1 0 0 0 0	1 1 0 0 0 0 0 0 1 2	1 1 0 0 1 0 0 1 0 2
1 2 0 0 0 1 0 0 0 2	2 2 0 0 1 0 0 0 0 2	1 1 0 0 0 0 2 0 1 0	1 1 0 0 1 0 2 1 0 0
1 2 0 0 0 1 2 0 0 0	1 2 0 0 1 0 1 0 0 1	2 2 0 0 1 0 2 0 0 0	1 1 0 2 0 0 0 0 1 0
1 1 0 1 0 0 0 1 0 1	2 2 0 1 0 0 0 0 0 1	1 2 0 1 0 0 1 0 0 0	1 2 0 2 0 1 0 0 0 0
2 2 0 2 1 0 0 0 0 0	1 1 0 2 1 0 0 1 0 0	1 1 1 1 0 0 0 0 0 0	2 1 1 0 1 0 1 0 0 0
1 1 2 0 1 0 0 1 0 0	2 2 2 0 1 0 0 0 0 0	1 1 1 0 1 0 0 0 0 1	1 2 2 0 0 1 0 0 0 0
1 1 1 0 0 1 1 0 0 0	1 1 2 0 0 0 0 0 1 0	2 0 1 1 1 0 0 0 1 0	2 0 2 2 1 0 0 0 0 0
1 0 1 1 0 1 0 0 1 0	1 0 2 2 0 1 0 0 0 0	1 0 2 1 0 0 1 0 0 0	2 0 2 1 0 0 0 0 0 1
2 0 1 1 0 0 0 1 0 0	2 0 2 0 1 0 0 0 2 0	1 0 2 0 0 1 0 0 2 0	2 0 2 0 1 0 2 0 0 0
1 0 2 0 1 0 1 0 0 1	1 0 2 0 0 1 2 0 0 0	2 0 2 0 1 0 0 0 0 2	1 0 2 0 0 1 0 0 0 2
2 0 2 0 1 0 0 2 0 0	2 0 1 0 1 0 0 1 0 1	2 0 2 0 0 0 0 1 1 0	1 0 1 0 0 1 0 1 0 1
1 0 2 0 0 1 0 2 0 0	2 0 0 2 1 0 0 0 2 0	2 0 0 0 1 0 2 0 2 0	2 0 0 0 1 0 0 0 2 2
1 0 0 0 1 0 1 0 2 1	1 0 0 2 0 1 0 0 2 0	1 0 0 0 0 1 2 0 2 0	1 0 0 0 0 1 0 0 2 2
2 0 0 2 1 0 0 2 0 0	2 0 0 1 0 0 0 2 0 1	2 0 0 2 0 0 0 1 1 0	2 0 0 0 1 0 2 2 0 0
1 0 0 0 0 1 2 2 0 0	2 0 0 0 0 0 2 1 1 0	2 0 0 0 1 0 0 2 0 2	1 0 0 0 0 1 0 2 0 2
1 0 0 1 0 0 1 2 0 0	1 0 0 2 0 1 0 2 0 0	1 0 0 0 1 0 1 2 0 1	2 0 0 0 0 0 0 1 1 2
1 0 0 0 0 0 1 1 1 1	1 0 1 0 0 0 1 0 1 0	2 0 1 0 0 0 0 0 1 1	1 0 1 0 1 0 1 1 0 0
2 0 0 1 0 0 0 0 2 1	1 0 0 1 0 0 1 0 2 0		

is empty). The following theorem from [18] gives a condition for showing the extreme points of polyhedron $P(G, s, t)$ are integral.

Theorem 2.2.3. *[18] Let G be a connected graph and let $P = \{x : Ax \leq b\}$ be any polyhedron with $X(G, s, t) \subset P$. Then $P = conv(X(G, s, t))$ if for any non-zero cost function c, we can show that there exists an inequality in $\{Ax \leq b\}$ satisfied at equality by* all *optimal solutions to* $\min\{cx : x \in X(G, s, t)\}$ *whenever this minimum is finite.*

We use this theorem to show that walk-perfection is preserved under duplication of degree-2 vertices. Let $G \in \mathcal{K}_{[C_6]}$, $s, t \in V(G)$, and consider the ear decomposition of G in Theorem 2.1.2. If s and t are obtained by duplicating a vertex u, then by Corollary 2.1.3, we can reorder the vertex duplications so that the operation of duplicating u to obtain s and t comes first in the ordering and all other vertex duplications follow. In this case, the sequence of ear operations gives graphs $G_1, G_2, \ldots G_k = G$, where G_{i+1} is obtained from

G_i by an edge addition for $i < j$, G_{j+1} is obtained from G_j by duplicating u to obtain s and t and G_{i+1} is obtained from G_i by a degree-2 vertex duplication for $i > j$. Otherwise, if s and t are not obtained by duplicating the same vertex, we can choose the first graph G_1 to be the largest cycle containing s and t and no subsequent vertex duplication relabels a new vertex as s or t. We first show that for $i > j$ and for fixed $s, t \in V(G_i)$, if G_i is s-t walk-perfect, then G_{i+1} is also s-t walk-perfect.

Lemma 2.2.4. *For fixed $s, t \in V(G)$, suppose G is s-t walk-perfect and contains a vertex u of degree 2 with $N(u) = \{a, b\}$ (possibly $u = s$ or $u = t$). Then the graph $G' = (V \cup \{u'\}, E \cup \{(a, u'), (u', b)\})$ is also s-t walk-perfect.*

Proof. For any cost function c on G', consider the set $\mathcal{P}$ of minimum cost s-t traveling salesman walks in G'. If c is negative then the optimum is not finite, so we can assume that c is nonnegative. We show that there is an inequality of the fractional s-t walk polyhedron satisfied at equality by all s-t traveling salesman walks in $\mathcal{P}$. If c does not satisfy the triangle inequality, then there is an edge (i, j) such that $c_{ij} > c_{ik} + c_{kj}$ and in all optimal solutions, $x_{ij} \geq 0$ is a tight inequality.

Now, let c be a cost function satisfying the triangle inequality on G', let $\mathcal{I} = N(a) \cap N(b)$ denote the set of vertices in G' adjacent to both a and b, and for any proper subset S, let $f(S) = 1$ if $|S \cap \{s, t\}| = 1$, $f(S) = 2$ otherwise. By abuse of notation, we will use $f(u)$ to denote $f(\{u\})$.

Case 1. $c_{aw} + c_{wb} > c_{av} + c_{vb}$ for some $v, w \in \mathcal{I}$.

If the inequality $x(\delta(w)) \geq f(w)$ is not tight for all optimal solutions $x \in \mathcal{P}$, there exists an optimal traveling salesman walk x^* such that $x^*(\delta(w)) > f(w)$. In this case, we show one of the edge constraints $x_{aw} \geq 0$ or $x_{wb} \geq 0$ is tight for all $x \in \mathcal{P}$. If $x^*_{aw} \geq 1, x^*_{wb} \geq 1$, decreasing both values by 1 and increasing x^*_{av}, x^*_{vb} by 1 results in a s-t traveling salesman walk of strictly smaller cost (since degree parity is preserved at every vertex and no vertex is disconnected), a contradiction to the optimality of x^*. Therefore, it must be the case that one of x^*_{aw} or x^*_{wb} is zero, say $x^*_{aw} = 0$. Then $x^*_{wb} \geq 3$ (since $x^*(\delta(w)) > f(w)$ and the degrees of s and t are odd). Since another traveling salesman walk is obtained by decreasing x^*_{wb} by 2, the optimality of x^* implies $c_{wb} = 0$. Now, $c_{aw} > c_{av} + c_{vb} = c_{av} + c_{vb} + c_{wb}$, so no optimal s-t traveling salesman walk uses edge (a, w), implying inequality $x_{aw} \geq 0$ is tight for all $x \in \mathcal{P}$.

Case 2 $c_{av} + c_{vb} = c_{aw} + c_{wb}$ for all $v, w \in \mathcal{I}$.

Case 2.1 c_{av} or $c_{vb} = 0$ for some $v \in \mathcal{I} \backslash \{s, t\}$.

Without loss of generality, let $c_{vb} = 0$. Then any s-t traveling salesman walk in $G = G' \backslash v$ can be extended by edge (v, b) (traversed twice) to an s-t traveling salesman walk in G' of the same cost. Conversely, since $c_{av} = c_{av} + c_{vb} = c_{aw} + c_{wb}$ for all $w \in \mathcal{I}, w \neq v$, any s-t traveling salesman walk x in G' can be converted into an s-t traveling salesman walk y in G of the same cost as follows. Choose some $w \in \mathcal{I} \backslash v$ and let $y_{aw} = x_{aw} + x_{av}$ and $y_{wb} = x_{wb} + x_{av}$. Since the parity of degrees at all vertices remain the same and the costs of solutions x and y are the same, the optimal s-t traveling salesman walks in G and the optimal s-t traveling salesman walks in G' have the same cost. Now, since $G = G' \backslash \{v\}$ is s-t walk-perfect, there exists some constraint that is tight for all optimal s-t traveling salesman walks in G. If this is an edge constraint $y_e \geq 0$, then constraint $x_e \geq 0$ is also tight for all optimal s-t traveling salesman walks x in G'. Otherwise, it is a cut constraint C and we can assume without loss of generality that $b \in C$. Then constraint $C' = C \cup \{v\}$ is tight for every $x \in \mathcal{P}$.

Case 2.2 $c_{av}, c_{vb} > 0$ for all $v \in \mathcal{I} \backslash \{s, t\}$.

We claim that for $v \in \mathcal{I} \backslash \{s, t\}$, any optimal integral solution x^* satisfies $x^*(\delta(v)) = f(v) = 2$. To prove this, assume $x^*(\delta(v)) \geq 3$. If x^*_{av} or $x^*_{vb} \geq 3$, decreasing x^* by 2 on this edge yields another integral solution of strictly smaller cost, contradicting minimality of x^*. Since $x^*(\delta(v))$ is even for $v \in \mathcal{I} \backslash \{s, t\}$, we must have $x^*_{av} = x^*_{vb} = 2$. For any other vertex $w \in \mathcal{I} \backslash v$, either $x^*_{aw} \geq 1$ or $x^*_{wb} \geq 1$, say $x^*_{aw} \geq 1$. Then by decreasing $x^*_{aw}, x^*_{av}, x^*_{vb}$ by 1 and increasing x^*_{wb} by 1, we obtain another s-t traveling salesman walk of strictly smaller cost, again a contradiction. Therefore, $x^*(\delta(v)) = f(v) = 2$ for all $v \in \mathcal{I} \backslash \{s, t\}$. □

We have shown that performing vertex duplication on G to obtain a new vertex not labelled s or t preserves s-t walk-perfection of G. Now, we show walk-perfection is also preserved under vertex duplication when the two resulting vertices are relabeled s and t. Consider the ear decomposition $G_1, G_2, \ldots G_k = G$ discussed above, where G_{i+1} is obtained from G_i by an edge addition for $i < j$ and G_{j+1} is obtained from G_j by duplicating u to obtain s and t.

Lemma 2.2.5. *If G_j is walk-perfect and G_{j+1} is obtained from G_j by duplicating vertex u to obtain s and t, then G_{j+1} is also walk-perfect.*

Proof. By construction of the ear decomposition, G_j is obtained from the cycle G_1 by edge additions and therefore, has no other vertex duplications (i.e., is a subgraph of the graph in Figure 2.7). Note that this graph is a subgraph of K_5 and is therefore walk-perfect.

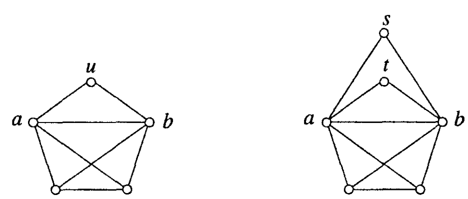


Figure 2.7: u is duplicated to obtain s and t.

Case 1. $c_{as} + c_{sb} > c_{at} + c_{tb}$ or $c_{as} + c_{sb} < c_{at} + c_{tb}$

The analysis of Case 1 in Lemma 2.2.4 gives a tight constraint for this case.

Case 2. $c_{as} + c_{sb} = c_{at} + c_{tb}$.

Case 2.1. One of c_{as}, c_{sb}, c_{at} or c_{tb} equals 0.

Without loss of generality, let $c_{sb} = 0$. For $\widehat{s} = b$ and $\widehat{t} = t$, any $\widehat{s}$-$\widehat{t}$ traveling salesman walk in $G = G' \backslash s$ can be extended by edge (s, b) to an s-t traveling salesman walk in G' of the same cost. Conversely, since $c_{as} = c_{as} + c_{sb} = c_{aw} + c_{wb}$ for all $w \neq s$, any s-t traveling salesman walk x in G' can be converted into an $\widehat{s}$-$\widehat{t}$ traveling salesman walk y in G of the same cost as follows. Choose $w \in \mathcal{I} \backslash s$ and let $y_{aw} = x_{aw} + x_{as}$ and $y_{wb} = x_{wb} + x_{as}$. Since the parity of degrees at all vertices remain the same except at vertex $\widehat{s} = b$ and the costs of solutions x and y are the same, the optimal $\widehat{s}$-$\widehat{t}$ traveling salesman walks in G and the optimal s-t traveling salesman walks in G' have the same cost. Now, since

$G = G'\backslash\{s\}$ is walk-perfect, there exists some constraint that is tight for all optimal $\widehat{s}$-$\widehat{t}$ traveling salesman walks in G. If this is an edge constraint $y_e \geq 0$, then constraint $x_e \geq 0$ is also tight for all optimal s-t traveling salesman walks x in G'. Otherwise, it is a cut constraint C and we can assume without loss of generality that $b \in C$. Then constraint $C' = C \cup \{s\}$ is tight for every $x \in \mathcal{P}$.

Case 2.2. $c_{as}, c_{sb}, c_{at}, c_{tb} > 0$.

If $c_{as} = c_{at}$ (and therefore $c_{sb} = c_{tb}$), then let F be the graph with vertices $V(F) = G'\backslash\{s,t\} \cup \{u\}$ and edges $E(F) = E(G') \cup \{(a,u),(u,b)\}$. Let $y_{au} = x^*_{as}+x^*_{at}$ and $y_{ub} = x^*_{sb}+x^*_{tb}$ and $y_e = x_e$ for all other edges e. Then y is a traveling salesman tour on F with cost at most the cost of x^* in G'. Also, any optimal traveling salesman tour on F can be converted to an s-t traveling salesman walk x in F of smaller cost by letting $x_{as} = y_{au}, x_{at} = 0, x_{sb} = x_{tb} = y_{ub}/2$ if y_{au}, y_{ub} are both even (and therefore equal to 2, by optimality of y) and $x_{as} = y_{au}, x_{at} = x_{sb} = 0, x_{tb} = y_{ub}$ if y_{au}, y_{ub} are both odd. This shows minimum s-t traveling salesman walks in G' and minimum traveling salesman tours in F have the same cost and since $F \simeq G$ is walk-perfect, there is a constraint that is tight for all optimal traveling salesman tours of F. If this is an edge constraint $y_e \geq 0$, then $x_e \geq 0$ is also tight for all $x \in \mathcal{P}$. Otherwise the tight constraint is a cut constraint C and we can assume without loss of generality that $u \in C$. Then $C' = C\backslash\{u\} \cup \{s,t\}$ is a tight constraint for all $x \in \mathcal{P}$.

Therefore, $c_{as} \neq c_{at}$ and $c_{sb} \neq c_{tb}$. If the inequality $x(\delta(s)) \geq f(s) = 1$ is not tight for all $x \in \mathcal{P}$, let x^* be an optimal solution with $x^*(\delta(s)) > 1$. Since deg(s) is odd and $x^*_{as}, x^*_{sb} < 3$ (by optimality of x^*), we can assume $x^*_{as} = 2, x^*_{sb} = 1$. Then $c_{as} < c_{at}$ and $c_{sb} > c_{tb}$ (otherwise, decreasing x^*_{as} by 2 and increasing x^*_{at} by 2 gives a solution of strictly smaller cost). If deg$(t) = 3$, we have the following cases.

Case 2.2.i. $x^*_{at} \geq 1, x^*_{tb} \geq 1$. In this case, decreasing x^*_{as} by 2 gives an s-t traveling salesman walk of strictly smaller cost, a contradiction.

Case 2.2.ii. One of x^*_{at}, x^*_{tb} is zero and the other is at least 3. Then subtracting

2 from the edge of value at least 3 gives an s-t traveling salesman walk of strictly smaller cost, again a contradiction.

Since $\deg(t)$ is odd, it must be the case that $x^*_{as} = 2, x^*_{sb} = 1$ and $\deg(t) = 1$. Now, consider the support graph $H = \{e \in E(V(G')\backslash\{s,t\}) : x^*_e > 0\}$ and let x^*_H denote the restriction of x^* to this graph. The remaining cases are the following.

Case 2.2.iii. $x^*_{at} = 1, x^*_{tb} = 0$. In this case, x^*_H contains an Eulerian walk from a to b in H since $x^*_H(w)$ is even for all $w \in H\backslash\{a,b\}$ and odd for $w = a$ or b. Therefore, H is connected and a traveling salesman walk of strictly smaller cost can be obtained from x^* by decreasing x^*_{as} by 2.

Case 2.2.iv. $x^*_{at} = 0, x^*_{tb} = 1$. If H is connected, the same argument in Case 2.2.iii gives a traveling salesman walk of strictly smaller cost, so we can assume H is not connected. Let C be the component of H containing a (note that $b \notin C$) and let $C' = C \cup \{s\}$. For any edge $e = (i,j) \in E(G)$ with $i \in C, j \notin C$, let q^s_{ij} (q^t_{ij}) denote the shortest path in x^* from i to a together with edges $(a,s),(s,b)$ (edges $(a,t),(t,b)$) and the shortest path in x^* from b to j. The cost of edge $e = (i,j)$ must be at least the cost of path q^s_{ij} (which is equal to the cost of path q^t_{ij}); otherwise, by replacing path q^s_{ij} by edge (i,j), we do not disconnect any vertices of the graph (since G_j is a subset of the graph in Figure 2.7) while preserving the degree parity at every vertex, which yields an s-t traveling salesman walk of strictly smaller cost.

We claim $x(\delta(C')) = 1$ for every $x \in \mathcal{P}$. Otherwise, if $x^*(\delta(C')) \geq 2$ for some $x^* \in \mathcal{P}$, then $s \in C', t \notin C'$ implies $x^*(\delta(C')) \geq 3$. One of x^*_{sb}, x^*_{at} must be zero, say $x^*_{at} = 0$ (otherwise, if $x^*_{sb}, x^*_{at} \geq 1$, then decreasing both of these by 1 and increasing x^*_{as}, x^*_{tb} by 1 gives an s-t traveling salesman walk of strictly smaller cost). Now, consider edges $(k_1,l_1),(k_2,l_2),(k_3,l_3)$ (possibly including multiple copies of the same edge) crossing C' in path x^*. By rerouting $x^*_{k_1l_1}, x^*_{k_2l_2}$ and $x^*_{k_3l_3}$ along the paths $q^s_{k_1l_1}, q^s_{k_2l_2}$ and $q^s_{k_3l_3}$ (or keeping $x^*_{k_i,l_i}$ if $(k_i,l_i) = (s,b)$), we obtain an s-t traveling salesman walk y of smaller or equal cost with either

$y_{as} \geq 3$ or $y_{sb} \geq 3$ (if $x^*_{sb} = 0$, then reroute along the paths $q^t_{k_1 l_1}, q^t_{k_2 l_2}$ and $q^t_{k_3 l_3}$). Now, by decreasing this value by 2, we obtain an s-t traveling salesman walk of strictly smaller cost, a contradiction. Therefore, $x(\delta(C')) = 1$ for every $x \in \mathcal{P}$. □

We now show that that walk perfection for any graph can be reduced to walk-perfection of its blocks.

Lemma 2.2.6. *s-t walk-perfection is preserved under operation Φ_1.*

Proof. Suppose vertices v_1 and v_2 in connected graphs G_1 and G_2 are identified to obtain graph G and let $s, t \in V(G)$. Consider the labeled minor H_1 obtained by contracting G_2 to a single vertex in G. The result is graph G_1 where vertex v_1 has label s if $s \in V(G_2)$, label t if $t \in V(G_2)$, labels s and t if $s, t \in V(G_2)$ and is unlabeled if $s, t \in V(G_1)\backslash\{v_1\}$. Similarly, conisder labeled minor H_2 obtained by contracting G_1. Since s-t walk-perfection is preserved under connected labeled minors, if G is s-t walk-perfect, then so are H_1 and H_2.

Conversely, suppose H_1 and H_2 are s-t walk-perfect, let $X(G, s, t)$ denote the set of optimal s-t traveling salesman walks in G, and let $x \in X(G, s, t)$. Then optimality and degree parity constraints imply that x is the union of two optimal s-t traveling salesman walks in labeled minors H_1 and H_2. For any non-zero cost function c, the restriction of c to one of H_1 or H_2 must be non-zero; without loss of generality, assume c restricted to H_1 is non-zero. By Theorem 2.2.3, there is a constraint C in $P(H_1)$ which is tight for all optimal traveling salesman tours in H_1. If constraint C is an edge constraint $x_e \geq 0$, then this edge constraint is tight for all $x \in X_{TSP}(H_1)$. Otherwise, we can assume constraint C is a cut constraint with $v_1 \notin C$; in this case, C is a tight constraint for all $x \in X_{TSP}(G)$. □

Now, any 1-connected graph is C_6 minor free if and only if can be built by repeated applications of Φ_1 from blocks which are C_6 minor free. Therefore, our main theorem follows from Lemmas 2.2.2, 2.2.4, 2.2.5, and 2.2.6.

Theorem 2.0.4 A connected graph G is walk-perfect if and only if G has no C_6 minor.

2.3 Connection with TSP-Perfection

In this section, we establish a connection between walk-perfection and TSP-perfection. Using this connection, we give a second proof of the characterization of walk-perfect graphs based on the characterization of TSP-perfect graphs.

If graph G is walk-perfect, then it is also TSP-perfect, since by choosing s and t to be identical vertices, s-t walk-perfection corresponds to TSP-perfection. Thus, walk-perfection is a sufficient condition for TSP-perfection. We would like a condition in the reverse direction, i.e., a sufficient condition for walk-perfection based on TSP-perfection. For graph $G = (V, E)$ and vertices $s, t \in V$, let $G_{s,t}(3)$ denote the graph obtained by adding a path of length 3 from s to t (see Figure 2.8), that is, $G_{s,t}(3)$ is the graph with vertices and edges

$$V(G_{s,t}(3)) = V(G) \cup \{u, v\} \ (u, v \notin V(G))$$

$$E(G_{s,t}(3)) = E \cup \{(s, u), (u, v), (v, t)\}.$$

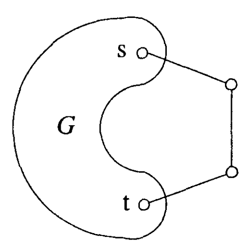


Figure 2.8: Graph $G_{s,t}(3)$.

Consider the fractional TSP polyhedron

$$P(G_{s,t}(3)) = \left\{ \begin{array}{lll} x \in \mathbb{R}^{|E|}: & x(\delta(S)) \geq 2 & \text{for } S \subsetneq V(G_{s,t}(3)), S \neq \emptyset \\ & x \geq 0 & \text{for all } e \in E(G_{s,t}(3)) \end{array} \right\}.$$

The following lemma relates the extreme points of the fractional traveling salesman walk polyhedron $P(G, s, t)$ with the extreme points of the fractional traveling salesman polyhedron $P(G_{s,t}(3))$.

Lemma 2.3.1. *If $x \in \mathbb{R}^{|E|}$ is an extreme point of $P(G,s,t)$, then $x' = (x,1,1,1) \in \mathbb{R}^{|E(G_{s,t}(3))|}$ is an extreme point of $P(G_{s,t}(3))$, where the three additional variables correspond to edges $(s,u),(u,v)$, and (v,t).*

Proof. Let x be an extreme point of $P(G,s,t)$. Then it is tight for $m = |E|$ of the constraints in $P(G,s,t)$. We will show that the point $x' = (x,1,1,1)$ is the unique solution to a set of $m+3$ inequalities involving edges $E(G_{s,t}(3))$ and therefore is an extreme point $P(G_{s,t}(3))$.

First, we show the m tight constraints for x in $P(G,s,t)$ generate m tight constraints for x' in $P(G_{s,t}(3))$. Each tight constraint $x(\delta(S)) = f(S)$ in $P(G,s,t)$ gives rise to a tight constraint $x'(\delta(S')) = 2$ in $P(G_{s,t}(3))$ with

$$S' = \begin{cases} S \cup \{u,v\} & \text{if } s,t \in S \\ S' = S \cup \{u\} & \text{if } s \in S, t \in \overline{S} \\ S' = S \cup \{v\} & \text{if } s \in \overline{S}, t \in S \\ S' = S & \text{if } s,t \in \overline{S}. \end{cases}$$

This gives m tight constraints for x' in $P(G_{s,t}(3))$. Consider these constraints together with the following three inequalities:

$$\begin{aligned} x(\delta(V)) &= x_{su} + x_{vt} &\geq 2 \\ x(\delta(V \cup \{u\})) &= x_{uv} + x_{vt} &\geq 2 \\ x(\delta(V \cup \{v\})) &= x_{su} + x_{uv} &\geq 2. \end{aligned}$$

The unique solution on edges $(s,u),(u,v),(v,t)$ satisfying the last three inequalities at equality is $x_{su} = x_{uv} = x_{vt} = 1$. Furthermore, since x is the unique solution to the m tight constraints in $P(G,s,t)$, it follows that $x' = (x,1,1,1)$ is the unique solution to the $m+3$ tight constraints in $P(G_{s,t}(3))$ and therefore, x' is a extreme point of $P(G_{s,t}(3))$. □

Lemma 2.3.2. *If $G_{s,t}(3)$ is TSP-perfect, then G is s-t walk-perfect. If $G_{s,t}(3)$ is TSP-perfect for every choice of s and t, then G is walk-perfect.*

Proof. By Lemma 2.3.1, if x is an extreme point of $P(G,s,t)$, then $(x,1,1,1)$ is an extreme point of $P(G_{s,t}(3))$. Since $G_{s,t}(3)$ is TSP-perfect, the extreme point $(x,1,1,1)$ is a tour of $G_{s,t}(3)$, which corresponds to an s-t traveling salesman walk in G together with the three edges $(s,u),(u,v)$, and (v,t). Thus, the extreme point x corresponds to an s-t traveling salesman walk, implying G is s-t walk-perfect. If this holds for every choice of s and t, G is walk-perfect. □

Lemma 2.3.3. *For any $i \in \{1,2,3\}$ and any edge $e \in M_i$, $M_i \setminus \{e\}$ contains C_6 as a minor.*

Proof. This follows by inspection of Figure 2.1. □

Theorem 2.3.4. *If G is C_6 minor free, then $G_{s,t}(3)$ is $[M_1, M_2, M_3]$ minor free for any choice of s and t.*

Proof. The theorem is clearly true if $s = t$, so we can assume $s \neq t$. Suppose $G_{s,t}(3)$ contains M_i ($i = 1, 2$, or 3) as a minor and label the edges of $G_{s,t}(3)$ according to whether they are contracted, deleted, or unchanged in the sequence of minor operations to obtain M_i. Consider the 3-path $(s,u),(u,v),(v,t)$. None of these edges can be marked for deletion, since this would imply G contains an M_i minor, and therefore a C_6 minor. If any of these edges is unchanged, then after performing the minor operations to obtain M_i, deleting this edge would leave a C_6 minor which must have been contained in G, a contradiction. Therefore, all 3 edges $(s,u),(u,v),(v,t)$ must be marked for contraction.

Note that we can interpret minor M_i as a partition of the vertices of $G_{s,t}(3)$; two vertices a, b are in the same member of the partition if and only if there is a path of edges marked for contraction between a and b and two members A and B of the partition are connected by an edge if and only if there are vertices $a \in A$ and $b \in B$ such that edge $e = (a,b)$ is in graph $G_{s,t}(3)$ and e is unchanged under the minor operations. This implies that performing the edge contractions and deletions in any order results in the same graph minor.

Therefore, we can perform the contraction of edges $(s,u),(u,v),(v,t)$ as the final three steps in the sequence of minor operations. Consider the graph at this stage, with only the three edge contractions remaining and let G' denote the subgraph of G with all minor operations on $E(G)$ carried out. At this stage, if edges $(s,u),(u,v),(v,t)$ are contracted in graph $G' \cup \{(s,u),(u,v),(v,t)\}$, the result is graph M_i. If the contraction results in any multi-edges, then arbitrarily mark all edges except one for deletion in G' (this does not change the final graph). Now, since all vertices in M_i have degree at most 3 and no multi-edges arise from the contraction of $(s,u),(u,v),(v,t)$, one of s or t (say t) satisfies $deg_{G'}(t) \leq 1$ in G'. Let e be the edge adjacent to t in G' if $deg_{G'}(t) = 1$, and let e be an arbitrary edge in G' if $deg_{G'}(t) = 0$. Then vertex t has degree 0 in $G' \backslash \{e\}$ and degree 1 in graph $(G' \backslash \{e\}) \cup \{(s,u),(u,v),(v,t)\}$ and therefore, any C_6 minor in the graph $(G' \backslash \{e\}) \cup \{(s,u),(u,v),(v,t)\}$ cannot contain vertices t, u, or v. By Lemma 2.3.3, deleting edge e from G' results in a graph with a C_6 minor and since this C_6 minor does not contain any of t, u, or v, it is also a minor of graph G, a contradiction. □

Note that since K_5 is C_6 minor free, this provides a second proof for the walk-perfection of K_5, which was shown by computational methods in Section 2.2.

Corollary 2.3.5. *K_5 is walk-perfect.*

2.4 *s-t* Walk-Perfection

Now that we have characterized the set of walk-perfect graphs, a natural problem is to characterize connected graphs G which are s-t walk-perfect for *fixed* vertices s and t. For graph G and specified vertices s and t, we first show that the condition of TSP-perfection of $G_{s,t}(3)$ is *not* a necessary condition for s-t walk-perfection of G by giving the following counterexample to the converse of Lemma 2.3.2.

Example 2.4.1. *In Table 2.1, labels s and t are chosen in graphs M_1, M_2, and M_3. Using* `polymake`, *we have verified each graph G is s-t walk-perfect (see Appendix). However, each graph $G_{s,t}(3)$ contains one of M_1, M_2, or M_3 as a minor and therefore, is not TSP-perfect.*

In fact, Table 2.1 is a *complete* list (up to isomorphism) of the choices of s and t resulting in s-t walk-perfect graphs. The remaining graphs, shown in Table 2.2, show the choices of s and t resulting in non s-t walk-perfect graphs. In each graph, two disjoint paths of length at least three from s to t are shown in bold. Note that in each of the s-t walk-perfect graphs, there are no such two disjoint paths of length at least three from s to t. This leads us to formulate the following conjecture.

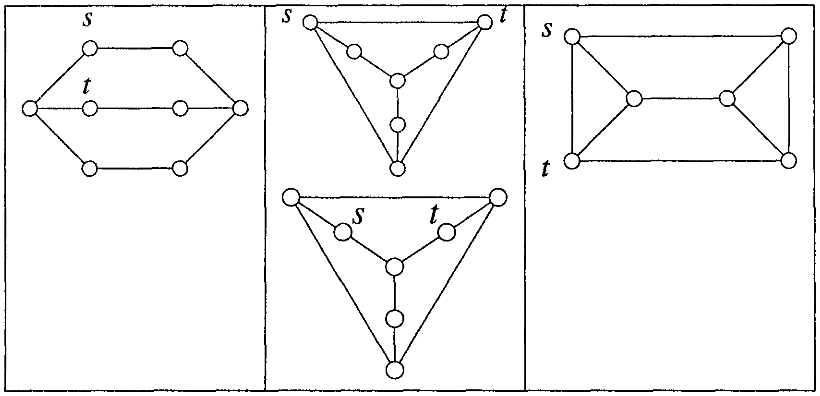


Table 2.1: Labelings of M_1, M_2, M_3 resulting in s-t walk-perfect graphs.

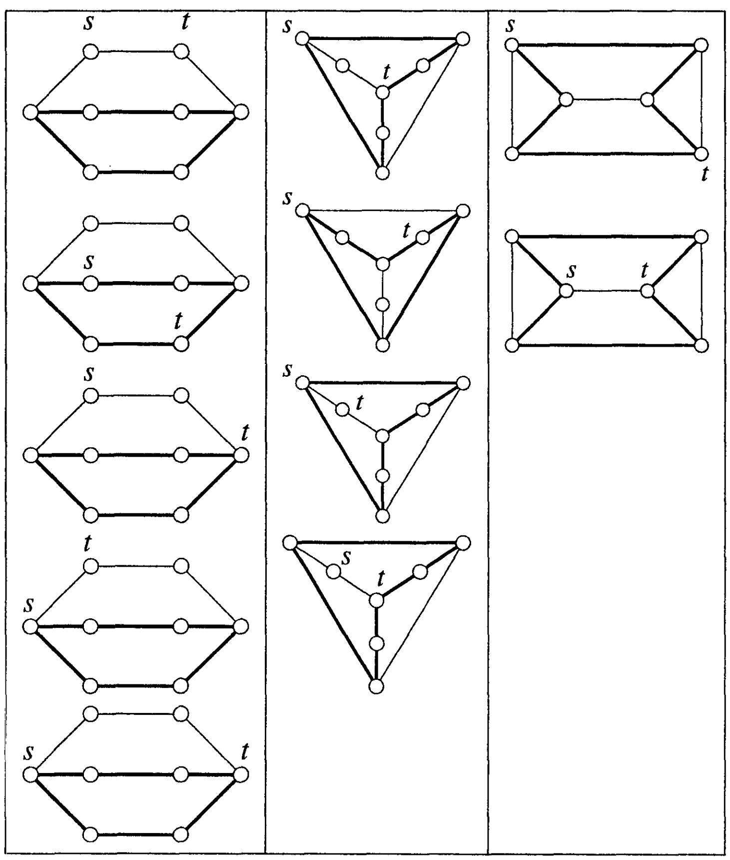


Table 2.2: Labelings of M_1, M_2, M_3 resulting in non-s-t walk-perfect graphs.

Conjecture 2.4.2. *For a connected graph G with fixed vertices $s, t \in V(G)$, G is s-t walk-perfect if and only if G does not have as a labeled minor two vertex disjoint paths of length at least 3 between s and t.*

2.5 Asymmetric Traveling Salesman Path Problem

In this section, we give an approximation algorithm for the *asymmetric traveling salesman path* (ATSPATH) problem. In this problem, we have fixed vertices s and t in a graph $G = (V, A)$ with directed arcs and possibly asymmetric arc costs. The objective is to find a minimum cost directed Hamiltonian path from s to t. The *asymmetric traveling salesman walk* (ATSW) problem is to find a minimum cost directed walk from s to t that visits all vertices *at least* once. This problem is equivalent to finding a minimum cost directed Hamiltonian path from s to t in the metric completion of graph G. Therefore, we focus our attention on complete graphs satisfying the triangle inequality and assume we are given such an instance in our approximation algorithm. Our results are stated for the ATSPATH problem, but apply to the ATSW problem by replacing each arc (i, j) in the solution with a shortest directed path in the graph from i to j. The algorithm we present is similar to the $O(\log n)$-approximation algorithm for the asymmetric traveling salesman problem due to Frieze, Galbiati, and Maffioli ([13]).

In the following example, we show that there are graphs for which the cost of the optimal asymmetric traveling salesman tour can be arbitrarily higher than that of the optimal asymmetric traveling salesman path. Thus, an α-approximation algorithm for the asymmetric traveling salesman tour problem does not immediately yield an α-approximation for the ATSPATH problem.

Example 2.5.1. *Figure 2.9 shows an instance for which the value of the minimum cost tour is arbitrarily higher than the value of the minimum cost s-t traveling salesman path. For this graph, arc (t, s) has arbitrarily high cost $c_{ts} = \alpha$, solid directed arcs have cost 1 and all remaining arcs have costs determined by metric completion. The minimum cost s-t path has value 10 and the minimum cost tour has value $\alpha + 10$.*

However, using a technique based on recursively building the asymmetric s-t traveling

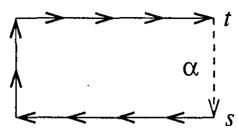


Figure 2.9: Example showing an α-approximation algorithm for the ATSP does not give an α-approximation for the ATSPATH problem.

salesman path, we prove that there is an $O(\sqrt{n})$-approximation algorithm for the ATSPATH problem.

2.5.1 Path/Cycle Covers

An *s-t-path/cycle cover* in a directed graph G is a directed path from s to t together with a collection of directed cycles such that every vertex in V is contained in exactly one of these subgraphs. In particular, this implies the path and cycles must be disjoint and cover all vertices $V(G)$. Note that the value of the minimum s-t-path/cycle cover on G is a lower bound on the minimum cost asymmetric traveling salesman path in G. We first show that we can find a minimum s-t path/cycle cover for G efficiently via a reduction to the minimum cost perfect matching problem.

Construct bipartite graph G' by including two copies of each vertex $v \in V \setminus \{s,t\}$; call these copies v and v'. For each pair $i, j \in V \setminus \{s,t\}$, assign cost c_{ij} to arc (i, j'). Now, include vertices s and t' and for all $i \in V \setminus \{s,t\}$, assign cost c_{si} to arc (s, i') and c_{it} to arc (i, t').

Lemma 2.5.2. *The cost of a minimum cost perfect matching in G' is equal to the cost of a minimum s-t-path/cycle cover in G.*

Proof. Let $d^-(v)$ and $d^+(v)$ denote the indegree and outdegree of vertex v respectively. An s-t-path/cycle cover is a subgraph of G in which vertices s and t satisfy $d^+(s) = d^-(t) = 1$ and $d^-(s) = d^+(t) = 0$, and every vertex $v \in V \setminus \{s,t\}$ satisfies $d^-(v) = d^+(v) = 1$. We first show that every s-t-path/cycle cover of G corresponds to a matching in G' with the same cost. For every directed arc (i, j) in the s-t-path/cycle cover, include arc (i, j') in the matching. Since every vertex in $i \in V \setminus \{s,t\}$ has in-degree 1 and out-degree 1, both i and i' are matched in G' and since s has out-degree 1 and t has in-degree 1, s and t are also matched. Thus, there is a minimum cost perfect matching with the same cost as the s-t-path/cycle cover. Conversely, a minimum cost perfect matching in G' yields a s-t-path/cycle cover in G with the same cost; for every arc (i, j') in the matching, include arc (i, j) in the path/cycle cover. $\square$

2.5.2 $O(\sqrt{n})$-Approximation

The first step of the algorithm is to find a minimum cost s-t-path/cycle cover. If this subgraph contains at least $\sqrt{n}$ cycles, then let $V' \subset V$ be the set of vertices in the path together with one vertex from each cycle and let G' be the graph induced by the vertices in V' (note that $|V'| \leq n - \sqrt{n}$). We then recurse on the graph G'. Such a recursion can occur at most $\sqrt{n}$ times. When we reach a stage in which the path/cycle cover returns fewer than $\sqrt{n}$ cycles, then we attach each cycle to the path resulting in a single s-t path.

This attachment operation proceeds as follows. For each cycle, pick an arbitrary vertex v in the cycle. The current s-t path contains an arc (a, b) such that in an optimal s-t traveling salesman path $\overrightarrow{p}$, vertex v falls after a and before b. To see why this is true, label all vertices in the current s-t path that appear after v in $\overrightarrow{p}$ by 1 and label all vertices that appear before v in $\overrightarrow{p}$ by 0. Then s has label 0 and t has label 1 and therefore, there is some arc (a, b) such that a has label 0 and b has label 1. Although we do not know which arc will satisfy the desired property, we can test all consecutive vertices along the s-t path and choose a and b to minimize the length of the sum of the two arcs (a, v) and (v, b). Then by connecting vertex v to the s-t path by adding these two arcs, the cost incurred is at most OPT (see Figure 2.10). Since there are at most $k \leq \sqrt{n}$ cycles, the total cost of adding all these arcs is at most $\sqrt{n} \cdot OPT$. In the final step, we have an s-t-path on a subset of the vertices and we expand each vertex that represented a cycle at some stage of the algorithm by replacing the vertex with a complete traversal of that cycle. If a vertex v is visited multiple times in the result, then let (i, v) and (v, j) be two arcs in the solution. Since the graph is assumed to be a complete directed graph satisfying the triangle inequality, we can shortcut the solution by including arc (i, j) and deleting arcs (i, v) and (v, j). Repeating this procedure until every vertex is visited exactly once results in a directed s-t traveling salesman path. $\square$

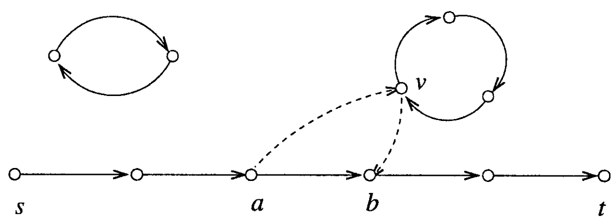


Figure 2.10: Attaching the cycles to the path.

ATSPATH-APPROX(G)

1. Find a minimum cost s-t path/cycle cover C for G.

   (i) If C has less than $\sqrt{n}$ cycles, then attach the cycles to the s-t path and let S be the resulting path.

   (ii) Else if C has more than $\sqrt{n}$ cycles, then let V' be the set of vertices in the s-t path plus one representative vertex from each cycle. Run ATSPATH-APPROX(G') for $G' = (V', A(V'))$.

2. For each vertex that represents a cycle in S, expand the cycle while traversing the path, shortcutting arcs through vertices which are visited multiple times.

Chapter 3

TSP-perfection

3.1 Bricks and TSP-Perfection Preserving Operations

As shown in Chapter 2, the families of TSP-perfect and walk-perfect graphs can be characterized by finite lists of forbidden minors. In general, giving a constructive description for a minor free family is a difficult problem. In the case of C_6 minor free graphs, Section 2.1 gave a constructive description starting from building block K_5 and repeatedly applying operations of edge deletion, edge contraction, and degree-2 vertex duplication. We used this construction to prove our characterization of walk-perfect graphs. In this chapter, we show we can extend this technique to TSP-perfect graphs, using a constructive description of $[M_1, M_2, M_3]$ minor free graphs to give an independent proof for the characterization of TSP-perfect graphs. We first give a constructive characterization of all $[M_1, M_2, M_3]$ minor free graphs, as being built from *bricks*, using operations to be defined together with the operations of edge contraction and deletion. We then prove that all bricks are TSP-perfect and that all operations used in the constructive characterization preserve TSP-perfection. This gives an alternate proof of the result of Fonlupt and Naddef and resolves the problem posed at the end of [12].

We first describe graph operations Φ_1, Φ_2, and degree-2 vertex duplication. Recall from Section 2.1 that for two connected graphs G_1, G_2, and vertices $v_1 \in G_1$, $v_2 \in G_2$, operation Φ_1 identifies vertices v_1 and v_2 to obtain graph G (see Figure 3.1). Note that since we are concerned with TSP-perfection rather than walk-perfection in this chapter, we do not need the specified vertices s_i or t_i for operation Φ_1 here.

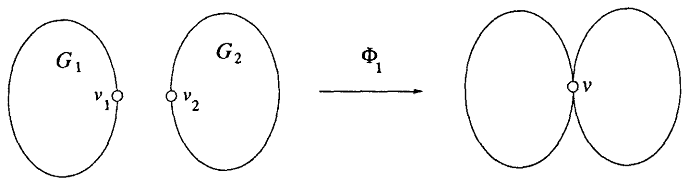


Figure 3.1: Operation Φ_1.

To describe operation Φ_2, suppose G has a 2-vertex disconnecting set $\{s,t\}$ and let *k-path* denote a path of k edges whose internal vertices have degree 2. Note that the graph $G \backslash \{s,t\}$ may have more than 2 components (for example, if there are any 2-paths from s to t). Let V_1 and V_2 be a partition of $V(G) \backslash \{s,t\}$ obtained by grouping connected components of $G \backslash \{s,t\}$ into two nonempty sets and for $i = 1,2$, let H_i denote the graph $G(V_i \cup \{s,t\})$. If both graphs H_1 and H_2 have a path of length at least 3 from s to t, then let G_i be the graph H_i together with an additional 3-path from s to t (see Figure 3.2). For both operations Φ_1

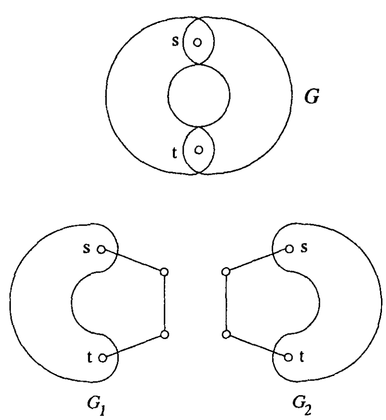


Figure 3.2: Operation Φ_2.

and Φ_2, we say that Φ_i *decomposes* G into G_1 and G_2 and that Φ_i *composes* G from G_1 and G_2. We will denote the operations by $G = G_1 \circ_{\Phi_i} G_2$. If one of the graphs H_i does not have a path of length at least 3 from s to t, then G cannot be decomposed by Φ_2 at $\{s,t\}$.

The operation of degree-2 vertex duplication (as introduced in Section 2.1) takes a graph G with a degree-2 vertex u and duplicates u to obtain graph $G_2(u)$ on vertices and edges

$$\begin{aligned} V(G_2(u)) &= V(G) \cup \{u'\} \\ E(G_2(u)) &= E(G) \cup \{(a,u'),(u',b)\}, \end{aligned}$$

where a and b are the two neighbors of u (see Figure 3.3).

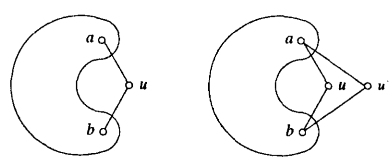


Figure 3.3: Vertex duplication of degree-2 vertex.

If Φ_i decomposes graph G into graphs G_1 and G_2, each of which has strictly fewer than $|V(G)|$ vertices, then we say Φ_i produces a *strict decomposition* of G. We would like to characterize all the graphs that cannot be decomposed by any of the three operations described above. Consider the family of TSP-perfect graphs with no strict decomposition by Φ_1 or Φ_2 and with at most one 2-path between the same vertices s and t (as any duplicate 2-path can be removed by the inverse operation to the duplication of degree-2 vertices). Such a graph in the family must be 2-connected. Moreover, if the graph has a 2-vertex disconnecting set $\{s,t\}$ into nonempty components, then because there is no strict decomposition by Φ_2, we claim that the only possibilities for the two graphs H_1 and H_2 are

(i) one connected component and one 2-path between s and t or

(ii) one connected component and one 3-path between s and t.

Otherwise, if either one of H_1 or H_2 contained more than one 3-path or a 3-path and a 2-path, operation Φ_2 would give a strict decomposition at $\{s,t\}$. If there were more than one 2-path between s and t, we could have eliminated all but one of them by the inverse operation to the duplication of degree-2 vertices. Thus, if we replace all 2-paths and 3-paths by 1-paths (edges) for any graph in this family, we obtain a simple graph which has no vertex disconnecting set of size 2 and is therefore 3-connected. We would like to find a list of graphs from this family, which we will call *bricks*, such that every $[M_1, M_2, M_3]$ minor free graph can be obtained from the list of bricks by the operations of edge deletion, edge contraction, Φ_1, Φ_2, and duplication of degree-2 vertices.

To describe the list of bricks, we first define two families of graphs, *wheels* and *propellers*. The *k-wheel* W_k is the graph on vertices $v_0, v_1, \dots v_k$ such that $G(V \backslash v_0)$ is a cycle of length k and vertex v_0 is adjacent to $v_1, v_2, \dots v_k$. The edges (v_0, v_i) will be called *spoke edges* and the edges $(v_i, v_{i+1}), (v_k, v_1)$ will be called *rim edges* (see Figure 3.4). The family of wheel graphs includes the k-wheels W_k as well as the graphs obtained from W_k by replacing rim edges in W_k by 2-paths and 3-paths. In particular, let $W_k^{(3)}$ denote the wheel graphs obtained from W_k by replacing every rim edge by a 3-path.

The *k-propeller* P_k is a graph on triangle a, b, c and k other vertices which are pairwise nonadjacent and adjacent to all of a, b, c. The edges $(a, b), (b, c), (a, c)$ will be called *rim edges* and all remaining edges will be called *spoke edges*; the vertices a, b, c will be called *rim vertices* and all remaining vertices will be called *spoke vertices.* For $0 \leq i_1, i_2, i_3 \leq 3$, $P_k(i_1, i_2, i_3)$ will denote the graph obtained from P_k by replacing the three rim edges of P_k with paths of i_1, i_2, and i_3 edges (where a path of 0 edges means the rim edge is removed). The family of propeller graphs includes all graphs $P_k(i_1, i_2, i_3)$ for $k \geq 1, 0 \leq i_1, i_2, i_3 \leq 3$.

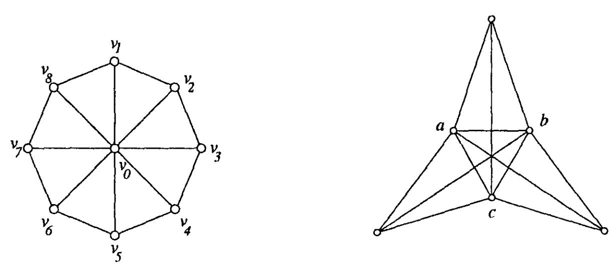


Figure 3.4: An 8-wheel and a 3-propeller.

As observed above, any brick must be 2-connected and if it has a 2-vertex disconnecting set $\{s, t\}$ into nonempty components, then one of the components must be an i-path for $i = 2$ or 3. Therefore, if we replace all such i-paths by edges, the resulting graph must be 3-connected. This shows that a complete set of bricks can be obtained from the set of 3-connected bricks by replacing certain edges with 2-paths and 3-paths.

The set of 3-connected M_3 minor free graphs is characterized by the following theorem.

Theorem 3.1.1. *[11] The following is a complete list of 3-connected M_3 minor free graphs:*

(i) K_i for $i = 1, 2, \ldots 5$

(ii) $K_5 \backslash \{e\}$ for any edge e

(iii) W_k for $k \geq 3$

(iv) $P_k(0,0,0), P_k(0,0,1), P_k(0,1,1), P_k(1,1,1)$ for $k \geq 3$.

Note that the graphs listed in Theorem 3.1.1 include *all* of their 3-connected subgraphs. For example, the only way to remove 2 disjoint edges from K_5 to obtain a 3-connected graph results in W_4; also, no proper subgraph of W_k is 3-connected, since every edge is adjacent to a vertex of degree 3. Furthermore, all graphs in Theorem 3.1.1 are also M_1 and M_2 minor free, so (i), (ii), (iii), and (iv) is in fact a complete list of 3-connected $[M_1, M_2, M_3]$ minor free graphs.

Let $\mathcal{B}$ be the set of propellers $P_k(3,3,3)$ and wheels $W_k^{(3)}$, together with the eight graphs in Figure 3.6. In Section 3.4, we will use Theorem 3.1.1 to show that $\mathcal{B}$ is an exhaustive list of bricks. This list appears in [12], except for graphs $K_5^{(2)}$, $P_3^{(2)}$, and $P_3^{(3)}$ (see Figure 3.6), which were omitted, and the second graph in Figure (17c) and Case 2 in the analysis of propeller graphs P_k of the paper, which are not $[M_1, M_2, M_3]$ minor free. In [12], Fonlupt and Naddef sketch a proof that this is an exhaustive list of bricks but omit the details, which we will fill in here.

Theorem 3.1.2. *[12] The family of $[M_1, M_2, M_3]$ minor free graphs is the family of graphs that can be obtained from $\mathcal{B}$ by repeated applications of*

(i) *edge deletion,*

(ii) *edge contraction,*

(iii) *operation Φ_1,*

(iv) *operation Φ_2,* and

(v) *duplication of degree-2 vertices.*

Our proof for the characterization of TSP-perfect graphs proceeds by showing that the brick graphs $\mathcal{B}$ are all TSP-perfect (Section 3.2), that operations Φ_1, Φ_2, and duplication

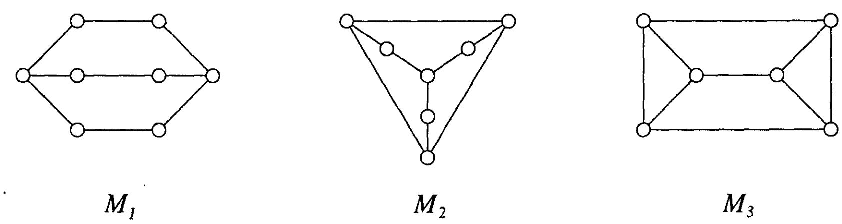


Figure 3.5: Forbidden minors M_1, M_2, M_3.

of degree-2 vertices preserve TSP-perfection (Section 3.3), and that the list of bricks is exhaustive (Section 3.4).

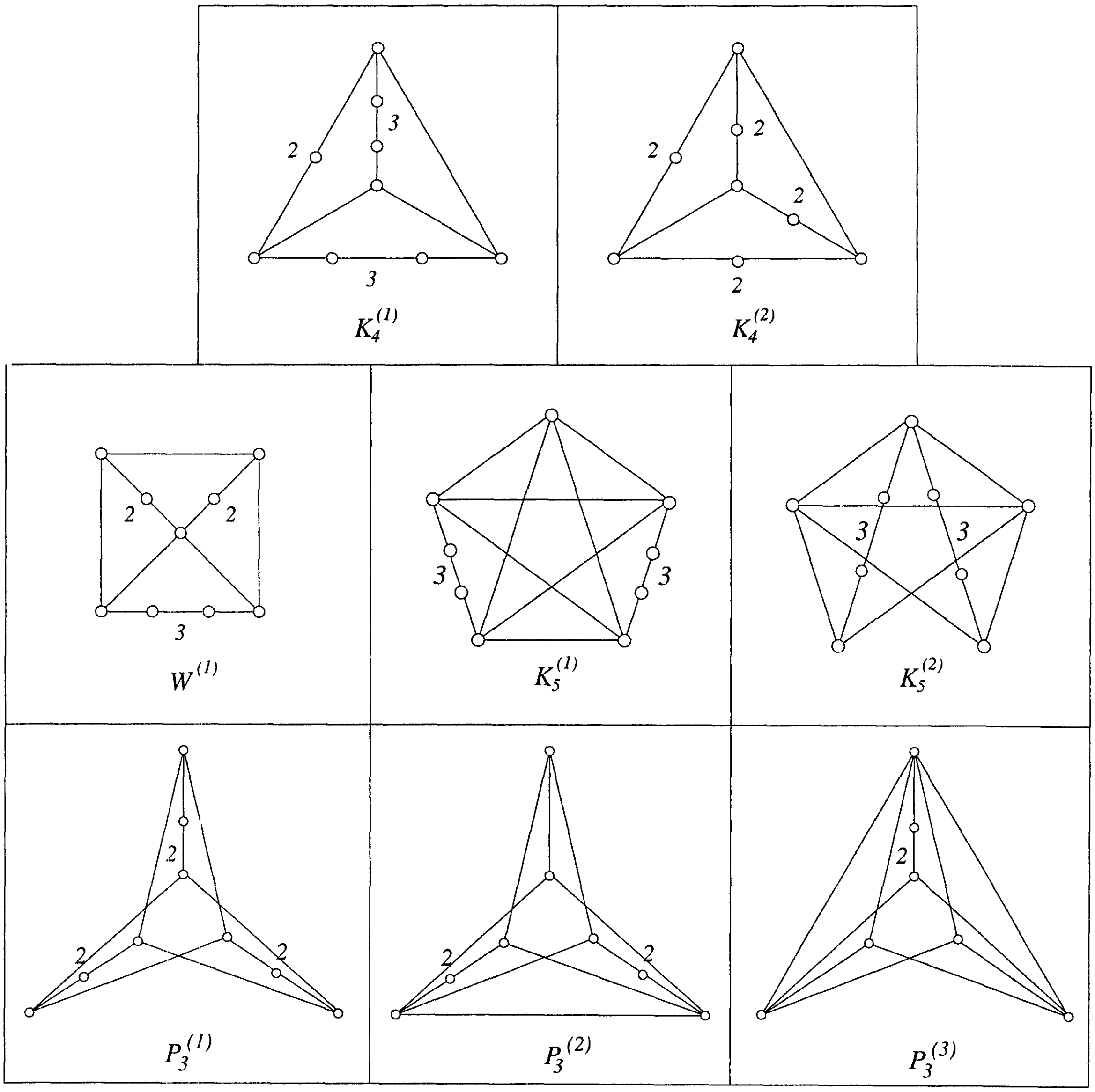


Figure 3.6: $[M_1, M_2, M_3]$ minor free bricks not including wheels and propellers (i-paths are labeled by i in the figure).

3.2 TSP-Perfection of bricks

We first show that all graphs in the list $\mathcal{B}$ are TSP-perfect. For the eight finite graphs $K_4^{(1)}$, $K_4^{(2)}$, $W^{(1)}$, $K_5^{(1)}$, $K_5^{(2)}$, $P_3^{(1)}$, $P_3^{(2)}$, and $P_3^{(3)}$ in Figure 3.6, we use `polymake` to prove TSP-perfection. For each of these graphs, we input the cut and nonnegativity constraints of the fractional TSP polyhedron into `polymake` to generate the extreme points of the polyhedron and verify that all of the extreme points correspond to traveling salesman tours. We leave the details for the Appendix.

Lemma 3.2.1. *Graphs $K_4^{(1)}, K_4^{(2)}, W^{(1)}, K_5^{(1)}$, $K_5^{(2)}$, $P_3^{(1)}$, $P_3^{(2)}$, and $P_3^{(3)}$ are TSP-perfect.*

Proof. (See Appendix.)

We now consider the infinite members of $\mathcal{B}$ and show TSP-perfection for these graphs.

Lemma 3.2.2. *The k-wheels W_k are TSP-perfect.*

Proof. For any non-zero cost function c, we will find a constraint in the fractional TSP polyhedron $P(W_k)$ satisfied at equality by all optimal integral tours. Theorem 2.2.3 then implies that $P(W_k)$ is equal to the convex hull of integer tours and therefore, W_k is TSP-perfect.

We proceed by induction with base case $W_2 = C_3$. In this case, any extreme point x satisfies three inequalities at equality among the cut and nonnegativity constraints. If all three tight constraints are cut constraints, i.e.,

$$x_{e_1} + x_{e_2} = x_{e_1} + x_{e_3} = x_{e_2} + x_{e_3} = 2,$$

then the unique solution is $x_e = 1$ for all edges e, which corresponds to a tour. Otherwise, x must satisfy two of the cut constraints and one of the nonnegativity constraints at equality. The unique solution to such a set of constraints has two edges of value 2 and one edge of value 0, which also corresponds to a tour.

Now, suppose W_{n-1} is TSP-perfect and consider $G = W_n$ with cost function c on the edges. If c does not satisfy the triangle inequality, then there is an edge (i, j) such that $c_{ij} > c_{ik} + c_{kj}$ and in all optimal solutions, $x_{ij} \geq 0$ is a tight constraint. Therefore, we can restrict our attention to cost functions satisfying the triangle inequality. If there is a rim edge $e = \{u, w\}$ in $E(G)$ with cost zero, consider the graph $G' \simeq W_{n-1}$ obtained by contracting the endpoints of edge e into a single vertex v and let $f_u, f_w \in E(G), f_v \in E(G')$ denote the spokes adjacent to u, w and v respectively. Then the triangle inequality and

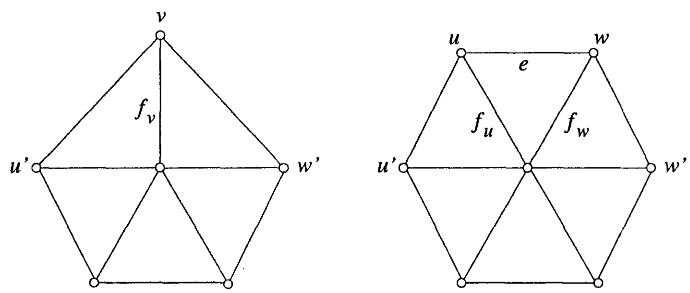


Figure 3.7: Vertex and edge labels for $G' = W_{k-1}$ and $G = W_k$.

$c_e = 0$ together imply $c_{f_u} = c_{f_w}$; assign this cost to edge f_v. We first show that the optimal traveling salesman tours in G and G' have the same cost. For any tour x in G, let $x'_f = x_f$ if $f \notin \{e, f_u, f_w\}$ and $x'_{f_v} = x_{f_u} + x_{f_w}$. Then x' is a tour in G' of the same cost as tour x in G. Also, we can extend any tour x' in G' to a tour x in G of the same cost in the following way. If x'_{f_v} is even, let

$$x_f = \begin{cases} \frac{x'_f}{2} & \text{for } f \in \{f_u, f_w\} \\ \frac{x'_f}{2} + 2 & \text{for } f = e \\ x'_f & \text{otherwise.} \end{cases}$$

Let u', w' denote the vertices adjacent to v on the rim of wheel G' (see Figure 3.7). If x'_{f_v} is odd, then exactly one of $x'_{v,u'}$ or $x'_{v,w'}$ is odd. By symmetry, assume $x'_{v,u'}$ is odd. Then x

defined as follows is a traveling salesman tour in G.

$$x_f = \begin{cases} 1 & \text{for } f = f_u \\ x'_{f_v} - 1 & \text{for } f = f_w \\ 2 & \text{for } f = e \\ x'_{v,u'} & \text{for } f = \{u, u'\} \\ x'_{v,w'} & \text{for } f = \{w, w'\} \\ x'_f & \text{otherwise.} \end{cases}$$

Therefore, the optimal traveling salesman tours in G and G' have the same cost. Since $G' = W_{n-1}$ is TSP-perfect, there is a constraint C that is tight for all optimal traveling salesman tours in G'. If this constraint is the edge constraint for edge f_v, then the edge constraints for f_u and f_v are satisfied at equality in G. If this constraint is any other edge constraint, then the same edge constraint is satisfied at equality for all optimal traveling salesman tours in G. If this constraint is a cut constraint, we can assume by possibly taking complements that vertex v is not in C. Then C is also a tight cut constraint for all optimal traveling salesman tours in G. Therefore, we can assume all rim edges have strictly positive

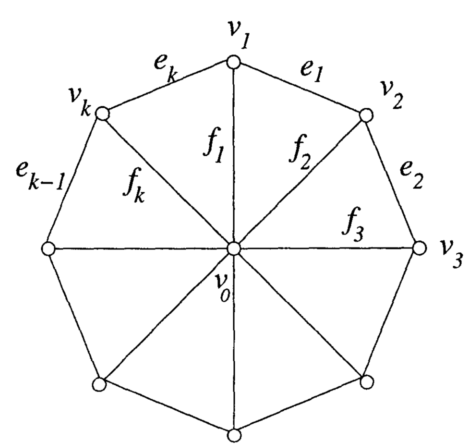


Figure 3.8: Vertex and edge labels for W_k.

cost, implying any optimal tour x satisfies $x_e \leq 2$ for all rim edges. Label the spokes of W_k by $f_1, f_2, \ldots f_k$ such that $c_{f_1} = \max_i\{c_{f_i}\}$, label the rim vertex adjacent to spoke f_i by

v_i, and label the rim edges by $e_1, e_2, \ldots e_k$ where $e_i = \{v_i, v_{i+1}\}$ for $i = 1, 2, \ldots k-1$ and $e_k = \{v_k, v_1\}$ (see Figure 3.8). Note that edge f_1 must have strictly positive cost (otherwise, all spokes would have cost zero, implying all rims have cost zero by the triangle inequality). Then $x_{f_1} \leq 2$ by optimality of x. Suppose $x(\delta(v_1)) > 2$. We first argue that it cannot be the case that $x_{f_1} \geq 1$ and $x_{e_1} = 2$. In such a case, consider x' defined by

$$\begin{aligned} x'_{f_2} &= x_{f_2} + 1 \\ x'_{e_1} &= x_{e_1} - 1 \\ x'_{f_1} &= x_{f_1} - 1 \\ x'_e &= x_e \quad \text{for all other edges } e. \end{aligned}$$

Since x' preserves parity at every vertex and does not disconnect any vertices, x' is also a traveling salesman tour and optimality of x implies $c_{f_2} \geq c_{f_1} + c_{e_1}$. However, $c_{e_1} > 0$ since all rim edges have strictly positive costs, contradicting the maximality of c_{f_1}. The same argument also shows the following cases cannot occur:

$$x_{f_1} \geq 1,\ x_{e_k} = 2$$
$$x_{e_1} \geq 1,\ x_{f_1} = 2$$
$$x_{e_k} \geq 1,\ x_{f_1} = 2.$$

The strictly positive costs on rim edges and edge f_1 together with optimality of x implies $x_e \leq 2$ for all rim edges and edge f_1. If $x(\delta(v_1)) \geq 6$, then $x_{f_1} = x_{e_1} = x_{e_k} = 2$, which cannot happen by the argument above. If $x(\delta(v_1)) = 4$, then the only case for which the above argument does not apply is the case $x_{e_k} = x_{e_1} = 2$, $x_{f_1} = 0$. In this case, consider the smallest i for which $x_{f_i} > 0$ and the largest j for which $x_{f_j} > 0$. Since the solution must be connected and have even degree at every vertex, we must have either $x_{e_1} = x_{e_2} = \cdots = x_{e_{i-1}} = 2$ or $x_{e_j} = x_{e_{j+1}} = \cdots = x_{e_k} = 2$. By symmetry, we can assume

$x_{e_1} = x_{e_2} = \cdots = x_{e_{i-1}} = 2$. Consider the tour x' with

$$\begin{aligned} x'_{f_1} &= x_{f_1} + 1 \\ x'_{e_j} &= x_{e_j} - 1 && \text{for } j \leq i-1 \\ x'_{f_i} &= x_{f_i} - 1 \\ x'_e &= x_e && \text{for all other edges } e. \end{aligned}$$

Then x' is also a traveling salesman tour; by optimality of x, $c_{f_1} \geq c_{e_2} + \ldots + c_{e_i} + c_{f_i}$ and by triangle inequality, equality holds. Now, consider tour x'' with $x''_{e_k} = x'_{e_k} - 1, x''_{f_1} = x'_{f_1} - 1, x''_{f_k} = x'_{f_k} + 1$ and $x''_e = x'_e$ for all other edges e. Since x'' preserves the parity of every vertex and no vertex is disconnected, optimality of x' implies $c_{f_k} \geq c_{e_k} + c_{f_1}$, a contradiction to the choice of f_1 (since $c_{e_k} > 0$). □

As a corollary, we have the following.

Corollary 3.2.3. *Graphs $W_k^{(3)}$ $(k \geq 2)$ are TSP-perfect.*

Proof. This follows from Lemma 2.2.1 and Lemma 3.2.2 since $W_k^{(3)}$ is a minor of W_{3k}. □

To prove propeller graphs are TSP-perfect, we first need the following theorems.

Theorem 3.2.4. *[9] If x is an extreme point of the fractional traveling salesman polyhedron $P(G)$, then x can be defined by a set of edge constraints $x_e = 0$ and cut constraints Θ such that $G(S)$ and $G(\overline{S})$ are both connected for any cut $S \in \Theta$.*

The next theorem follows from two claims in [12]; since it is not stated explicitly in the paper and is proved only for a special class of graphs, we include the proof here for completeness.

Theorem 3.2.5. *[12, Claims 4.4, 4.5] If x is an extreme point of $P(G)$ and e is an edge such that $x_e > 1$, then x restricted to graph $G.e$ is an extreme point of $P(G.e)$.*

Proof. Let $\Theta(x)$ denote the set of tight constraints satisfied by x. We first show that edge e belongs to at most one tight cut in $\Theta(x)$. Otherwise, if there are cuts C_1 and C_2 both containing e, then by possibly considering the complements of C_1 and C_2, we can assume

$e \in (C_1, C_2)$ and $\overline{C_1} \cap \overline{C_2} \neq \emptyset$. Then we have

$$x(\delta(C_1)) = x(C_1, C_2 \cap \overline{C_1}) + x(C_1, \overline{C_2} \cap \overline{C_1}) = 2,$$

implying $x(C_1, \overline{C_1} \cap \overline{C_2}) < 1$. The same argument shows $x(C_2, \overline{C_2} \cap \overline{C_1}) < 1$. Since $\overline{C_1} \cap \overline{C_2} \neq \emptyset$, $C_1 \cup C_2$ is a cut of G and

$$x(\delta(C_1 \cup C_2)) \leq x(C_1, \overline{C_1} \cap \overline{C_2}) + x(C_2, \overline{C_2} \cap \overline{C_1}) < 2,$$

a contradiction.

Therefore, e is contained in at most one tight cut constraint C in $\Theta(x)$ and the constraints $\Theta(x) \backslash \{C\}$ are all tight for the solution $x.e$ induced by x in $G.e$. Since x is an extreme point in $P(G)$ and since at most one constraint for x becomes violated for $x.e$, this implies $x.e$ is an extreme point in $P(G.e)$. □

For any $F \subseteq P(G)$, let

$$\begin{aligned} B_F &= \{j \in E(G) \mid x_j = 0 \text{ for all } x \in F\} \\ D_F &= \{S \subset V(G) \mid |S| \leq n-2 \text{ and } x(\delta(S)) = 2 \text{ for all } x \in F\}. \end{aligned}$$

Two sets $C_1, C_2 \subseteq V(G)$ *cross* if $C_1 \cap C_2 \neq \emptyset$ and neither $C_1 \subseteq C_2$ nor $C_2 \subseteq C_1$. A *nested family* is a family of sets with no pair of crossing sets. In [9], Cornuejols, Fonlupt, and Naddef prove the following theorem.

Theorem 3.2.6. *[9, Theorem 4.9] For graph G, let x be an extreme point of the fractional TSP polyhedron $P(G)$. For any face F of $P(G)$, F can be defined by*

$$F = \{x \in P(G) \mid x_e = 0 \textit{ for all } e \in B_F \textit{ and } x(\delta(S)) = 2 \textit{ for all } S \in D^*\}$$

for some $D^* \subseteq D_F$ such that D^* is a nested family.

For any $x \in P(G)$, let G_x denote the support graph of x. Note that for the nested family D^* in Theorem 3.2.6, we can assume that $V(G) \notin D^*$ and for any $S \in D^*$, $\overline{S} \notin D^*$. Then Theorem 3.2.6 implies the following bound on the number of edges in G_x for an extreme point x.

Theorem 3.2.7. *If x is an extreme point of $P(G)$, then*

$$|E(G_x)| \leq 2|V(G)| - 3.$$

We now prove the TSP-perfection of propellers.

Lemma 3.2.8. *The propeller graphs $P_k(i_1, i_2, i_3)$ are TSP-perfect for $0 \leq i_1, i_2, i_3 \leq 3$.*

Proof. We proceed by induction. $P_1(3,3,3)$ is wheel graph $W_3^{(3)}$ and therefore the graphs $P_1(i_1, i_2, i_3)$ are all TSP-perfect.

Now, for some $k \geq 2$, suppose graphs $P_{k-1}(i_1, i_2, i_3)$ are TSP-perfect for all values of $i_1, i_2, i_3 \in \{0, 1, 2, 3\}$ and suppose there is an extreme point x of the fractional traveling salesman polyhedron of propeller $P_k(i_1, i_2, i_3)$ which does not correspond to a traveling salesman tour. Let G denote the support graph of x in $P_k(i_1, i_2, i_3)$ and let k_2 and k_3 denote the number of spoke vertices v with $deg(v) = 2$ and $deg(v) = 3$ respectively in graph G. Note that there are no spoke vertices of degree 1 in the support graph since the incident edge to this vertex would have value 2 and therefore could be contracted to obtain a counterexample to the TSP-perfection of $P_{k-1}(i_1, i_2, i_3)$ by Theorem 3.2.5.

Now, if $k_2 > 0$, let v be a spoke vertex of degree 2, let a and b be the neighbors of v, and suppose i_1 is the number of edges in the rim path between a and b. Consider the following cases.

Case I. $i_1 = 0, 1, 2$. Then consider the graph G' obtained from G by removing the rim path of i_1 edges between a and b and replacing the rim by edges (a, v) and (b, v). Then G' is a subgraph of $P_{k-1}(2, i_2, i_3)$ and is TSP-perfect by induction. By Lemma 2.2.4, we can duplicate vertex v in G' to obtain a TSP-perfect graph G''. Then graph G is a minor of G'' and is therefore TSP-perfect.

Case II. $i_1 = 3$. In this case, consider the subgraph G' of $P_{k-1}(i_1, i_2, i_3)$ obtained by removing vertex v and edges (a, v) and (b, v). By induction, graph G' is TSP-perfect. If there are any other spoke vertices w of degree 2 adjacent to a and b, then by Lemma 2.2.4, we can duplicate w to obtain v while preserving TSP-perfection. Otherwise, graph G' contains at least two disjoint paths of length 3 from a to b and therefore, can be decomposed by operation Φ_2 at cutset $\{a, b\}$. Then by Corollary 3.3.5, we can add the 2-path $(a, v), (b, v)$ back to graph G' while preserving TSP-perfection.

Therefore, we can assume $k_2 = 0$ and $k_3 = k$. Assume our counterexample minimizes $i_1 + i_2 + i_3$; by Theorem 3.2.5, we can furthermore assume all edges satisfy $x_e \leq 1$. We first show that we can assume at least one of $i_1, i_2, i_3 \leq 1$. Otherwise, if all of the rim paths have two or more edges then by considering the cuts crossing only rim edges along the same rim path, the value of x along then entire path must be equal to 1. By Theorem 3.2.4, there is a set of tight cuts $\Theta(x)$ such that $G(S)$ and $G(\overline{S})$ are both connected for any cut $S \in \Theta(x)$. Any cut S separating rim vertices a, b, c cannot be tight since $\delta(S)$ must contain at least two edges of the paths of value 1 as well as some edge of strictly positive value adjacent to a spoke vertex of degree 3 (which exists since $k_3 > 0$). Thus, the only possible tight constraints are the sets of singleton spoke vertices $\{u_1\}, \{u_2\}, \ldots \{u_k\}$ and constraints containing only vertices along the same rim path (i.e., not separating vertices a, b, c). For rim paths of length i_1, i_2, i_3, let $r(i_1, i_2, i_3)$ denote the number of tight constraints containing only rim edges along the same rim path. Since

$$r(i_1, i_2, i_3) = 2(i_1 + i_2 + i_3) - 9 \text{ for } i_1, i_2, i_3 \geq 2,$$

we have $i_1 + i_2 + i_3 \geq r(i_1, i_2, i_3)$ if $i_1, i_2, i_3 \geq 2$. Therefore

$$3k_3 + (i_1 + i_2 + i_3) > k_3 + r(i_1 + i_2 + i_3). \tag{3.1}$$

The left hand side of Equation (3.1) is the number of nonzero edges in our example and the right hand side is the maximum number of tight constraints. This shows that x cannot be an extreme point. Therefore, one of i_1, i_2, or i_3 is at most 1, implying $i_1 + i_2 + i_3 \leq 7$.

Then by Theorem 3.2.7,

$$\begin{aligned}
|E(G)| &\leq 2|V(G)| - 3 \\
(i_1 + i_2 + i_3) + 3k_3 &\leq 2((i_1 + i_2 + i_3) + k_3) - 3 \\
3k_3 &\leq (i_1 + i_2 + i_3) + 2k_3 - 3 \\
k_3 &\leq (i_1 + i_2 + i_3) - 3 \\
k_3 &\leq 7 - 3 = 4.
\end{aligned}$$

Now, if $k_3 = 4$, then $i_1 + i_2 + i_3 = 7$. Furthermore, since one of i_1, i_2, or i_3 is at most 1, it must be the case that two of i_1, i_2, or i_3 are equal to 3 and the third is equal to 1. Without loss of generality, let $i_1 = i_2 = 3$ and $i_3 = 1$. In graph $P_4(3, 3, 1)$, the two rim paths of length three must have value 1 on all edges and therefore the cut containing the vertex adjacent to these two rim edges cannot be a tight cut (since it contains two edges of value 1 and at least one nonzero edge adjacent to a spoke vertex). This implies the maximum number of tight nested sets on these vertices is at most $2|V(P_4(3, 3, 1))| - 4 = 2(11) - 4 = 18$ while the number of edges is $|E(P_4(3, 3, 1))| = (i_1 + i_2 + i_3) + 3k_3 = 7 + 3(4) = 19$ and therefore, x cannot be an extreme point.

It follows that $k_3 \leq 3$. We show the graph $P_3(3, 3, 1)$ cannot be a counterexample by enumerating the extreme points of the corresponding fractional traveling salesman polytope in `polymake` and verifying all extreme points are traveling salesman tours (see Appendix).

□

3.3 Operations Φ_1 and Φ_2

Now that we have demonstrated the set of bricks are TSP-perfect, we turn to the two operations Φ_1 and Φ_2, which give the remaining $[M_1, M_2, M_3]$ minor free graphs. We show that both operations preserve TSP-perfection.

Theorem 3.3.1. *TSP-perfection is preserved under Φ_1.*

Proof. This follows from Lemma 2.2.6 by setting $s = t$. □

To prove TSP-perfection is also preserved under Φ_2, we recall the following lemma. For graph $G = (V, E)$ and vertices $s, t \in V$, recall $G_{s,t}(3)$ is the graph obtained by adding a path of length 3 from s to t.

Lemma 2.3.2 If $G_{s,t}(3)$ is TSP-perfect, then G is s-t walk perfect.

In the next two theorems, let $\{s, t\}$ be a 2-vertex disconnecting set of G into nonempty components and suppose Φ_2 decomposes G into G_1 and G_2 at vertices s and t. Recall that H_i is the subgraph of G_i before the addition of the 3-path between s and t.

Theorem 3.3.2. *If G is TSP-perfect and can be decomposed by Φ_2 into graphs G_1 and G_2 (i.e., both H_1 and H_2 have paths of length at least 3 between s and t), then G_1 and G_2 are also TSP-perfect.*

Proof. Since H_1 and H_2 both have paths of length at least three between s and t, G_1 and G_2 are minors of G. Since TSP-perfection is preserved under minors, it follows that G_1 and G_2 are TSP-perfect. □

Theorem 3.3.3. *If G_1 and G_2 are TSP-perfect, then G is TSP-perfect.*

Proof. For a fixed cost function c on G, let $X_{TSP}(G)$ be the set of minimum cost traveling salesman tours on G and let $x \in X_{TSP}(G)$. An s-t *2-cycle cover* will denote a union of two cycles, one containing s and the other containing t such that every vertex is covered by at least one of the cycles. Note that every traveling salesman tour in G is either the union of s-t traveling salesman walks in both H_1 and H_2 or the union of an s-t 2-cycle cover in one and a traveling salesman tour in the other. Let p_i, t_i, c_i denote the costs of the optimal s-t traveling salesman walk, optimal traveling salesman tour and optimal s-t 2-cycle cover in

H_i respectively. Since G_i is TSP-perfect, Lemma 2.3.2 implies H_i is s-t walk perfect. Since any tour in H_i is a feasible point in the fractional s-t walk polyhedron and any extreme point of $P(H_i, s, t)$ is an s-t traveling salesman walk by s-t walk-perfection, we have $p_i \leq t_i$.

Claim 3.3.4. $p_i - c_i \leq t_i - p_i$.

To see why this is true, let y_i be a minimal s-t 2-cycle cover in H_i and let z_i be a minimal tour in H_i. Then

$$\begin{aligned} y_i(C) + z_i(C) &\geq 2 \text{ for } |\{s,t\} \cap C| = 1 \\ y_i(C) + z_i(C) &\geq 4 \text{ for } |\{s,t\} \cap C| = 0 \text{ or } 2 \end{aligned}$$

Therefore, $\frac{y_i+z_i}{2}$ is a feasible point in the fractional s-t walk polyhedron of H_i and since H_i is s-t walk perfect, this implies the minimal s-t walk has cost

$$p_i \leq \frac{cost(y_i) + cost(z_i)}{2} = \frac{c_i + t_i}{2}.$$

This gives $2p_i \leq c_i + t_i$, or $p_i - c_i \leq t_i - p_i$ as claimed. □

Without loss of generality, assume $p_1 - c_1 \leq p_2 - c_2$. Note that the optimal traveling salesman tour in G has cost

$$cost(x) = \min\{c_1 + t_2, p_1 + p_2, c_2 + t_1\}.$$

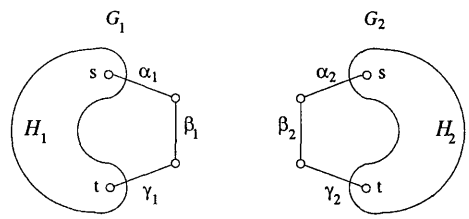
Case I. Suppose $c_1 + t_2 = p_1 + p_2 = c_2 + t_1$. In this case, $c_1 \leq p_1$ and $c_2 \leq p_2$ (otherwise $p_1 + p_2 < c_1 + t_2$ or $p_1 + p_2 < t_1 + c_2$). Furthermore, $t_2 - p_2 = p_1 - c_1$ implies the inequalities

$$p_1 - c_1 \leq p_2 - c_2 \leq t_2 - p_2$$

must all hold with equality and therefore

$$p_1 - c_1 = t_1 - p_1 = p_2 - c_2 = t_2 - p_2.$$

For $i = 1, 2$, let $\alpha_i, \beta_i, \gamma_i$ be the following edge costs on the 3-path from s to t:



$$\alpha_i = \gamma_i = 0$$

$$\beta_i = \frac{t_i - c_i}{2}.$$

For these edge costs (all of which are nonnegative), the optimal s-t 2-cycle covers, s-t traveling salesman walks and traveling salesman tours in H_i can all be extended to optimal traveling salesman tours in G_i with costs

$$\begin{aligned} c_i + 2(\alpha_i + \beta_i + \gamma_i) &= c_i + (t_i - c_i) \\ &= t_i \\ p_i + (\alpha_i + \beta_i + \gamma_i) &= p_i + \frac{t_i - c_i}{2} \\ &= t_i \\ t_i + 2(\alpha_i + \gamma_i) &= t_i. \end{aligned}$$

Furthermore, these are the only optimal traveling salesman tours of G_i. Since G_i is TSP-perfect, there is a constraint C_i in polyhedron $P(G_i)$ that is tight for all optimal traveling salesman tours. If one of the tight constraints is an edge constraint $x_e \geq 0$, then e cannot be an edge in $G_i \backslash H_i$ since there are optimal traveling salesman tours in G_i which use each edge of $G_i \backslash H_i$. Therefore, the edge constraint $x_e \geq 0$ is also tight for all $x \in X_{TSP}(G)$. If one of the constraints is a cut constraint C satisfying $s, t \notin C$ then the constraint C is tight for all $x \in T$. Otherwise, we can assume the cut constraints are C_1 and C_2 with $s \in C_i, t \notin C_i$. In this case, $C = C_1 \cup C_2$ satisfies $x(\delta(C)) = 2$ for all $x \in T$.

Case II. If $c_1 + t_2, p_1 + p_2$ and $c_2 + t_1$ are not all equal, we can assume without loss of generality that $p_1 - c_1 < t_2 - p_2$. Then $p_1 + p_2 < c_1 + t_2$, so the optimal s-t 2-cycle cover in H_1 together with the optimal traveling salesman tour in H_2 is not optimal. Suppose $\min\{c_1 + t_2, p_1 + p_2, c_2 + t_1\}$ is achieved exactly twice with $c_2 + t_1 = p_1 + p_2 < c_1 + t_2$. Consider edge costs on the 3-path from s to t given by

$$\alpha_i = \gamma_i = 0$$

$$\beta_i = t_1 - p_1 (= p_2 - c_2).$$

For these edge costs (all of which are nonnegative), the optimal traveling salesman tours in H_1, optimal s-t 2-cycle cover in H_2, and optimal s-t traveling salesman walks in H_i can all be extended to optimal traveling salesman tours in G_1 and G_2 with costs

$$\begin{aligned} p_1 + (\alpha_1 + \beta_1 + \gamma_1) &= p_1 + (t_1 - p_1) \\ &= t_1 \\ t_1 + 2(\alpha_1 + \gamma_1) &= t_1 \end{aligned} \qquad \begin{aligned} p_2 + (\alpha_2 + \beta_2 + \gamma_2) &= p_2 + (p_2 - c_2) \\ &= 2p_2 - c_2 \\ c_2 + 2(\alpha_2 + \beta_2 + \gamma_2) &= c_2 + 2(p_2 - c_2) \\ &= 2p_2 - c_2. \end{aligned}$$

Note that the extension of the minimum 2-cycle cover in H_1 to a tour in G_1 has cost $c_1 + 2(t_1 - p_1) = c_1 + 2t_1 - 2p_1$, which is at least t_1 by Claim 3.3.4. Similarly, the extension of the minimum traveling salesman tour in H_2 to a tour in G_2 has cost t_2 which is at least $2p_2 - c_2$. Since G_1 and G_2 are TSP-perfect, there is a constraint C_i in each polyhedron $P(G_i)$ that is tight for all optimal traveling salesman tours. We argue as above to find a tight constraint C from C_i for all optimal traveling salesman tours $x \in X_{TSP}(G)$.

Case III. Finally, suppose $c_1 + t_2, p_1 + p_2$ and $c_2 + t_1$ are not all equal and the minimum of the three is achieved exactly once. We again assume without loss of generality that $p_1 - c_1 < t_2 - p_2$. The two cases are $c_2 + t_1 < p_1 + p_2$ and $p_1 + p_2 < c_2 + t_1$. In both cases, for edge costs

$$\alpha_i = \gamma_i = 0$$

$$\beta_i = \frac{t_i - c_i}{2},$$

the optimal s-t 2-cycle covers, optimal s-t traveling salesman walks and traveling salesman tours in H_i can be extended to optimal traveling salesman tours in G_i with costs

$$\begin{aligned}
c_i + 2(\alpha_i + \beta_i + \gamma_i) &= c_i + (t_i - c_i) \\
&= t_i \\
p_i + (\alpha_i + \beta_i + \gamma_i) &= p_i + \frac{t_i - c_i}{2} \\
&= p_i + \frac{(t_i - p_i) + (p_i - c_i)}{2} \\
&\leq p_i + \frac{2(t_i - p_i)}{2} = t_i \\
t_i + 2(\alpha_i + \gamma_i) &= t_i.
\end{aligned}$$

Therefore, in the case $c_2+t_1 < p_1+p_2$, the optimal tours in G_i are achieved by extending the optimal s-t 2-cycle covers in H_1 and the optimal traveling salesman tours in H_2. Similarly, in the case $p_1+p_2 < c_2+t_1$, the optimal tours in G_i are achieved by extending the optimal traveling salesman walks in H_i to tours in G_i. Since G_1 and G_2 are TSP-perfect, there is a constraint C_i in each polyhedron $P(G_i)$ that is tight for all optimal traveling salesman tours. We argue as above to find a tight constraint C from C_i for all optimal traveling salesman tours $x \in X_{TSP}(G)$. □

Corollary 3.3.5. *Let G be a graph with a 2-vertex disconnecting set $\{s, t\}$ which can be decomposed into graphs G_1 and G_2 by operation Φ_2. Consider the graph G' obtained from G by adding a 2-path between s and t. If G is TSP-perfect, then G' is also TSP-perfect.*

Proof. First, suppose G has no 2-path between s and t and denote the added 2-path by $e_1 = (s, u), e_2 = (u, t)$ (for some vertex $u \notin V(G)$). For $G'_1 = G_1 \cup \{e_1, e_2\}$, $G'_2 = G_2$, and H as shown in Figure 3.9, we have

$$\begin{aligned}
G' &= G'_1 \circ_{\Phi_2} G'_2 \\
&= (G_1 \circ_{\Phi_2} H) \circ_{\Phi_2} G_2.
\end{aligned}$$

Since G is TSP-perfect and decomposes into G_1 and G_2 by operation Φ_2, Theorem 3.3.2

implies graphs G_1 and G_2 are TSP-perfect. Also, H is TSP-perfect because it is a subset of wheel graph W_6. Then applying Theorem 3.3.3 twice implies G' is TSP-perfect.

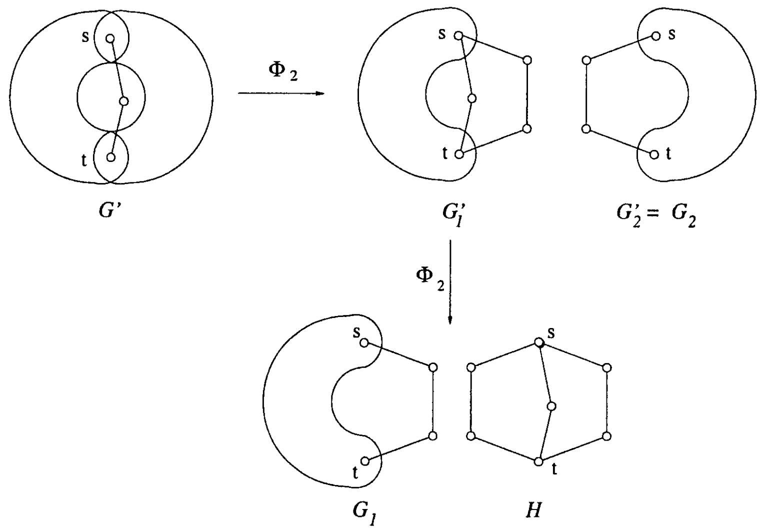


Figure 3.9: Adding 2-paths.

Now, if G has a 2-path $(s,u),(u,t)$ between s and t, then adding another 2-path between s and t is the same as duplicating vertex u, which preserves TSP-perfection by Lemma 2.2.4. □

3.4 Exhaustive List of Bricks

In this section, we show that the set $\mathcal{B}$ of graphs in Figure 3.12 together with wheels and propellers is an exhaustive list of bricks. From Theorem 3.1.1, the only 3-connected M_3 minor free graphs are the following:

(i) K_i for $i = 1, 2, \ldots 5$

(ii) $K_5 \backslash \{e\}$ for any edge e

(iii) W_k for $k \geq 3$

(iv) $P_k(0,0,0), P_k(0,0,1), P_k(0,1,1), P_k(1,1,1)$ for $k \geq 3$.

For these graphs, we consider replacing each edge by a 2-path or 3-paths and show that the result either

(a) is a minor of a wheel graph, propeller graph, or one of the graphs in Figure 3.12, or

(b) contains one of M_1, M_2, or M_3 as a minor.

If the graph contains M_1 as a minor, we will indicate M_1 in the figure by two vertices with black shading together with three paths of length at least 3 between these two vertices (shown by dotted lines in Figure 3.10). If the graph contains M_2 as a minor, the cycle which

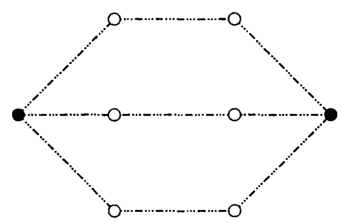


Figure 3.10: Vertices s and t and paths indicating minor M_1.

corresponds to the triangle in M_2 after the minor contractions will be lightly shaded. Also, the vertex connected to the triangle by three paths of length at least 2 will be shaded black and the three paths will be dotted (see Figure 3.11).

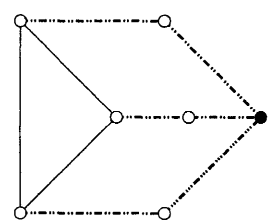


Figure 3.11: Shaded triangle and paths indicating minor M_2.

Note that Lemmas 3.2.1, 3.2.2, and 3.2.8 together show that all graphs in $\mathcal{B}$ are TSP-perfect and are therefore $[M_1, M_2, M_3]$ minor free.

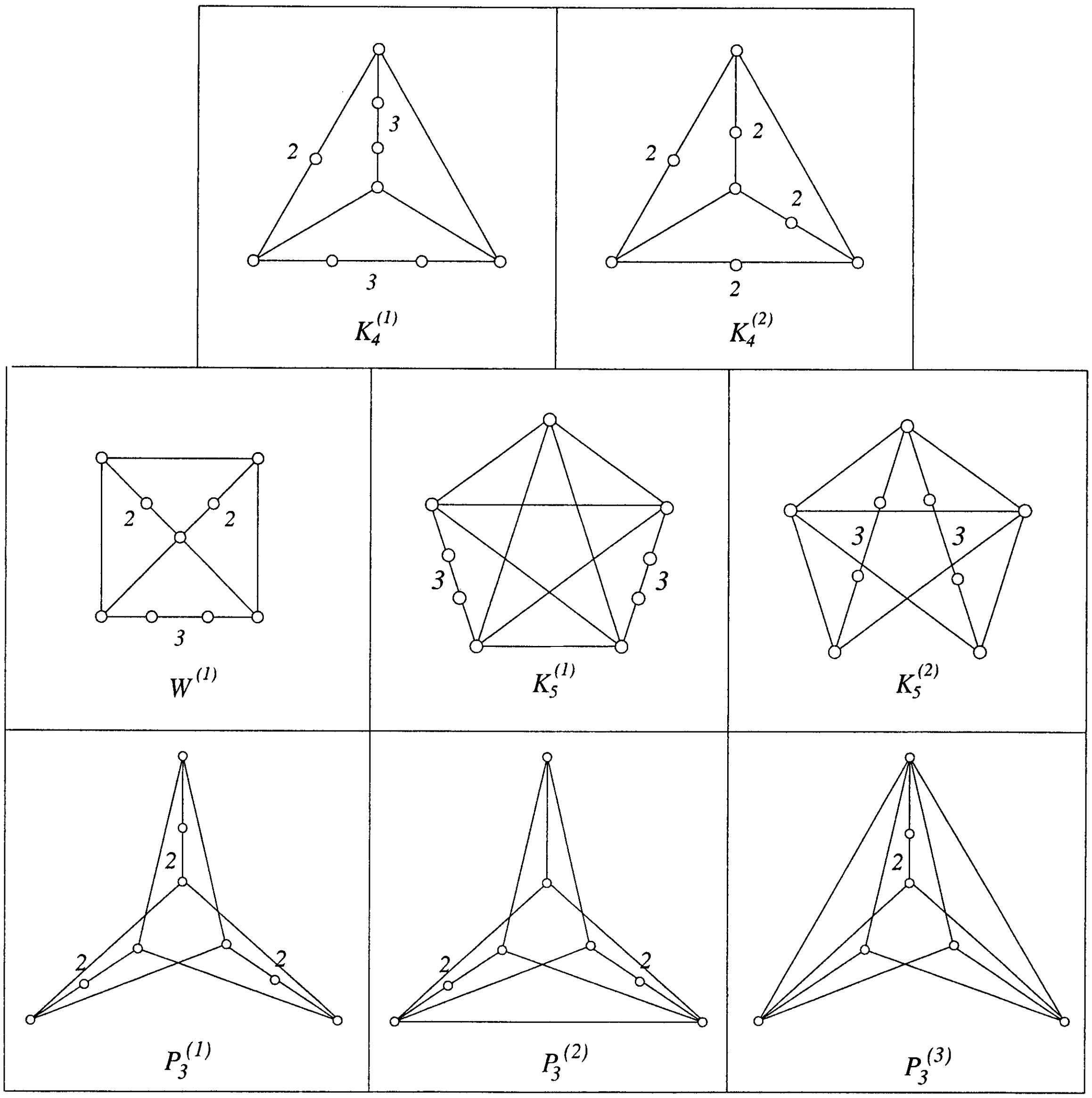


Figure 3.12: $[M_1, M_2, M_3]$ minor free bricks not including wheels and propellers.

3.4.1 Bricks from K_2 and K_3

In K_2 and K_3, replacing all edges with 3-paths results in a minor of wheel graph $W_3^{(3)}$ (see Figure 3.13).

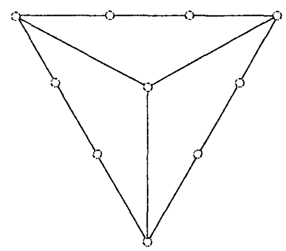


Figure 3.13: Wheel graph W_3^3.

3.4.2 Bricks from K_4 (= W_3)

In this section, we show the following graphs and their minors are the only $[M_1, M_2, M_3]$ minor free graphs obtained from K_4 by replacing edges by 2-paths and 3-paths.

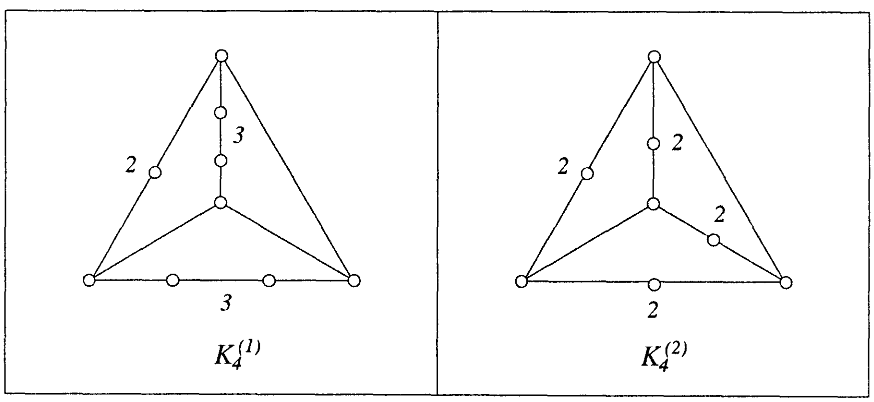


Figure 3.14: Bricks from K_4.

Cases K4.I and K4.II If any edge or any two edges in K_4 are replaced by 3-paths, the resulting graph is a minor of $K_4^{(1)}$ or wheel graph $W_3^{(3)}$.

Case K4.III Replacing three edges:

Case K4.III.i If the three edges are adjacent to the same vertex, the result is graph M_2 (see Figure 3.15(a)).

Case K4.III.ii Suppose the three edges form a path with different initial and final vertices. If the path sequence replacing the edges is 2-path, 3-path, 2-path, the resulting graph contains an M_1 minor (see Figure 3.15(b)). For any other path sequence with different initial and final vertices, the resulting graph is either a minor of $K_4^{(1)}$ or contains a 2-path, 3-path, 2-path minor.

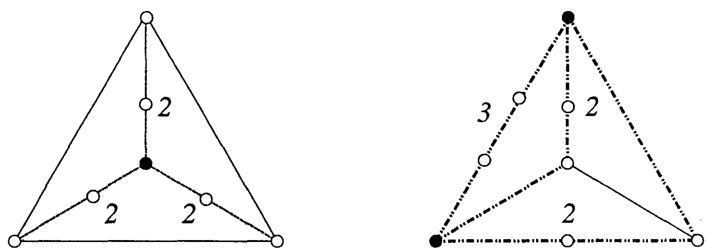


Figure 3.15: (a) Case K4.III.i (b) Case K4.III.ii.

Case K4.IV Replacing four edges:

By Case K4.III.i, if three of the edges replaced by paths are adjacent to the same vertex, then the resulting graph contains an M_2 minor. Otherwise, the four edges form a cycle. If any of the edges is a 3-path, then it contains the graph in Figure 3.15(b) (and therefore M_1) as a minor. Otherwise, all edges are replaced by 2-paths, resulting in graph $K_4^{(2)}$ (see Figure 3.14).

Case K4.V Replacing five edges:

Since there is no 5-cycle in K_4, three of the edges replaced by paths must be adjacent to the same vertex, which is forbidden by Case K4.III.i.

3.4.3 Bricks from W_4 ($= K_5\backslash\{e_1, e_2\}$)

In this section, we show the following graph and its minors are the only $[M_1, M_2, M_3]$ minor free graphs obtained from W_4 by replacing edges by 2-paths and 3-paths.

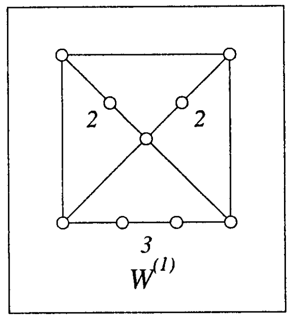


Figure 3.16: Bricks from W_4.

Case W4.I Replacing one edge in W_4 results in a minor of wheel graph $W_4^{(3)}$ or propeller graph $P_2(3, 1, 0)$ (see Figure 3.17).

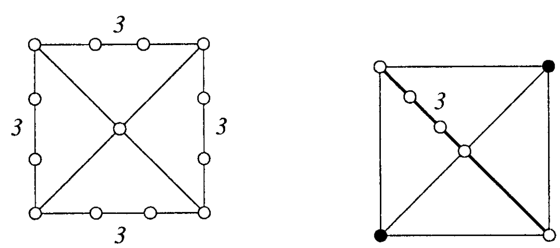


Figure 3.17: Case W4.I (a) Graph $W_4^{(3)}$ (b) Graph $P_2(3, 1, 0)$. Rim edges are darkened and spoke vertices are indicated by black shading.

Case W4.II Replacing two edges:

Case W4.II.i If the two edges are adjacent spokes and are both replaced by 2-paths, the resulting graph is a minor of $W^{(1)}$.

Case W4.II.ii If the two edges are adjacent spokes and are replaced by a 3-path and a 2-path, the result contains an M_1 minor (see Figure 3.18(a)).

Case W4.II.iii If the two edges are nonadjacent spokes, the result is a minor of propeller $P_2(3, 3, 0)$ (see Figure 3.18(b)).

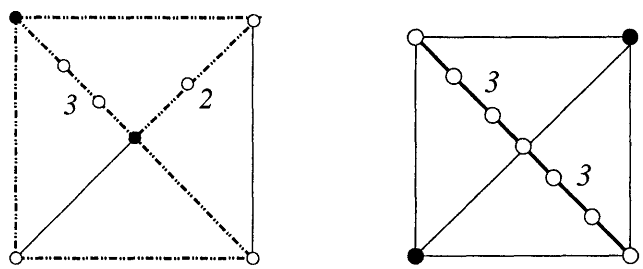


Figure 3.18: (a) Case W4.II.ii (b) Case W4.II.iii (graph $P_2(3,3,0)$). Rim edges are darkened and spoke vertices are indicated by black shading.

Case W4.II.iv If the two edges are a spoke and a nonadjacent rim, the result is a minor of $K_5^{(1)}$ (since W_4 is a subgraph of K_5; see Figure 3.22).

Case W4.II.v If the two edges are a spoke and an adjacent rim, the result contains an M_2 minor (see Figure 3.19).

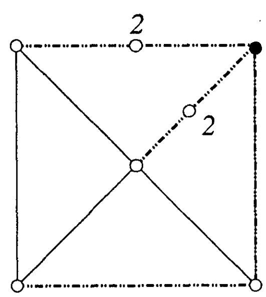


Figure 3.19: Case W.4.II.v.

Case W4.III Replacing three edges:

Case W4.III.i If all three edges are rim edges, then the resulting graph is a subgraph of $W_4^{(3)}$.

Case W4.III.ii If all three edges are spoke edges, the result contains an M_2 minor (see Figure 3.20).

Case W4.III.iii If the three edges are two spokes and a rim, then by Case W4.II.v, the rim cannot be adjacent to either spoke, implying the spokes are

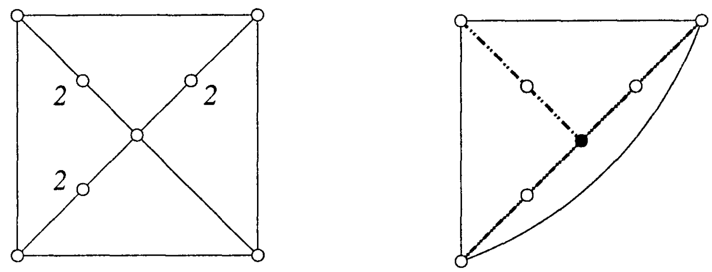


Figure 3.20: Case W4.III.ii. Minor M_2 is shown in figure to the right.

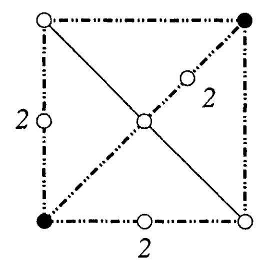


Figure 3.21: Case W4.III.iv.

adjacent. Then by Case W4.II.ii, the two spokes must both be replaced by 2-paths, which results in a minor of $W^{(1)}$ (see Figure 3.16).

Case W4.III.iv. If the three edges are two rims and a spoke, then by Case W4.II.v, the spoke must not be adjacent to either rim. Figure 3.21 shows that such a graph contains an M_1 minor.

Case W4.IV Replacing four edges:

Case W4.IV.i If the four edges are all rims, the result is a subgraph of $W_4^{(3)}$ (see Figure 3.17(a)).

Case W4.IV.ii The four edges cannot all be spokes by Case W4.III.ii.

Case W4.IV.iii If the four edges contain both rims and spokes, then it must contain an adjacent rim and spoke, which is forbidden by Case W4.II.v.

Case W4.V Any five edges must contain an adjacent rim and spoke, which is forbidden by Case W4.II.v.

3.4.4 Bricks from K_5

In this section, we show the following graph and its minors are the only $[M_1, M_2, M_3]$ minor free graphs obtained from K_5 by replacing edges by 2-paths and 3-paths.

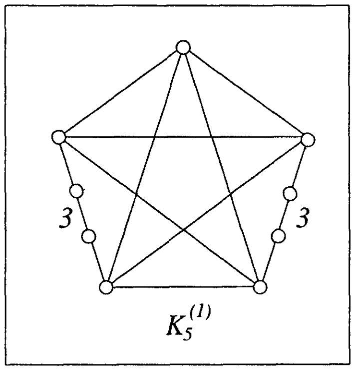


Figure 3.22: Bricks from K_5.

Case K5.I Replacing one edge in K_5 results in a minor of $K_5^{(1)}$.

Case K5.II. Replacing two edges:

> **Case K5.II.i** If the two edges are nonadjacent, the result is a subgraph of $K_5^{(1)}$.
>
> **Case K5.II.ii** If the two edges are adjacent, the result contains an M_2 minor (see Figure 3.23).

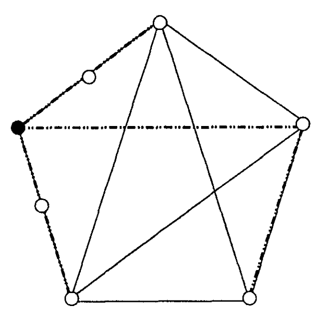


Figure 3.23: Case K5.II.ii.

Case K5.III Since there are two adjacent edges among any three edges in K_5, Case K5.II.ii implies that no three or more edges can be replaced.

3.4.5 Bricks from $K_5\backslash e$ (= P_2)

In this section, we show the following graph and its minors are the only $[M_1, M_2, M_3]$ minor free graphs obtained from $K_5\backslash e$ by replacing edges by 2-paths and 3-paths.

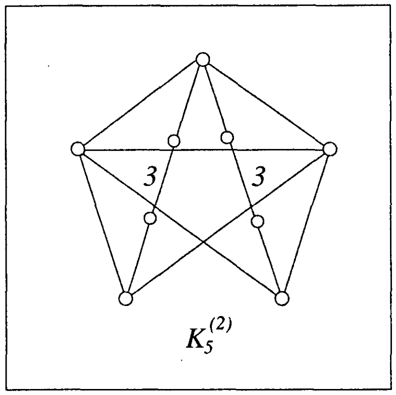


Figure 3.24: Bricks from K_5.

Note that if we partition the vertices of $K_5\backslash e$ into classes A and B, where B contains the two endpoints of e and $A = V\backslash B$, then all vertices within class A are isomorphic and all vertices within class B are isomorphic.

Case P2.I Replacing any single edge results in a subgraph of $K_5^{(1)}$ (see Figure 3.22).

Case P2.II Replacing two edges:

> **Case P2.II.i** If the two edges e_1, e_2 are such that e_1 lies within $E(A)$, e_2 crosses cut (A, B), and e_1 and e_2 are adjacent, the result contains an M_2 minor (see Figure 3.25(a)).
>
> **Case P2.II.ii** If the two edges e_1, e_2 are such that e_1 lies within $E(A)$, e_2 crosses cut (A, B), and e_1 and e_2 are nonadjacent, then the result is a minor of $K_5^{(1)}$.
>
> **Case P2.II.iii** If both edges are adjacent to the same vertex in B, the result again contains an M_2 minor (see Figure 3.25(b)).
>
> **Case P2.II.iv** If both edges cross cut (A, B) and are not both adjacent to the same vertex in B, the resulting graph is a minor of one of $K_5^{(1)}$ or $K_5^{(2)}$.

Case P2.II.v If both edges are in $E(A)$, then the result is a minor of propeller graph $P_2(3,3,3)$.

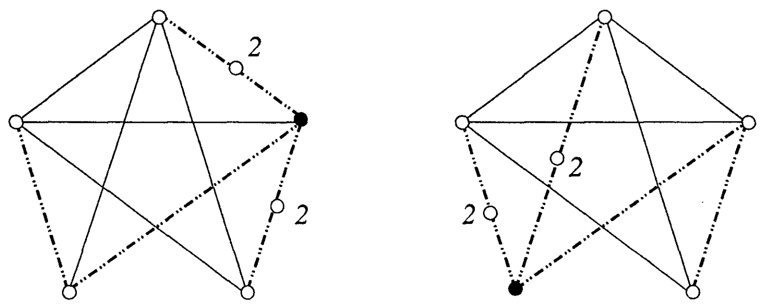


Figure 3.25: (a) Case P2.II.i (b) Case P2.II.ii.

Case P2.III Replacing three edges:

Case P2.III.i If all three edges are in $E(A)$, the graph is a minor of $P_2(3,3,3)$.

Case P2.III.ii If two edges e_1, e_2 are in $E(A)$ and the third e_3 is not, then e_3 must be adjacent to one of e_1 or e_2, which is forbidden by Case P2.II.i.

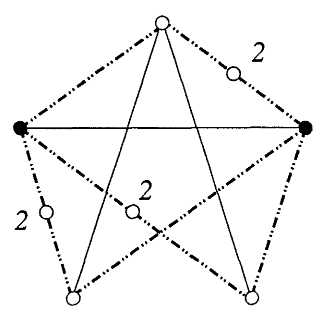


Figure 3.26: Case P2.III.iii

Case P2.III.iii If one edge is in $E(A)$ and the other two are not, then the only graphs not forbidden by Cases P2.II.i and P2.II.iii must have two edges crossing cut (A, B) which are adjacent to the same vertex in A and nonadjacent to the third edge. Any such graph contains the graph in Figure 3.26, which contains M_1 as a minor.

Case P2.III.iv If all three edges are in cut (A, B), then two of these edges must be adjacent to the same vertex in B, which is forbidden by Case P2.II.iii.

Case P2.IV Among any four edges in $K_5\backslash e$, there must be two edges in the pattern considered in either Case P2.II.i or Case P2.II.iii, so no replacement of four edges by 2-paths and 3-paths results in an $[M_1, M_2, M_3]$ minor free graph.

3.4.6 Bricks from wheels

In the wheel graphs W_k with $k \geq 5$, replacing all rim edges by 3-paths results in $[M_1, M_2, M_3]$ minor free wheel graph $W_k^{(3)}$. However, Figure 3.27 shows that replacing any spoke results in a graph containing an M_2 minor (see Figure 3.27).

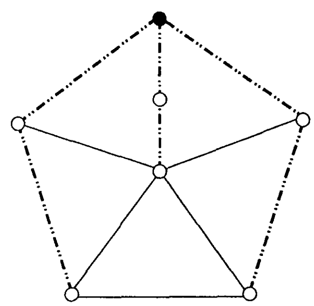


Figure 3.27: Replacing spoke in W_k.

3.4.7 Bricks from Propellers P_k for $k \geq 4$

In the propeller graphs P_k, replacing all rim edges results in a minor of $[M_1, M_2, M_3]$ minor free graph $P_k(3,3,3)$. However, Figure 3.28 shows that replacing any spoke edge in $P_k(0,0,0)$ for $k \geq 4$ (and hence replacing any spoke edge in $P_k(i_1, i_2, i_3)$ for $k \geq 4$) results in a graph containing an M_2 minor.

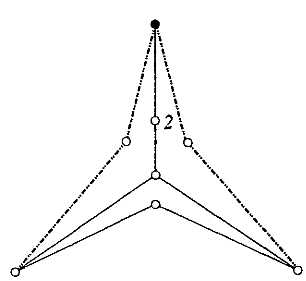


Figure 3.28: Replacing spoke by 2-path in $P_4(0,0,0)$.

3.4.8 Bricks from $P_3(0,0,0), P_3(0,0,1), P_3(0,1,1)$ and $P_3(1,1,1)$

In this section, we show the following graphs and their minors are the only $[M_1, M_2, M_3]$ minor free graphs obtained from $P_3(0,0,0), P_3(0,0,1), P_3(0,1,1)$ and $P_3(1,1,1)$ by replacing edges by 2-paths and 3-paths.

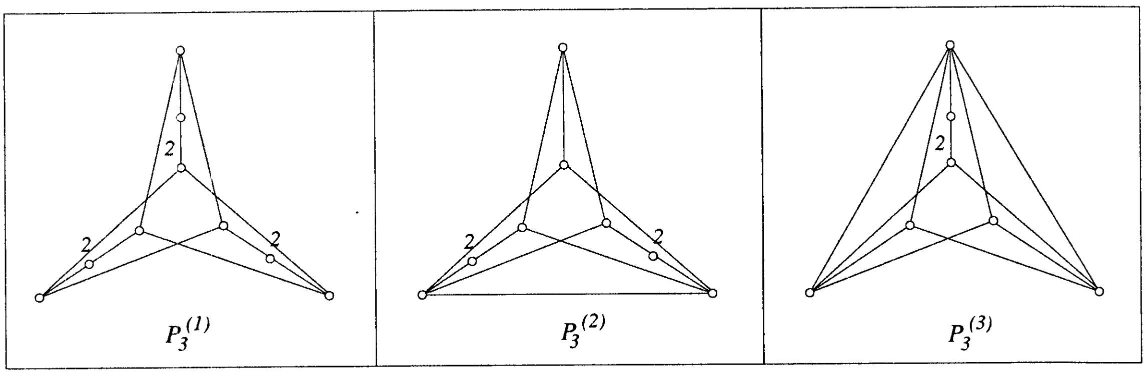


Figure 3.29: Bricks from $P_3(0,0,0), P_3(0,0,1), P_3(0,1,1)$, and $P_3(1,1,1)$.

In graphs $P_3(0,0,0), P_3(0,0,1), P_3(0,1,1)$, and $P_3(1,1,1)$, replacing all rim edges by 3-paths results in minors of propeller graphs $P_3(3,3,3)$. Therefore, we can consider replacements involving at least one spoke edge.

Case $P_3(0,0,0)$.I If we replace one spoke edge of $P_3(0,0,0)$ by a 2-path, the result is a minor of $P_3^{(1)}$. If we replace one spoke edge of $P_3(0,0,0)$ by a 3-path, the result contains an M_1 minor (see Figure 3.30(a)).

Case $P_3(0,0,0)$.II Since $P_3(0,0,0)$ is the complete bipartite graph $K(3,3)$, the graph is vertex transitive and therefore, the pattern of edges replaced depends only on whether the edges are adjacent or not.

> **Case** $P_3(0,0,0)$.II.i If the two edges are adjacent spokes, then the result contains an M_2 minor (see Figure 3.30(b)).
>
> **Case** $P_3(0,0,0)$.II.ii If the two edges are non-adjacent spokes, then they must both be replaced by 2-paths by Case $P_3(0,0,0)$.I. The result is then a minor of $P_3^{(1)}$.

Case $P_3(0,0,0)$.III If we replace three edges in $P_3(0,0,0)$, then by Case $P_3(0,0,0)$.II.i, the

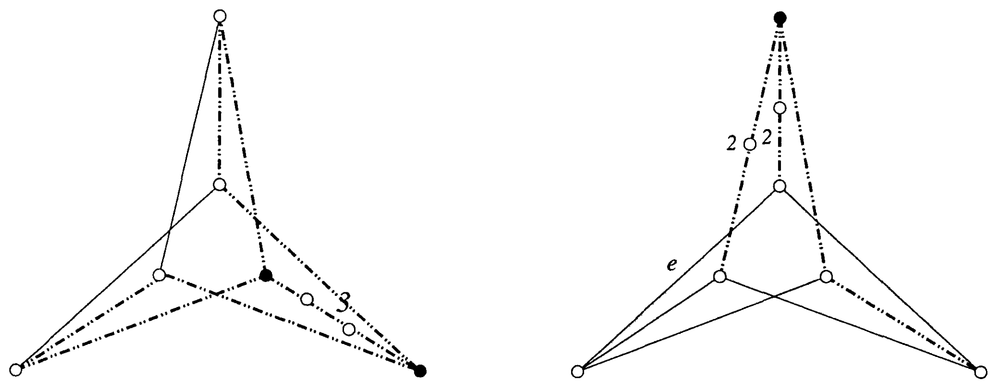


Figure 3.30: (a) Case $P_3(0,0,0)$.I (b) Case $P_3(0,0,0)$.II.i. M_2 minor is obtained by contracting edge e.

three edges must all be non-adjacent spokes and by Case $P_3(0,0,0)$.I, the three edges must all be replaced by 2-paths. The resulting graph is a minor of $P_3^{(1)}$.

Case $P_3(0,0,0)$.IV Any four edges in $P_3(0,0,0)$ must contain two adjacent spoke edges and therefore Case $P_3(0,0,0)$.II.i forbids replacing any four or more edges.

In graph $P_3(0,0,1)$, let v_1, v_2, v_3 denote the rim vertices and suppose the rim edge present in $P_3(0,0,1)$ is edge (v_2, v_3).

Case $P_3(0,0,1)$.I Replacing one edge:

> **Case** $P_3(0,0,1)$.I.i If any spoke edge of $P_3(0,0,1)$ is replaced by a 3-path, then by Case $P_3(0,0,0)$.I, the resulting graph contains an M_1 minor (see Figure 3.30(a)).
>
> **Case** $P_3(0,0,1)$.I.ii If a spoke edge adjacent to rim edge (v_2, v_3) is replaced by 2-path, the resulting graph is a minor of graph $P_3^{(2)}$.
>
> **Case** $P_3(0,0,1)$.I.iii If a spoke edge adjacent to the rim vertex v_1 is replaced by a 2-path, the resulting graph contains an M_2 minor (see Figure 3.31).

Case $P_3(0,0,1)$.II Replacing two edges:

> **Case** $P_3(0,0,1)$.II.i If the two edges are adjacent spokes, the resulting graph contains an M_2 minor by case $P_3(0,0,0)$.II.i (see Figure 3.30(b)).
>
> **Case** $P_3(0,0,1)$.II.ii If the two edges are non-adjacent spokes, then they must both be replaced by 2-paths by Case $P_3(0,0,0)$.I. Also, neither spoke can be

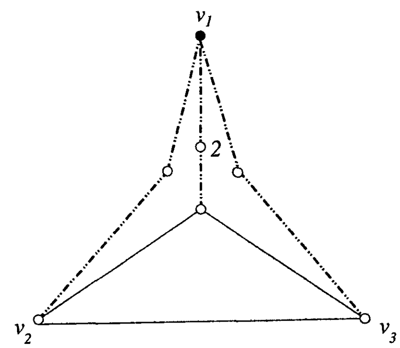


Figure 3.31: Case $P_3(0,0,1)$.I.iii

adjacent to rim vertex v_1 by Case $P_3(0,0,1)$.I.iii. Therefore, the resulting graph is a minor of $P_3^{(2)}$.

Case $P_3(0,0,1)$.II.iii If the two edges are an adjacent spoke edge and rim edge, then the result contains an M_2 minor (see Figure 3.32).

Case $P_3(0,0,1)$.II.iv If the two edges are a non-adjacent spoke edge and rim edge, then the spoke edge must be adjacent to rim vertex v_1, which is forbidden by Case $P_3(0,0,1)$.I.iii (see Figure 3.31).

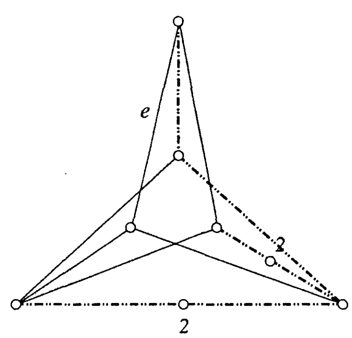


Figure 3.32: Case $P_3(0,0,1)$.I.iii. M_2 minor is obtained by contracting edge e.

Case $P_3(0,0,1)$.III If three edges of $P_3(0,0,1)$ are replaced, these edges cannot include a spoke adjacent to rim vertex v_1 by Case $P_3(0,0,1)$.I.iii. Therefore, the three edges must contain either two adjacent spoke edges or an adjacent spoke edge and rim edge, which are forbidden by Cases $P_3(0,0,0)$.II.i and $P_3(0,0,1)$.II.iii. Therefore, no three or more edges of $P_3(0,0,1)$ can be replaced by 2-paths or 3-paths.

In graph $P_3(0,1,1)$, let (v_1, v_2) and (v_2, v_3) be the two rim edges present in the graph.
Case $P_3(0,1,1)$.I If we replace one spoke edge in $P_3(0,1,1)$, then it must be a spoke edge adjacent to both rim edges, i.e., to vertex v_2 (otherwise if it is adjacent to v_1 or v_2, the resulting graph contains an M_2 minor by Figure 3.31). Furthermore, the spoke edge must be replaced by a 2-path by Case $P_3(0,0,0)$.I. The resulting graph is a minor of $P_3^{(3)}$.
Case $P_3(0,1,1)$.II Replacing two edges:

> **Case** $P_3(0,1,1)$.II.i If the two edges are both spoke edges, then since the spokes cannot be adjacent by Case $P_3(0,0,0)$.II.i, at least one of these spokes is adjacent to either v_1 or v_2. Then there is a rim edge non-adjacent to this spoke and the resulting graph contains an M_2 minor (see Figure 3.31).
>
> **Case** $P_3(0,1,1)$.II.ii If the two edges are a spoke edge and a rim edge, then the two edges cannot be adjacent by Case $P_3(0,0,1)$.II.iii. However, for non-adjacent spoke and rim edges, Case $P_3(0,1,1)$.I implies the resulting graph contains an M_2 minor (see Figure 3.31).

Therefore, no two or more edges other than rim edges can be replaced in by 2-paths and 3-paths in $P_3(0,1,1)$. Finally, we consider the graph $P_3(1,1,1)$.

Case $P_3(1,1,1)$.I If we replace any spoke edge in $P_3(1,1,1)$, then there is a rim edge non-adjacent to this spoke edge and the result contains an M_2 minor (see Figure 3.31). Therefore, no edge other than rim edges can be replaced by 2-paths and 3-paths in $P_3(1,1,1)$. □

Chapter 4

Integrality Gap Preserving Operations

In Chapter 2 and Chapter 3, we considered several graph operations which preserve walk-perfection and TSP-perfection. We now study the relationship between these graph operations and the integrality gaps of the traveling salesman and traveling salesman walk relaxations. As defined in Chapter 1, the integrality gap of relaxation P for polyhedron Q is the smallest r such that for any cost function c,

$$\min\{cx : x \in P\} \leq r \min\{cx : x \in Q\}.$$

The TSP integrality gap is the smallest such r for TSP polyhedron $Q = conv(X_{TSP}(G))$ and its fractional TSP relaxation $P = P(G)$. For fixed vertices s and t, the s-t TSW integrality gap is the smallest such r for TSW polyhedron $Q = conv(X(G, s, t))$ and its fractional TSW relaxation $P = P(G, s, t)$; the TSW integrality gap is the maximum s-t TSW integrality gap over all choices of s and t.

Since TSP-perfection corresponds to TSP integrality gap $r = 1$ and walk-perfection corresponds to TSW integrality gap $r = 1$, a natural question is whether the TSP-perfection and walk-perfection preserving operations are also integrality gap preserving. Note that if the initial and final vertices are identical, then the fractional TSW polyhedron and the fractional TSP polyhedron are the same, as are the the set of traveling salesman walks and traveling salesman tours. Therefore, if an operation is TSW integrality gap preserving, then it is also TSP integrality gap preserving.

In this chapter, we show that some of the graph operations we have considered indeed preserve TSP and TSW integrality gap.

4.1 Integrality Gap Under Graph Minors

We first show that the TSW integrality gap of the fractional traveling salesman walk relaxation does not increase under the graph minor operations. This generalizes Lemma 2.2.1 which states that walk-perfection (TSW integrality gap $r = 1$) is preserved under the graph minor operations.

Theorem 4.1.1. *Suppose G is a graph with specified vertices $s, t \in V(G)$ and suppose G' is a labeled minor of G. If the s-t TSW integrality gap of $P(G', s, t)$ is r, then the s-t TSW integrality gap of $P(G, s, t)$ is at least r.*

Proof. Since G' can be obtained from G by a sequence of edge deletions and edge contractions, it suffices to show that the integrality gap does not increase under these edge operations. If labeled minor G' is disconnected, then the s-t TSW integrality gap of G' is 1 and the integrality gap of G is greater than or equal to 1, so the theorem follows. We can therefore assume G' is connected.

Consider any non-zero cost function c in $G\backslash\{e\}$ and consider the following cost function on the edges of G:

$$\widetilde{c}_f = \begin{cases} c_f & \text{if } f \neq e \\ \infty & \text{if } f = e. \end{cases}$$

Then any s-t traveling salesman walk in G with minimum cost under $\widetilde{c}$ does not use edge e, implying it is also an s-t traveling salesman walk in $G\backslash\{e\}$ with minimum cost under c. This shows $\min\{cx : x \in X(G\backslash\{e\}, s, t)\} = \min\{\widetilde{c}x : x \in X(G, s, t)\}$. Furthermore, any feasible solution in $P(G\backslash\{e\}, s, t)$ is also a feasible solution in $P(G, s, t)$, implying $\min\{cx : x \in P(G\backslash\{e\}, s, t)\} \geq \min\{\widetilde{c}x : x \in P(G, s, t)\}$. Therefore,

$$\frac{\min\{cx : x \in X(G\backslash\{e\}, s, t)\}}{\min\{cx : x \in P(G\backslash\{e\}, s, t)\}} \leq \frac{\min\{\widetilde{c}x : x \in X(G, s, t)\}}{\min\{\widetilde{c}x : x \in P(G, s, t)\}}. \tag{4.1}$$

Since the s-t TSW integrality gap of G is the maximum over all cost functions of the expression on the right in Equation (4.1) and the s-t TSW integrality gap of $G\backslash e$ is the maximum over all cost functions of the expression on the left, the s-t TSW integrality gap of G is at least that of $G\backslash\{e\}$.

Similarly, consider any non-zero cost function c in $G.e$ and define the following cost function on the edges of G:

$$\widetilde{c}_f = \begin{cases} c_f & \text{if } f \neq e \\ 0 & \text{if } f = e. \end{cases}$$

Consider an s-t traveling salesman walk p in G with minimum cost under $\widetilde{c}$. Then the walk $p.e$ obtained by contracting edge e is an s-t traveling salesman walk in $G.e$ with minimum cost under cost c. This shows $\min\{cx : x \in X(G.e, s, t)\} = \min\{\widetilde{c}x : x \in X(G, s, t)\}$. Furthermore, any feasible solution in $P(G.e, s, t)$ is also a feasible solution in $P(G, s, t)$, implying $\min\{cx : x \in P(G.e, s, t)\} \geq \min\{\widetilde{c}x : x \in P(G, s, t)\}$. Therefore,

$$\frac{\min\{cx : x \in X(G.e, s, t)\}}{\min\{cx : x \in P(G.e, s, t)\}} \leq \frac{\min\{\widetilde{c}x : x \in X(G, s, t)\}}{\min\{\widetilde{c}x : x \in P(G, s, t)\}}. \tag{4.2}$$

Since the s-t TSW integrality gap of G is the maximum over all cost functions of the expression on the right in Equation (4.2) and the s-t TSW integrality gap of $G.e$ is the maximum over all cost functions of the expression on the left, the s-t TSW integrality gap of G is at least that of $G.e$ and the theorem follows. □

We now have the following corollaries.

Corollary 4.1.2. *Suppose G' is a labeled minor of a graph G. If the TSW integrality gap of G' is r, then the TSW integrality gap of G is at least r.*

This gives a second proof that walk-perfection is preserved under graph minors (which was proved independently in Lemma 2.2.1).

Corollary 4.1.3. *If graph G is walk-perfect, then G' is also walk-perfect for any labeled minor G' of G.*

By computational methods, we can verify that the TSP integrality gaps of M_1, M_2, M_3 are all equal to $\frac{10}{9}$ and the TSW integrality gap of C_6 is $\frac{7}{6}$. Then Theorem 4.1.1 implies the following integrality gap lower bounds for connected graphs that are not TSP-perfect and not walk-perfect.

Corollary 4.1.4. *For any connected graph G, either G is TSP-perfect or G has TSP integrality gap at least $\frac{10}{9}$.*

Corollary 4.1.5. *For any connected graph G, either G is walk-perfect or G has TSW integrality gap at least $\frac{7}{6}$.*

Theorem 4.1.1 also implies the following corollary.

Corollary 4.1.6. *For any $r \geq 1$, the set of graphs with TSP (or TSW) integrality gap at most r is a minor closed family.*

By the excluded minor theory of Robertson, Seymour, and Thomas, this implies that the set of graphs with TSP or TSW integrality gap at most r can be characterized by a finite list of excluded minors. From Chapter 2, the list of excluded minors for TSP integrality gap $r = 1$ is M_1, M_2, M_3, and the list of excluded minors for TSW integrality gap $r = 1$ is C_6. It is an interesting open problem to characterize the forbidden minors for TSP integrality gap at most r with $r > \frac{10}{9}$ and for TSW integrality at most r with $r > \frac{7}{6}$. Such a characterization for TSP integrality gap $r = \frac{4}{3}$ would resolve the Held-Karp conjecture, which can also be formulated as follows.

Conjecture 4.1.7. *The forbidden minors characterizing the set of graphs with TSP integrality gap at most $\frac{4}{3}$ is the empty set.*

4.2 Integrality Gap under Degree-2 Vertex Duplication

We consider the operation of degree-2 vertex duplication as introduced in Section 2.1. Suppose graph G has a degree-2 vertex u with neighbors $N(u) = \{a, b\}$. Let $G_2(u)$ denote the graph obtained from G by duplicating u to obtain vertices v and w (see Figure 4.1). It was shown in Lemmas 2.2.4 and 2.2.5 that the operation of degree-2 vertex duplication

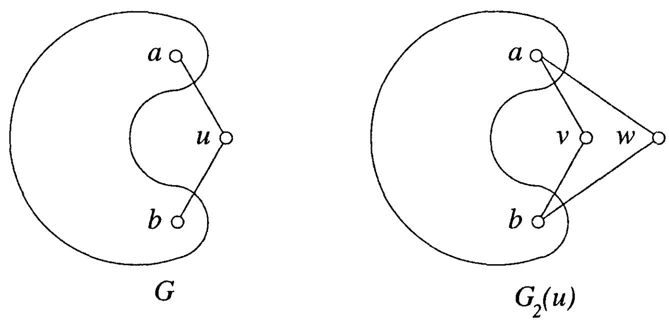


Figure 4.1: Duplicating degree-2 vertex.

preserves walk-perfection. We generalize this result to show that degree-2 vertex duplication also preserves integrality gap. To do this, we first define the *dominant* $\mathcal{D}(P)$ of a polyhedron P as the set of points which dominate some point in P, that is,

$$\mathcal{D}(P) = \{y \in \mathbb{R}^n : \exists x \in P \text{ such that } y_i \geq x_i \text{ for all } i = 1, 2, \ldots n\}.$$

A polyhedron is said of be of *blocking type* of $\mathcal{D}(P) = P$. The following theorem from [6] and [19] characterizes the integrality gap of a relaxation using the dominant.

Theorem 4.2.1. *The integrality gap of a relaxation P of an integral polyhedron Z in the positive orthant is r if and only if r is the smallest real number such that $rx \in D(Z)$ for any $x \in P$.*

In particular, if the integrality gap of relaxation P is r, then rx dominates a convex combination of extreme points in integral polyhedron Z. In [7], Carr and Vempala present a polynomial algorithm to construct this convex combination. Note that if Z is a polyhedron of blocking type with integrality gap r, then $rx \in D(Z) = Z$ for any feasible solution $x \in P$.

In the traveling salesman problem, the integral polyhedra we consider are the convex hulls of traveling salesman tours ($Z = conv(X_{TSP}(G))$ and traveling salesman walks ($Z = conv(X(G, s, t))$). The relaxations are the fractional TSP polyhedron ($P = P(G)$) and fractional TSW polyhedron ($P = P(G, s, t)$). Note that these polyhedra are all of blocking type and therefore, if the TSP (TSW) integrality gap is r, then for any feasible solution $x \in P(G)$ ($x \in P(G, s, t)$), rx is equal to a convex combination of s-t traveling salesman tours (s-t traveling salesman walks). We use this theorem to prove that integrality gap is preserved under vertex duplication of degree-2 vertices.

Theorem 4.2.2. *Suppose the TSP integrality gap of G is r and suppose G has a vertex u of degree 2 with neighbors $N(u) = \{a, b\}$. Then $G_2(u)$ has TSP integrality gap r.*

Proof. Since G is a minor of $G_2(u)$, the TSP integrality gap of $G_2(u)$ is at least r by Lemma 2.2.1.

To show the TSP integrality gap of $G_2(u)$ is at most r, let x be any feasible solution in $P(G_2(u))$. First, we show that we can assume $x_{av} \leq x_{aw} \leq x_{bw}$ and $x_{av} \leq x_{bv}$. Otherwise, if $x_{av} > x_{aw}$, the solution x' defined by switching v and w and thus defined by

$$x'_{av} = x_{aw} \qquad x'_{aw} = x_{av}$$

$$x'_{bv} = x_{bw} \qquad x'_{bw} = x_{bv}$$

$$x'_e = x_e \text{ for all other edges } e$$

is a feasible solution satisfying $x'_{av} \leq x'_{aw}$. Its feasibility follows from the observation that the set of cuts is unaffected by the switching of two vertices of degree 2 with the same neighbors. If $x_{aw} > x_{bw}$, then the solution x' defined by switching edges (a, w) and (b, w) and thus defined by

$$x'_{aw} = x_{bw} \qquad x'_{bw} = x_{aw}$$

$$x'_e = x_e \text{ for all other edges } e$$

is a feasible solution satisfying $x'_{aw} \leq x'_{bw}$. Its feasibility follows from the observation that the set of cuts is unaffected by the switching of the two edges incident to a degree-2 vertex. We can therefore swap the edges adjacent to a and b if necessary so that the edges adjacent to b have larger value and then swap the vertices v and w if necessary in order to guarantee $x_{av} \leq x_{aw} \leq x_{bw}$ and $x_{av} \leq x_{bv}$. We use the feasible solution x in $P(G_2(u))$ to define feasible solution $\widetilde{x}$ in $P(G)$ by

$$\widetilde{x}_{au} = x_{av} + x_{aw}$$

$$\widetilde{x}_{bu} = \max\{2 - (x_{av} + x_{aw}), x_{av} + x_{aw}\}.$$

The feasibility of $\widetilde{x}$ follows from the observation that any cut in G containing both edges (a, u) and (b, u) is valid and for any other cut in G, there is a corresponding valid cut in $G_2(u)$ of no larger value. Since the TSP integrality gap of G is r, Theorem 4.2.1 implies $r\widetilde{x}$ dominates a convex combination of tours in G, i.e., there are tours $\widetilde{T}_i$ and values α_i satisfying $\alpha_i > 0, \sum_i \alpha_i = 1$, and

$$\sum_i \alpha_i \widetilde{T}_i \leq r\widetilde{x}. \tag{4.3}$$

Let $\widetilde{y} = \sum_i \alpha_i \widetilde{T}_i$. For simplicity, we assume without loss of generality that $x_e \leq 2$ and $(\widetilde{T}_i)_e \leq 2$ for all edges $e \in E(G)$ (note that by imposing this assumption, Equation (4.3) may become a strict inequality for some edges). Now, partition the tours $\widetilde{T}_i$ into classes $\Lambda_T, \Lambda_P, \Lambda_{au}$ and Λ_{bu} according to whether $\widetilde{y}$ restricted to the two edges (a, u) and (b, u) is a tour, path, or 2-cycle cover (see Figure 4.2) and let

$$\begin{aligned}
\alpha_T &= \sum_{i \in \Lambda_T} \alpha_i, \\
\alpha_P &= \sum_{i \in \Lambda_P} \alpha_i, \\
\alpha_{au} &= \sum_{i \in \Lambda_{au}} \alpha_i, \\
\alpha_{bu} &= \sum_{i \in \Lambda_{bu}} \alpha_i.
\end{aligned}$$

The idea will be to use the tours $\widetilde{T}_i$ in G to construct tours T_i in $G_2(u)$ in such a way that after a suitable redistribution of the weights α_i, rx will dominate a convex combination of the modified tours T_i, i.e.,

$$rx \geq \sum_i \alpha'_i T_i. \tag{4.4}$$

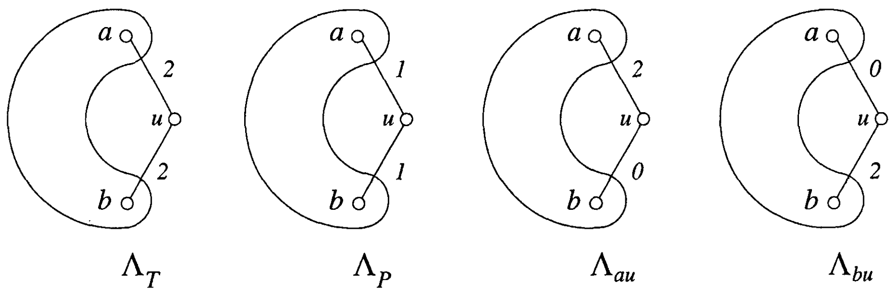


Figure 4.2: Partition of tours.

For the weights α as given by Equation (4.3), consider the following cases.

Case I. $rx_{av} \leq \alpha_T$.

In this case, consider redistributing the weights α_i for $i \in \Lambda_T \Lambda_P, \Lambda_{au}, \Lambda_{bu}$ on tours of $G_2(u)$ as shown in Figure 4.3. The figure also labels the classes $\Lambda_T^{(1)}, \Lambda_T^{(2)}, \Lambda_P^{(1)}, \Lambda_{au}^{(1)}$, and $\Lambda_{bu}^{(1)}$ of modified tours in graph $G_2(u)$. Let $y = \sum_i \alpha_i' T_i$, where the α_i' are the redistributed weights

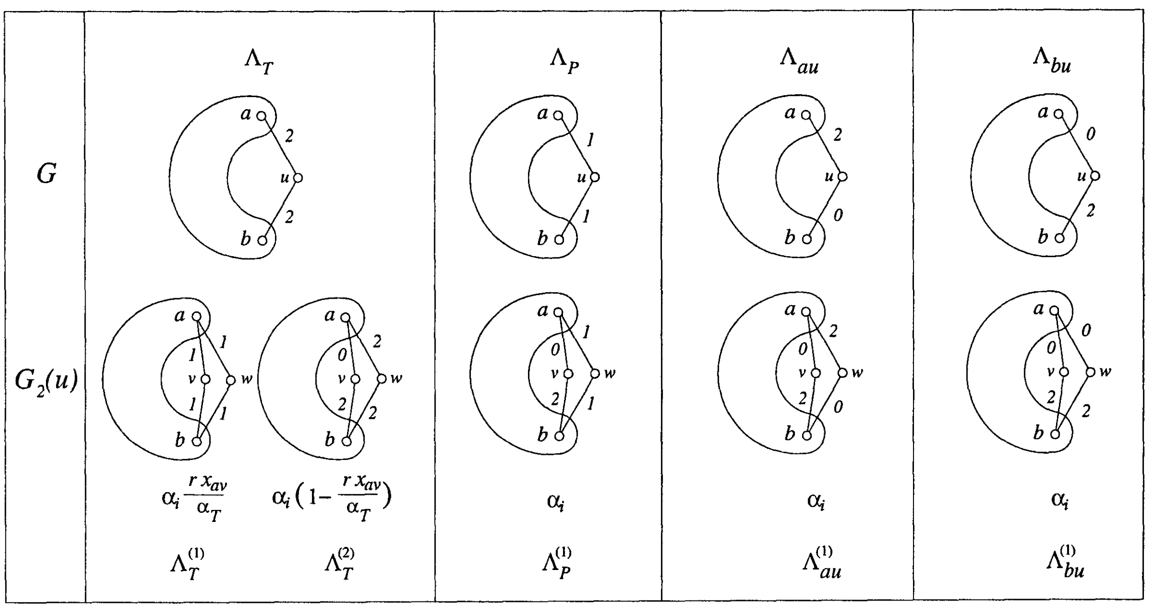


Figure 4.3: Redistribution in Case I.

on tours T_i in $G_2(u)$ as shown in Figure 4.3. We will show that either this redistribution or a slightly modified redistribution of weights gives $y_e \leq rx_e$ for all edges $e \in E(G_2(u))$. This will show rx dominates a convex combination of tours in $G_2(u)$.

Case I: Edge (a, v). The weight y_{av} on edge (a, v) is

$$y_{av} = \sum_{\alpha_i \in \Lambda_T} \alpha_i \frac{r x_{av}}{\alpha_T} = r x_{av}.$$

Case I: Edge (b, v). Note that each tour T_i in the decomposition satisfies $(T_i)_{bv} = 2 - (T_i)_{av}$, implying the weight y_{bv} on edge (b, v) is

$$\begin{aligned} y_{bv} &= 2 - y_{av} \\ &= 2 - r x_{av} \\ &\leq 2r - r x_{av} \\ &= r(2 - x_{av}) \\ &\leq r x_{bv}. \end{aligned}$$

Case I: Edge (a, w). Since $2\alpha_T + \alpha_P + 2\alpha_{au} \leq r(x_{av} + x_{aw})$ by Equation (4.3), the weight y_{aw} on edge (a, w) is

$$\begin{aligned} y_{aw} &= \sum_{\alpha_i \in \Lambda_T} \left(\alpha_i \frac{r x_{av}}{\alpha_T} + 2\alpha_i \left(1 - \frac{r x_{av}}{\alpha_T} \right) \right) + \sum_{\alpha_i \in \Lambda_P} \alpha_i + 2 \sum_{\alpha_i \in \Lambda_{au}} \alpha_i && (4.5) \\ &= r x_{av} + 2\alpha_T \left(1 - \frac{r x_{av}}{\alpha_T} \right) + \alpha_P + 2\alpha_{au} && (4.6) \\ &= r x_{av} + 2\alpha_T - 2r x_{av} + \alpha_P + 2\alpha_{au} && (4.7) \\ &= (2\alpha_T + \alpha_P + 2\alpha_{au}) - r x_{av} && (4.8) \\ &\leq r(x_{av} + x_{aw}) - r x_{av} && (4.9) \\ &= r x_{aw}. && (4.10) \end{aligned}$$

This completes the analysis for the edges (a, v), (a, w), and (b, v). The final edge to consider is edge (b, w).

Case I: Edge (b, w). We can assume that either $\sum_{i \in \Lambda_{bu}^{(1)}} \alpha'_i = 0$ or the weight y_{aw} on edge (a, w) is equal to $r x_{aw}$. Otherwise, if there are tours in $\Lambda_{bu}^{(1)}$ with positive weight α'_i and $y_{aw} < r x_{aw}$, then we can modify tours T_i in $\Lambda_{bu}^{(1)}$ by exchanging the values $(T_i)_{aw}$ and

$(T_i)_{bw}$ as long as such modification does not violate the inequality (4.4). Note that after performing these modifications, the resulting tours belong to $\Lambda_{au}^{(1)}$ instead of $\Lambda_{bu}^{(1)}$ (see Figure 4.4) and the process terminates when either there are no more tours in $\Lambda_{bu}^{(1)}$ or the constraint $y_{aw} \leq rx_{aw}$ is satisfied at equality. Therefore, we consider the following two cases.

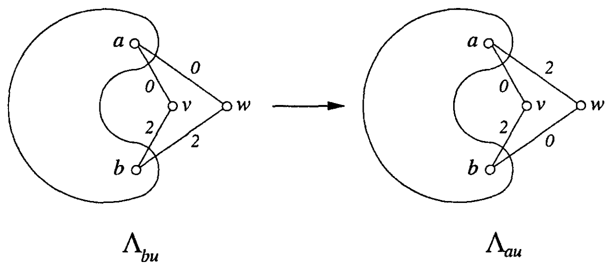


Figure 4.4: Modifying tours in Λ_{bu}.

Case I: Edge (b, w) (i) No tour in $\Lambda_{bu}^{(1)}$ has positive weight.

In this case, each tour T_i in $G_2(u)$ satisfies $(T_i)_{bw} \leq (T_i)_{aw}$ and therefore

$$y_{bw} \leq y_{aw} \leq rx_{aw} \leq rx_{bw}.$$

Case I: Edge (b, w) (ii) Edge (a, w) is saturated (i.e., $y_{aw} = rx_{aw}$) and some tour in $\Lambda_{bu}^{(1)}$ has positive weight.

To analyze this case, recall that $\widetilde{x}_{bu} = \max\{2-(x_{av}+x_{aw}), x_{av}+x_{aw}\}$. Then $\widetilde{x}_{bu}$ is equal to the first argument in the maximum if $x_{av} + x_{aw} \leq 1$ and the second if $x_{av} + x_{aw} \geq 1$. We again consider two separate cases.

(A) $\widetilde{x}_{bu} = x_{av} + x_{aw}$. In this case, we have

$$2\alpha_T + \alpha_P + 2\alpha_{bu} \leq r\widetilde{x}_{bu} = r(x_{av} + x_{aw})$$

and the weight on edge (b, w) is

$$\begin{aligned} y_{bw} &= \sum_{\alpha_i \in \Lambda_T} \left(\alpha_i \frac{r x_{av}}{\alpha_T} + 2\alpha_i \left(1 - \frac{r x_{av}}{\alpha_T} \right) \right) + \sum_{\alpha_i \in \Lambda_P} \alpha_i + 2 \sum_{\alpha_i \in \Lambda_{bu}} \alpha_i \\ &= r x_{av} + 2\alpha_T \left(1 - \frac{r x_{av}}{\alpha_T} \right) + \alpha_P + 2\alpha_{bu} \\ &= r x_{av} + 2\alpha_T - 2 r x_{av} + \alpha_P + 2\alpha_{bu} \\ &= (2\alpha_T + \alpha_P + 2\alpha_{bu}) - r x_{av} \\ &\leq r(x_{av} + x_{aw}) - r x_{av} \\ &= r x_{aw}, \end{aligned}$$

which is at most $r x_{bw}$ by assumption.

(B) $\widetilde{x}_{bu} = 2 - (x_{av} + x_{aw})$. In this case, $x_{av} + x_{aw} \leq 1$ and $\widetilde{x}$ satisfies

$$\begin{aligned} r\widetilde{x}\left(\delta(\{u\})\right) &= r(\widetilde{x}_{au} + \widetilde{x}_{bu}) \\ &= r(x_{av} + x_{aw} + 2 - (x_{av} + x_{aw})) \\ &= 2r. \end{aligned}$$

By Equation (4.3), $\sum_i \alpha_i \widetilde{T}_i \leq r\widetilde{x}$, implying

$$\begin{aligned} \widetilde{y}(\delta(\{u\})) &\leq r\widetilde{x}(\delta(\{u\})) \\ 4\alpha_T + 2(\alpha_P + \alpha_{au} + \alpha_{bu}) &\leq 2r \\ 4\alpha_T &\leq 2(r - (\alpha_P + \alpha_{au} + \alpha_{bu})) \\ 2\alpha_T &\leq r - (1 - \alpha_T) \\ \alpha_T &\leq r - 1. \end{aligned}$$

Since $x_{av} + x_{aw} \leq 1$, we have $x_{av} \leq 1$, $x_{aw} \leq 1$, and

$$x_{bv} \geq 2 - x_{av}, \tag{4.11}$$

$$x_{bw} \geq 2 - x_{aw}. \tag{4.12}$$

We now show we can assume constraints (4.11) and (4.12) are satisfied at equality. We first make the argument for constraint (4.11) and then the assumption for constraint (4.12) will follow by replacing v by w in the argument. We need to show that by letting $x_{bv} = 2 - x_{av}$, any cut involving edge (b, v) remains valid. First, cut $C = \{v\}$ is valid and therefore, any cut C such that $\delta(C)$ contains both edges (a, v) and (b, v) is valid. Otherwise, if $\delta(C)$ contains edge (b, v) but not (a, v), we can assume by possibly taking complements that C contains vertices a and v but not b. Then $\delta(C \backslash \{v\}) = \delta(C) \backslash (b, v) \cup (a, v)$ is a cut not containing edge (b, v) and therefore $x(\delta(C \backslash \{v\})) \geq 2$. Now, since $x_{bv} \geq 1 \geq x_{av}$, we have $x(\delta(C)) \geq x(\delta(C) \backslash (b, v) \cup (a, v)) = x(\delta(C \backslash \{v\})) \geq 2$ and therefore, C is a valid cut. Now, we have

$$\alpha_T \leq r - 1$$

$$\alpha_T - r x_{av} \leq r - 1$$

$$x_{aw}(\alpha_T - r x_{av}) \leq (r - 1) x_{bw}$$

$$x_{aw} \alpha_T \left(1 - \frac{r x_{av}}{\alpha_T}\right) \leq (r - 1) x_{bw}$$

$$x_{bw} + x_{aw} \alpha_T \left(1 - \frac{r x_{av}}{\alpha_T}\right) \leq r x_{bw}$$

$$(2 - x_{aw}) + x_{aw} \alpha_T \left(1 - \frac{r x_{av}}{\alpha_T}\right) \leq r x_{bw}$$

$$(2 - x_{aw}) \left(1 - \alpha_T \left(1 - \frac{r x_{av}}{\alpha_T}\right)\right) + 2 \left(\alpha_T \left(1 - \frac{r x_{av}}{\alpha_T}\right)\right) \leq r x_{bw}. \tag{4.13}$$

Note that all tours T_i in $G_2(u)$ except those in $\Lambda_T^{(2)}$ satisfy $(T_i)_{bw} = 2 - (T_i)_{aw}$ and therefore, the left hand side of Equation (4.13) is precisely the weight y_{bw} on edge (b, w).

Case I: All other edges. All other edges in $G_2(u)$ have the same weight after the redistribution as before, so rx dominates a convex combination of tours T_i.

Case II. $r x_{av} > \alpha_T$.

In this case, let

$$\begin{aligned} x'_{av} &= rx_{av} - \alpha_T \\ x'_{aw} &= rx_{aw} - \alpha_T \\ x'_{bv} &= rx_{bv} - \alpha_T \\ x'_{bw} &= rx_{bw} - \alpha_T. \end{aligned}$$

Note that x' is non-negative because $r \min\{x_{av}, x_{aw}, x_{bv}, x_{bw}\} = rx_{av} > \alpha_T$. Now, consider redistributing the weights α_i for $i \in \Lambda_P, \Lambda_{au}, \Lambda_{bu}$ on tours T_i of $G_2(u)$ as shown in Figure 4.5. The figure also labels the classes $\Lambda_T^{(1)}, \Lambda_P^{(1)}, \Lambda_P^{(2)}, \Lambda_{au}^{(1)}, \Lambda_{au}^{(2)}, \Lambda_{bu}^{(1)}$ of modified tours in $G_2(u)$. Note that from Equation (4.3),

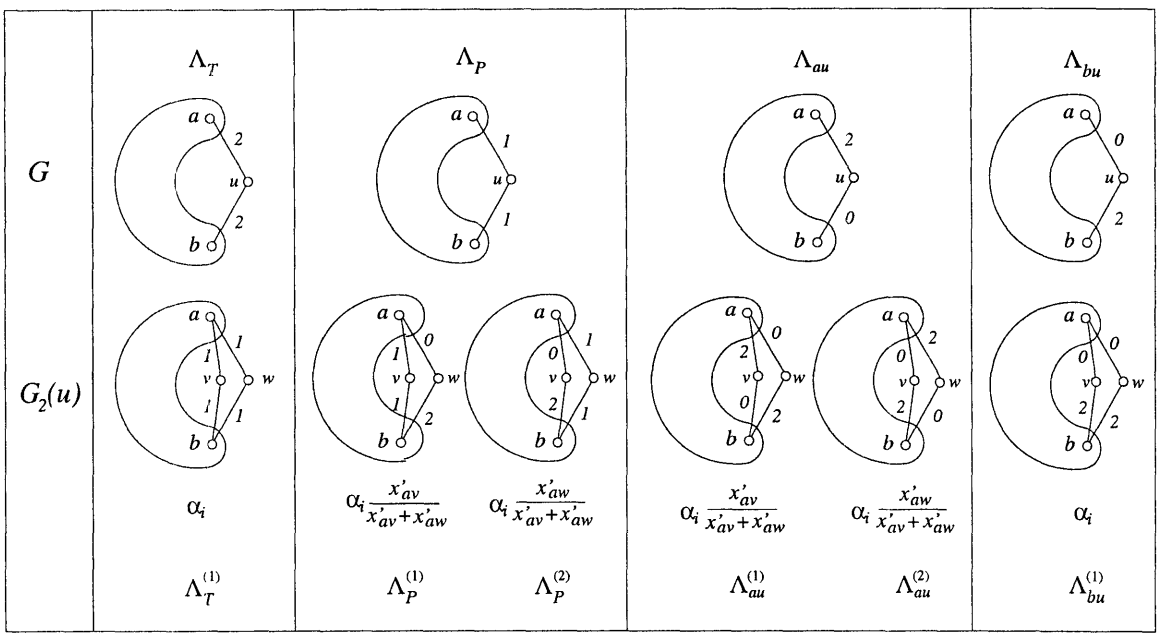


Figure 4.5: Redistribution in Case II.

$$2\alpha_T + \alpha_P + 2\alpha_{au} \leq r(x_{av} + x_{aw}),$$

implying

$$\alpha_P + 2\alpha_{au} \leq r(x_{av} + x_{aw}) - 2\alpha_T = x'_{av} + x'_{aw}.$$

Case II: Edge (a, v)**.** In the given redistribution, the weight on edge (a, v) is

$$\begin{aligned}\sum_{\alpha_i \in \Lambda_T} \alpha_i + \sum_{\alpha_i \in \Lambda_p} \alpha_i \frac{x'_{av}}{x'_{av} + x'_{aw}} + 2 \sum_{\alpha_i \in \Lambda_{au}} \alpha_i \frac{x'_{av}}{x'_{av} + x'_{aw}} &= \alpha_T + (\alpha_P + 2\alpha_{au}) \frac{x'_{av}}{x'_{av} + x'_{aw}} \\ &\leq \alpha_T + (x'_{av} + x'_{aw}) \frac{x'_{av}}{x'_{av} + x'_{aw}} \\ &= \alpha_T + x'_{av} \\ &= r x_{av}.\end{aligned}$$

Case II: Edge (a, w)**.** Note that the redistribution is symmetric with respect to vertices v and w. Therefore, the argument for the case of edge (a, v) with w in place of v shows that we can redistribute weights on tours T_i so that

$$y_{aw} \leq r x_{aw}.$$

Case II: Edge (b, v)**.** Suppose the inequality for edge (a, v) is tight, so the weight on (a, v) is equal to $r x_{av}$. Then each tour T_i in in the decomposition satisfies $(T_i)_{bv} = 2 - (T_i)_{av}$, implying the weight on edge (b, v) is at most

$$\begin{aligned}2 - r x_{av} &\leq 2r - r x_{av} \\ &= r(2 - x_{av}) \\ &\leq r x_{bv}.\end{aligned}$$

If the inequality corresponding to edge (a, v) is strict, then in every tour T_i with $(T_i)_{bv} = 2$ and $(T_i)_{av} = 0$ (tours in $\Lambda_P^{(2)}, \Lambda_{au}^{(2)}$, and $\Lambda_{bu}^{(1)}$), consider the modified tour obtained by swapping the values of edges (a, v) and (b, v). We perform this exchange of weight from edge (b, v) to edge (a, v) until either the inequality corresponding to edge (a, v) is tight or there is no remaining weight on edge (b, v) in these graphs to move.

If the inequality corresponding to edge (a, v) becomes tight, then we are in the case previously considered with the weight on edge (a, v) equal to $r x_{av}$. Otherwise, if there is no more remaining weight on edge (b, v) in these graphs to move, then in every tour T_i in the decomposition, we now have $(T_i)_{bv} \leq (T_i)_{av}$, implying

$$y_{bv} \leq y_{av} \leq rx_{av} \leq rx_{bv}.$$

Case II: Edge (b, w)**.** Note that the redistribution is symmetric with respect to vertices v and w. Therefore, the argument for the case of edge (b, v) with w in place of v shows that we can redistribute weights on tours T_i so that

$$y_{bw} \leq rx_{bw}.$$

Case II: All other edges. All other edges in $G_2(u)$ have the same weight after the redistribution as before, so rx dominates the convex combination of tours T_i. □

4.3 Integrality Gap under Operations Φ_1 and Φ_2

In this section, we consider the integrality gap of graphs under the operations Φ_1 and Φ_2 introduced in Section 2.1. We prove that operation Φ_1 preserves integrality gap while operation Φ_2 does not. Thus, all operations we have shown to preserve TSP-perfection and walk-perfection except Φ_2 also preserve integrality gap.

We first show operation Φ_1 preserves s-t TSW integrality gap. For vertices v_1 and v_2 in connected graphs G_1 and G_2, operation Φ_1 identifies vertices v_1 and v_2 to obtain graph G. Let $s, t \in V(G)$. In the following theorem, H_1 will denote the labeled minor obtained by contracting G_2 to a single vertex in G. The result is graph G_1 where vertex v_1 has label s if $s \in V(G_2)$, label t if $t \in V(G_2)$, labels s and t if $s, t \in V(G_2)$ and is unlabeled if $s, t \in V(G_1)\backslash\{v_1\}$. Similarly, H_2 will denote the labeled minor obtained by contracting G_1 to a single vertex.

Theorem 4.3.1. *If the s-t TSW integrality gaps of H_1 and H_2 are r_1 and r_2 respectively, then the s-t TSW integrality gap of G is* $\max\{r_1, r_2\}$.

Proof. By Theorem 4.1.1, if G has s-t TSW integrality gap r, then both H_1 and H_2 have s-t TSW integrality gap at most r.

Conversely, suppose the s-t TSW integrality gaps of H_1 and H_2 are r_1 and r_2 respectively. Let x be any feasible point in the fractional walk polyhedron $P(G,s,t)$. Let x_1 and x_2 denote the restriction of x to graphs H_1 and H_2; then x_1 and x_2 are feasible solutions in $P(H_1,s,t)$ and $P(H_2,s,t)$ respectively. By Theorem 4.2.1 and since all polyhedra considered here are of blocking type, there are s-t traveling salesman walks $p_i^1 \in G_1, p_i^2 \in G_2$ and weights α_i^1, α_i^2 satisfying $\sum_i \alpha_i^1 = \sum_i \alpha_i^2 = 1$, $\alpha_i^1, \alpha_i^2 > 0$, and

$$\sum_i \alpha_i^1 p_i^1 = r_1 x_1$$
$$\sum_i \alpha_i^2 p_i^2 = r_2 x_2.$$

Let $p_i^1 \circ_{\Phi_1} p_j^2$ denote the result of combining s-t traveling salesman walks p_i^1 in H_1 and p_j^2 in H_2. By the vertex degree constraints, $p_i^1 \circ_{\Phi_1} p_j^2$ is an s-t traveling salesman walk in G for any i, j. Similarly, for feasible solutions $x_1 \in P(H_1,s,t)$ and $x_2 \in P(H_2,s,t)$, let $x_1 \circ_{\Phi_1} x_2$ denote the result of combining the two feasible solutions to a feasible solution in G. Then for $r = \max\{r_1, r_2\}$,

$$\begin{aligned} rx &\geq r_1 x_1 \circ_{\Phi_1} r_2 x_2 \\ &= \left(\sum_i \alpha_i^1 p_i^1\right) \circ_{\Phi_1} \left(\sum_j \alpha_j^2 p_j^2\right) \\ &= \sum_i \sum_j \alpha_i^1 \alpha_j^2 (p_i^1 \circ_{\Phi_1} p_j^2), \end{aligned}$$

where $\sum_i \sum_j \alpha_i^1 \alpha_j^2 = \sum_i \alpha_i^1 \sum_j \alpha_j^2 = 1$. This shows rx dominates a convex combination of s-t traveling salesman walks in G and therefore, the s-t TSW integrality gap of G is at most r. □

Corollary 4.3.2. *If the TSW integrality gaps of H_1 and H_2 are r_1 and r_2 respectively, then the TSW integrality gap of G is* $\max\{r_1, r_2\}$.

However, the operation Φ_2 does *not* preserve TSP integrality gap (and therefore does not preserve TSW integrality gap). We demonstrate this with the following example.

Example 4.3.3. Consider the graphs G_1 and G_2 in Figure 4.6, where the path labeled by

k denotes a path of k edges from s to t.

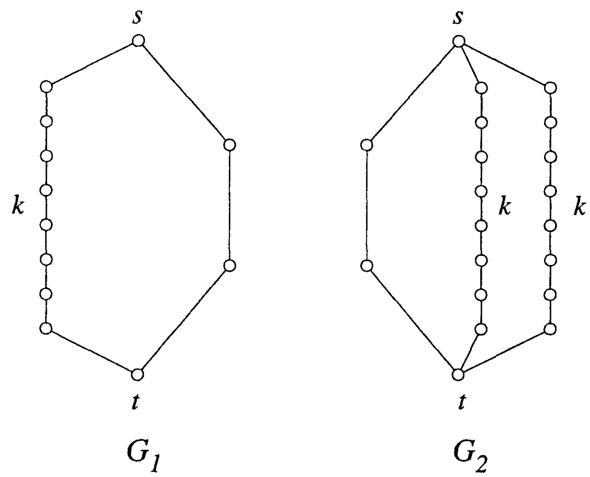


Figure 4.6: Graphs G_1 and G_2.

Then Φ_2 composes graphs G_1 and G_2 at vertices s and t to obtain graph G in Figure 4.7.

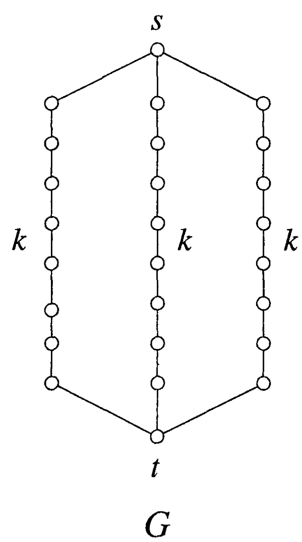


Figure 4.7: Counterexample showing Φ_2 does not preserve TSP integrality gap.

Note that G_1 is TSP-perfect because it is $[M_1, M_2, M_3]$ minor free.

Claim: G_2 has integrality gap $\frac{6}{5}$.

For any cost function on G_2, let c_1 be the cost of the path of length 3, and let c_2 and

c_3 be the costs on the two other paths of length k. The solution $x_e = 1$ for all edges e is a feasible solution in the fractional TSP polyhedron. We will show that any other extreme point corresponds to a tour and therefore gives a ratio of 1. First, this is true for the case $k = 2$, which is a TSP-perfect graph. Now, suppose it is true for any path lengths k_1, k_2 with $k_1, k_2 \leq k, k_1 + k_2 < 2k$ and suppose x is any extreme point other than $x = 1$. Then $x_e > 1$ for some edge e and by Theorem 3.2.5, the solution $x.e$ (x restricted to the graph with edge e contracted) is an extreme point in $(G_2).e$. This extreme point must contain at least one edge that does not have value 1 (otherwise x would not have been an extreme point) and by assumption, corresponds to a tour. Now, in order for x to be an extreme point, there must be a tight cut constraint containing e and since $x_e > 1$, it follows that $x_e = 2$. Then x corresponds to the tour obtained by extending tour $x.e$ by traveling edge e twice. Therefore, all extreme points other than $x = 1$ correspond to tours. This shows that in order to find the integrality gap for G_2, we can assume that the optimum LP solution is obtained at $x_e = 1$ for all edges e and has value $c_1 + c_2 + c_3$.

We can obtain a tour of G_2 by taking two of the paths together with twice all but one edge of the third path. By discarding the most expensive edge along this third path, this means that the minimum cost tour has value at most

$$\min\left(\frac{4}{3}c_1 + c_2 + c_3, c_1 + \frac{2(k-1)}{k}c_2 + c_3, c_1 + c_2 + \frac{2(k-1)}{k}c_3\right).$$

The worst-case ratio between the optimum tour and the LP solution is obtained when the three quantities in the minimum are equal, i.e. when

$$\frac{c_1}{3} = \left(1 - \frac{2}{k}\right)c_2 = \left(1 - \frac{2}{k}\right)c_3 = c.$$

Therefore, $c_1 = 3c$, $c_2 = \frac{kc}{k-2}$ and $c_3 = \frac{kc}{k-2}$. The LP value is then $\left(5 + \frac{4}{k-2}\right)c$ while the minimum cost tour has value $\left(6 + \frac{4}{k-2}\right)c$, for a ratio that attains $\frac{6}{5}$ when k is arbitrarily large.

Therefore, both G_1 and G_2 have integrality gap at most $\frac{6}{5}$ while the integrality gap of G is arbitrarily close to $\frac{4}{3}$ for sufficiently large path length k.

Chapter 5

Appendix

We complete the proofs of TSP-perfection for several graphs by computational methods using the software package `polymake`.

`Polymake` is a versatile software system for computation on convex polyhedra and finite simplicial complexes. It was developed by the Discrete Geometry group at the Institute of Mathematics of Technische Universitt Berlin by authors Ewgenij Gawrilow and Michael Joswig ([16] and [17]). In addition to implementing many computational algorithms on polytopes, `polymake` includes a large array of interfaces to other software packages. More details on `polymake` can be found at the website

`http://www.math.tu-berlin.de/polymake/`

For each graph G under consideration, we first generate the cut and nonnegativity constraints defining the fractional traveling salesman polyhedron $P(G)$ or fractional traveling salesman walk polyhedron $P(G, s, t)$. In `polymake`, an inequality of the form $a_0+a_1x_1+\ldots+a_dx_d \geq 0$ is input as vector $(a_0, a_1, \ldots a_d)$. We then use `polymake` to generate the extreme points of each polyhedron, which are also given in vector format. Thus, $(x_1, x_2, \ldots x_d)$ is the solution with value x_1 on edge 1, x_2 on edge 2, etc. Finally, we verify that each extreme point x corresponds to a traveling salesman tour. In the case of the traveling salesman problem (or the traveling salesman walk problem with $s = t$), this means checking that x_e is integral for every edge e and every vertex has even degree in G_x. In the case of the traveling salesman walk problem with $s \neq t$, this means checking x_e is integral for every edge e, that s and t have odd degree and every vertex $v \neq s, t$ has even degree in G_x.

5.1 Graphs $K_4^{(1)}, K_4^{(2)}, W^{(1)}, K_5^{(1)}$, $K_5^{(2)}$, $P_3^{(1)}$, $P_3^{(2)}$, and $P_3^{(3)}$

In this section, we give a proof of Lemma 3.2.1.

Lemma 3.2.1 Graphs $K_4^{(1)}, K_4^{(2)}, W^{(1)}, K_5^{(1)}$, $K_5^{(2)}$, $P_3^{(1)}$, $P_3^{(2)}$, and $P_3^{(3)}$ (see Figure 5.1) are TSP-perfect.

Proof of Lemma 3.2.1. The inequalities and extreme points for each of $K_4^{(1)}, K_4^{(2)}, W^{(1)}, K_5^{(1)}$, $K_5^{(2)}$, $P_3^{(1)}$, $P_3^{(2)}$, and $P_3^{(3)}$ are enumerated in the following tables. We verify that each extreme point corresponds to a traveling salesman tour, proving the lemma. □

$K_4^{(1)}$ INEQUALITIES

-2 0 0 0 0 0 0 0 0 1 1 1	-2 0 0 0 0 0 0 0 1 1 0 0	-2 0 0 0 0 0 0 0 1 0 1 1	-2 0 0 0 0 0 0 1 1 0 0 0	-2 0 0 0 0 0 0 1 1 1 1 1
-2 0 0 0 0 0 0 1 0 1 0 0	-2 0 0 0 0 0 0 1 0 0 1 1	-2 0 0 0 0 1 1 0 0 0 0 1	-2 0 0 0 0 1 1 0 0 1 1 0	-2 0 0 0 0 1 1 0 1 1 0 1
-2 0 0 0 0 1 1 0 1 0 1 0	-2 0 0 0 0 1 1 1 1 0 0 1	-2 0 0 0 0 1 1 1 1 1 1 0	-2 0 0 0 0 1 1 1 0 1 0 1	-2 0 0 0 0 1 1 1 0 0 1 0
-2 0 0 0 1 1 0 0 0 0 0 0	-2 0 0 0 1 1 0 0 0 1 1 1	-2 0 0 0 1 1 0 0 1 1 0 0	-2 0 0 0 1 1 0 0 1 0 1 1	-2 0 0 0 1 1 0 1 1 0 0 0
-2 0 0 0 1 1 0 1 1 1 1 1	-2 0 0 0 1 1 0 1 0 1 0 0	-2 0 0 0 1 1 0 1 0 0 1 1	-2 0 0 0 1 0 1 0 0 0 0 1	-2 0 0 0 1 0 1 0 0 1 1 0
-2 0 0 0 1 0 1 0 1 1 0 1	-2 0 0 0 1 0 1 0 1 0 1 0	-2 0 0 0 1 0 1 1 1 0 0 1	-2 0 0 0 1 0 1 1 1 1 1 0	-2 0 0 0 1 0 1 1 0 1 0 1
-2 0 0 0 1 0 1 1 0 0 1 0	-2 0 0 1 1 0 0 0 0 0 0 0	-2 0 0 1 1 0 0 0 0 1 1 1	-2 0 0 1 1 0 0 0 1 1 0 0	-2 0 0 1 1 0 0 0 1 0 1 1
-2 0 0 1 1 0 0 1 1 0 0 0	-2 0 0 1 1 0 0 1 1 1 1 1	-2 0 0 1 1 0 0 1 0 1 0 0	-2 0 0 1 1 0 0 1 0 0 1 1	-2 0 0 1 1 1 1 0 0 0 0 1
-2 0 0 1 1 1 1 0 0 1 1 0	-2 0 0 1 1 1 1 0 1 1 0 1	-2 0 0 1 1 1 1 0 1 0 1 0	-2 0 0 1 1 1 1 1 1 0 0 1	-2 0 0 1 1 1 1 1 1 1 1 0
-2 0 0 1 1 1 1 1 0 1 0 1	-2 0 0 1 1 1 1 1 0 0 1 0	-2 0 0 1 0 1 0 0 0 0 0 0	-2 0 0 1 0 1 0 0 0 1 1 1	-2 0 0 1 0 1 0 0 1 1 0 0
-2 0 0 1 0 1 0 0 1 0 1 1	-2 0 0 1 0 1 0 1 1 0 0 0	-2 0 0 1 0 1 0 1 1 1 1 1	-2 0 0 1 0 1 0 1 0 1 0 0	-2 0 0 1 0 1 0 1 0 0 1 1
-2 0 0 1 0 0 1 0 0 0 0 1	-2 0 0 1 0 0 1 0 0 1 1 0	-2 0 0 1 0 0 1 0 1 1 0 1	-2 0 0 1 0 0 1 0 1 0 1 0	-2 0 0 1 0 0 1 1 1 0 0 1
-2 0 0 1 0 0 1 1 1 1 1 0	-2 0 0 1 0 0 1 1 0 1 0 1	-2 0 0 1 0 0 1 1 0 0 1 0	-2 0 1 1 0 0 0 0 0 0 1 0	-2 0 1 1 0 0 0 0 0 1 0 1
-2 0 1 1 0 0 0 0 1 1 1 0	-2 0 1 1 0 0 0 0 1 0 0 1	-2 0 1 1 0 0 0 1 1 0 1 0	-2 0 1 1 0 0 0 1 1 1 0 1	-2 0 1 1 0 0 0 1 0 1 1 0
-2 0 1 1 0 0 0 1 0 0 0 1	-2 0 1 1 0 1 1 0 0 0 1 1	-2 0 1 1 0 1 1 0 0 1 0 0	-2 0 1 1 0 1 1 0 1 1 1 1	-2 0 1 1 0 1 1 0 1 0 0 0
-2 0 1 1 0 1 1 1 1 0 1 1	-2 0 1 1 0 1 1 1 1 1 0 0	-2 0 1 1 0 1 1 1 0 1 1 1	-2 0 1 1 0 1 1 1 0 0 0 0	-2 0 1 1 1 1 0 0 0 0 1 0
-2 0 1 1 1 1 0 0 0 1 0 1	-2 0 1 1 1 1 0 0 1 1 1 0	-2 0 1 1 1 1 0 0 1 0 0 1	-2 0 1 1 1 1 0 1 1 0 1 0	-2 0 1 1 1 1 0 1 1 1 0 1
-2 0 1 1 1 1 0 1 0 1 1 0	-2 0 1 1 1 1 0 1 0 0 0 1	-2 0 1 1 1 0 1 0 0 0 1 1	-2 0 1 1 1 0 1 0 0 1 0 0	-2 0 1 1 1 0 1 0 1 1 1 1
-2 0 1 1 1 0 1 0 1 0 0 0	-2 0 1 1 1 0 1 1 1 0 1 1	-2 0 1 1 1 0 1 1 1 1 0 0	-2 0 1 1 1 0 1 1 0 1 1 1	-2 0 1 1 1 0 1 1 0 0 0 0
-2 0 1 0 1 0 0 0 0 0 1 0	-2 0 1 0 1 0 0 0 0 1 0 1	-2 0 1 0 1 0 0 0 1 1 1 0	-2 0 1 0 1 0 0 0 1 0 0 1	-2 0 1 0 1 0 0 1 1 0 1 0
-2 0 1 0 1 0 0 1 1 1 0 1	-2 0 1 0 1 0 0 1 0 1 1 0	-2 0 1 0 1 0 0 1 0 0 0 1	-2 0 1 0 1 1 1 0 0 0 1 1	-2 0 1 0 1 1 1 0 0 1 0 0
-2 0 1 0 1 1 1 0 1 1 1 1	-2 0 1 0 1 1 1 0 1 0 0 0	-2 0 1 0 1 1 1 1 1 0 1 1	-2 0 1 0 1 1 1 1 1 1 0 0	-2 0 1 0 1 1 1 1 0 1 1 1
-2 0 1 0 1 1 1 1 0 0 0 0	-2 0 1 0 0 1 0 0 0 0 1 0	-2 0 1 0 0 1 0 0 0 1 0 1	-2 0 1 0 0 1 0 0 1 1 1 0	-2 0 1 0 0 1 0 0 1 0 0 1
-2 0 1 0 0 1 0 1 1 0 1 0	-2 0 1 0 0 1 0 1 1 1 0 1	-2 0 1 0 0 1 0 1 0 1 1 0	-2 0 1 0 0 1 0 1 0 0 0 1	-2 0 1 0 0 0 1 0 0 0 1 1
-2 0 1 0 0 0 1 0 0 1 0 0	-2 0 1 0 0 0 1 0 1 1 1 1	-2 0 1 0 0 0 1 0 1 0 0 0	-2 0 1 0 0 0 1 1 1 0 1 1	-2 0 1 0 0 0 1 1 1 1 0 0
-2 0 1 0 0 0 1 1 0 1 1 1	-2 0 1 0 0 0 1 1 0 0 0 0	-2 1 1 0 0 0 0 0 0 0 0 0	-2 1 1 0 0 0 0 0 0 1 1 1	-2 1 1 0 0 0 0 0 1 1 0 0
-2 1 1 0 0 0 0 0 1 0 1 1	-2 1 1 0 0 0 0 1 1 0 0 0	-2 1 1 0 0 0 0 1 1 1 1 1	-2 1 1 0 0 0 0 1 0 1 0 0	-2 1 1 0 0 0 0 1 0 0 1 1
-2 1 1 0 0 1 1 0 0 0 0 1	-2 1 1 0 0 1 1 0 0 1 1 0	-2 1 1 0 0 1 1 0 1 1 0 1	-2 1 1 0 0 1 1 0 1 0 1 0	-2 1 1 0 0 1 1 1 1 0 0 1
-2 1 1 0 0 1 1 1 1 1 1 0	-2 1 1 0 0 1 1 1 0 1 0 1	-2 1 1 0 0 1 1 1 0 0 1 0	-2 1 1 0 1 1 0 0 0 0 0 0	-2 1 1 0 1 1 0 0 0 1 1 1
-2 1 1 0 1 1 0 0 1 1 0 0	-2 1 1 0 1 1 0 0 1 0 1 1	-2 1 1 0 1 1 0 1 1 0 0 0	-2 1 1 0 1 1 0 1 1 1 1 1	-2 1 1 0 1 1 0 1 0 1 0 0
-2 1 1 0 1 1 0 1 0 0 1 1	-2 1 1 0 1 0 1 0 0 0 0 1	-2 1 1 0 1 0 1 0 0 1 1 0	-2 1 1 0 1 0 1 0 1 1 0 1	-2 1 1 0 1 0 1 0 1 0 1 0
-2 1 1 0 1 0 1 1 1 0 0 1	-2 1 1 0 1 0 1 1 1 1 1 0	-2 1 1 0 1 0 1 1 0 1 0 1	-2 1 1 0 1 0 1 1 0 0 1 0	-2 1 1 1 1 0 0 0 0 0 0 0
-2 1 1 1 1 0 0 0 0 1 1 1	-2 1 1 1 1 0 0 0 1 1 0 0	-2 1 1 1 1 0 0 0 1 0 1 1	-2 1 1 1 1 0 0 1 1 0 0 0	-2 1 1 1 1 0 0 1 1 1 1 1
-2 1 1 1 1 0 0 1 0 1 0 0	-2 1 1 1 1 0 0 1 0 0 1 1	-2 1 1 1 1 1 1 0 0 0 0 1	-2 1 1 1 1 1 1 0 0 1 1 0	-2 1 1 1 1 1 1 0 1 1 0 1
-2 1 1 1 1 1 1 0 1 0 1 0	-2 1 1 1 1 1 1 1 1 0 0 1	-2 1 1 1 1 1 1 1 1 1 1 0	-2 1 1 1 1 1 1 1 0 1 0 1	-2 1 1 1 1 1 1 1 0 0 1 0
-2 1 1 1 0 1 0 0 0 0 0 0	-2 1 1 1 0 1 0 0 0 1 1 1	-2 1 1 1 0 1 0 0 1 1 0 0	-2 1 1 1 0 1 0 0 1 0 1 1	-2 1 1 1 0 1 0 1 1 0 0 0
-2 1 1 1 0 1 0 1 1 1 1 1	-2 1 1 1 0 1 0 1 0 1 0 0	-2 1 1 1 0 1 0 1 0 0 1 1	-2 1 1 1 0 0 1 0 0 0 0 1	-2 1 1 1 0 0 1 0 0 1 1 0
-2 1 1 1 0 0 1 0 1 1 0 1	-2 1 1 1 0 0 1 0 1 0 1 0	-2 1 1 1 0 0 1 1 1 0 0 1	-2 1 1 1 0 0 1 1 1 1 1 0	-2 1 1 1 0 0 1 1 0 1 0 1
-2 1 1 1 0 0 1 1 0 0 1 0	-2 1 0 1 0 0 0 0 0 0 1 0	-2 1 0 1 0 0 0 0 0 1 0 1	-2 1 0 1 0 0 0 0 1 1 1 0	-2 1 0 1 0 0 0 0 1 0 0 1
-2 1 0 1 0 0 0 1 1 0 1 0	-2 1 0 1 0 0 0 1 1 1 0 1	-2 1 0 1 0 0 0 1 0 1 1 0	-2 1 0 1 0 0 0 1 0 0 0 1	-2 1 0 1 0 1 1 0 0 0 1 1
-2 1 0 1 0 1 1 0 0 1 0 0	-2 1 0 1 0 1 1 0 1 1 1 1	-2 1 0 1 0 1 1 0 1 0 0 0	-2 1 0 1 0 1 1 1 1 0 1 1	-2 1 0 1 0 1 1 1 1 1 0 0
-2 1 0 1 0 1 1 1 0 1 1 1	-2 1 0 1 0 1 1 1 0 0 0 0	-2 1 0 1 1 1 0 0 0 0 1 0	-2 1 0 1 1 1 0 0 0 1 0 1	-2 1 0 1 1 1 0 0 1 1 1 0
-2 1 0 1 1 1 0 0 1 0 0 1	-2 1 0 1 1 1 0 1 1 0 1 0	-2 1 0 1 1 1 0 1 1 1 0 1	-2 1 0 1 1 1 0 1 0 1 1 0	-2 1 0 1 1 1 0 1 0 0 0 1
-2 1 0 1 1 0 1 0 0 0 1 1	-2 1 0 1 1 0 1 0 0 1 0 0	-2 1 0 1 1 0 1 0 1 1 1 1	-2 1 0 1 1 0 1 0 1 0 0 0	-2 1 0 1 1 0 1 1 1 0 1 1
-2 1 0 1 1 0 1 1 1 1 0 0	-2 1 0 1 1 0 1 1 0 1 1 1	-2 1 0 1 1 0 1 1 0 0 0 0	-2 1 0 0 1 0 0 0 0 0 1 0	-2 1 0 0 1 0 0 0 0 1 0 1
-2 1 0 0 1 0 0 0 1 1 1 0	-2 1 0 0 1 0 0 0 1 0 0 1	-2 1 0 0 1 0 0 1 1 0 1 0	-2 1 0 0 1 0 0 1 1 1 0 1	-2 1 0 0 1 0 0 1 0 1 1 0
-2 1 0 0 1 0 0 1 0 0 0 1	-2 1 0 0 1 1 1 0 0 0 1 1	-2 1 0 0 1 1 1 0 0 1 0 0	-2 1 0 0 1 1 1 0 1 1 1 1	-2 1 0 0 1 1 1 0 1 0 0 0
-2 1 0 0 1 1 1 1 1 0 1 1	-2 1 0 0 1 1 1 1 1 1 0 0	-2 1 0 0 1 1 1 1 0 1 1 1	-2 1 0 0 1 1 1 1 0 0 0 0	-2 1 0 0 0 1 0 0 0 0 1 0
-2 1 0 0 0 1 0 0 0 1 0 1	-2 1 0 0 0 1 0 0 1 1 1 0	-2 1 0 0 0 1 0 0 1 0 0 1	-2 1 0 0 0 1 0 1 1 0 1 0	-2 1 0 0 0 1 0 1 1 1 0 1
-2 1 0 0 0 1 0 1 0 1 1 0	-2 1 0 0 0 1 0 1 0 0 0 1	-2 1 0 0 0 0 1 0 0 0 1 1	-2 1 0 0 0 0 1 0 0 1 0 0	-2 1 0 0 0 0 1 0 1 1 1 1
-2 1 0 0 0 0 1 0 1 0 0 0	-2 1 0 0 0 0 1 1 1 0 1 1	-2 1 0 0 0 0 1 1 1 1 0 0	-2 1 0 0 0 0 1 1 0 1 1 1	-2 1 0 0 0 0 1 1 0 0 0 0
0 1 0 0 0 0 0 0 0 0 0 0	0 0 1 0 0 0 0 0 0 0 0 0	0 0 0 1 0 0 0 0 0 0 0 0	0 0 0 0 1 0 0 0 0 0 0 0	0 0 0 0 0 1 0 0 0 0 0 0
0 0 0 0 0 0 1 0 0 0 0 0	0 0 0 0 0 0 0 1 0 0 0 0	0 0 0 0 0 0 0 0 1 0 0 0	0 0 0 0 0 0 0 0 0 1 0 0	0 0 0 0 0 0 0 0 0 0 1 0

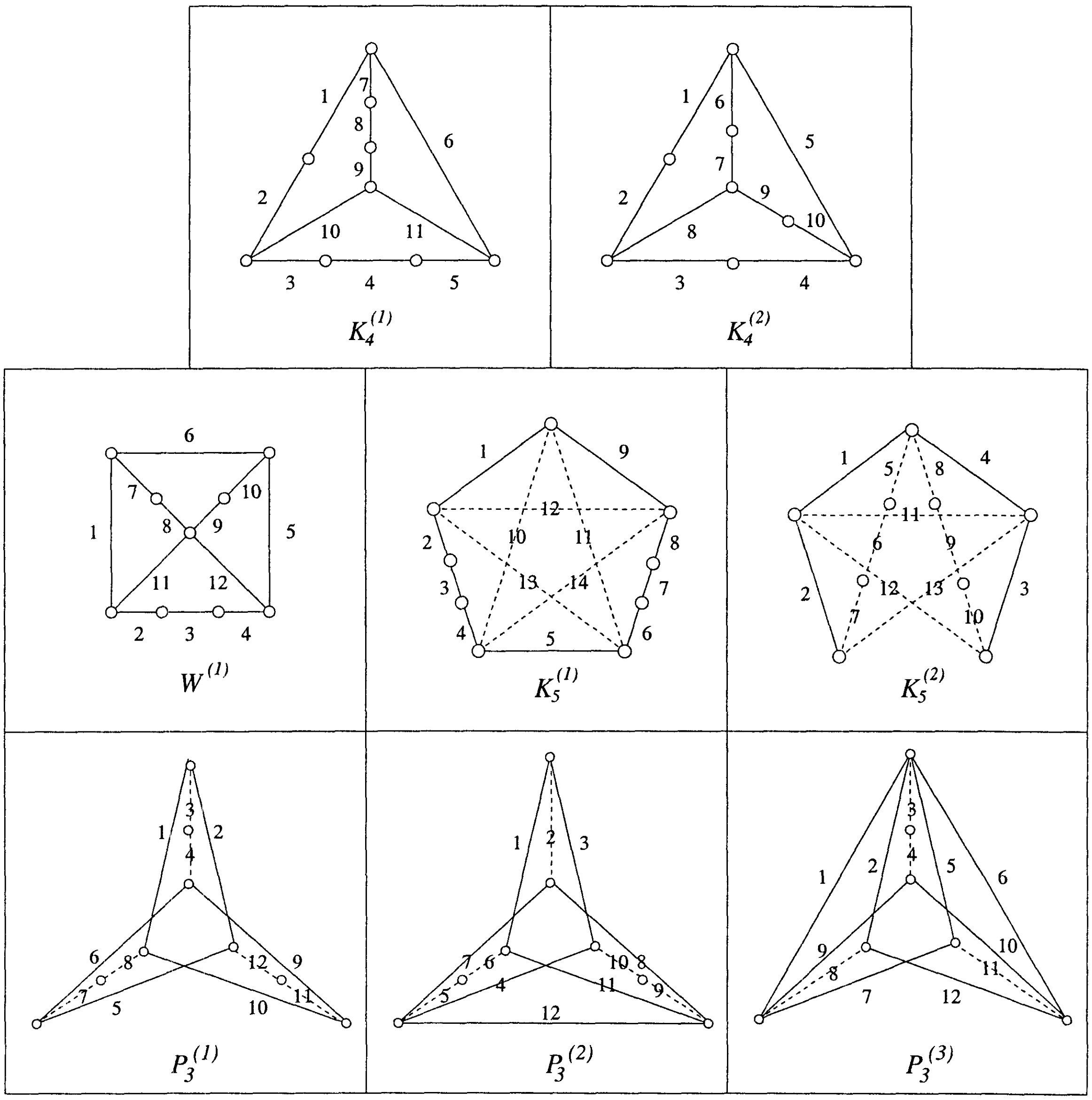


Figure 5.1: Edge labels for $[M_1, M_2, M_3]$ minor free bricks not including wheels and propellers.

$K_4^{(1)}$ EXTREME POINTS

0 2 2 0 2 1 1 1 1 2 1	0 2 1 1 1 2 2 0 2 1 1	0 2 1 1 1 1 1 1 1 1 0	0 2 1 1 1 2 2 2 0 1 1	0 2 1 1 1 2 0 2 2 1 1
0 2 2 2 0 1 1 1 1 2 1	0 2 0 2 2 1 1 1 1 2 1	0 2 0 2 2 2 2 2 2 2 0	0 2 0 2 2 0 2 2 2 2 2	0 2 0 2 2 2 2 0 2 2 2
0 2 0 2 2 2 2 2 0 2 2	0 2 0 2 2 2 0 2 2 2 2	0 2 2 0 2 2 2 2 2 2 0	0 2 2 0 2 0 2 2 2 2 2	0 2 2 0 2 2 0 2 2 2 2
0 2 2 0 2 2 2 2 0 2 2	0 2 2 0 2 2 2 0 2 2 2	0 2 2 2 0 2 2 2 2 2 0	0 2 2 2 0 0 2 2 2 2 2	0 2 2 2 0 2 2 0 2 2 2
0 2 2 2 0 2 2 2 0 2 2	0 2 2 2 0 2 0 2 2 2 2	0 2 2 2 2 0 2 2 2 0 2	0 2 2 2 2 0 2 2 2 2 0	0 2 1 1 1 0 2 2 2 1 1
0 2 2 2 2 2 0 2 2 2 0	0 2 2 2 2 2 0 2 2 0 2	0 2 2 2 2 2 2 0 2 2 0	0 2 2 2 2 2 2 0 2 0 2	0 2 2 2 2 2 2 2 0 2 0
0 2 2 2 2 2 2 2 0 0 2	0 2 2 2 2 2 2 2 2 0 0	0 2 2 2 2 1 1 1 1 0 1	1 1 0 2 2 1 2 0 2 1 1	1 1 0 2 2 2 1 1 1 1 0
1 1 0 2 2 1 2 2 0 1 1	1 1 0 2 2 1 0 2 2 1 1	2 2 0 2 2 0 2 2 2 0 2	2 2 0 2 2 0 0 2 2 2 2	2 2 0 2 2 0 2 2 0 2 2
1 1 0 2 2 0 1 1 1 1 2	2 2 0 2 2 0 2 0 2 2 2	2 2 0 2 2 2 0 2 2 2 0	2 2 0 2 2 2 0 2 2 0 2	2 2 0 2 2 2 2 0 2 2 0
2 2 0 2 2 2 2 0 2 0 2	2 2 0 2 2 2 2 2 0 2 0	2 2 0 2 2 2 2 2 0 0 2	2 2 0 2 2 2 2 2 2 0 0	2 2 0 2 2 1 1 1 1 0 1
1 1 2 2 0 1 2 0 2 1 1	1 1 2 2 0 2 1 1 1 1 0	1 1 2 2 0 1 2 2 0 1 1	1 1 2 2 0 1 0 2 2 1 1	2 2 2 2 0 0 2 2 2 0 2
2 2 2 2 0 0 0 2 2 2 2	2 2 2 2 0 0 2 2 0 2 2	1 1 2 2 0 0 1 1 1 1 2	2 2 2 2 0 0 2 0 2 2 2	2 2 2 2 0 2 0 2 2 2 0
2 2 2 2 0 2 0 2 2 0 2	2 2 2 2 0 2 2 0 2 2 0	2 2 2 2 0 2 2 0 2 0 2	2 2 2 2 0 2 2 2 0 2 0	2 2 2 2 0 2 2 2 0 0 2
2 2 2 2 0 2 2 2 2 0 0	2 2 2 2 0 1 1 1 1 0 1	1 1 1 1 1 1 0 2 2 2 0	1 1 1 1 1 1 0 2 2 0 2	1 1 1 1 1 1 2 2 0 2 0
1 1 1 1 1 1 2 2 0 0 2	1 1 1 1 1 1 2 2 2 0 0	1 1 1 1 1 1 2 0 2 0 2	1 1 1 1 1 1 2 0 2 2 0	2 2 2 2 2 0 2 2 2 0 0
2 2 2 2 2 0 2 2 0 0 2	2 2 2 2 2 0 2 2 0 2 0	2 2 2 2 2 0 2 0 2 0 2	2 2 2 2 2 0 2 0 2 2 0	2 2 2 2 2 0 0 2 2 0 2
2 2 2 2 2 0 0 2 2 2 0	2 2 1 1 1 0 2 0 2 1 1	1 1 1 1 1 0 1 1 1 0 1	1 1 2 2 2 0 1 1 1 1 0	2 2 1 1 1 0 2 2 0 1 1
2 2 1 1 1 0 0 2 2 1 1	2 2 2 0 2 1 1 1 1 0 1	2 2 2 0 2 2 2 2 2 0 0	2 2 2 0 2 2 2 2 0 0 2	2 2 2 0 2 2 2 2 0 2 0
2 2 2 0 2 2 2 0 2 0 2	2 2 2 0 2 2 2 0 2 2 0	2 2 2 0 2 2 0 2 2 0 2	2 2 2 0 2 2 0 2 2 2 0	2 2 2 0 2 0 2 0 2 2 2
1 1 2 0 2 0 1 1 1 1 2	2 2 2 0 2 0 2 2 0 2 2	2 2 2 0 2 0 0 2 2 2 2	2 2 2 0 2 0 2 2 2 0 2	1 1 2 0 2 1 2 0 2 1 1
1 1 2 0 2 2 1 1 1 1 0	1 1 2 0 2 1 2 2 0 1 1	1 1 2 0 2 1 0 2 2 1 1	2 0 2 2 2 1 1 1 1 0 1	2 0 2 2 2 2 2 2 2 0 0
2 0 2 2 2 2 2 2 0 0 2	2 0 2 2 2 2 2 2 0 2 0	2 0 2 2 2 2 2 0 2 0 2	2 0 2 2 2 2 2 0 2 2 0	2 0 2 2 2 2 0 2 2 0 2
2 0 2 2 2 2 0 2 2 2 0	2 0 1 1 1 0 2 2 2 1 1	2 0 2 2 2 0 2 2 2 2 0	2 0 2 2 2 0 2 2 2 0 2	2 0 2 2 0 2 0 2 2 2 2
2 0 2 2 0 2 2 2 0 2 2	2 0 2 2 0 2 2 0 2 2 2	2 0 2 2 0 0 2 2 2 2 2	2 0 2 2 0 2 2 2 2 2 0	2 0 2 0 2 2 2 0 2 2 2
2 0 2 0 2 2 2 2 0 2 2	2 0 2 0 2 2 0 2 2 2 2	2 0 2 0 2 0 2 2 2 2 2	2 0 2 0 2 2 2 2 2 2 0	2 0 0 2 2 2 0 2 2 2 2
2 0 0 2 2 2 2 2 0 2 2	2 0 0 2 2 2 2 0 2 2 2	2 0 0 2 2 0 2 2 2 2 2	2 0 0 2 2 2 2 2 2 2 0	2 0 2 0 2 1 1 1 1 2 1
2 0 1 1 1 2 2 0 2 1 1	2 0 1 1 1 1 1 1 1 1 0	2 0 1 1 1 2 2 2 0 1 1	2 0 1 1 1 2 0 2 2 1 1	2 0 2 2 0 1 1 1 1 2 1

$K_4^{(2)}$ INEQUALITIES

-2 0 0 0 0 0 0 0 0 1 1	-2 0 0 0 0 0 0 1 1 1 0	-2 0 0 0 0 0 0 1 1 0 1	-2 0 0 0 0 0 1 1 0 0 0	-2 0 0 0 0 0 1 1 0 1 1
-2 0 0 0 0 0 1 0 1 1 0	-2 0 0 0 0 0 1 0 1 0 1	-2 0 0 0 1 1 0 0 0 0 1	-2 0 0 0 1 1 0 0 0 1 0	-2 0 0 0 1 1 0 1 1 1 1
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-2 0 0 1 1 0 0 0 0 0 0	-2 0 0 1 1 0 0 0 0 1 1	-2 0 0 1 1 0 0 1 1 1 0	-2 0 0 1 1 0 0 1 1 0 1	-2 0 0 1 1 0 1 1 0 0 0
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$K_4^{(2)}$ EXTREME POINTS

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$K_5^{(1)}$ INEQUALITIES

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$K_5^{(1)}$ EXTREME POINTS

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$K_5^{(1)}$ EXTREME POINTS (continued)

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$K_5^{(1)}$ EXTREME POINTS (continued)

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$K_5^{(1)}$ EXTREME POINTS (continued)

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$K_5^{(1)}$ EXTREME POINTS (continued)

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$K_5^{(2)}$ INEQUALITIES

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$K_5^{(2)}$ EXTREME POINTS

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$K_5^{(2)}$ EXTREME POINTS (continued)

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$W^{(1)}$ INEQUALITIES

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$W^{(1)}$ EXTREME POINTS

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$P_3^{(1)}$ INEQUALITIES

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$P_3^{(1)}$ EXTREME POINTS

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$P_3^{(2)}$ EXTREME POINTS

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$P_3^{(2)}$ EXTREME POINTS (continued)

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222020200202	222020200220	222020202002	222020202020	222020222000
112020212010	222020220200	112020210210	222020110201	222020112001
222020020202	222020022002	222020002202	222020002022	222020000222
222002112001	222002110201	112002210210	222002220200	112002212010
222002222000	222002202020	222002202002	222002200220	222002200202
121002201110	222002202200	222002022002	222002020202	222002002202
222002000222	222002002022	211020011102	112020102011	211020101101
112020100211	121020001112	112020012012	112020010212	211020211100
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112011122000	112011120200	222011002011	222011000211	121022001110
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202220202020	202220222000	202220220200	202220110201	202220112001
202220020202	202220022002	202220020220	202220022020	202220022200
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202202022200	202020202202	202002202202	202022200220	101022201110
202022202020	202022200202	202022202002	202022202200	202022222000
202022220200	202022110201	202022112001	202022020202	202022022002
202020202022	202020200222	202002202022	202002200222	202022020220
202022022020	202020222020	202020220220	202002220220	202002222020
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202011022011	202002020222	202002022022	202002112021	202002110221
202022022200	202020022202	202020112201	202020222200	202002222200
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200022202220	200222112001	200122111100	200222110201	200222220200
200222222000	200122201101	200222202200	200222202002	200222200202
200222202020	200222200220	200022202202	200022112201	200222022002
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200202202022	200220200222	200120201121	200220202022	200020202222
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200202022022	200102021121	200202020222	200202022220	200211022011
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101111200202	101111202002	101111202200	101111222000	101111112001
101111110201	101111220200	101111022002	101111020202	202102111100
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101102112010	101102202011	101102200211	200211202011	200211200211
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$P_3^{(3)}$ INEQUALITIES

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-2 0 1 1 1 0 1 0 1 0 1 1 0	-2 0 1 0 0 1 1 1 1 0 1 0 0	-2 0 1 1 1 1 1 1 1 0 1 0 0	-2 0 0 0 1 0 1 0 0 1 0 1 1
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-2 0 1 1 0 0 1 0 1 1 0 1 0	-2 0 1 0 1 1 1 1 1 1 0 0 0	-2 0 1 1 0 1 1 1 1 1 0 0 0	-2 1 0 0 0 0 0 1 1 1 0 0 0
-2 1 0 1 1 0 0 1 1 1 0 0 0	-2 1 0 0 0 1 0 0 1 1 0 1 0	-2 1 0 1 1 1 0 0 1 1 0 1 0	-2 1 1 0 0 0 0 1 0 1 0 0 1
-2 1 1 1 1 0 0 1 0 1 0 0 1	-2 1 1 0 0 1 0 0 0 1 0 1 1	-2 1 1 1 1 1 0 0 0 1 0 1 1	-2 1 0 0 1 0 0 1 1 0 1 0 0
-2 1 0 1 0 0 0 1 1 0 1 0 0	-2 1 0 0 1 1 0 0 1 0 1 1 0	-2 1 0 1 0 1 0 0 1 0 1 1 0	-2 1 1 0 1 0 0 1 0 0 1 0 1
-2 1 1 1 0 0 0 1 0 0 1 0 1	-2 1 1 0 1 1 0 0 0 0 1 1 1	-2 1 1 1 0 1 0 0 0 0 1 1 1	-2 1 0 0 0 0 1 1 1 1 1 1 1
-2 1 0 1 1 0 1 1 1 1 1 1 1	-2 1 0 0 0 1 1 0 1 1 1 0 1	-2 1 0 1 1 1 1 0 1 1 1 0 1	-2 1 1 0 0 0 1 1 0 1 1 1 0
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-2 1 1 1 0 0 1 1 0 0 0 1 0	-2 1 1 0 1 1 1 0 0 0 0 0 0	-2 1 1 1 0 1 1 0 0 0 0 0 0	-2 1 1 1 0 1 1 0 0 0 0 0 0
0 1 0 0 0 0 0 0 0 0 0 0 0	0 0 1 0 0 0 0 0 0 0 0 0 0	0 0 0 1 0 0 0 0 0 0 0 0 0	0 0 0 0 1 0 0 0 0 0 0 0 0
0 0 0 0 0 1 0 0 0 0 0 0 0	0 0 0 0 0 0 1 0 0 0 0 0 0	0 0 0 0 0 0 0 1 0 0 0 0 0	0 0 0 0 0 0 0 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 1 0 0 0	0 0 0 0 0 0 0 0 0 0 1 0 0	0 0 0 0 0 0 0 0 0 0 0 1 0	0 0 0 0 0 0 0 0 0 0 0 0 1

$P_3^{(3)}$ EXTREME POINTS

0 0 0 2 1 1 1 1 0 2 0 1	0 0 0 2 1 1 1 1 2 0 0 1	0 0 1 1 0 1 0 1 1 0 2 1	0 0 1 1 0 1 2 1 1 0 0 1	0 0 1 1 2 1 0 1 1 0 0 1
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0 0 1 1 0 1 0 2 2 1 2 0	0 0 1 1 0 1 2 2 2 1 0 0	0 0 2 2 0 0 1 1 0 2 1 1	0 0 1 1 0 1 1 1 0 1 1 1	0 0 1 1 0 1 1 0 1 0 1 2
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$P_3^{(3)}$ EXTREME POINTS (continued)

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1 0 1 1 0 2 2 2 1 0 0 0	2 0 2 2 0 2 2 2 0 0 0 0	2 0 1 1 0 1 2 2 0 1 0 0	1 0 1 1 0 2 0 2 1 0 2 0	2 0 2 2 0 2 0 2 0 0 2 0
2 0 1 1 0 1 0 2 0 1 2 0	2 0 2 2 0 0 0 2 0 2 2 0	2 0 2 2 0 0 0 2 0 0 2 2	1 0 1 1 0 0 0 2 1 0 2 2	1 0 1 1 0 0 2 2 1 0 2 0
1 0 1 1 0 0 2 2 1 0 0 2	1 0 1 1 0 0 2 2 1 2 0 0	2 0 2 2 0 0 2 2 0 2 0 0	2 0 2 2 0 0 2 2 0 0 2 0	2 0 2 2 0 0 2 2 0 0 0 2
1 0 2 2 0 1 1 2 0 0 1 0	1 0 1 1 0 0 0 2 1 2 2 0	2 0 2 2 0 0 1 1 0 0 1 1	1 0 1 1 0 0 1 1 1 0 1 1	1 0 1 1 0 0 1 2 0 1 1 0
2 0 2 0 2 0 0 0 2 0 2 2	1 0 2 0 1 0 1 0 2 0 2 2	2 0 2 0 2 0 0 0 0 2 2 2	1 0 2 0 1 0 1 0 0 2 2 2	2 0 2 0 0 0 2 0 2 0 2 2
2 0 2 0 0 0 2 0 0 2 2 2	1 0 2 0 1 2 1 0 2 0 0 2	1 0 2 0 1 2 1 0 0 2 0 2	2 0 2 0 2 2 0 0 2 0 0 2	2 0 2 0 2 2 0 0 0 2 0 2
2 0 2 0 1 1 0 0 2 0 1 2	2 0 2 0 0 2 2 0 0 2 0 2	2 0 2 0 0 2 0 0 0 2 2 2	2 0 2 0 0 2 2 0 2 0 0 2	2 0 2 0 0 2 0 0 2 0 2 2
1 0 2 0 0 1 1 0 2 0 1 2	1 0 2 0 2 1 0 0 1 1 0 2	2 0 2 0 1 1 0 0 0 2 1 2	1 0 2 0 0 1 2 0 1 1 0 2	1 0 2 0 0 1 1 0 0 2 1 2
1 0 2 0 0 1 0 0 1 1 2 2	2 0 2 0 2 0 0 0 2 2 0 2	1 0 2 0 1 0 1 0 2 2 0 2	2 0 2 0 0 0 2 0 2 2 0 2	2 0 2 0 0 0 0 0 2 2 2 2
1 0 2 0 1 2 1 2 2 0 0 0	1 0 2 0 1 2 1 2 0 2 0 0	2 0 2 0 1 1 0 2 2 0 1 0	2 0 2 0 2 2 0 2 2 0 0 0	2 0 2 0 2 2 0 2 0 2 0 0
2 0 2 0 1 1 0 2 0 2 1 0	1 0 2 0 1 0 1 2 0 2 2 0	2 0 2 0 2 0 0 2 0 2 2 0	1 0 2 0 1 0 1 2 0 2 0 2	2 0 2 0 2 0 0 2 0 2 0 2
1 0 2 0 1 0 1 2 2 0 2 0	1 0 2 0 1 0 1 2 2 0 0 2	1 0 2 0 1 0 1 2 2 2 0 0	2 0 2 0 2 0 0 2 2 0 2 0	2 0 2 0 2 0 0 2 2 0 0 2
2 0 2 0 2 0 0 2 2 2 0 0	2 0 2 0 0 0 2 2 0 2 2 0	2 0 2 0 0 2 2 2 0 2 0 0	2 0 2 0 0 2 0 2 0 2 2 0	1 0 2 0 0 1 1 2 0 2 1 0
2 0 2 0 0 0 2 2 0 2 0 2	2 0 2 0 0 0 0 2 0 2 2 2	1 0 2 0 0 1 1 2 2 0 1 0	2 0 2 0 0 2 2 2 2 0 0 0	2 0 2 0 0 2 0 2 2 0 2 0
2 0 2 0 0 0 0 2 2 0 2 2	2 0 2 0 0 0 2 2 2 0 2 0	2 0 2 0 0 0 2 2 2 0 0 2	2 0 2 0 0 0 2 2 2 2 0 0	2 0 2 0 0 0 0 2 2 2 2 0
2 0 2 0 0 0 1 1 2 0 1 1	2 0 2 0 0 0 1 2 1 1 1 0	1 0 2 0 1 0 0 2 1 1 1 0	2 0 2 0 2 0 0 1 1 1 0 1	1 0 2 0 1 0 1 1 1 1 0 1
1 0 2 0 2 1 0 2 1 1 0 0	1 0 2 0 0 1 2 2 1 1 0 0	1 0 2 0 0 1 0 2 1 1 2 0	2 0 2 0 0 0 2 1 1 1 0 1	2 0 2 0 0 0 1 1 0 2 1 1
2 0 2 0 0 0 0 1 1 1 2 1	2 0 0 2 2 0 0 0 2 0 2 2	1 0 0 2 1 0 1 0 2 0 2 2	1 0 0 2 1 0 1 0 0 2 2 2	2 0 0 2 2 0 0 0 0 2 2 2

$P_3^{(3)}$ EXTREME POINTS (continued)

2 0 0 2 0 0 2 0 2 0 2 2	2 0 0 2 0 0 2 0 0 2 2 2	1 0 0 2 1 2 1 0 2 0 0 2	1 0 0 2 1 2 1 0 0 2 0 2	2 0 0 2 2 2 0 0 2 0 0 2
2 0 0 2 2 2 0 0 0 2 0 2	2 0 0 2 1 1 0 0 2 0 1 2	2 0 0 2 0 2 2 0 0 2 0 2	2 0 0 2 0 2 0 0 0 2 2 2	2 0 0 2 0 2 2 0 2 0 0 2
2 0 0 2 0 2 0 0 2 0 2 2	1 0 0 2 0 1 1 0 2 0 1 2	1 0 0 2 0 1 0 0 1 1 2 2	1 0 0 2 0 1 1 0 0 2 1 2	1 0 0 2 0 1 2 0 1 1 0 2
2 0 0 2 1 1 0 0 0 2 1 2	1 0 0 2 2 1 0 0 1 1 0 2	2 0 0 2 0 0 0 0 2 2 2 2	2 0 0 2 0 0 2 0 2 2 0 2	1 0 0 2 1 0 1 0 2 2 0 2
2 0 0 2 2 0 0 0 2 2 0 2	1 0 0 2 1 2 1 2 2 0 0 0	1 0 0 2 1 2 1 2 0 2 0 0	2 0 0 2 1 1 0 2 2 0 1 0	2 0 0 2 2 2 0 2 2 0 0 0
2 0 0 2 2 2 0 2 0 2 0 0	2 0 0 2 1 1 0 2 0 2 1 0	1 0 0 2 1 0 1 2 0 2 2 0	2 0 0 2 2 0 0 2 0 2 2 0	1 0 0 2 1 0 1 2 0 2 0 2
2 0 0 2 2 0 0 2 0 2 0 2	1 0 0 2 1 0 1 2 2 0 2 0	1 0 0 2 1 0 1 2 2 0 0 2	1 0 0 2 1 0 1 2 2 2 0 0	2 0 0 2 2 0 0 2 2 0 2 0
2 0 0 2 2 0 0 2 2 0 0 2	2 0 0 2 2 0 0 2 2 2 0 0	2 0 0 2 0 0 2 2 0 2 2 0	2 0 0 2 0 2 2 2 0 2 0 0	2 0 0 2 0 2 0 2 0 2 2 0
1 0 0 2 0 1 1 2 0 2 1 0	2 0 0 2 0 0 2 2 0 2 0 2	2 0 0 2 0 0 0 2 0 2 2 2	1 0 0 2 0 1 1 2 2 0 1 0	2 0 0 2 0 2 2 2 2 0 0 0
2 0 0 2 0 2 0 2 2 0 2 0	2 0 0 2 0 0 0 2 2 0 2 2	2 0 0 2 0 0 2 2 2 0 2 0	2 0 0 2 0 0 2 2 2 0 0 2	2 0 0 2 0 0 2 2 2 2 0 0
2 0 0 2 0 0 0 2 2 2 2 0	2 0 0 2 0 0 1 1 2 0 1 1	2 0 0 2 0 0 1 2 1 1 1 0	2 0 0 2 0 0 0 1 1 1 2 1	2 0 0 2 0 0 1 1 0 2 1 1
2 0 0 2 0 0 2 1 1 1 0 1	1 0 0 2 0 1 0 2 1 1 2 0	1 0 0 2 0 1 2 2 1 1 0 0	1 0 0 2 2 1 0 2 1 1 0 0	1 0 0 2 1 0 1 1 1 1 0 1
2 0 0 2 2 0 0 1 1 1 0 1	1 0 0 2 1 0 0 2 1 1 1 0	1 0 2 0 1 0 0 1 0 2 1 1	1 0 2 0 1 0 0 0 1 1 1 2	2 0 2 0 0 0 1 0 1 1 1 2
1 0 2 0 0 1 0 1 2 0 2 1	1 0 2 0 0 1 2 1 2 0 0 1	1 0 2 0 0 1 0 1 0 2 2 1	1 0 2 0 0 1 2 1 0 2 0 1	1 0 2 0 1 0 0 1 2 0 1 1
1 0 2 0 2 1 0 1 0 2 0 1	1 0 2 0 2 1 0 1 2 0 0 1	1 0 2 2 1 0 0 1 0 0 1 1	1 0 1 1 2 0 0 1 0 1 0 1	2 0 1 1 1 0 0 0 0 1 1 2
1 0 1 1 2 0 0 0 1 2 0 2	1 0 2 2 2 1 0 1 0 0 0 1	1 0 2 2 0 1 2 1 0 0 0 1	1 0 2 2 0 1 0 1 0 0 2 1	1 0 1 1 0 0 0 0 1 2 2 2
1 0 1 1 0 0 2 0 1 2 0 2	1 0 1 1 0 0 2 1 0 1 0 1	1 0 1 1 0 0 1 0 0 1 1 2	1 0 1 1 0 0 0 1 0 1 2 1	1 0 0 2 2 1 0 1 2 0 0 1
1 0 0 2 2 1 0 1 0 2 0 1	1 0 0 2 1 0 0 1 2 0 1 1	1 0 0 2 0 1 2 1 0 2 0 1	1 0 0 2 0 1 0 1 0 2 2 1	1 0 0 2 0 1 2 1 2 0 0 1
1 0 0 2 0 1 0 1 2 0 2 1	2 0 0 2 0 0 1 0 1 1 1 2	1 0 0 2 1 0 0 1 0 2 1 1	1 0 0 2 1 0 0 0 1 1 1 2	

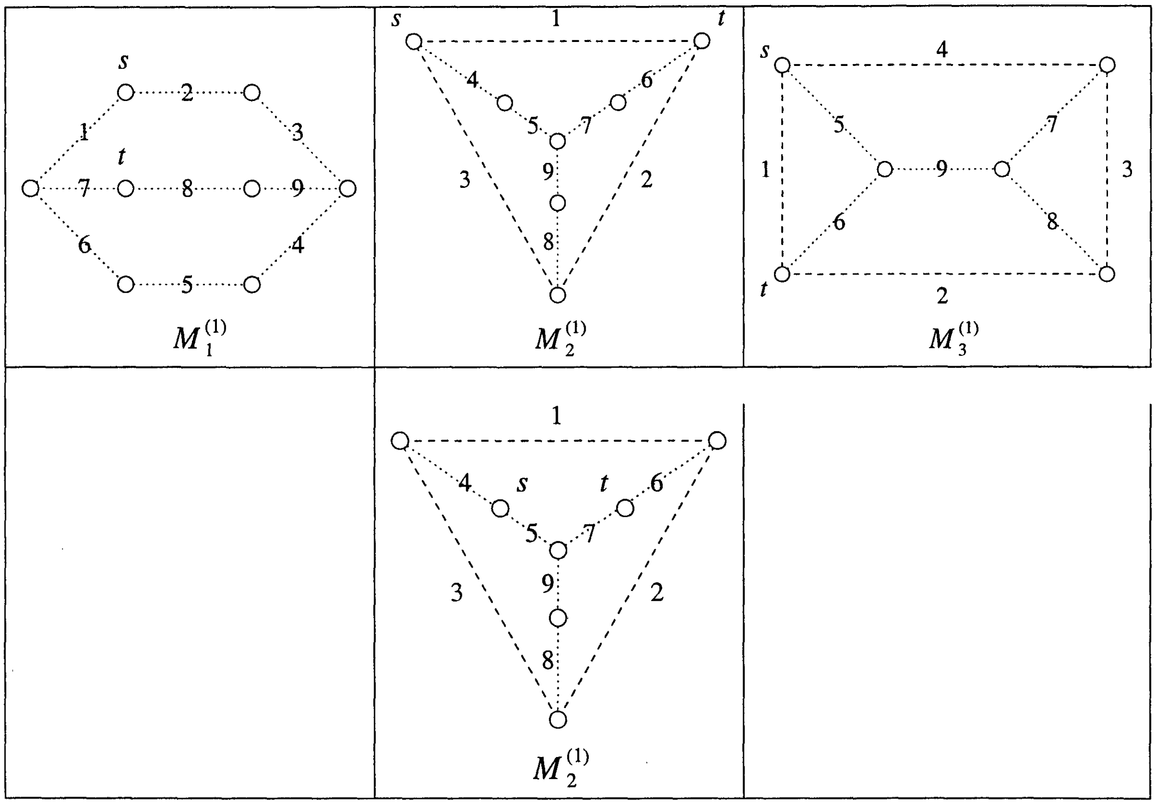

Table 5.1: Labelings of M_1, M_2, M_3 resulting in s-t walk-perfect graphs.

5.2 s-t Walk-Perfect Labelings of M_1, M_2, M_3

We prove the s-t labelings of graphs M_1, M_2, and M_3 in Table 5.1 are s-t walk perfect. The inequalities and extreme points for each of the polyhedra are enumerated in the following tables. We verify that each extreme point corresponds to an s-t traveling salesman walk, showing these graphs are s-t walk-perfect.

$M_1^{(1)}$ INEQUALITIES

-2 0 0 0 0 0 0 0 1 1	-1 0 0 0 0 0 0 1 1 0	-1 0 0 0 0 0 0 1 0 1	-2 0 0 0 0 1 1 0 0 0	-2 0 0 0 0 1 1 0 1 1	-1 0 0 0 0 1 1 1 1 0
-1 0 0 0 0 1 1 1 0 1	-2 0 0 0 1 1 0 0 0 0	-2 0 0 0 1 1 0 0 1 1	-1 0 0 0 1 1 0 1 1 0	-1 0 0 0 1 1 0 1 0 1	-2 0 0 0 1 0 1 0 0 0
-2 0 0 0 1 0 1 0 1 1	-1 0 0 0 1 0 1 1 1 0	-1 0 0 0 1 0 1 1 0 1	-2 0 0 1 1 0 0 0 0 1	-2 0 0 1 1 0 0 0 1 0	-1 0 0 1 1 0 0 1 1 1
-1 0 0 1 1 0 0 1 0 0	-2 0 0 1 1 1 1 0 0 1	-2 0 0 1 1 1 1 0 1 0	-1 0 0 1 1 1 1 1 1 1	-1 0 0 1 1 1 1 1 0 0	-2 0 0 1 0 1 0 0 0 1
-2 0 0 1 0 1 0 0 1 0	-1 0 0 1 0 1 0 1 1 1	-1 0 0 1 0 1 0 1 0 0	-2 0 0 1 0 0 1 0 0 1	-2 0 0 1 0 0 1 0 1 0	-1 0 0 1 0 0 1 1 1 1
-1 0 0 1 0 0 1 1 0 0	-2 0 1 1 0 0 0 0 0 0	-2 0 1 1 0 0 0 0 1 1	-1 0 1 1 0 0 0 1 1 0	-1 0 1 1 0 0 0 1 0 1	-2 0 1 1 0 1 1 0 0 0
-2 0 1 1 0 1 1 0 1 1	-1 0 1 1 0 1 1 1 1 0	-1 0 1 1 0 1 1 1 0 1	-2 0 1 1 1 1 0 0 0 0	-2 0 1 1 1 1 0 0 1 1	-1 0 1 1 1 1 0 1 1 0
-1 0 1 1 1 1 0 1 0 1	-2 0 1 1 1 0 1 0 0 0	-2 0 1 1 1 0 1 0 1 1	-1 0 1 1 1 0 1 1 1 0	-1 0 1 1 1 0 1 1 0 1	-2 0 1 0 1 0 0 0 0 1
-2 0 1 0 1 0 0 0 1 0	-1 0 1 0 1 0 0 1 1 1	-1 0 1 0 1 0 0 1 0 0	-2 0 1 0 1 1 1 0 0 1	-2 0 1 0 1 1 1 0 1 0	-1 0 1 0 1 1 1 1 1 1
-1 0 1 0 1 1 1 1 0 0	-2 0 1 0 0 1 0 0 0 1	-2 0 1 0 0 1 0 0 1 0	-1 0 1 0 0 1 0 1 1 1	-1 0 1 0 0 1 0 1 0 0	-2 0 1 0 0 0 1 0 0 1
-2 0 1 0 0 0 1 0 1 0	-1 0 1 0 0 0 1 1 1 1	-1 0 1 0 0 0 1 1 0 0	-1 1 1 0 0 0 0 0 0 0	-1 1 1 0 0 0 0 0 1 1	-2 1 1 0 0 0 0 1 1 0
-2 1 1 0 0 0 0 1 0 1	-1 1 1 0 0 1 1 0 0 0	-1 1 1 0 0 1 1 0 1 1	-2 1 1 0 0 1 1 1 1 0	-2 1 1 0 0 1 1 1 0 1	-1 1 1 0 1 1 0 0 0 0
-1 1 1 0 1 1 0 0 1 1	-2 1 1 0 1 1 0 1 1 0	-2 1 1 0 1 1 0 1 0 1	-1 1 1 0 1 0 1 0 0 0	-1 1 1 0 1 0 1 0 1 1	-2 1 1 0 1 0 1 1 1 0
-2 1 1 0 1 0 1 1 0 1	-1 1 1 1 1 0 0 0 0 1	-1 1 1 1 1 0 0 0 1 0	-2 1 1 1 1 0 0 1 1 1	-2 1 1 1 1 0 0 1 0 0	-1 1 1 1 1 1 1 0 0 1
-1 1 1 1 1 1 1 0 1 0	-2 1 1 1 1 1 1 1 1 1	-2 1 1 1 1 1 1 1 0 0	-1 1 1 1 0 1 0 0 0 1	-1 1 1 1 0 1 0 0 1 0	-2 1 1 1 0 1 0 1 1 1
-2 1 1 1 0 1 0 1 0 0	-1 1 1 1 0 0 1 0 0 1	-1 1 1 1 0 0 1 0 1 0	-2 1 1 1 0 0 1 1 1 1	-2 1 1 1 0 0 1 1 0 0	-1 1 0 1 0 0 0 0 0 0
-1 1 0 1 0 0 0 0 1 1	-2 1 0 1 0 0 0 1 1 0	-2 1 0 1 0 0 0 1 0 1	-1 1 0 1 0 1 1 0 0 0	-1 1 0 1 0 1 1 0 1 1	-2 1 0 1 0 1 1 1 1 0
-2 1 0 1 0 1 1 1 0 1	-1 1 0 1 1 1 0 0 0 0	-1 1 0 1 1 1 0 0 1 1	-2 1 0 1 1 1 0 1 1 0	-2 1 0 1 1 1 0 1 0 1	-1 1 0 1 1 0 1 0 0 0
-1 1 0 1 1 0 1 0 1 1	-2 1 0 1 1 0 1 1 1 0	-2 1 0 1 1 0 1 1 0 1	-1 1 0 0 1 0 0 0 0 1	-1 1 0 0 1 0 0 0 1 0	-2 1 0 0 1 0 0 1 1 1
-2 1 0 0 1 0 0 1 0 0	-1 1 0 0 1 1 1 0 0 1	-1 1 0 0 1 1 1 0 1 0	-2 1 0 0 1 1 1 1 1 1	-2 1 0 0 1 1 1 1 0 0	-1 1 0 0 0 1 0 0 0 1
-1 1 0 0 0 1 0 0 1 0	-2 1 0 0 0 1 0 1 1 1	-2 1 0 0 0 1 0 1 0 0	-1 1 0 0 0 0 1 0 0 1	-1 1 0 0 0 0 1 0 1 0	-2 1 0 0 0 0 1 1 1 1
-2 1 0 0 0 0 1 1 0 0	0 1 0 0 0 0 0 0 0 0	0 0 1 0 0 0 0 0 0 0	0 0 0 1 0 0 0 0 0 0	0 0 0 0 1 0 0 0 0 0	0 0 0 0 0 1 0 0 0 0
0 0 0 0 0 0 1 0 0 0	0 0 0 0 0 0 0 1 0 0	0 0 0 0 0 0 0 0 1 0	0 0 0 0 0 0 0 0 0 1		

$M_1^{(1)}$ EXTREME POINTS

0 1 1 0 2 2 2 1 1	0 1 1 2 2 0 2 1 1	0 1 1 1 1 1 1 0 2	0 1 1 1 1 1 1 2 0	0 1 1 2 2 2 0 1 1	0 1 1 2 0 2 2 1 1
1 2 0 0 2 2 1 2 2	1 2 0 2 2 0 1 2 2	1 2 0 1 1 1 0 1 1	1 2 0 2 0 2 1 2 2	1 2 0 2 2 2 1 0 2	1 2 0 2 2 2 1 2 0
2 1 1 2 0 2 0 1 1	1 2 2 2 0 2 1 0 2	1 2 2 2 0 2 1 2 0	1 2 2 2 2 0 1 2 0	1 2 2 2 2 0 1 0 2	2 1 1 2 2 0 0 1 1
1 2 2 0 2 2 1 2 0	1 2 2 0 2 2 1 0 2	2 1 1 0 2 2 0 1 1	1 0 2 2 2 2 1 2 0	1 0 2 2 2 2 1 0 2	1 0 2 0 2 2 1 2 2
1 0 2 2 2 0 1 2 2	1 0 2 1 1 1 0 1 1	1 0 2 2 0 2 1 2 2			

$M_2^{(1)}$ INEQUALITIES

-2 0 0 0 0 1 0 1 0 1	-2 0 0 0 0 0 0 0 1 1	-2 0 0 0 0 1 0 1 1 0	-2 0 0 0 0 0 1 1 0 0	-2 0 0 0 0 1 1 0 0 1	-2 0 0 0 0 0 1 1 1 1
-2 0 0 0 0 1 1 0 1 0	-2 0 0 0 1 1 0 0 0 0	-2 0 0 0 1 0 0 1 0 1	-2 0 0 0 1 1 0 0 1 1	-2 0 0 0 1 0 0 1 1 0	-2 0 0 0 1 1 1 1 0 0
-2 0 0 0 1 0 1 0 0 1	-2 0 0 0 1 1 1 1 1 1	-2 0 0 0 1 0 1 0 1 0	-2 0 1 1 0 0 0 0 1 0	-2 0 1 1 0 1 0 1 1 1	-2 0 1 1 0 0 0 0 0 1
-2 0 1 1 0 1 0 1 0 0	-2 0 1 1 0 0 1 1 1 0	-2 0 1 1 0 1 1 0 1 1	-2 0 1 1 0 0 1 1 0 1	-2 0 1 1 0 1 1 0 0 0	-2 0 1 1 1 1 0 0 1 0
-2 0 1 1 1 0 0 1 1 1	-2 0 1 1 1 1 0 0 0 1	-2 0 1 1 1 0 0 1 0 0	-2 0 1 1 1 1 1 1 1 0	-2 0 1 1 1 0 1 0 1 1	-2 0 1 1 1 1 1 1 0 1
-2 0 1 1 1 0 1 0 0 0	-1 1 1 0 0 0 1 0 0 0	-1 1 1 0 0 1 1 1 0 1	-1 1 1 0 0 0 1 0 1 1	-1 1 1 0 0 1 1 1 1 0	-1 1 1 0 0 0 0 1 0 0
-1 1 1 0 0 1 0 0 0 1	-1 1 1 0 0 0 0 1 1 1	-1 1 1 0 0 1 0 0 1 0	-1 1 1 0 1 1 1 0 0 0	-1 1 1 0 1 0 1 1 0 1	-1 1 1 0 1 1 1 0 1 1
-1 1 1 0 1 0 1 1 1 0	-1 1 1 0 1 1 0 1 0 0	-1 1 1 0 1 0 0 0 0 1	-1 1 1 0 1 1 0 1 1 1	-1 1 1 0 1 0 0 0 1 0	-1 1 0 1 0 0 1 0 1 0
-1 1 0 1 0 1 1 1 1 1	-1 1 0 1 0 0 1 0 0 1	-1 1 0 1 0 1 1 1 0 0	-1 1 0 1 0 0 0 1 1 0	-1 1 0 1 0 1 0 0 1 1	-1 1 0 1 0 0 0 1 0 1
-1 1 0 1 0 1 0 0 0 0	-1 1 0 1 1 1 1 0 1 0	-1 1 0 1 1 0 1 1 1 1	-1 1 0 1 1 1 1 0 0 1	-1 1 0 1 1 0 1 1 0 0	-1 1 0 1 1 1 0 1 1 0
-1 1 0 1 1 0 0 0 1 1	-1 1 0 1 1 1 0 1 0 1	-1 1 0 1 1 0 0 0 0 0	0 1 0 0 0 0 0 0 0 0	0 0 1 0 0 0 0 0 0 0	0 0 0 1 0 0 0 0 0 0
0 0 0 0 1 0 0 0 0 0	0 0 0 0 0 1 0 0 0 0	0 0 0 0 0 0 1 0 0 0	0 0 0 0 0 0 0 1 0 0	0 0 0 0 0 0 0 0 1 0	0 0 0 0 0 0 0 0 0 1

$M_2^{(1)}$ EXTREME POINTS

0 0 0 1 1 1 1 2 2	0 0 1 2 0 1 1 1 1	0 0 1 0 2 1 1 1 1	0 0 2 1 1 1 1 0 2	0 0 2 1 1 1 1 2 0	0 1 1 0 2 0 2 2 2
0 1 1 0 2 2 0 2 2	0 1 1 0 2 2 2 0 2	0 1 1 0 2 2 2 2 0	0 1 1 2 2 0 2 0 2	0 1 1 2 2 0 2 2 0	0 1 1 2 2 2 0 2 0
0 1 1 2 2 2 0 0 2	0 1 1 2 0 2 2 2 0	0 1 1 2 0 2 2 0 2	0 1 1 2 0 2 0 2 2	0 1 1 2 0 0 2 2 2	0 2 0 1 1 1 1 2 0
0 2 0 1 1 1 1 0 2	0 1 0 1 1 2 0 1 1	0 1 0 1 1 0 2 1 1	1 1 0 0 2 1 1 1 1	1 2 0 0 2 0 2 2 2	1 2 0 0 2 2 0 2 2
1 2 0 0 2 2 2 0 2	1 2 0 0 2 2 2 2 0	1 1 0 2 0 1 1 1 1	1 2 0 2 0 0 2 2 2	1 2 0 2 0 2 0 2 2	1 2 0 2 0 2 2 0 2
1 2 0 2 0 2 2 2 0	1 2 0 2 2 0 2 0 2	1 2 0 2 2 0 2 2 0	1 2 0 2 2 2 0 0 2	1 2 0 2 2 2 0 2 0	1 0 2 2 2 2 0 2 0
1 0 2 2 2 2 0 0 2	1 0 1 1 1 2 0 1 1	1 0 2 2 2 0 2 2 0	1 0 2 2 2 0 2 0 2	1 0 1 1 1 0 2 1 1	1 0 2 2 0 2 2 2 0
1 0 2 2 0 2 2 0 2	1 0 2 2 0 2 0 2 2	1 0 2 2 0 0 2 2 2	1 0 2 0 2 2 2 2 0	1 0 2 0 2 2 2 0 2	1 0 2 0 2 2 0 2 2
1 0 2 0 2 0 2 2 2	1 0 0 2 2 2 0 2 2	1 0 0 2 2 0 2 2 2	1 0 0 2 0 2 2 2 2	1 0 0 0 2 2 2 2 2	

$M_2^{(2)}$ INEQUALITIES

-2 0 0 0 0 1 0 1 0 1	-2 0 0 0 0 0 0 0 1 1	-2 0 0 0 0 1 0 1 1 0	-1 0 0 0 0 0 1 1 0 0	-1 0 0 0 0 1 1 0 0 1	-1 0 0 0 0 0 1 1 1 1
-1 0 0 0 0 1 1 0 1 0	-1 0 0 0 1 1 0 0 0 0	-1 0 0 0 1 0 0 1 0 1	-1 0 0 0 1 1 0 0 1 1	-1 0 0 0 1 0 0 1 1 0	-2 0 0 0 1 1 1 1 0 0
-2 0 0 0 1 0 1 0 0 1	-2 0 0 0 1 1 1 1 1 1	-2 0 0 0 1 0 1 0 1 0	-2 0 1 1 0 0 0 0 1 0	-2 0 1 1 0 1 0 1 1 1	-2 0 1 1 0 0 0 0 0 1
-2 0 1 1 0 1 0 1 0 0	-1 0 1 1 0 0 1 1 1 0	-1 0 1 1 0 1 1 0 1 1	-1 0 1 1 0 0 1 1 0 1	-1 0 1 1 0 1 1 0 0 0	-1 0 1 1 1 1 0 0 1 0
-1 0 1 1 1 0 0 1 1 1	-1 0 1 1 1 1 0 0 0 1	-1 0 1 1 1 0 0 1 0 0	-2 0 1 1 1 1 1 1 1 0	-2 0 1 1 1 0 1 0 1 1	-2 0 1 1 1 1 1 1 0 1
-2 0 1 1 1 0 1 0 0 0	-2 1 1 0 0 0 1 0 0 0	-2 1 1 0 0 1 1 1 0 1	-2 1 1 0 0 0 1 0 1 1	-2 1 1 0 0 1 1 1 1 0	-1 1 1 0 0 0 0 1 0 0
-1 1 1 0 0 1 0 0 0 1	-1 1 1 0 0 0 0 1 1 1	-1 1 1 0 0 1 0 0 1 0	-1 1 1 0 1 1 1 0 0 0	-1 1 1 0 1 0 1 1 0 1	-1 1 1 0 1 1 1 0 1 1
-1 1 1 0 1 0 1 1 1 0	-2 1 1 0 1 1 0 1 0 0	-2 1 1 0 1 0 0 0 0 1	-2 1 1 0 1 1 0 1 1 1	-2 1 1 0 1 0 0 0 1 0	-2 1 0 1 0 0 1 0 1 0
-2 1 0 1 0 1 1 1 1 1	-2 1 0 1 0 0 1 0 0 1	-2 1 0 1 0 1 1 1 0 0	-1 1 0 1 0 0 0 1 1 0	-1 1 0 1 0 1 0 0 1 1	-1 1 0 1 0 0 0 1 0 1
-1 1 0 1 0 1 0 0 0 0	-1 1 0 1 1 1 1 0 1 0	-1 1 0 1 1 0 1 1 1 1	-1 1 0 1 1 1 1 0 0 1	-1 1 0 1 1 0 1 1 0 0	-2 1 0 1 1 1 0 1 1 0
-2 1 0 1 1 0 0 0 1 1	-2 1 0 1 1 1 0 1 0 1	-2 1 0 1 1 0 0 0 0 0	0 1 0 0 0 0 0 0 0 0	0 0 1 0 0 0 0 0 0 0	0 0 0 1 0 0 0 0 0 0
0 0 0 0 1 0 0 0 0 0	0 0 0 0 0 1 0 0 0 0	0 0 0 0 0 0 1 0 0 0	0 0 0 0 0 0 0 1 0 0	0 0 0 0 0 0 0 0 1 0	0 0 0 0 0 0 0 0 0 1

$M_2^{(2)}$ EXTREME POINTS

0 0 1 1 0 2 1 1 1	0 0 0 2 1 2 1 2 2	0 0 2 2 1 2 1 0 2	0 0 2 2 1 2 1 2 0	0 1 1 1 2 1 0 2 0	0 1 1 1 2 1 0 0 2
0 1 1 1 0 1 0 2 2	0 1 1 1 0 1 2 2 0	0 1 1 1 0 1 2 0 2	0 2 0 2 1 2 1 2 0	0 2 0 2 1 2 1 0 2	0 1 0 2 1 1 0 1 1
0 0 2 0 1 2 1 2 2	0 2 0 2 1 0 1 2 2	0 1 2 0 1 1 0 1 1	0 2 2 0 1 2 1 2 0	0 2 2 0 1 2 1 0 2	0 2 2 0 1 0 1 2 2
0 2 1 1 0 0 1 1 1	0 2 2 2 1 0 1 2 0	0 2 2 2 1 0 1 0 2	1 1 0 1 0 0 1 1 1	2 1 0 0 1 1 0 1 1	2 2 0 0 1 2 1 2 0
2 2 0 0 1 2 1 0 2	2 2 0 0 1 0 1 2 2	1 2 0 1 0 1 2 0 2	1 2 0 1 0 1 2 2 0	1 2 0 1 0 1 0 2 2	2 2 0 2 1 0 1 2 0
2 2 0 2 1 0 1 0 2	1 2 0 1 2 1 0 0 2	1 2 0 1 2 1 0 2 0	1 1 1 2 1 0 1 0 2	1 1 1 2 1 0 1 2 0	1 1 1 0 1 0 1 2 2
1 1 1 0 1 2 1 0 2	1 1 1 0 1 2 1 2 0	1 0 2 1 2 1 0 2 0	1 0 2 1 2 1 0 0 2	2 0 2 2 1 0 1 0 2	2 0 2 2 1 0 1 2 0
1 0 2 1 0 1 0 2 2	1 0 2 1 0 1 2 2 0	1 0 2 1 0 1 2 0 2	2 0 1 1 0 0 1 1 1	2 0 2 0 1 0 1 2 2	2 0 2 0 1 2 1 0 2
2 0 2 0 1 2 1 2 0	2 0 0 2 1 0 1 2 2	2 0 0 0 1 2 1 2 2	1 0 0 1 0 1 2 2 2	1 0 1 0 1 1 0 1 1	1 0 0 1 2 1 0 2 2

$M_3^{(1)}$ INEQUALITIES

-2 0 0 0 0 0 0 1 1 1	-2 0 0 0 0 1 1 0 0 1	-2 0 0 0 0 1 1 1 1 0	-2 0 0 1 1 0 0 0 1 0	-2 0 0 1 1 0 0 1 0 1	-2 0 0 1 1 1 1 0 1 1
-2 0 0 1 1 1 1 1 0 0	-2 0 1 1 0 0 0 1 0 0	-2 0 1 1 0 0 0 0 1 1	-2 0 1 1 0 1 1 1 0 1	-2 0 1 1 0 1 1 0 1 0	-2 0 1 0 1 0 0 1 1 0
-2 0 1 0 1 0 0 0 0 1	-2 0 1 0 1 1 1 1 1 1	-2 0 1 0 1 1 1 0 0 0	-1 1 1 0 0 0 1 0 0 0	-1 1 1 0 0 0 1 1 1 1	-1 1 1 0 0 1 0 0 0 1
-1 1 1 0 0 1 0 1 1 0	-1 1 1 1 1 0 1 0 1 0	-1 1 1 1 1 0 1 1 0 1	-1 1 1 1 1 1 0 0 1 1	-1 1 1 1 1 1 0 1 0 0	-1 1 0 1 0 0 1 1 0 0
-1 1 0 1 0 0 1 0 1 1	-1 1 0 1 0 1 0 1 0 1	-1 1 0 1 0 1 0 0 1 0	-1 1 0 0 1 0 1 1 1 0	-1 1 0 0 1 0 1 0 0 1	-1 1 0 0 1 1 0 1 1 1
-1 1 0 0 1 1 0 0 0 0	0 1 0 0 0 0 0 0 0 0	0 0 1 0 0 0 0 0 0 0	0 0 0 1 0 0 0 0 0 0	0 0 0 0 1 0 0 0 0 0	0 0 0 0 0 1 0 0 0 0
0 0 0 0 0 0 1 0 0 0	0 0 0 0 0 0 0 1 0 0	0 0 0 0 0 0 0 0 1 0	0 0 0 0 0 0 0 0 0 1		

$M_3^{(1)}$ EXTREME POINTS

0 0 0 1 0 1 2 1 1	0 0 1 1 0 1 1 0 1	0 0 2 1 0 1 0 1 1	0 0 0 2 1 1 2 0 2	0 0 0 0 1 1 2 2 2	0 0 0 2 1 1 2 2 0
0 0 2 0 1 1 2 0 2	0 0 1 0 1 1 1 1 2	0 0 2 0 1 1 0 2 2	0 0 2 2 1 1 0 0 2	0 0 2 2 1 1 0 2 0	0 0 2 2 1 1 2 0 0
0 0 1 2 1 1 1 1 0	0 1 2 0 1 0 1 0 1	0 1 1 0 1 0 0 1 1	0 2 2 0 1 1 0 0 2	0 2 2 0 1 1 0 2 0	0 2 2 0 1 1 2 0 0
0 2 1 0 1 1 1 1 0	0 1 1 1 2 0 0 0 2	0 1 1 1 2 0 0 2 0	0 1 1 1 2 0 2 0 0	0 1 1 1 0 2 2 0 0	0 1 1 1 0 2 0 2 0
0 1 1 1 0 2 0 0 2	0 1 1 1 0 0 0 2 2	0 1 1 1 0 0 2 0 2	0 2 0 2 1 1 2 0 0	0 2 0 2 1 1 0 2 0	0 2 0 2 1 1 0 0 2
0 2 0 0 1 1 0 2 2	0 2 0 0 1 1 2 2 0	0 1 0 0 1 0 1 2 1	0 1 0 1 0 0 1 1 2	0 2 0 1 0 1 0 1 1	0 1 0 1 0 2 1 1 0
0 1 0 1 2 0 1 1 0	0 1 0 2 1 0 1 0 1	1 2 0 0 2 0 0 2 2	1 1 0 0 0 1 1 2 1	1 2 0 0 0 0 2 2 2	1 2 0 0 0 2 2 2 0
1 2 0 0 2 0 2 2 0	1 2 0 0 0 2 0 2 2	1 2 0 2 0 0 2 0 2	1 1 0 2 0 1 1 0 1	1 2 0 2 0 0 0 2 2	1 2 0 2 0 2 0 0 2
1 2 0 2 0 2 0 2 0	1 2 0 2 0 2 2 0 0	1 2 0 1 1 0 0 1 1	1 2 0 2 2 0 0 0 2	1 2 0 2 2 0 0 2 0	1 2 0 2 2 0 2 0 0
1 2 1 0 2 0 1 1 0	1 2 2 0 2 0 2 0 0	1 2 2 0 2 0 0 2 0	1 2 2 0 2 0 0 0 2	1 2 1 0 0 2 1 1 0	1 2 2 0 0 2 2 0 0
1 2 2 0 0 2 0 2 0	1 2 2 0 0 2 0 0 2	1 2 2 0 0 0 0 2 2	1 1 2 0 0 1 1 0 1	1 2 2 0 0 0 2 0 2	1 2 1 0 0 0 1 1 2
1 1 1 0 0 1 0 1 1	1 0 1 2 2 0 1 1 0	1 0 2 2 2 0 2 0 0	1 0 2 2 2 0 0 2 0	1 0 2 2 2 0 0 0 2	1 0 2 1 1 0 0 1 1
1 0 1 2 0 2 1 1 0	1 0 2 2 0 2 2 0 0	1 0 2 2 0 2 0 2 0	1 0 2 2 0 2 0 0 2	1 0 2 2 0 0 0 2 2	1 0 2 2 0 0 2 0 2
1 0 1 2 0 0 1 1 2	1 0 1 0 2 0 1 1 2	1 0 2 0 2 0 2 0 2	1 0 2 0 0 2 0 2 2	1 0 2 0 0 2 2 0 2	1 0 1 0 0 2 1 1 2
1 0 2 0 2 0 0 2 2	1 0 0 2 0 0 2 2 2	1 0 0 2 0 2 2 2 0	1 0 0 2 2 0 2 2 0	1 0 0 0 2 0 2 2 2	1 0 0 2 2 0 2 0 2
1 0 0 2 0 2 2 0 2	1 0 0 0 0 2 2 2 2	1 0 1 1 1 0 1 0 1	1 0 0 1 1 0 2 1 1		

5.3 TSP-perfection of $P_3(3,3,1)$

We now prove the final step of Lemma 3.2.8.

Final Claim in Lemma 3.2.8: Propeller graph $P_3(3,3,1)$ is TSP-perfect.

Proof. Figure 5.2 shows the edge labels for graph $P_3(3,3,1)$ (the rim edges in the propeller are shown in bold). The inequalities and extreme points of $P(P_3(3,3,1))$ generated by `polymake` are enumerated in the following tables. We verify each extreme point corresponds to a traveling salesman tour, which completes the proof of Lemma 3.2.8. □

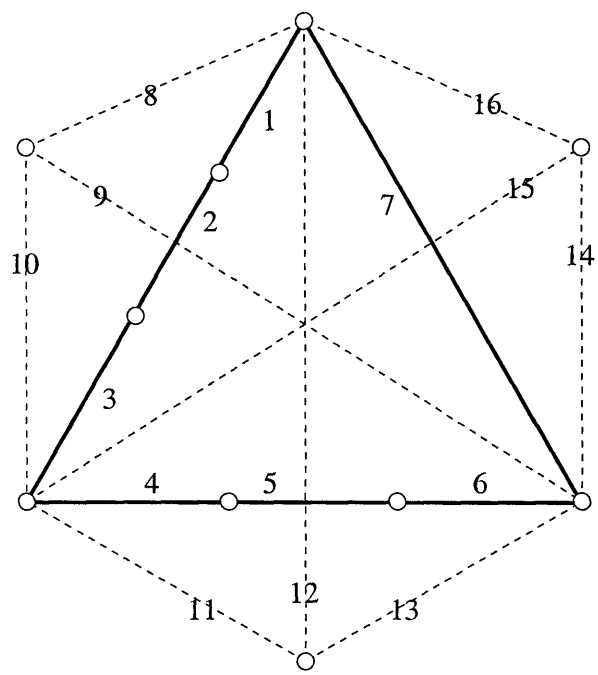

Figure 5.2: Edge labels for graph $P_3(3,3,1)$.

$P_3(3,3,1)$ INEQUALITIES

-2 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1	-2 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0 0	-2 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1
-2 0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0	-2 0 0 0 0 0 0 0 1 1 1 0 0 0 1 1 1	-2 0 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0
-2 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1	-2 0 0 0 0 0 1 1 0 1 0 0 0 1 1 0 0	-2 0 0 0 0 0 1 1 0 1 0 0 0 1 0 1 1
-2 0 0 0 0 0 1 1 0 1 0 1 1 0 1 0 0	-2 0 0 0 0 0 1 1 0 1 0 1 1 0 0 1 1	-2 0 0 0 0 0 1 1 1 0 1 0 0 1 1 0 0
-2 0 0 0 0 0 1 1 1 0 1 0 0 1 0 1 1	-2 0 0 0 0 0 1 1 1 0 1 1 1 0 1 0 0	-2 0 0 0 0 0 1 1 1 0 1 1 1 0 0 1 1
-2 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0	-2 0 0 0 0 1 1 0 0 0 0 0 0 0 1 1 1	-2 0 0 0 0 1 1 0 0 0 0 1 1 1 0 0 0
-2 0 0 0 0 1 1 0 0 0 0 1 1 1 1 1 1	-2 0 0 0 0 1 1 0 1 1 1 0 0 0 0 0 0	-2 0 0 0 0 1 1 0 1 1 1 0 0 0 1 1 1
-2 0 0 0 0 1 1 0 1 1 1 1 1 1 0 0 0	-2 0 0 0 0 1 1 0 1 1 1 1 1 1 1 1 1	-2 0 0 0 0 1 0 1 0 1 0 0 0 1 1 0 0
-2 0 0 0 0 1 0 1 0 1 0 0 0 1 0 1 1	-2 0 0 0 0 1 0 1 0 1 0 1 1 0 1 0 0	-2 0 0 0 0 1 0 1 0 1 0 1 1 0 0 1 1
-2 0 0 0 0 1 0 1 1 0 1 0 0 1 1 0 0	-2 0 0 0 0 1 0 1 1 0 1 0 0 1 0 1 1	-2 0 0 0 0 1 0 1 1 0 1 1 1 0 1 0 0
-2 0 0 0 0 1 0 1 1 0 1 1 1 0 0 1 1	-2 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0	-2 0 0 0 1 1 0 0 0 0 0 0 0 0 1 1 1
-2 0 0 0 1 1 0 0 0 0 0 1 1 1 0 0 0	-2 0 0 0 1 1 0 0 0 0 0 1 1 1 1 1 1	-2 0 0 0 1 1 0 0 1 1 1 0 0 0 0 0 0
-2 0 0 0 1 1 0 0 1 1 1 0 0 0 1 1 1	-2 0 0 0 1 1 0 0 1 1 1 1 1 1 0 0 0	-2 0 0 0 1 1 0 0 1 1 1 1 1 1 1 1 1
-2 0 0 0 1 1 1 1 0 1 0 0 0 1 1 0 0	-2 0 0 0 1 1 1 1 0 1 0 0 0 1 0 1 1	-2 0 0 0 1 1 1 1 0 1 0 1 1 0 1 0 0
-2 0 0 0 1 1 1 1 0 1 0 1 1 0 0 1 1	-2 0 0 0 1 1 1 1 1 0 1 0 0 1 1 0 0	-2 0 0 0 1 1 1 1 1 0 1 0 0 1 0 1 1
-2 0 0 0 1 1 1 1 1 0 1 1 1 0 1 0 0	-2 0 0 0 1 1 1 1 1 0 1 1 1 0 0 1 1	-2 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0
-2 0 0 0 1 0 1 0 0 0 0 0 0 0 1 1 1	-2 0 0 0 1 0 1 0 0 0 0 1 1 1 0 0 0	-2 0 0 0 1 0 1 0 0 0 0 1 1 1 1 1 1
-2 0 0 0 1 0 1 0 1 1 1 0 0 0 0 0 0	-2 0 0 0 1 0 1 0 1 1 1 0 0 0 1 1 1	-2 0 0 0 1 0 1 0 1 1 1 1 1 1 0 0 0
-2 0 0 0 1 0 1 0 1 1 1 1 1 1 1 1 1	-2 0 0 0 1 0 0 1 0 1 0 0 0 1 1 0 0	-2 0 0 0 1 0 0 1 0 1 0 0 0 1 0 1 1
-2 0 0 0 1 0 0 1 0 1 0 1 1 0 1 0 0	-2 0 0 0 1 0 0 1 0 1 0 1 1 0 0 1 1	-2 0 0 0 1 0 0 1 1 0 1 0 0 1 1 0 0
-2 0 0 0 1 0 0 1 1 0 1 0 0 1 0 1 1	-2 0 0 0 1 0 0 1 1 0 1 1 1 0 1 0 0	-2 0 0 0 1 0 0 1 1 0 1 1 1 0 0 1 1
-2 0 0 1 1 0 0 0 0 0 1 1 0 0 0 1 0	-2 0 0 1 1 0 0 0 0 0 1 1 0 0 1 0 1	-2 0 0 1 1 0 0 0 0 0 1 0 1 1 0 1 0
-2 0 0 1 1 0 0 0 0 0 1 0 1 1 1 0 1	-2 0 0 1 1 0 0 0 1 1 0 1 0 0 0 1 0	-2 0 0 1 1 0 0 0 1 1 0 1 0 0 1 0 1
-2 0 0 1 1 0 0 0 1 1 0 0 1 1 0 1 0	-2 0 0 1 1 0 0 0 1 1 0 0 1 1 1 0 1	-2 0 0 1 1 0 1 1 0 1 1 1 0 1 1 1 0
-2 0 0 1 1 0 1 1 0 1 1 1 0 1 0 0 1	-2 0 0 1 1 0 1 1 0 1 1 0 1 0 1 1 0	-2 0 0 1 1 0 1 1 0 1 1 0 1 0 0 0 1
-2 0 0 1 1 0 1 1 1 0 0 1 0 1 1 1 0	-2 0 0 1 1 0 1 1 1 0 0 1 0 1 0 0 1	-2 0 0 1 1 0 1 1 1 0 0 0 1 0 1 1 0
-2 0 0 1 1 0 1 1 1 0 0 0 1 0 0 0 1	-2 0 0 1 1 1 1 0 0 0 1 1 0 0 0 1 0	-2 0 0 1 1 1 1 0 0 0 1 1 0 0 1 0 1
-2 0 0 1 1 1 1 0 0 0 1 0 1 1 0 1 0	-2 0 0 1 1 1 1 0 0 0 1 0 1 1 1 0 1	-2 0 0 1 1 1 1 0 1 1 0 1 0 0 0 1 0
-2 0 0 1 1 1 1 0 1 1 0 1 0 0 1 0 1	-2 0 0 1 1 1 1 0 1 1 0 0 1 1 0 1 0	-2 0 0 1 1 1 1 0 1 1 0 0 1 1 1 0 1
-2 0 0 1 1 1 0 1 0 1 1 1 0 1 1 1 0	-2 0 0 1 1 1 0 1 0 1 1 1 0 1 0 0 1	-2 0 0 1 1 1 0 1 0 1 1 0 1 0 1 1 0
-2 0 0 1 1 1 0 1 0 1 1 0 1 0 0 0 1	-2 0 0 1 1 1 0 1 1 0 0 1 0 1 1 1 0	-2 0 0 1 1 1 0 1 1 0 0 1 0 1 0 0 1
-2 0 0 1 1 1 0 1 1 0 0 0 1 0 1 1 0	-2 0 0 1 1 1 0 1 1 0 0 0 1 0 0 0 1	-2 0 0 1 0 1 0 0 0 0 1 1 0 0 0 1 0
-2 0 0 1 0 1 0 0 0 0 1 1 0 0 1 0 1	-2 0 0 1 0 1 0 0 0 0 1 0 1 1 0 1 0	-2 0 0 1 0 1 0 0 0 0 1 0 1 1 1 0 1
-2 0 0 1 0 1 0 0 1 1 0 1 0 0 0 1 0	-2 0 0 1 0 1 0 0 1 1 0 1 0 0 1 0 1	-2 0 0 1 0 1 0 0 1 1 0 0 1 1 0 1 0
-2 0 0 1 0 1 0 0 1 1 0 0 1 1 1 0 1	-2 0 0 1 0 1 1 1 0 1 1 1 0 1 1 1 0	-2 0 0 1 0 1 1 1 0 1 1 1 0 1 0 0 1
-2 0 0 1 0 1 1 1 0 1 1 0 1 0 1 1 0	-2 0 0 1 0 1 1 1 0 1 1 0 1 0 0 0 1	-2 0 0 1 0 1 1 1 1 0 0 1 0 1 1 1 0
-2 0 0 1 0 1 1 1 1 0 0 1 0 1 0 0 1	-2 0 0 1 0 1 1 1 1 0 0 0 1 0 1 1 0	-2 0 0 1 0 1 1 1 1 0 0 0 1 0 0 0 1
-2 0 0 1 0 0 1 0 0 0 1 1 0 0 0 1 0	-2 0 0 1 0 0 1 0 0 0 1 1 0 0 1 0 1	-2 0 0 1 0 0 1 0 0 0 1 0 1 1 0 1 0
-2 0 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1	-2 0 0 1 0 0 1 0 1 1 0 1 0 0 0 1 0	-2 0 0 1 0 0 1 0 1 1 0 1 0 0 1 0 1
-2 0 0 1 0 0 1 0 1 1 0 0 1 1 0 1 0	-2 0 0 1 0 0 1 0 1 1 0 0 1 1 1 0 1	-2 0 0 1 0 0 0 1 0 1 1 1 0 1 1 1 0
-2 0 0 1 0 0 0 1 0 1 1 1 0 1 0 0 1	-2 0 0 1 0 0 0 1 0 1 1 0 1 0 1 1 0	-2 0 0 1 0 0 0 1 0 1 1 0 1 0 0 0 1
-2 0 0 1 0 0 0 1 1 0 0 1 0 1 1 1 0	-2 0 0 1 0 0 0 1 1 0 0 1 0 1 0 0 1	-2 0 0 1 0 0 0 1 1 0 0 0 1 0 1 1 0
-2 0 0 1 0 0 0 1 1 0 0 0 1 0 0 0 1	-2 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0	-2 0 1 1 0 0 0 0 0 0 0 0 0 0 1 1 1
-2 0 1 1 0 0 0 0 0 0 0 1 1 1 0 0 0	-2 0 1 1 0 0 0 0 0 0 0 1 1 1 1 1 1	-2 0 1 1 0 0 0 0 1 1 1 0 0 0 0 0 0
-2 0 1 1 0 0 0 0 1 1 1 0 0 0 1 1 1	-2 0 1 1 0 0 0 0 1 1 1 1 1 1 0 0 0	-2 0 1 1 0 0 0 0 1 1 1 1 1 1 1 1 1
-2 0 1 1 0 0 1 1 0 1 0 0 0 1 1 0 0	-2 0 1 1 0 0 1 1 0 1 0 0 0 1 0 1 1	-2 0 1 1 0 0 1 1 0 1 0 1 1 0 1 0 0
-2 0 1 1 0 0 1 1 0 1 0 1 1 0 0 1 1	-2 0 1 1 0 0 1 1 1 0 1 0 0 1 1 0 0	-2 0 1 1 0 0 1 1 1 0 1 0 0 1 0 1 1
-2 0 1 1 0 0 1 1 1 0 1 1 1 0 1 0 0	-2 0 1 1 0 0 1 1 1 0 1 1 1 0 0 1 1	-2 0 1 1 0 1 1 0 0 0 0 0 0 0 0 0 0
-2 0 1 1 0 1 1 0 0 0 0 0 0 0 1 1 1	-2 0 1 1 0 1 1 0 0 0 0 1 1 1 0 0 0	-2 0 1 1 0 1 1 0 0 0 0 1 1 1 1 1 1
-2 0 1 1 0 1 1 0 1 1 1 0 0 0 0 0 0	-2 0 1 1 0 1 1 0 1 1 1 0 0 0 1 1 1	-2 0 1 1 0 1 1 0 1 1 1 1 1 1 0 0 0
-2 0 1 1 0 1 1 0 1 1 1 1 1 1 1 1 1	-2 0 1 1 0 1 0 1 0 1 0 0 0 1 1 0 0	-2 0 1 1 0 1 0 1 0 1 0 0 0 1 0 1 1
-2 0 1 1 0 1 0 1 0 1 0 1 1 0 1 0 0	-2 0 1 1 0 1 0 1 0 1 0 1 1 0 0 1 1	-2 0 1 1 0 1 0 1 1 0 1 0 0 1 1 0 0
-2 0 1 1 0 1 0 1 1 0 1 0 0 1 0 1 1	-2 0 1 1 0 1 0 1 1 0 1 1 1 0 1 0 0	-2 0 1 1 0 1 0 1 1 0 1 1 1 0 0 1 1
-2 0 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0	-2 0 1 1 1 1 0 0 0 0 0 0 0 0 1 1 1	-2 0 1 1 1 1 0 0 0 0 0 1 1 1 0 0 0
-2 0 1 1 1 1 0 0 0 0 0 1 1 1 1 1 1	-2 0 1 1 1 1 0 0 1 1 1 0 0 0 0 0 0	-2 0 1 1 1 1 0 0 1 1 1 0 0 0 1 1 1
-2 0 1 1 1 1 0 0 1 1 1 1 1 1 0 0 0	-2 0 1 1 1 1 0 0 1 1 1 1 1 1 1 1 1	-2 0 1 1 1 1 1 1 0 1 0 0 0 1 1 0 0
-2 0 1 1 1 1 1 1 0 1 0 0 0 1 0 1 1	-2 0 1 1 1 1 1 1 0 1 0 1 1 0 1 0 0	-2 0 1 1 1 1 1 1 0 1 0 1 1 0 0 1 1
-2 0 1 1 1 1 1 1 1 0 1 0 0 1 1 0 0	-2 0 1 1 1 1 1 1 1 0 1 0 0 1 0 1 1	-2 0 1 1 1 1 1 1 1 0 1 1 1 0 1 0 0
-2 0 1 1 1 1 1 1 1 0 1 1 1 0 0 1 1	-2 0 1 1 1 0 1 0 0 0 0 0 0 0 0 0 0	-2 0 1 1 1 0 1 0 0 0 0 0 0 0 1 1 1
-2 0 1 1 1 0 1 0 0 0 0 1 1 1 0 0 0	-2 0 1 1 1 0 1 0 0 0 0 1 1 1 1 1 1	-2 0 1 1 1 0 1 0 1 1 1 0 0 0 0 0 0
-2 0 1 1 1 0 1 0 1 1 1 0 0 0 1 1 1	-2 0 1 1 1 0 1 0 1 1 1 1 1 1 0 0 0	-2 0 1 1 1 0 1 0 1 1 1 1 1 1 1 1 1
-2 0 1 1 1 0 0 1 0 1 0 0 0 1 1 0 0	-2 0 1 1 1 0 0 1 0 1 0 0 0 1 0 1 1	-2 0 1 1 1 0 0 1 0 1 0 1 1 0 1 0 0
-2 0 1 1 1 0 0 1 0 1 0 1 1 0 0 1 1	-2 0 1 1 1 0 0 1 1 0 1 0 0 1 1 0 0	-2 0 1 1 1 0 0 1 1 0 1 0 0 1 0 1 1
-2 0 1 1 1 0 0 1 1 0 1 1 1 0 1 0 0	-2 0 1 1 1 0 0 1 1 0 1 1 1 0 0 1 1	-2 0 1 0 1 0 0 0 0 0 1 1 0 0 0 1 0
-2 0 1 0 1 0 0 0 0 0 1 1 0 0 1 0 1	-2 0 1 0 1 0 0 0 0 0 1 0 1 1 0 1 0	-2 0 1 0 1 0 0 0 0 0 1 0 1 1 1 0 1
-2 0 1 0 1 0 0 0 1 1 0 1 0 0 0 1 0	-2 0 1 0 1 0 0 0 1 1 0 1 0 0 1 0 1	-2 0 1 0 1 0 0 0 1 1 0 0 1 1 0 1 0
-2 0 1 0 1 0 0 0 1 1 0 0 1 1 1 0 1	-2 0 1 0 1 0 1 1 0 1 1 1 0 1 1 1 0	-2 0 1 0 1 0 1 1 0 1 1 1 0 1 0 0 1
-2 0 1 0 1 0 1 1 0 1 1 0 1 0 1 1 0	-2 0 1 0 1 0 1 1 0 1 1 0 1 0 0 0 1	-2 0 1 0 1 0 1 1 1 0 0 1 0 1 1 1 0
-2 0 1 0 1 0 1 1 1 0 0 1 0 1 0 0 1	-2 0 1 0 1 0 1 1 1 0 0 0 1 0 1 1 0	-2 0 1 0 1 0 1 1 1 0 0 0 1 0 0 0 1
-2 0 1 0 1 1 1 0 0 0 1 1 0 0 0 1 0	-2 0 1 0 1 1 1 0 0 0 1 1 0 0 1 0 1	-2 0 1 0 1 1 1 0 0 0 1 0 1 1 0 1 0
-2 0 1 0 1 1 1 0 0 0 1 0 1 1 1 0 1	-2 0 1 0 1 1 1 0 1 1 0 1 0 0 0 1 0	-2 0 1 0 1 1 1 0 1 1 0 1 0 0 1 0 1
-2 0 1 0 1 1 1 0 1 1 0 0 1 1 0 1 0	-2 0 1 0 1 1 1 0 1 1 0 0 1 1 1 0 1	-2 0 1 0 1 1 0 1 0 1 1 1 0 1 1 1 0
-2 0 1 0 1 1 0 1 0 1 1 1 0 1 0 0 1	-2 0 1 0 1 1 0 1 0 1 1 0 1 0 1 1 0	-2 0 1 0 1 1 0 1 0 1 1 0 1 0 0 0 1
-2 0 1 0 1 1 0 1 1 0 0 1 0 1 1 1 0	-2 0 1 0 1 1 0 1 1 0 0 1 0 1 0 0 1	-2 0 1 0 1 1 0 1 1 0 0 0 1 0 1 1 0
-2 0 1 0 1 1 0 1 1 0 0 0 1 0 0 0 1	-2 0 1 0 0 1 0 0 0 0 1 1 0 0 0 1 0	-2 0 1 0 0 1 0 0 0 0 1 1 0 0 1 0 1
-2 0 1 0 0 1 0 0 0 0 1 0 1 1 0 1 0	-2 0 1 0 0 1 0 0 0 0 1 0 1 1 1 0 1	-2 0 1 0 0 1 0 0 1 1 0 1 0 0 0 1 0
-2 0 1 0 0 1 0 0 1 1 0 1 0 0 1 0 1	-2 0 1 0 0 1 0 0 1 1 0 0 1 1 0 1 0	-2 0 1 0 0 1 0 0 1 1 0 0 1 1 1 0 1
-2 0 1 0 0 1 1 1 0 1 1 1 0 1 1 1 0	-2 0 1 0 0 1 1 1 0 1 1 1 0 1 0 0 1	-2 0 1 0 0 1 1 1 0 1 1 0 1 0 1 1 0
-2 0 1 0 0 1 1 1 0 1 1 0 1 0 0 0 1	-2 0 1 0 0 1 1 1 1 0 0 1 0 1 1 1 0	-2 0 1 0 0 1 1 1 1 0 0 1 0 1 0 0 1
-2 0 1 0 0 1 1 1 1 0 0 0 1 0 1 1 0	-2 0 1 0 0 1 1 1 1 0 0 0 1 0 0 0 1	-2 0 1 0 0 0 1 0 0 0 1 1 0 0 0 1 0

$P_3(3,3,1)$ INEQUALITIES (continued)

-2 0 1 0 0 0 1 0 0 0 1 1 0 0 1 0 1	-2 0 1 0 0 0 1 0 0 0 1 0 1 1 0 1 0	-2 0 1 0 0 0 1 0 0 0 1 0 1 1 1 0 1
-2 0 1 0 0 0 1 0 1 1 0 1 0 0 0 1 0	-2 0 1 0 0 0 1 0 1 1 0 1 0 0 1 0 1	-2 0 1 0 0 0 1 0 1 1 0 0 1 1 0 1 0
-2 0 1 0 0 0 1 0 1 1 0 0 1 1 1 0 1	-2 0 1 0 0 0 0 1 0 1 1 1 0 1 1 1 0	-2 0 1 0 0 0 0 1 0 1 1 1 0 1 0 0 1
-2 0 1 0 0 0 0 1 0 1 1 0 1 0 1 1 0	-2 0 1 0 0 0 0 1 0 1 1 0 1 0 0 0 1	-2 0 1 0 0 0 0 1 1 0 0 1 0 1 1 1 0
-2 0 1 0 0 0 0 1 1 0 0 1 0 1 0 0 1	-2 0 1 0 0 0 0 1 1 0 0 0 1 0 1 1 0	-2 0 1 0 0 0 0 1 1 0 0 0 1 0 0 0 1
-2 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0	-2 1 1 0 0 0 0 0 0 0 0 0 0 0 1 1 1	-2 1 1 0 0 0 0 0 0 0 0 1 1 1 0 0 0
-2 1 1 0 0 0 0 0 0 0 0 1 1 1 1 1 1	-2 1 1 0 0 0 0 0 1 1 1 0 0 0 0 0 0	-2 1 1 0 0 0 0 0 1 1 1 0 0 0 1 1 1
-2 1 1 0 0 0 0 0 1 1 1 1 1 1 0 0 0	-2 1 1 0 0 0 0 0 1 1 1 1 1 1 1 1 1	-2 1 1 0 0 0 1 1 0 1 0 0 0 1 1 0 0
-2 1 1 0 0 0 1 1 0 1 0 0 0 1 0 1 1	-2 1 1 0 0 0 1 1 0 1 0 1 1 0 1 0 0	-2 1 1 0 0 0 1 1 0 1 0 1 1 0 0 1 1
-2 1 1 0 0 0 1 1 1 0 1 0 0 1 1 0 0	-2 1 1 0 0 0 1 1 1 0 1 0 0 1 0 1 1	-2 1 1 0 0 0 1 1 1 0 1 1 1 0 1 0 0
-2 1 1 0 0 0 1 1 1 0 1 1 1 0 0 1 1	-2 1 1 0 0 1 1 0 0 0 0 0 0 0 0 0 0	-2 1 1 0 0 1 1 0 0 0 0 0 0 0 1 1 1
-2 1 1 0 0 1 1 0 0 0 0 1 1 1 0 0 0	-2 1 1 0 0 1 1 0 0 0 0 1 1 1 1 1 1	-2 1 1 0 0 1 1 0 1 1 1 0 0 0 0 0 0
-2 1 1 0 0 1 1 0 1 1 1 0 0 0 1 1 1	-2 1 1 0 0 1 1 0 1 1 1 1 1 1 0 0 0	-2 1 1 0 0 1 1 0 1 1 1 1 1 1 1 1 1
-2 1 1 0 0 1 0 1 0 1 0 0 0 1 1 0 0	-2 1 1 0 0 1 0 1 0 1 0 0 0 1 0 1 1	-2 1 1 0 0 1 0 1 0 1 0 1 1 0 1 0 0
-2 1 1 0 0 1 0 1 0 1 0 1 1 0 0 1 1	-2 1 1 0 0 1 0 1 1 0 1 0 0 1 1 0 0	-2 1 1 0 0 1 0 1 1 0 1 0 0 1 0 1 1
-2 1 1 0 0 1 0 1 1 0 1 1 1 0 1 0 0	-2 1 1 0 0 1 0 1 1 0 1 1 1 0 0 1 1	-2 1 1 0 1 1 0 0 0 0 0 0 0 0 0 0 0
-2 1 1 0 1 1 0 0 0 0 0 0 0 0 1 1 1	-2 1 1 0 1 1 0 0 0 0 0 1 1 1 0 0 0	-2 1 1 0 1 1 0 0 0 0 0 1 1 1 1 1 1
-2 1 1 0 1 1 0 0 1 1 1 0 0 0 0 0 0	-2 1 1 0 1 1 0 0 1 1 1 0 0 0 1 1 1	-2 1 1 0 1 1 0 0 1 1 1 1 1 1 0 0 0
-2 1 1 0 1 1 0 0 1 1 1 1 1 1 1 1 1	-2 1 1 0 1 1 1 1 0 1 0 0 0 1 1 0 0	-2 1 1 0 1 1 1 1 0 1 0 0 0 1 0 1 1
-2 1 1 0 1 1 1 1 0 1 0 1 1 0 1 0 0	-2 1 1 0 1 1 1 1 0 1 0 1 1 0 0 1 1	-2 1 1 0 1 1 1 1 1 0 1 0 0 1 1 0 0
-2 1 1 0 1 1 1 1 1 0 1 0 0 1 0 1 1	-2 1 1 0 1 1 1 1 1 0 1 1 1 0 1 0 0	-2 1 1 0 1 1 1 1 1 0 1 1 1 0 0 1 1
-2 1 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0	-2 1 1 0 1 0 1 0 0 0 0 0 0 0 1 1 1	-2 1 1 0 1 0 1 0 0 0 0 1 1 1 0 0 0
-2 1 1 0 1 0 1 0 0 0 0 1 1 1 1 1 1	-2 1 1 0 1 0 1 0 1 1 1 0 0 0 0 0 0	-2 1 1 0 1 0 1 0 1 1 1 0 0 0 1 1 1
-2 1 1 0 1 0 1 0 1 1 1 1 1 1 0 0 0	-2 1 1 0 1 0 1 0 1 1 1 1 1 1 1 1 1	-2 1 1 0 1 0 0 1 0 1 0 0 0 1 1 0 0
-2 1 1 0 1 0 0 1 0 1 0 0 0 1 0 1 1	-2 1 1 0 1 0 0 1 0 1 0 1 1 0 1 0 0	-2 1 1 0 1 0 0 1 0 1 0 1 1 0 0 1 1
-2 1 1 0 1 0 0 1 1 0 1 0 0 1 1 0 0	-2 1 1 0 1 0 0 1 1 0 1 0 0 1 0 1 1	-2 1 1 0 1 0 0 1 1 0 1 1 1 0 1 0 0
-2 1 1 0 1 0 0 1 1 0 1 1 1 0 0 1 1	-2 1 1 1 1 0 0 0 0 0 1 1 0 0 0 1 0	-2 1 1 1 1 0 0 0 0 0 1 1 0 0 1 0 1
-2 1 1 1 1 0 0 0 0 0 1 0 1 1 0 1 0	-2 1 1 1 1 0 0 0 0 0 1 0 1 1 1 0 1	-2 1 1 1 1 0 0 0 1 1 0 1 0 0 0 1 0
-2 1 1 1 1 0 0 0 1 1 0 1 0 0 1 0 1	-2 1 1 1 1 0 0 0 1 1 0 0 1 1 0 1 0	-2 1 1 1 1 0 0 0 1 1 0 0 1 1 1 0 1
-2 1 1 1 1 0 1 1 0 1 1 1 0 1 1 1 0	-2 1 1 1 1 0 1 1 0 1 1 1 0 1 0 0 1	-2 1 1 1 1 0 1 1 0 1 1 0 1 0 1 1 0
-2 1 1 1 1 0 1 1 0 1 1 0 1 0 0 0 1	-2 1 1 1 1 0 1 1 1 0 0 1 0 1 1 1 0	-2 1 1 1 1 0 1 1 1 0 0 1 0 1 0 0 1
-2 1 1 1 1 0 1 1 1 0 0 0 1 0 1 1 0	-2 1 1 1 1 0 1 1 1 0 0 0 1 0 0 0 1	-2 1 1 1 1 1 1 0 0 0 1 1 0 0 0 1 0
-2 1 1 1 1 1 1 0 0 0 1 1 0 0 1 0 1	-2 1 1 1 1 1 1 0 0 0 1 0 1 1 0 1 0	-2 1 1 1 1 1 1 0 0 0 1 0 1 1 1 0 1
-2 1 1 1 1 1 1 0 1 1 0 1 0 0 0 1 0	-2 1 1 1 1 1 1 0 1 1 0 1 0 0 1 0 1	-2 1 1 1 1 1 1 0 1 1 0 0 1 1 0 1 0
-2 1 1 1 1 1 1 0 1 1 0 0 1 1 1 0 1	-2 1 1 1 1 1 0 1 0 1 1 1 0 1 1 1 0	-2 1 1 1 1 1 0 1 0 1 1 1 0 1 0 0 1
-2 1 1 1 1 1 0 1 0 1 1 0 1 0 1 1 0	-2 1 1 1 1 1 0 1 0 1 1 0 1 0 0 0 1	-2 1 1 1 1 1 0 1 1 0 0 1 0 1 1 1 0
-2 1 1 1 1 1 0 1 1 0 0 1 0 1 0 0 1	-2 1 1 1 1 1 0 1 1 0 0 0 1 0 1 1 0	-2 1 1 1 1 1 0 1 1 0 0 0 1 0 0 0 1
-2 1 1 1 0 1 0 0 0 0 1 1 0 0 0 1 0	-2 1 1 1 0 1 0 0 0 0 1 1 0 0 1 0 1	-2 1 1 1 0 1 0 0 0 0 1 0 1 1 0 1 0
-2 1 1 1 0 1 0 0 0 0 1 0 1 1 1 0 1	-2 1 1 1 0 1 0 0 1 1 0 1 0 0 0 1 0	-2 1 1 1 0 1 0 0 1 1 0 1 0 0 1 0 1
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$P_3(3,3,1)$ INEQUALITIES (continued)

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$P_3(3,3,1)$ EXTREME POINTS

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0220221200110110	0220221200101011	0220221020101011	0220221020110110
0220221002110110	0220221002101011	0220221011200011	0220221011110200
0220221011110020	0220221011110002	0220221011020011	0220221011002011
0220220002110211	0220220020110211	0220220110011220	0220220101110220
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$P_3(3,3,1)$ EXTREME POINTS

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$P_3(3,3,1)$ EXTREME POINTS (continued)

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$P_3(3,3,1)$ EXTREME POINTS

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1 1 1 1 1 1 0 0 1 1 2 0 0 0 1 1	1 1 1 2 2 2 0 0 0 2 2 0 0 0 1 1	1 1 1 2 2 2 0 0 0 2 1 1 0 2 0 0	1 1 1 2 2 2 0 0 0 2 1 1 0 0 2 0
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$P_3(3,3,1)$ EXTREME POINTS

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$P_3(3,3,1)$ EXTREME POINTS

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1110221200002110	1110221200020110	2220220110200101	2220220110020101

$P_3(3,3,1)$ EXTREME POINTS

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$P_3(3,3,1)$ EXTREME POINTS

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2022201200200121	2022201200002121	2022201200020121	2022200220200022
2022200220020022	2022200220002022	2022200200022022	2022200020022022
2022200002022022	2022200200011121	2022200200101112	2022200110011022
2022200110200121	2022200110002121	2022200110020121	2022200011101022
2022200020101112	2022200020011121	2022200011200112	2022200011002112
2022200011020112	2022200002101112	2022200002011121	2022021002011220
2022021020011220	2022021110020220	2022021110002220	2022021110200220
2022021200011220	2022022200020220	2022022200002220	2022022200200220
2022022020200220	2022022020002220	2022022020020220	2022022002200220
2022022002020220	2022022002002220	2022021002202101	2022021020202101
2022021110202002	2022021110202020	2022021110202200	2022021200202101
2022022200202002	2022022200202020	2022022200202200	2022022020202200
2022022020202020	2022022020202002	2022022002202002	2022022002202020
2022022002202200	2022021022011002	2022021022011020	2022021022011200
2022021022020101	2022021022002101	2022021022200101	2022022022200002
2022022022200020	2022022022200200	2022022022002200	2022022022002020
2022022022002002	2022022022020002	2022022022020020	2022022022020200
2022020220202002	2022020220202020	2022020220202200	2022020220020220
2022020220002220	2022020220200220	2022020022022002	2022020022022020
2022020022022200	2022020002022220	2022020020022220	2022020200022220
2022020022020202	2022020022002202	2022020022200202	2022020002202202
2022020020202202	2022020200202202	2022020222200002	2022020222200020
2022020222200200	2022020222020020	2022020222020002	2022020222020200
2022020222002200	2022020222002002	2022020222002020	2022020202202002
2022020202202020	2022020202202200	2022020202200220	2022020202020220
2022020202002220	2022020112011002	2022020112011020	2022020112011200
2022020112020101	2022020112002101	2022020112200101	2022020211020110
2022020211002110	2022020211101002	2022020211101020	2022020211101200
2022020211200110	2022020202101110	2022020202011101	2022020202020202
2022020202002202	2022020202200202	2022020202022002	2022020202022020
2022020202022200	2022021202011002	2022021202011020	2022021202011200
2022021202020101	2022022202020200	2022022202020020	2022022202020002
2022022202002002	2022022202002020	2022021202002101	2022022202002200
2022022202200002	2022022202200020	2022021202200101	2022022202200200
2022021112200002	2022021112200020	2022021112200200	2022021112002200
2022021112002020	2022021112002002	2022021112020002	2022021112020020
2022021112020200	2022020022220200	2022020022220020	2022020022220002
2022020200222020	2022020200222002	2022020200222200	2022020020222200
2022020020222002	2022020020222020	2022020002222002	2022020002222020
2022020002222200	2022020200220220	2022020020220220	2022020002220220
2022020002121110	2022020002211101	2022020011121002	2022020011121020
2022020011121200	2022020020121110	2022020020211101	2022020011220110
2022020110211002	2022020110211020	2022020110211200	2022020110220101
2022020200211101	2022020200121110	2022020002220202	2022020020220202
2022020200220202	2022020220220020	2022020220220002	2022020220220200
2022021200211002	2022021200211020	2022021200211200	2022022200220020
2022022200220002	2022021200220101	2022022200220200	2022021110220200
2022021110220002	2022021110220020	2022022020220200	2022021020220101
2022022020220002	2022022020220020	2022021020211200	2022021020211020
2022021020211002	2022022002220002	2022022002220020	2022022002220200
2022021002220101	2022021002211002	2022021002211020	2022021002211200
2022020022200022	2022020022020022	2022020022002022	2022020200202022
2022020020202022	2022020002202022	2022020200002222	2022020200020222

$P_3(3,3,1)$ EXTREME POINTS

2022020200200222	2022020020200222	2022020020020222	2022020020002222
2022020002002222	2022020002020222	2022020002200222	2022020002011121
2022020002101112	2022020011020112	2022020011002112	2022020011200112
2022020020011121	2022020020101112	2022020011101022	2022020110020121
2022020110002121	2022020110200121	2022020110011022	2022020200101112
2022020200011121	2022020002022022	2022020020022022	2022020200022022
2022020220002022	2022020220020022	2022020220200022	2022021200020121
2022021200002121	2022021200200121	2022022200002022	2022021200011022
2022022200020022	2022022200200022	2022021110200022	2022021110020022
2022021110002022	2022022020200022	2022022020020022	2022021020011022
2022022020002022	2022021020200121	2022021020002121	2022021020020121
2022021002011022	2022022002002022	2022022002020022	2022022002200022
2022021002200121	2022021002020121	2022021002002121	2020222002002220
2020222002020220	2020222002200220	2020222020020220	2020222020002220
2020222020200220	2020222200200220	2020222200002220	2020222200020220
2020221200011220	2020221110200220	2020221110002220	2020221110020220
2020221020011220	2020221002011220	2020222002202200	2020222002202020
2020222002202002	2020222020202002	2020222020202020	2020222020202200
2020222200202200	2020222200202020	2020222200202002	2020221200202101
2020221110202200	2020221110202020	2020221110202002	2020221020202101
2020221002202101	2020222022020200	2020222022020020	2020222022020002
2020222022002002	2020222022002020	2020222022002200	2020222022200200
2020222022200020	2020222022200002	2020221022200101	2020221022002101
2020221022020101	2020221022011200	2020221022011020	2020221022011002
2020220220202200	2020220220202020	2020220220202002	2020220220200220
2020220220002220	2020220220020220	2020220022022200	2020220022022020
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2020220222002200	2020220222002002	2020220222002020	2020220202202002
2020220202202020	2020220202202200	2020220202200220	2020220202020220
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2020221112002002	2020221112002020	2020221112002200	2020221112200200
2020221112200020	2020221112200002	2020222202200200	2020221202200101
2020222202200020	2020222202200002	2020222202002200	2020221202002101
2020222202002020	2020222202002002	2020222202020002	2020222202020020
2020222202020200	2020221202020101	2020221202011200	2020221202011020
2020221202011002	2020220202022200	2020220202022020	2020220202022002
2020220202200202	2020220202002202	2020220202020202	2020220202011101
2020220202101110	2020220211200110	2020220211101200	2020220211101020
2020220211101002	2020220211002110	2020220211020110	2020220112200101
2020220112002101	2020220112020101	2020220112011200	2020220112011020
2020220112011002	2020220022220200	2020220022220020	2020220022220002
2020220200222020	2020220200222002	2020220200222200	2020220020222200
2020220020222002	2020220020222020	2020220002222002	2020220002222020
2020220002222200	2020220200220220	2020220020220220	2020220002220220
2020221002211200	2020221002211020	2020221002211002	2020221002220101
2020222002220200	2020222002220020	2020222002220002	2020221020211002
2020221020211020	2020221020211200	2020222020220020	2020222020220002
2020221020220101	2020222020220200	2020221110220020	2020221110220002
2020221110220200	2020222200220200	2020221200220101	2020222200220002
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2020220220220200	2020220220220002	2020220220220020	2020220200220202
2020220020220202	2020220002220202	2020220200121110	2020220200211101
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2020220011220110	2020220020211101	2020220020121110	2020220011121200
2020220011121020	2020220011121002	2020220002211101	2020220002121110
2020220022200022	2020220022020022	2020220022002022	2020220200202022
2020220020202022	2020220002202022	2020220200002222	2020220200020222
2020220200200222	2020220020200222	2020220020020222	2020220020002222
2020220002002222	2020220002020222	2020220002200222	2020221002002121
2020221002020121	2020221002200121	2020222002200022	2020222002020022
2020222002002022	2020221002011022	2020221020020121	2020221020002121
2020221020200121	2020222020002022	2020221020011022	2020222020020022
2020222020200022	2020221110002022	2020221110020022	2020221110200022
2020222200200022	2020222200020022	2020221200011022	2020222200002022
2020221200200121	2020221200002121	2020221200020121	2020220220200022
2020220220020022	2020220220002022	2020220200022022	2020220020022022
2020220002022022	2020220200011121	2020220200101112	2020220110011022
2020220110200121	2020220110002121	2020220110020121	2020220011101022
2020220020101112	2020220020011121	2020220011200112	2020220011002112
2020220011020112	2020220002101112	2020220002011121	2020220011011011
2020220011110101	2020220110110110	2020220110101011	2020220101011110
2020220101101101	2020221101101200	2020221101101020	2020221101101002
2020221101200110	2020221101020110	2020221101002110	2020221200110110
2020221200101011	2020221020101011	2020221020110110	2020221002110110
2020221002101011	2020221011200011	2020221011110200	2020221011110020
2020221011110002	2020221011020011	2020221011002011	2020220002110211
2020220020110211	2020220110011220	2020220110110220	2020220200110211
2020220101002211	2020220101020211	2020220101200211	2020220002112011
2020220020112011	2020220110202101	2020220101202011	2020220200112011
2020220101112020	2020220101112002	2020220101112200	2020220022011101
2020220022110011	2020220121002011	2020220121020011	2020220121110020
2020220121110002	2020220121110200	2020220121200011	2020220011022110
2020220011101202	2020220220101110	2020220101110202	2020220101022011
2020220220110011	2020222002101110	2020221011011110	2020222011020110
2020222011002110	2020222011101002	2020222011101020	2020222011101200
2020221011101101	2020222011200110	2020222002110011	2020222020101110
2020222020110011	2020222200101110	2020222200110011	2020222101002011

$P_3(3,3,1)$ EXTREME POINTS

2020222101020011	2020221101011011	2020222101200011	2020222101110002
2020222101110020	2020221101110101	2020222101110200	2020221110101110
2020221110110011	2022200011011011	2022200011110101	2022200110110110
2022200110101011	2022200101011110	2022200101101101	2022201101101200
2022201101101020	2022201101101002	2022201101200110	2022201101020110
2022201101002110	2022201200110110	2022201200101011	2022201020101011
2022201020110110	2022201002110110	2022201002101011	2022201011200011
2022201011110200	2022201011110020	2022201011110002	2022201011020011
2022201011002011	2022200002110211	2022200020110211	2022200110011220
2022200101110220	2022200200110211	2022200101002211	2022200101020211
2022200101200211	2022200002112011	2022200020112011	2022200110202101
2022200101202011	2022200200112011	2022200101112020	2022200101112002
2022200101112200	2022200022011101	2022200022110011	2022200121002011
2022200121020011	2022200121110020	2022200121110002	2022200121110200
2022200121200011	2022200011022110	2022200011101202	2022200220101110
2022200101110202	2022200101022011	2022200220110011	2022202002101110
2022201011011110	2022202011020110	2022202011002110	2022202011101002
2022202011101020	2022202011101200	2022201011101101	2022202011200110
2022202002110011	2022202020101110	2022202020110011	2022202200101110
2022202200110011	2022202101002011	2022202101020011	2022201101011011
2022202101200011	2022202101110002	2022202101110020	2022201101110101
2022202101110200	2022201110101110	2022201110110011	2021111002200011
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2021111002002011	2021111002011110	2021112002002110	2021112002020110
2021111002101101	2021112002101200	2021112002101020	2021112002101002
2021112002200110	2021111020002011	2021111020020011	2021111020110020
2021111020110002	2021111020110200	2021111020200011	2021111020011110
2021112020020110	2021112020002110	2021112020200110	2021111020101101
2021112020101200	2021112020101020	2021112020101002	2021112011002020
2021112011002002	2021112011002200	2021111011002101	2021111011011020
2021111011011002	2021111011011200	2021112011020020	2021112011020002
2021112011020200	2021111011020101	2021112011200002	2021112011200020
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2022220101002011	2022220200110011	2022220200011101	2021110200022110
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2021110101110110	2021110110101101	2021110110011110	2021110110200011
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2021110110002011	2021110011110011	2021110011011101	2021110020110101
2021110020011011	2021110002011011	2021110002110101	2022021110110011
2022021110101110	2022022101110200	2022021101110101	2022022101110020
2022022101110002	2022022101200011	2022021101011011	2022022101020011
2022022101002011	2022022200110011	2022022200101110	2022022020110011
2022022020101110	2022022002110011	2022022011200110	2022021011101101
2022022011101200	2022022011101020	2022022011101002	2022022011002110
2022022011020110	2022021011011110	2022022002101110	2022020220110011
2022020101022011	2022020101110202	2022020220101110	2022020011101202
2022020011022110	2022020121200011	2022020121110200	2022020121110002
2022020121110020	2022020121020011	2022020121002011	2022020022110011
2022020022011101	2022020101112200	2022020101112002	2022020101112020
2022020200112011	2022020101202011	2022020110202101	2022020020112011
2022020002112011	2022020101200211	2022020101020211	2022020101002211
2022020200110211	2022020101110220	2022020110011220	2022020020110211
2022020002110211	2022020011011011	2022020011110101	2022020110110110
2022020110101011	2022020101011110	2022020101101101	2022021101101200
2022021101101020	2022021101101002	2022021101200110	2022021101020110
2022021101002110	2022021200110110	2022021200101011	2022021020101011
2022021020110110	2022021002110110	2022021002101011	2022021011200011
2022021011110200	2022021011110020	2022021011110002	2022021011020011

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