

## The Traveling Salesman Problem: A Linear Programming Formulation

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**Abstract:** - In this paper, we present a polynomial-sized linear programming formulation of the *Traveling Salesman Problem* (TSP). The proposed linear program is a network flow-based model. Numerical implementation issues and results are discussed.

**Key-Words:** - Linear Programming; Network Optimization; Integer Programming; Traveling Salesman Problem; Combinatorial Optimization; Scheduling; Sequencing.

### 1 Introduction

The *Traveling Salesman Problem* (TSP) is the problem of finding a least-cost sequence in which to visit a set of cities, starting and ending at the same city, and in such a way that each city is visited exactly once. This problem has received a tremendous amount of attention over the years due in part to its wide applicability in practice (see Lawler et al. [1985] among others, for examples). Also, since its formal formulation as a mathematical programming problem in the 1950's (Dantzig, Fulkerson, and Johnson [1954]), the problem has been at the core of many of the developments in the area of Combinatorial Optimization (see Nemhauser and Wolsey [1988], among others). A key issue has been the question of whether there exists a polynomial-time algorithm for solving the problem (see Garey and Johnson [1979]).

In this paper, we present a polynomial-sized linear programming formulation of the *Traveling Salesman Problem* (TSP). The proposed linear program is a network flow-based model. Numerical implementation issues and results are discussed.

The plan of the paper is as follows. The proposed linear programming formulation is developed in section 2. Numerical implementation and computational results are discussed in section 3. Conclusions are discussed in section 4.

### 2 Problem Formulation

Different classical formulations of the TSP are analyzed and compared in Padberg and Sung [1991]. The approach used in this paper is different from that of any of the existing models that we know of. In this section, we first present a nonlinear integer

programming (NIP) formulation of the TSP. Then, we develop an integer linear programming (ILP) reformulation of this NIP model using a network flow modeling framework. Finally, we show that the linear programming (LP) relaxation of our ILP reformulation has extreme points that correspond to TSP tours respectively.

#### 2.1 NIP Model

Consider the TSP defined on  $n$  nodes belonging to the set  $N = \{1, 2, \dots, n\}$ , with arc set  $C = N^2$ , and travel costs  $t_{ij}$ ,  $(i, j) \in C$ ;  $t_{ij} = \infty$ ,  $\forall i = N$  associated with the arcs. Assume, without loss of generality, that city 1 is the starting point and the ending point of travel. Denote the set of the remaining cities as  $M = N \setminus \{1\}$ . Define  $S = N \setminus \{n\}$  as the index set for the stage of travel corresponding to the order of visit of the cities in  $M$ . Let  $K = S \setminus \{n-1\}$ .

Let  $x_{ij}$ ,  $(i \in M, s \in S)$  be a 0/1 binary variable that takes on the value "1" if city  $i \in M$  is visited at stage  $s \in S$ . Then, in order to properly account the TSP travel costs, consecutive travel stages must be considered jointly. Hence, re-define the travel costs as:

$$c_{ij} = \begin{cases} t_{ij}, & s = 1, (i, j) \in M^2; \\ t_{ij} + t_{ij}, & s \in K \setminus \{1, n-2\}, (i, j) \in M^2; \\ t_{ij} + t_{ij}, & s = n-2, (i, j) \in M^2. \end{cases} \quad (2.1)$$

Thus, the cost incurred if city  $i \in M$  is visited at stage  $s \in K$  followed by city  $j \in M$  at stage  $(s+1) \in K$  can be expressed as  $c_{ij}x_{ij}x_{j(s+1)}$ ,  $(i, j) \in M^2$ ,  $s \in K$ . For example,  $c_{210}x_{21}x_{10}$  would represent the cost function associated with the situation where

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**M Carnoy**



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