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TSS Dissertation Abstracts—Abstracts for the 1994 Transportation Science Section Dissertation Prize Competition

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TSS Dissertation Abstracts

Abstracts for the 1994 Transportation Science Section Dissertation Prize Competition

HANI S. MAHMASSANI

Chair, 1994 TSS Dissertation Prize Competition

Twelve dissertations were submitted to the 1994 Transportation Science Section dissertation prize competition. The judges were:

- Professor Siamak Ardekani, The University of Texas at Arlington;
- Professor Dimitris Bertsimas, Massachusetts Institute of Technology;
- Professor Martine Labbé, Université Libre de Bruxelles;
- Professor Jeff McGill, Queen's University:

with Professor Hani S. Mahmassani of The University of Texas at Austin initially serving as Chair of the Committee, and Professor Bertsimas chairing the final deliberations.

The judges were asked to read and evaluate all dissertations, except those from their home institutions. This year's submissions continued the tradition of this competition, reflecting the variety and intellectual depth of research activity in transportation science.

The first prize was awarded to Dr. SRINIVAS PEETA for his dissertation titled: "System Optimal Dynamic Traffic Assignment in Congested Networks with Advanced Information Systems."

The committee also awarded two honorable mentions: to Dr. RENÉ SÉGUIN, "Problèmes Stochastiques de Tournées de Véhicules"; and Dr. ATHANASIOS ZILIASKOPOULOS, "Optimum Path Algorithms on Multidemensional Networks: Analysis, Design, Implementation and Computational Experience."

The awards were formally announced at the Transportation Science Section meeting at the INFORMS November meeting in Detroit.

On behalf of the dissertation prize committee and the Transportation Science community, I extend warmest congratulations to the winners and all other entrants, as well as their dissertation supervisors, and thank them for their participation in this competition.

I also wish to extend my sincere gratitude to all the judges for the time and care they devoted to this activity. The abstracts of the twelve theses submitted to the competition are given below.

System Optimal Dynamic Traffic Assignment in Congested Networks with Advanced Traveler Information Systems (ATIS) Capabilities

SRINIVAS PEETA

Growing concern over urban and suburban congestion on traffic networks has led to technologies broadly labeled as Intelligent Vehicle Highway Systems (IVHS), that integrate advances in telecommunications, information systems, automation and

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electronics to alleviate recurrent and non-recurrent congestion by augmenting the efficiency of the existing network. One class of IVHS technologies, Advanced Traveler Information Systems (ATIS), provides traffic control centers the ability to communicate with suitably equipped road users on a real-time basis and supplies routing information and/or route guidance instructions.

Existing methodological and algorithmic constructs for real-time control in large-scale traffic systems do not adequately exploit the available sophistication in technological and hardware capabilities, as highlighted by the paucity of suitable dynamic route assignment algorithms and associated real-time network traffic simulation capabilities. This research addresses dynamic traffic assignment problems in the ATIS context, where a central controller with partial or complete information on time-dependent origin destination (O-D) trip desires aims at achieving certain systemwide objectives by providing real-time routing information and/or route guidance instructions to suitably equipped vehicles. Conceptual and mathematical formulations are developed for the single user class (SUC) system optimal (SO) dynamic traffic assignment problem based on the information available to the controller.

A simulation-based solution algorithm is presented for the SUC SO dynamic traffic assignment problem in which the controller has complete a priori information on O-D desires for the planning horizon. It utilizes a traffic simulation model that evaluates the SO objective function and circumvents principal difficulties that have precluded analytical approaches from solving realistic formulations of the problem by obviating the need for link performance and link exist functions, implicitly ensuring the first-in, first-out-property and precluding holding of traffic. The associated user equilibrium (UE) solution is detailed. Experiments are conducted to obtain SO and UE solutions under alternative network loading intensities. They provide key insights into the nature and extent of benefits obtainable under advanced information systems and characterize the quality of benefits obtainable under advanced information systems and characterize the quality of service from a network flow theory perspective.

A multiple user classes (MUC) time-dependent traffic assignment problem that considers different user classes in terms of information availability, information supply strategy, and driver response behavior is formulated. A solution algorithm obtained by extending the SUC algorithm is implemented. The MUC solution algorithm is then embedded within a rolling horizon framework for real-work on-line implementation.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Civil Engineering at The University of Texas at Austin. The thesis advisor was Professor Hani S. Mahmassani.

Problèmes Stochastiques de Tournées de Véhicules (Stochastic Vehicle Routing Problems)

RENÉ SÉGUIN

In this work, we study a class of *Capacitated Vehicle Routing Problems* with stochastic demands and customers, denoted by the abbreviation VRPSDC. These problems are defined on a graph where each vertex has a probability of being present and has a stochastic demand. In a *first stage*, a set of routes are determined such that each route starts and ends at the depot and each customer is visited exactly once by one vehicle. The set of vertices with zero demand is revealed soon enough for some action to be taken, but the positive demand of every remaining customer becomes known only when vehicles arrive at the customers' location. In a *second stage*, the first stage routes are followed as planned, with the following two exceptions: 1) any absent customer is skipped; 2) whenever the vehicle capacity becomes exceeded, it returns to the depot to unload, and resumes collections starting at the last visited customer; if for any customer the vehicle capacity becomes exactly attained, the vehicle then returns to the depot and resumes collections at the next present customer along its route. The VRPSDC consists of designing a first stage solution so as to minimize the expected cost of the second stage solution. This problem belongs to the class of "*a priori* optimization problems," and to the family of stochastic integer programs with complete recourse. It generalizes two classes of problems that have been treated separately by a number of authors: the *Probabilistic Traveling Salesman Problem* and the *VRP with Stochastic Demands*.

Following an exhaustive survey of the literature found on every kind of *Stochastic Vehicle Routing Problems*, we formaly define the problem in the context of stochastic programming and provide a two-stage non-linear stochastic integer program with recourse. To solve the problem, we propose using the integer L-shaped method which works

with a relaxation of the objective function and of some of the constraints. A branch and cut scheme is applied to regain feasibility and to gradually approach the original objective from below. Three different implementations of the method have been used and analyzed. Our results show that of the two stochastic components of the problem, stochastic customers are more difficult to handle than stochastic demands. Depending on parameter values, fully stochastic problems can be solved exactly for small to medium sizes. Problems with only stochastic demands are easier and exact solutions for this case can be obtained for larger problems.

As exact methods cannot be used for large scale problems, we also develop a tabu search heuristic for the VRPSDC. Due to the particular objective function of the problem, we are forced to develop a fairly complex approximation function to evaluate candidate moves. Furthermore, since we allow the generation of infeasible solutions, we also used a dynamically self-adjusting penalty function which is designed to allow the heuristic to find its way back to feasibility by identifying which moves will improve the situation and which will not. The algorithm is fast and produces good quality solutions. The mean optimality gap over 825 test problems is 0.38%, and for 98% of all problems the gap is less than 5%.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Département d'Informatique et de Recherche Opérationnelle at the Université de Montréal. The thesis advisors were Professors Michel Gendreau and Gilbert Laporte.

Optimum Path Algorithms on Multidimensional Networks: Analysis, Design, Implementation and Computational Experience

ATHANASIOS ZILIASKOPLOULOS

The thesis is concerned with the problem of simultaneously computing many paths between two nodes on networks with arcs characterized by multiple attributes. These networks are referred to as multidimensional networks and their properties are defined in this thesis. The motivation is the emerging need for complex path algorithms arising from the development of *intelligent vehicle-highway systems* (IVHS). A variety of problems can be modeled and solved efficiently by the proposed approach: least-time and least-cost path problems on networks with general time-dependent arc costs, k-shortest path problems on uni- or multidimensional networks, optimum path problems on networks with multiple user groups, intermodal route planning problems, shortest path problems with penalties for intersection movements, and stochastic shortest path problems.

The general objective of this thesis is to study the problem of computing optimum paths on a multidimensional network from every node and dimensional element to a destination node and a final dimensional element. One general approach to model and solve these problems is to augment the network by adding nodes and arcs, and applying conventional shortest path algorithms on the resulting augmented network. However, augmentation is not always possible, as in the case of continuous cost functions, and when it is possible, it creates prohibitively large networks that are difficult to represent, and code, and inflexible to alter. The proposed approach does not require explicit expansion. It computes the paths for all the dimensional elements simultaneously. It drives its efficiency by exploiting the fact that the various dimensions share a common network topology. The whole scheme can be easily expanded to include additional dimensions, reflecting additional complexities of actual networks, without altering the underlying network topology. The definition of the dimensions is left open so the proposed approach is general and applicable to a broad range of optimum path problems. For some dimension realizations, this approach provides a solution to problems that were not addressed previously. In other cases, it yields algorithms that are more efficient than existing methods. The general solution approach is a dynamic programming approach, both for the continuous and for the discrete time case. The general algorithms have computational disadvantages that restrict their applicability; these disadvantages are identified and discussed along with a number of common properties of the general optimum paths.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Civil Engineering at The University of Texas at Austin. The thesis advisor was Professor Hani S. Mahmassani.

Facility Location in the Presence of Forbidden Regions and Congested Regions

STEVEN ERIC BUTT

Creating useful mathematical models of real location problems always involves abstraction and frequently involves simplifying assumptions.

Therefore, there are many practical applications to which classical facility location problems are not directly applicable. In this thesis, we consider a constrained form of several l-median and p-median location problems which cannot adequately be modeled as classical minimum problems. Specifically, we have analyzed these problems in the presence of forbidden regions and congested regions. A forbidden region is defined as an area in which travel and facility location are not permitted and a congested region is defined as an area where facility location is prohibited but through which one can travel at an additional cost per unit distance while in the region. Transportation models involving barriers, such as lakes and parks, seem to be among the most visual examples of these problems, but there are many applications ranging from building a circuit board to routing pipe on a ship.

In this thesis, we present solution procedures for several median problems in the presence of forbidden regions and congested regions. Among the problems studied are the l-median and p-median problems on a line, in a network, and in the plane, where distances were measured using either the rectilinear or Euclidean distance metric. We were able to show that the linear, network, and rectilinear problems, in the presence of congested regions, can be transformed from constrained median problems into equivalent classical median problems to which there are many exact and heuristic procedures available. For the Euclidean problems, we developed a solution procedure for each type of region and for both the single and multiple facility cases. All cases are shown to terminate at a local optimum to the corresponding problem. Through testing, we were able to show that the local optimum found by these procedures almost always coincides with the global optimum. Further, the procedures were shown to be efficient and adaptable to related location models.

Finally, in the development of the solution procedures to these median problems, other solution procedures were also developed. These included procedures that can (1) find the shortest path between points in the presence of convex polygonal forbidden regions, (2) locate a l-median in the presence of linear constraints and (3) determine the least cost path between two points in the presence of a convex polygonal congested region.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Industrial and Management Systems Engineering at The Pennsylvania State University. The thesis advisor was Professor Tom M. Cavalier.

Nouvelles Méthodes Séquentielles et Parallèles pour l'Optimisation de Réseaux à Coûts Linéaires et Convexes (Network Optimization Methods)

ISMAÏ CHABINI

This thesis presents a large collection of new theoretical contributions combined with empirical analysis. Also, it establishes many new results dealing with convex (linear and nonlinear) transportation problems, extensions and issues involved with developing effective parallel implementations. The theoretical basis has a potential for the development of efficient parallel methods for more general network flow problems in the same manner we have treated bipartite networks. In the following, we present an overview of each chapter.

In chapter 1, we introduce the relatively new field of parallel computing and we review the literature dealing with the development, implementation and testing a parallel methods for convex network optimization with an emphasis on the class of asynchronous algorithms. We analyze the difficulties inherent to the performance evaluation of parallel systems. We propose a new metric, the relative burden, which is shown to be useful.

Chapter 2 introduces the matrix balancing problem which is a basic problem for the thesis. A new adaptation of the primal projected gradient algorithm is introduced and implemented on a network of Transputers. The classical balancing algorithm is also tested for comparison.

In Chapter 3, a general primal-dual method is developed for the class of Bregman functions. Many known methods are obtained as special cases.

Chapter 4 generalizes the classical proximal minimization algorithm by replacing the quadratic term with the gap of a Bregman function. When the objective function is differentiable, we give a new variant of the proximal minimization algorithm. We demonstrate the convergence and show that it generalizes the projected gradient algorithm. Also, we analyze some relationships between the proximal minimization algorithm and the method of multipliers. Moreover, we present and analyze a new entropy proximal minimization algorithm and explore its relationships with other methods.

In Chapter 5 we consider transportation networks with convex costs, and show how to adapt the methods introduced in Chapter 3. Then the methods proposed in Chapter 4 are specialized to give a new method for transportation problems with convex differentiable costs. These are tested numer-

ically and compared to other methods. Also, we propose efficient parallel implementations on a network of Transputers and on a distributed network of Sparc Workstations. Convex capacitated transportation problems with six million arcs are solved within 10 minutes.

In Chapter 6, we present another new class of primal-dual methods for the convex and linear cost capacitated transportation problems. First, we consider the double entropy transportation problem for which a new balancing procedure is developed that extends the classical RAS algorithm. Then it is used as a subproblem for the solution of linear and convex cost transportation problems. These are implemented on serial and coarse-grain parallel platforms. The numerical results are very encouraging; the serial implementation outperforms specialized codes such as RELAXT-II and RNET. Substantial speedups are obtained.

In Chapter 7, we show how to extend the methods of the previous chapters to multicommodity transportation problems and to general network flow problems. We present different algorithms that take advantage of the structure of the constraints and some special forms of the objective function (quadratic and entropy type objective). We also present a new transformation of a general network to a capacitated transportation network.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Département d'Informatique et de Recherche Opérationnelle at the Université de Montréal. The thesis advisor was Professor Michael Florian.

Algorithms and Solutions to Multi-Level Routing Problems

I-MING CHAO

In the famous classical Vehicle Routing Problem (VRP), a fleet of vehicle services a set of customers from a distribution depot to deliver or collect products. Each vehicle has a fixed capacity which cannot be exceeded and each customer has a known demand that must be fully satisfied. The objective is to provide each vehicle with a sequence of deliveries so that all customers are serviced and the total distance traveled by the fleet (or the total travel cost-incurred by the fleet) is minimized without violating some other specified constraints. The Multi-Level Vehicle Routing Problems (MLVRP) addressed in this dissertation contain at least two levels of decision making optimization in which the VRP is a specific level or a variant. However, the lowest level of the MLVRP is always a Traveling Salesman Problem (TSP) or a TSP-variant. The TSP is an NP-hard optimization problem, so the MLVRP's are at least as difficult as the TSP. For a large scale MLVRP, an exact method will be hard to get an optimal solution to the problem in a limited real world computation time. In the real world application, a heuristic method that can get a near optimal solution to the problem by using a reasonable computation is preferred and practical. In the dissertation, five prototypes of the MLVRP are addressed. They are the orienteering problem, the team orienteering problem, the multi-depot vehicle routing problem, the period vehicle routing, and the period traveling salesman problem. For each type of problem, an effective heuristic method based upon a same simple basic idea is developed. The basic idea is that the algorithms accept some worse solutions when the searching procedure continues. When we make the decision of transmitting a solution to another one, a set of candidates are considered one after one. Whenever a candidate can improve the objective function value, it is performed right away and all others are ignored. When no candidate can improve the objective function value, then one that losses the objective function value at the least will be performed if the amount of loosing value is not too many. The heuristics are implemented on the benchmark test problems taken from the literatures and the results are compared to those published along with the existing methods. A variety of new test problems are also operated for each type of addressed MLVRP and are solved by the newly developed heuristics and by a new code of an existing methods or a carefully inspection. The comparisons for both sets of test problems for all five types of MLVRP show the superiority of the new heuristics. Finally, we synthesize the heuristics developed in this dissertation as a new general heuristic method for solving the MLVRP related optimization problems.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Management Science and Statistics at the University of Maryland. The thesis advisor was Professor Bruce L. Golden.

Bilevel Programming Problems: Analysis, Algorithms and Applications

YANG CHEN

In this thesis, we study the bilevel mathematical programming problem (BLPP), an optimization problem with a special constraint structure which is implicitly determined by another optimization

problem and which may be defined in the field of global and nonsmooth optimization. This work covers some major issues on the study of BLPP, ranging from its theoretical analysis, the development of solution procedures and applications to some large-scale real world problems.

A comprehensive review of the research advances in the study of the BLPP is provided and a new classification of the existing solution procedures is suggested.

In order to provide a theoretical framework for the study, we propose and investigate a general mathematical programming formulation with a marginal function of the lower level problem. Some fundamental issues are studied for the BLPP within this framework. Among them, the existence results of solutions are derived in a general sense, regularity conditions of the problem are discussed and necessary optimality conditions are established, where a Fritz-John type condition is obtained for general nonlinear: BLPP, and KKT type conditions for a class of nonlinear and linear ones. The geometric structure of the problem is extensively studied for linear and quadratic BLPPs. The relationship between the new formulation and existing ones is also discussed.

A dual successive linear programming approach is developed for solving the linear BLPP. An optimality criterion for the bilevel problem is derived based on the information of optimal solutions of some related linear programs. By making use of the global optimal criterion and the geometric properties of the dual constraint set of the lower level problem, the proposed method implicitly searches the vertices of the dual polyhedron and guarantees the descent property at each iteration. It is shown that the algorithm converges finitely to an e-optimal solution of the problem.

A cutting plane method is investigated for solving the linear BLPP. An optimality criterion is derived from two related linear programs constructed by using the complementarity conditions for the lower level problem. Two types of cutting planes are developed in order to obtain efficient cuts and guarantee a finite convergency. The method combines the techniques of cutting plane and implicit vertex enumeration and it converges to an optimal solution finitely. Test examples are given to illustrate how these methods work.

An application of the BLPP to a class of important real world problems, which occur in the context of transportation planning problems, is highlighted in a unified approach. A theoretical model is given to embed a large variety of transportation planning problems into the framework of the BLPP. Emphasis is put on theoretical and algorithmic developments for a difficult problem, the origin-destination demand adjustment problem (DAP). A locally convergent Augmented Lagranagian method and a heuristic Gauss-Seidel type method are proposed to solve the DAP. Implementation issues are discussed and computational results are provided. Some possible research directions for the further study on the BLPP are proposed and outlined briefly.

The contributions of the thesis are as follows:

1. A comprehensive, up-to-date review of the research advances in the study of the BLPP and a new classification of the existing solution methods on certain criteria is presented.
2. A general formulation of BLPP is proposed and investigated. This formulation subsurnes many existing formulations of BLPP and provides a framework and a theoretical basis to handle the BLPP.
3. The existence results of optimal solutions of the BLPP are derived under the proposed formulation.
4. The geometric structure of the dual feasible region of the linear BLPP is investigated. The obtained results complete the description of the problem structure and lead to some solution methods for the linear BLPP.
5. The geometric properties of the feasible region of a class of nonlinear BLPP are investigated. These results are new in the BLPP literature and coincide with some existing results in a more general setting.
6. The degeneracy of the BLPP with the marginal function formulation is characterized by obtaining a necessary regularity condition which the BLPP fails to meet in general. The commonly used constraint qualifications are shown not to be satisfied by the BLPP.
7. A Fritz-John type optimality condition is derived for general BLPP in the framework of nonsmooth analysis. A set of KKT optimality conditions is obtained for a class of nonlinear BLPPs and all linear BLPP.
8. A dual successive linear programming method is developed for finding global optimal solutions of the problem. The finite convergence of an ϵ-optimality of the problem is guaranteed.
9. A cutting plane method is proposed for solving the linear BLPP. The method finitely converges to a global optimal solution of the problem.
10. A theoretical model is established for a class of transportation planning problems by relating the problem to the BLPP. An extensive study of

a special class of transportation planning problem, DAP, is undertaken from a theoretical aspect which include the existence of solutions and optimality conditions.

11. An augmented Lagrangian algorithm is proposed for the DAP and the convergency of the algorithm is derived.
12. A heuristic approach is investigated and implemented for solving the DAP problem related to real traffic networks.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Département of d'Informatique et de Recherche Opérationnelle at the Université de Montréal. The thesis advisor was Professor Michael Florian.

Assessing the Impact of Real-Time Information on Transit Passenger Behavior

MARK DAVID HICKMAN

This thesis develops a modeling framework to examine the impacts of real-time information on transit passenger behavior, particularly the passenger's choice of path and departure time. By examining how passengers may alter their travel decisions in response to various types of real-time information, the quantitative impacts of passenger information systems can be evaluated.

As a foundation for the research, an analytical framework for both transit service and passenger path and departure time choice is presented. A transit service model is developed that explicitly incorporates several elements which most influence the passenger's trip travel time reliability: stochastic departure and running times, connections between routes, and time-dependence. These elements are critical in examining travel times in a transit network where real-time information may be most useful. Based on these transit service characteristics, two path choice models are developed: a *static* model, which assumes that the passenger determines a vehicle boarding strategy upon his/her arrival at the origin terminal; and a dynamic model which assumes that the passenger decides his/her boarding strategy as vehicles arrive at the terminal. The dynamic model is also shown to be useful in describing adaptive path choice decisions made during the passenger's trip. In addition, two passenger departure time choice models are considered: one in which passengers arrive at the origin stop entirely at random, and a second in which arrivals at the origin stop are coordinated with scheduled vehicle departures.

The passenger's path choice decision may also be affected by the availability of real-time information and the passenger's experience with the transit service. A set of scenarios is developed to examine several dimensions of real-time passenger information systems, including: the type of information given; the time when the passenger receives the information; and, the accuracy of the information in predicting network conditions. Variations in passengers' level of experience with the transit service and with the real-time information are also included in the modeling framework.

These scenarios are examined using a corridor-level network simulation that is based on the transit service model and incorporates the path and departure time choice models. A case study from the Massachusetts Bay Transportation Authority is used to assess the anticipated passenger response to different levels of real-time information, using the measures of origin-to-destination travel times and path choices. The results of the simulation model suggest that the potential reduction of travel times resulting from real-time information are very modest, on the order of 2% to 3% of the total origin-to-destination time. Yet, this amount accounts for 70% to 95% of the possible travel time savings in the selected networks. The results also suggest more significant changes in path choices from this real-time information. The overall magnitude of travel time savings, however, raises significant questions about the benefits of real-time passenger information systems to the transit passenger.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Civil and Environmental Engineering at the University of California at Berkeley. The thesis advisor was Professor David Bernstein.

Airline Schedule Perturbation Management

SONGJUN LUO

Airlines spend tremendous effort in designing flight schedules. Management Science and Operations Research play an important role in this challenging environment in order to efficiently utilize available resources and take advantage of consumer demands. A consequence of this pursuit of resource utilization efficiency is the lack of idle time between consecutive activities for all resources (aircraft, crew, ground facilities, etc.) built in the flight schedule. If no perturbation occurs in the course of executing the schedule, lack of idle time

translates to high resource utilization. However, perturbations do occur due to various reasons. Schedule perturbations of any magnitude pose challenges for airlines in keeping their original schedules. Not being able to cope with the perturbation problem effectively could lead to collapse of the original schedule, which is devastating for airlines.

The major objective of this study is to devise strategies that can be used for addressing the schedule perturbation problems as they occur. Various models have been built for handling the problem under different situations and with different objectives. Strategies for solving the models have been designed and tested with realistic data from American Airlines. Special-purpose algorithms were designed to exploit the problem structure.

The models that we have built range from the simplest assignment model to NP-hard models. Solution Strategies that we have employed include straight-forward applications of assignment algorithm. Several models are solved to proven optimality by greedy algorithms. Polynomial algorithms were also designed for some models. Some complexity results are shown. To solve the most difficult model, we have derived many valid inequalities for the integer program formulation for strengthening the LP relaxation bound. The number of integer variables was reduced dramatically based on the problem properties and its impacts on the problem solvabilities were shown to be of significant importance. Heuristic based on solving restricted version of the original model has been designed for finding good feasible solutions. Realistic problems have been solved to optimality in seconds on microcomputers. The potential of gain from implementing the models is shown to be substantial.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Management Science and Information Systems at The University of Texas at Austin. The thesis advisor was Professor Leon Lasdon.

Élaboration de Tournés de Véhicules sous Contraintes d'Accessibilité (Routing Problems under Accessibility Constraints)

FRÉDÉRIC SEMET

Due to the reduction of production costs observed during the recent years, distribution costs have increased significantly as a percentage of the cost price of a product. Therefore the minimization of these costs is a new challenge for many companies which can addressed through solving numerous combinatorial problems, e.g., location problems or vehicle routing problems.

In this thesis, we deal specifically with the vehicle routing problem when different means of transportation are used, e.g., trains and trucks. This leads us to define a new class of constraints: the accessibility constraints.

We begin by proposing a new feature of the traveling salesman problem when these constraints have to be taken into account. After introducing an integer programming formulation of the problem, we describe three heuristic methods; one of them is based on the tabu search metaheuristic. A comparison study of these procedures is then given on the basis of numerical results obtained on a large set of test problems having various characteristics. Finally, we indicate how different lower bounds on the optimal solution can be calculated.

We then tackle the vehicle routing problem under accessibility constraints. Due to the variety of real-life situations, we define precisely the problem we are interested in. We propose next in integer programming formulation and we develop a heuristic method which extends a classical vehicle routing routine. Our approach embodies a branch and bound method for solving a combinatorial problem having some similarities to the generalized assignment problem. The procedure provides very encouraging results on a set of test problems.

Next, we turn to solving real-life vehicle routing problems. We first describe two case studies in which a variety of restrictions, including accessibility constraints, have to be fulfilled. Then, we present tabu search approaches adapted to the specifics of each problem. In spite of the intricacy of the problems, the proposed tabu search methods are simple to implement and obtain solutions significantly better than those previously used by the companies.

For solving such problems, we have to estimate or determine the distances between the customers. In both cases, we suggest using a new lower bound based on a modelling of natural obstacles obtained in the road network instead of the classical Euclidean distance. Indeed, numerical results obtained on the Swiss road network indicate that distances are then estimated with a low percentage error on average and CPU times required by a modified version of the Dijkstra method are lower than those previously measured.

Finally, we describe a decision support system for vehicle routing that we developed. We highlight the main required characteristics of the software through a detailed presentation of such a system now being being used by a company.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the

Département de Mathématiques at the Ecole Polytechnique Fédérale de Lausanne. The thesis advisor was Professor Dominique de Werra.

Algoritmi Esatti ed Approssimati per Problemi di Routing e di Scheduling (Exact and Approximate Algorithms for Routing and Scheduling Problems)

DANIELE VIGO

In this thesis we collect the main original results of our research activity carried out during the years of our System Engineering Ph.D. program at the Electronics, Informatics and Systems Department of the University of Bologna under the supervision of Professor Paolo Toth.

The research has been conducted in the field of Operations Research and Combinatorial Optimization, particularly focusing on the application of the main analysis and solution techniques of these disciplines to some phases of the planning and management of production and distribution of goods. In particular the thesis examines some problems arising in the optimal routing of vehicles from a central depot to a set of customers (Vehicle Routing Problems), and the problem of determining the optimal processing sequence for a single machine in a "just in time" context.

The Vehicle Routing Problem (VRP) is of primary importance in many physical distribution problems. It can be described as follows. We are given a set of customers and a depot where a certain number of vehicles is stationed. The problem consists of determining a set of routes for the vehicles, so as to serve all the customers and subject to operational constraints. The objective is to satisfy all customer demands while minimizing the number of vehicles used and the global routing cost.

In this thesis we consider two particular cases of the general VRP. The first one is known as the asymmetric *Capacitated Vehicle Routing Problem* (CVRP), while the second is known as the symInetric Vehicle Routing Problem with Backhauls (VRPB).

In the CVRP only the vehicle capacity constraint is imposed, all the vehicles are identical and can perform at most one route each. The problem is known to be NP-hard in the strong sense and finds many practical applications in distribution and scheduling.

The first chapter of the thesis is devoted to the exact solution of CVRP. We present two new bounding procedures for CVRP, based on disjunction on infeasible arc subsets, and on a new min-cost flow relaxation of the problem. Each procedure computes a sequence of nondecreasing lower bounds, according to the *additive approach* proposed by Fischetti and Toth in 1989. Effective implementations of the procedures are also outlined which considerably reduce the computational effort. The two procedures are imbedded into a branch-and-bound algorithm for the exact solution of CVRP, whose performance is enhanced by means of reduction procedures, dominance criteria, and feasibility checks. Extensive computational results on both real-world and random test problems involving up to 300 customers are finally presented, showing that the proposed approach favourably compares with previous algorithms from the literature. A paper based on this work, co-authored by Matteo Fischetti and Paolo Toth has been accepted for publication in *Operations Research*.

In the second chapter we examine the heuristic solution of CVRP. We first describe the extension to CVRP of the two well known Clarke-Wright and Fisher-Jaikumar heuristic algorithms, originally proposed for the symmetric case. We also present a new heuristic algorithm for CVRP that, starting with an initial infeasible solution, determines the final set of vehicle routes through an insertion procedure as well as intra-route and inter-route arc exchanges. The initial infeasible solution is obtained by using the additive bounding procedures previously described. Extensive computational results on several classes of randomly generated test problems involving up to 300 customers and on some real instances concerning the distribution in urban areas, are presented. The results obtained show that the proposed approach favourably compares with previous algorithms from the literature. A paper based on this work has been accepted for publication in the *European Journal of Operational Research*.

In the VRPB the customer set is partitioned into two subsets. The first subset contains the *Linehaul customers*, each requiring a given quantity of product to be delivered. The second subset contains the *Blackhaul customers*, where a given quantity of inbound product must be picked up. This customer partition is extremely frequent in practical situations. A common example is represented by the grocery industry, where supermarkets and shops are the Linehaul customers, and grocery suppliers are the Backhaul customers. In recent years it has been widely recognized that in this mixed distribution/collection context a significant saving in terms of transportation costs can be achieved by visiting Backhaul customers in distribution routes. VRPB is known to be NP-hard in the strong sense, and many heuristic algorithms have been proposed for its approximate solution.

In the third chapter we present a new Integer Linear Programming formulation of VRPB, based on its reformulation as an asymmetric problem. A new Lagrangian lower bound, based on projection of the solution space is described. The lower bound requires the determination of shortest spanning arborescences with fixed degree at the depot vertex, and the optimal solution of min-cost flow problems. We also present a new cluster-first-route-second heuristic algorithm for VRPB which starts from an infeasible solution obtained from the Lagrangian relaxation and tries VRPB which starts from an infeasible solution obtained from the Lagrangian relaxation and tries to build a feasible set of routes through inter-route arc exchanges. The presented computational tests show the effectiveness of the proposed approach compared to other algorithms presented in the literature. A paper based on this work, co-authored by Paolo Toth, has been presented at the Second Meeting of the EURO Working Group on Urban Traffic and Transportation (Landshut, October 1992), at Netflow '93 Conference (Pisa, October 1993), and at Tristan II Conference (Capri, June 1994).

In the fourth chapter we present a lower bound based on a preemptive relaxation, which extends a previous bound proposed by Posner for a related problem, and whose efficient implementation is described. A new approximation algorithm that eliminates the preemptions present in the lower bound solution is also proposed. Extensive computational experiments show the effectiveness of the proposed approach that obtains better results and requires computing times that are more than one order of magnitude smaller compared to previous algorithms from the literature. An extension of this work, co-authored by Mauro Dell'Amico and Silvano Martello, has been accepted for publication on Discrete Applied Mathematics.

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Solving Large-Scale Nonlinear Network Problems with Relaxation and Decomposition Algorithms

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Due to its rich variety of application in transportation, engineering, management, and economics, the problem of optimizing a nonlinear cost function subject to network constraints has been widely explored over the last three decades. In practice, these problems are characterized by their large size and complicated network topology. Therefore, fortified algorithms that take advantage of the problem structure must be developed.

In the first part of this research, an active set algorithm based on the Lagrangian dual formulation is developed for solving large-scale quadratic network flow problems. Then, the global convergance proof of the proposed algorithm is discussed when the objective function is global convergence proof of the proposed algorithm is discussed when the objective function is strictly convex and its corresponding dual cost function has bounded level sets. Several gradient based direction generators are introduced to generalize the active set algorithm. Moreover, three based direction generators are introduced to generalize the active set algorithm. Moreover, three different finite procedures are proposed to solve the line search subproblems. Motivated by a preliminary computational study, a line search combination algorithm is developed to ameliorate the performance of the exact line searches. Finally, an extensive computational study is performed to evaluate the effectiveness of the dual active set algorithm by using different direction generators and line search procedures. Both quadratic transshipment and transportation problems are randomly generated using the modified NETGEN code. The computational study has shown that the conjugate gradient direction generator along with the active set strategy and the line search combination algorithm outperforms the Quasi-Newton and coordinate ascent direction generators.

In the second part of this research, the convex network flow problem with additional non-network (side) constraints is considered. A decomposition algorithm based on the restricted simplicial decomposition (RSD) scheme is developed for solving the side constrained optimization problems. In this new algorithm, the side constraints are first relaxed based on the Dantzig-Wolfe decomposition procedure. Upon this decomposition, the resulting two optimization problems, a linear subproblem and a nonlinear master problem, are solved using the RSD scheme. The global convergence of the proposed decomposition algorithm is proven under the following two conditions: (1) the maximum number of retained extreme points (solutions of the subproblem) must be greater than the number of side constraints plus one, and (2) a special rule must be applied to determine the extreme points that can dropped. Furthermore, the finite convergence proof is also discussed when the objective function is

strictly pseudoconvex and the maximum number of retained extreme points is greater than the dimension of the manifold defined by the network constraints that contains the optimal solution. When the objective is convex and differentiable, a solution lower bound is also developed using the gap function. This can be used to develop a practical stopping criterion for the proposed algorithm. The proposed algorithm is then implemented to solve capacitated traffic assignment problems with a convex cost function. Finally, computational results of several existing example problems of small to large sizes are presented to study the properties of this new approach.

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