MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 44/1999

Traffic and Transport Optimization

07.11.–13.11.1999

This 5 day meeting was organized by Martin Grötschel (Berlin), Warren Powell (Princeton), and Uwe Zimmermann (Braunschweig). 47 scientists from 11 countries participated (Germany: #19, USA: #12, Italy: #5, Canada: #3, Netherlands: #2, Chile, Denmark, New Zealand, Sweden, Switzerland, and UK: #1).
This meeting was one in a special series of application oriented Oberwolfach conferences. The aim was to bring scientists and practitioners from a variety of different disciplines together as a step toward the creation of a mathematical science base in traffic and transportation. More than one third of the participants were first time Oberwolfach visitors, 4 were from industry.
35 talks were given. 2 special evening presentations invited for participation in the DLR's new research focus "Traffic" and presented the economics of deregulation in the transportation sector, respectively. An evening panel discussion on the future of traffic and transport optimization took place.
The subjects of the presentations and discussions spanned the entire spectrum of traffic and transportation optimization:

- the traffic segments from airlines, railroads, mass transit, road traffic, to shipping,
- areas from (classical) optimization to distributed and cooperative decision making and to questions of regulation and deregulation,
- fields from operational planning via system design and analysis to operations control and the routing of traffic flows,
- problem characteristics from off-line to stochastic and dynamic real time planning,
- methodologies from integer programming to equilibrium models and simulation environments,
- applications from train timetabling and container terminal operation, vehicle and crew scheduling and rostering to supply chain management, vendor managed inventory, and dynamic resource management,
- techniques from modelling and parallel computing to software engineering.

The organizers and participants thank the "Mathematisches Forschungsinstitut Oberwolfach" for the excellent conference organization and the resulting stimulating atmosphere.

List of Abstracts (in Order of Presentation)

Monday, November 08, Morning Session

Alexander Martin
Solving Integer Programs

Mixed Integer Programming (MIP) deals with the solution of minimizing a linear objective function subject to a set of linear inequalities, where some or all of the variables must be integer. MIP problems have a wide range of applications, including traffic and transport, finance, telecommunication and others. Among the most successful solution methods for MIP problems are LP based branch-and-bound algorithms, where the original formulation is possibly strengthened by cutting planes.
In this and the talk given by Bob Bixby we discuss the main components of this method: preprocessing, branch-and-bound issues (i.e., node and variable selection), cutting plane generation, primal heuristics, and the solution of the underlying linear programs. We especially focus on cutting plane generation and show on a practical problem arising in the transportation area that leads to a multiple knapsack problem (MKP) how useful cutting planes can be. We then extend the ideas for the MKP, which turns out to be an integer program with block structure, to general MIP problems, where nothing is a priori known about the underlying structure. We will see that many MIP problems have (after reordering the columns and rows) block structure. We exploit this information and develop a new (very general) class of inequalities that help to solve various MIP problems more efficiently.

Bob Bixby
Mixed Integer Programming

This talk was part of a two-part series, the first being given by Alexander Martin. In this part computational advances in LP (linear programming) and MIP were discussed. LP is the key enabling technology for MIP. We focused on “large models” with at least 10,000 constraints. The first step was to use known methods from the sparse linear algebra community for solving large, sparse linear systems in “linear time”. With this bottleneck broken, it was possible to introduce other fundamental algorithmic improvements in the classical simplex methods for LP. The results were quite striking with improvements exceeding 8x in the dual simplex method on a large set of models from practice.
MIP advances were based upon features, “mining” on existing backlog of theoretical advances from integer programming and combinatorial optimization. The basic approach was to implement a “barrage” of different ideas, giving great care to developing good defaults so that ideas help when they should, and get them in the way as little as possible when they don’t. Three specific topics were discussed: Node presolve, node heuristics, and cutting planes. The cutting plane discussion was the most extensive, and the most important single result was that Gomory mixed-integer cuts, rejected in the 60s and 70s as a useful computational tool, really do work. Finally computational results and some examples were given.

Jaques Desrosiers
Crew Scheduling: Past and Future

This talk presents an overview of Crew Scheduling. It mainly focuses on some modeling aspects and mathematical decomposition approaches used in the past 10 years to solve this type of problems. Modeling aspects involve a multi-commodity network flow structure together with non linaer cost and resource extension functions. The main decomposition approaches are based on Lagrangean relaxation, Dantzig-Wolfe decomposition, and Kelley's cutting plane method. All these methods rely on the so-called Column Generation approach. Beside these methods, we also present various fundamental research aspects that should be useful in the near future. Amongst these, we focus on a primal-dual stabilization method, on a dynamic constraint aggregation, on a resource projection algorithm for constrained shortest path problems, on Benders decomposition for two-level problems, and finally, on the Analytic Center Cutting Plane Method, an interior point method developed by Vial and Goffin, up to now the only one compatible with the Column Generation approach.

Monday, November 08, Afternoon Session

David Ryan
Simultaneous Optimization of Trains and Driver Schedules

Scheduling and rostering problems involving valuable resources such as vehicles, machines or personnel occur in many organizations. Efficient utilization of these resources is obviously an important management consideration. From a mathematical point of view, scheduling applications give rise to many very challenging problems in combinatorial and computational optimization.
In this talk we discuss the development of a single optimization model which schedules both trains and their associated train drivers. The train scheduling (or timetabling) problem seeks to construct a legal timetable for a specified number of trains that minimizes train delays. The driver scheduling constructs minimal cost driver shifts for a given train timetable. These two problems are usually considered in sequence and their obvious interaction is ignored. The combined model includes a continuous linear component and a set partitioning like zero-one integer component which are related through a set of linking constraints. These constraints are dynamically generated as required during the solution process. Further constraints associated with train crossings are implemented during the branch and bound procedure used to generate integer solutions.
The model is applied to a specific train scheduling problem in New Zealand and results are presented to demonstrate that the simultaneous optimization approach provides better solutions than those obtained from the standard sequential approach.

Aristide Mingozzi
Exact Methods for the Capacitated Vehicle Routing and its Extensions

The Capacitated Vehicle Routing Problem (CVRP) is the problem in which a vehicle fleet stationed at a central depot is to be optimally routed to supply customers with known demands subject to vehicle capacity constraints. The CVRP has been shown to be NP-hard. The fact that few algorithms have been produced to date, which can solve capacitated vehicle routing problems of reasonable size to optimality, reflects the difficulty of this problem. Moreover, these algorithms can not be easily extended to deal with real-world constraints like time windows to visit customers, mixed delivery and collections on the same route, multiple interacting depots, etc. In this talk we describe two exact methods for the CVRP that can be extended to solve real-world constraints. The first method, based on the set partitioning formulation of the CVRP, has been used to solve the CVRP with time windows and the CVRP with backhauls. We describe several bounding procedures and an exact solution method that require the generation of a limited subset of the set partitioning columns. The second exact method is based on a two commodity network flow approach. This method is used to derive new integer programming formulations of the CVRP with mixed deliveries and collections, the CVRP with backhauls and the CVRP with different vehicle capacities. New lower bounds are obtained from the LP relaxation of the formulations which are further strengthened by new valid inequalities. The computational results show the effectiveness of the two proposed approaches.

Oli Madsen

Vehicle Routing with Time Windows—Some New Ideas for Speeding Up the Solution Process

The paper presents some new ideas concerning optimization methods for the vehicle routing problem with time windows. The basic method is based on Dantzig-Wolfe decomposition in which the coupling constraints are the constraint set requiring that each customer must be serviced. The subproblem is a Shortest Path Problem with Time Windows and Capacity Constraints.
The decomposition schemes combined with branch and bound techniques has proven effective in solving a large number of instances of the VRPTW. To get better bounds a number of strong valid inequalities are generated and incorporated in the master problem as needed. The 2-path cuts seems to produce very good bounds within a reasonable computation time.
Branch and Bound is applied to obtain an integer solution to the VRPTW. The branching strategy is primarily based on branching on the number of vehicles (if it is fractional), and secondary on branching on the flow variables.
In this presentation a method for speeding up the separation algorithm for 2-path cuts and methods for speeding up the column generation will be discussed.
The algorithm has been implemented and tested on a series of well known data sets of size up to 100 customers. The algorithm turns out to be faster than other algorithms considered in the literature, and the algorithm has succeeded in solving several previously unsolved problems to optimality.

Anton Kleywegt

Stochastic Shortest Path Problems

We propose a solution method for stochastic discrete optimization problems of the form

$$\min_{x \in S} \{g(x) \equiv E[G(x,W)]\}$$

where S is a known discrete set, W is random, $G(x,W)$ is easy to compute for given x and w, but $g(x)$ is hard to compute. We study a method which involves solving sample average approximation problems of the form

$$\min_{x \in S} \frac{1}{N} \sum_{n=1}^{N} G(x, W_n),$$

where $\{W_1, \ldots, W_N\}$ is an iid random sample. Convergence properties are established, including asymptotic convergence rates. An algorithm is presented. Numerical results on a stochastic shortest path application are presented.

Cynthia Barnhart
Airline Schedule Design

We consider the Airline Service Network Design problem involving the selection of flights, flight departure times, aircraft fleet assignments, and freight and/or passenger flows. In the case of freight transport, the objective is to minimize the total cost of transporting all freight, while the objective for passenger airlines is to maximize the difference between revenues and flight operating costs. The design of the service networks are constrained by fleet composition and size, aircraft capacity, passenger and/or freight demand, and service level requirements. We present models and algorithms for solving this class of problems and provide computational results achieved in solving the service network design problems faced by a large carrier providing express parcel delivery.

Dag Wedelin
Paros Overview and Experiences

The PAROS project is an ESPRIT project including Lufthansa, Carmen Systems, Chalmers Univ of Tech ad Univ of Patras. It has been concerned mainly with basic technology for improving the performance of crew scheduling applications. The starting point has been the existing Carmen system, and in the project both the generator and the optimizer have been parallelized. A new set of algorithms based on column generation and the new paqs optimizer has also been developed. Both the improved existing system and the new system gives an order of magnitude speedup, and in some cases significantly higher quality.

Monday, November 08, Evening Presentation

Achim Bachem
Aerospace Technologies for Mobility, the DLR and its New Program "Transport Research"

In this talk various research and development activities of the DLR (Deutsches Zentrum für Luft- und Raumfahrt) are introduced and some of the projects that are relevant for transportation are outlined. In particular, an overview is given on the new program "Transport Research" that will be carried out by scientists in universities and research institutes all over Germany and that will be coordinated by the DLR. Funding is provided by the federal government, several of the states of Germany, and partners in industry. Public-private partnerships are especially encouraged. To steer this work DLR has decided to found several research institutes.

Martin Savelsbergh
Vendor Managed Inventory

Vendor Managed Inventory (VMI) is an emerging trend in logistics sand refers to situations in which a supplier manages the inventory replenishment of its customers. Vendors save on distribution and inventory costs by being able to better coordinate deliveries for different customers, and customer benefit because they do not have to dedicate resources to inventory management. Inventory routing problems are very different from vehicle routing problems. Vehicle routing problems occur when customers place orders and the supplier assigns orders received for that day to routes for trucks (You call - we haul). In inventory routing problems, the supplier, not the customer, decides how much to deliver to which customers each day (You rely - we supply). Two important variants of the inventory routing problem (IRP) deserve attention: the deterministic IRP, in which it is assumed that we only know the average usage of customers, and the stochastic IRP, in which it is assumed that we know the probability distribution of customer usage. For the deterministic IRP a two-phase approach using integer programming and insertion heuristics has been developed, and for the stochastic IRP an approximate dynamic programming algorithm has been developed. Computational experiments have revealed the value of both approaches.

Michael O. Ball
Optimization Problems in Air Traffic Flow Management

In this talk we discuss optimization models arising in the context of Air Traffic Flow Management (ATFM). The underlying decision problems have a time scale of an hour to one or two days and have the objective of managing aircraft flows so as to achieve efficient utilization of airspace resources. In recent years a new paradigm for ATFM, called Collaborative Decision Making (CDM), has been developed. One of the principal goals of CDM is to distribute decision making responsibility between airspace managers and airlines so as to allow the airlines to control decisions that require consideration of economic tradeoffs. The resultant systems typically involve an iteration between the airspace managers and the airlines, where the airspace managers perform basic constraint identification and resource allocation, and the airlines perform more refined allocation among their own flights. The CDM paradigm provides a new challenge for optimization modeling. In this talk we review air traffic flow management optimization models in general and describe models that have been specifically developed for use in the context of CDM. Some of the CDM-specific issues that arise are: the incorporation of "fairness" criteria into constraints and objective functions, insuring that resource allocation procedures encourage information disclosure and allocation procedures that iterate between an aggregate airspace manager problem and a detailed airline problem.

Warren Powell
An Information Theoretic Approach to Dynamic Resource Management

Complex resource management problems (railroads, trucking companies, airlines) are characterized by dynamic information processes, and compartmentalized information. We identify four classes of information: knowledge, forecasts, plans, and values. Inclusion of each information class produces a specific class of algorithms: myopic, rolling horizon, proximal point algorithms, and dynamic programming. We show how approximate value functions can be estimated for very large scale problems, opening up our ability to handle entirely new problem classes.

Tuesday, November 09, Afternoon Session

Roberto Cominetti

An Equilibrium Model for Passenger Assignment in Congested Mass Transportation Networks

Consider a directed graph $G = (N,A)$ where each arc $a \in A$ represents a transfer link characterized by a fixed travel time $t_a \geq 0$ and a variable service frequency $f_a(v_a)$ which depends on the arc flow v_a, so that the cost of traversing a given arc includes both *travel* and *waiting* times, with congestion affecting mainly the latter.
Given a set of demands $d_{ij} \geq 0$ of passengers going from node $i \in N$ to node $j \in N$, we describe an equilibrium model to compute the flows in the network when passengers behave non-cooperatively, looking for a *minimum time hyperpath* to reach their destination.
The model is expressed as a set of non-monotone variational inequalities (one for each node $i \in N$), linked together by flow conservation conditions.
We prove existence of equilibria, and we characterize them showing that congestion may lead to inefficient equilibria. We also point out a phase-transition phenomenon in the passenger's optimal strategies (hyperpaths), when demand increases and congestion builds up.

Terry Friesz

A New Formulation of Dynamic Traffic Network Equilibrium

The dynamic traffic network equilibrium problem for road networks is re-formulated as a controlled variational inequality recognizing that if arc inflows and outflows are to be employed as control variables a flow propagation constraint must be added which accounts for the deformation (expansion and contraction) of waves/platoons. It is shown that "naive" flow propagation constraints which equate flow entering an arc or a cell to flow exiting at a later time which accounts for arc traversal time are invalid for they explicitly contradict the normal assumptions made for such problems, namely the point queue model of arc delay and its extensions to include non separable arc delay functions. [Furthermore, inclusion of the new flow propagation constraints allows state dynamics and path delay operators to be restated in a way that requires *no* explicit knowledge of arc exit time functions (or their inverses) or of arc exit flow functions. A previous difficulty with the resulting formulation was that it could not be rigorously proven that controlling both inflows and outflows with "proper" flow propagation constraints resulted in necessary conditions which are equivalent to a dynamic user equilibrium. This difficulty arises because the flow propagation constraints involve state-dependent time lags.] New necessary conditions for optimal control with state dependent time lags are derived and employed to rigorously establish that the new formulation yields dynamic user equilibrium.

Kai Nagel
Large Scale Traffic Simulations

TRANSIMS (TRansportation ANalysis and SIMulation System) is an example of a large scale microsimulation project for transportation planning. The goal is to have a tool where changes in the transportation infrastructure, such as the addition of a train or of a road, can be modelled and the resulting changes in the traffic patterns can be analysed. TRANSIMS approaches this problem by simulating, for each individual traveller, all aspects of his or her transportation-related decision-making, from the planning of his/her daily schedule, via modal and route choice, to second-by-second driving decisions. Consistency between making and execution of plans is achieved by iterations, which model human learning. About 50 such iterations are usually needed in practice. For Portland/Oregon, a city with 1.5 mio people and 200000 transportation links, the currently most realistic version of TRANSIMS needs, for these 50 iterations, 500 days of computing time on a single CPU and 17 hours on a supercomputer with 1000 CPUs.

Teodor Gabriel Crainic
Freight Transportation, Service Network Design, Network Design

Consolidation-type of freight transportation firms use the same vehicle or convoy to serve the demand of many diverse customers. A transportation plan is then build to insure service quality, efficient resource utilisation, and coordination of transportation services, consolidation activities in terminals, and freight routing for each market. This forms the so-called Service Network Design problem, usually formulated as capacitated, multicommodity network design models. We rapidly survey the main Service Network Design models and review our current and planned research activities in these areas.

Sven Krumke & Jörg Rambau
Performance Guarantees for Online Dial-a-Ride Problems

The fully-automated pallet transportation system in the large distribution center of Herlitz PSB AG in Falkensee, near Berlin, consists of various modules that are of interest in combinatorial optimization. The elevator system used to transport pallets from the ground floor to the production floors, resp., warehouse has to be controlled online in real time so that the maximal time a pallet spends in the elevator system does not become "too large" and the average time is as fast as possible. This problem can be modeled by the Dial-A-Ride Problem (DARP), where we would like to minimize maximal/average flow times. Since we are concerned with an online-situation, requests arrive over time and do not become known before they arrive.
In an intermediate step we perform competitive analysis on the problem of minimizing the total completion time (makespan), thereby presenting results that are interesting in their own right in the context of competitive analysis. For example, there is a two-competitive algorithm (SMARTSTART) meeting the known lower bound.
In a further effort, we introduce the concept of "reasonable load" to achieve performance guarantees for the problem of minimizing the maximal/average flow time for the well-known online-paradigm IGNORE: Follow the current schedule; if the schedule is done, compute a new schedule out of all yet unserved requests minimizing the makespan. We show that under δ-reasonable load the maximal/average flow time is always bounded from above by 2δ. In contrast to this result it is shown that there can be no competitive algorithms for the problem.

Rolf H. Möhring
Optimal Routing of Traffic Flows with Length Restrictions in Networks with Congestion

When traffic flows are routed through a road network it is desirable to minimize the total road usage. Since a route guidance system can only recommend paths to the drivers, special care has to be taken not to route them over paths that they perceive as too long. This leads in a simplified model to a nonlinear min cost multicommodity flow problem with length restrictions on the available paths and nonlinear link delay functions that model arc transit times under congestion.
We present an algorithm for this problem that combines the convex combinations algorithm by Frank and Wolfe with column generation and algorithms for the constrained shortest path problem. Computational results stemming from a cooperation with DaimlerChrysler are presented.
(joint work with Olaf Jahn, Fachbereich Mathematik, Technische Universität Berlin, and Andreas S. Schulz, Sloan School of Management, MIT)

Tuesday, November 09, Evening Presentation

Hans-Jürgen Ewers
The Economics of Deregulation in the Transport Industry

In this talk an economic analysis of the monopolistic and highly subsidized structures in important sectors of the transport industry is given and deregulatory measures that are needed to reinstall market mechanisms are discussed. Examples of such transport monopolies in airlines, railroads, mass transit, and road traffic are described and the historical developments that lead to their establishment are sketched. The economic effects and consequences that these monopolies entail are discussed and possible ways toward competitive, service oriented, and cost efficient market economies in the transport sector are outlined. Deregulation on a Europe wide scale will be a key factor in the transition period. The evolving markets must be directed by new regulatory schemes that further innovation, efficiency, and transparence of costs and benefits.

Wednesday, November 10, Morning Session

Dirk Steenken
The Use of Optimization Methods in Container Terminals

Container traffic is continuously growing, ship capacity is growing, operation in ports has to be fast, container terminal logistics apply automation including methods of optimization. The logistic system of the Container Terminal Burchardkai of HHLA, Hamburg, is composed of the following main components:

- online stacking decision systems automatically select optimal container yard positions
- satellite positioning systems (DGPS) uniquely identify the position within the yard. Both systems together managed to reduce the rate of the yard shifters form

35% to less than 15% while the quayside productivity was enhanced by about 6%.

- real time routing systems minimize empty ways based on OR methods (linear assignment, m-TSP)
- a workload manager dynamically engages vehicles according to the actual workload of different operation areas. The result in short: savings of 50,000 km/year, gain in productivity of more than 40%.
- semi-automatic ship planning ensures optimal loading sequences

System in development is the synchronization of loading and transport sequences for the ship operation by minimizing the delays of container deliveries to the quay cranes (just-in-time-deliveries in a fixed frequency). Gain in productivity is expected in a range of 10–20%.

David Simchi-Levi
Optimal and Approximation Algorithms for Large Scale Supply Chain Management Systems

In this talk, we analyze the problems faced by companies that rely on TL (Truckload) and LTL (Less-Than-Truckload) carriers for the distribution of products across their supply chain. The goal is to design an inventory policy and a transportation strategy so as to minimize systemwide cost by taking advantage of the transportation cost structure. We propose strong reformulations for the problems and develop structural properties for two common transportation cost functions, (i) the incremental discount, and (ii) the all unit discount cost functions. In the former case, we model the problem using a set partitioning approach and characterize structural properties of the resulting formulation. These properties are used to identify cases in which the linear programming relaxation of the set partitioning is tight, and to suggest an efficient algorithm. In the case of all unit discount cost functions, we develop approximation algorithms with fixed bounds for the single warehouse multi-retailer model. These algorithms focus on finding the best ZIO policy, a policy in which a facility orders only when its inventory level is down to zero. We show that the best zero-inventory-ordering policy is a 4/3-approximation algorithm for the single warehouse multi-retailer model, for general, all unit discount cost functions. If the cost function does not change over time, but may change from retailer to retailer, our algorithm is a 5.6/4.6-approximation algorithm.

Ralf Borndörfer & Andreas Löbel
Operational Planning Trends in Public Transport

Operational planning in public transport, i.e., airlines, railways, and mass transit, deals with mid to short term allocation of resources. There is a natural decomposition such that the planning is organized in a vertical, hierarchical sequence of individual steps such as timetabling, vehicle scheduling, crew scheduling and crew rostering. Size and complexity give rise to further horizontal decompositions such as depot wise planning, line planning, etc.
We survey the developments in the mathematics of operational planning. Three trends are horizontal integration, vertical integration, and efforts to put the human in control.

- Efforts on horizontal integration include the development of dynamic column generation techniques both on the primal and the dual side. These allow to deal with large search spaces.

- Vertical integration has just started. The integration of timetabling and vehicle scheduling and that of vehicle and crew scheduling are among the first problems studied.
- Human in control activities include the development of flexible models, rule languages, and new planning techniques such as preferential bidding.

Future trends are real time systems, distributed decisions, and system design.

Thursday, November 11, Morning Session

Michael R. Bussieck
Optimal Line Plans

This talk deals with the line planning problem for public transportation networks based on periodic schedules. The models and algorithms represented in this talk take care of peculiarities of public rail transport.

A comprehensive discussion of the line planning problem including its modeling and solution applying mathematical programming methods, constitutes the core of this talk. The line planning problem consists of selecting a set of routes in a network and assigning a frequency and a capacity to these routes. The data for the line planning problem comes in different flavors, e.g. the passenger data is specified by an OD matrix or by traveler counts on the edges.
We discuss two different approaches to the line planing problem. The first approach concentrates on maximizing the quality of a line plan by maximizing the number of direct travelers. Direct travelers are passengers who can travel from origin to destination without changing lines. We formulate a huge mixed integer linear programming model, reduce the size by applying heuristics and relaxation methods. Although we significantly changed the model we can still find solutions for the original problems that are in 2% of the optimal solution.
The second approach to the line optimization problem is concerned with cost minimization. Costs in line planning arise when the line plan is implemented and vehicles and crew are required to operate the line plan. As a rough estimation for the number of vehicles required for operating a line we make use of the “tram formula”. The natural formulation of the resulting model is a discontinuous non linear model with integer variables. We derive two linear integer models and apply those models to four instances provided by the Dutch railroad company. Standard properties of models like the number of variables/equations/non zeros, the LP relaxation, etc. help to compare the models. For practical modeling development rapid prototyping is required to find the “right” model. Computational results for all models will be given

Alexander Schrijver
Train Timetabling

We discuss a system made for the Nederlandse Spoorwegen (Dutch Rail) to make the periodic time-table (with Adri Steenbeck). In the Netherlands, the basis of the time-table is an hourly pattern, run throughout the day (and evening). Designing it amounts to solving a system of inequalities in integers mod 60. Each inequality is the difference of two variables, corresponding to departure or arrival times. The system of constraints can be represented by a graph, with vertices corresponding to times to be set, and edges corresponding to constraints to be satisfied. Constraint programming and search of cycles in this graph helps in finding a time-table, and in optimizing it. Our system CADANS generally solves the inequality system for NS in a few minutes.

Matteo Fischetti
Algorithms for Railway Crew Management

Crew management is concerned with building the work schedules of crews needed to cover a planned timetable. This is a well-known problem in Operations Research and has been historically associated with airlines and mass-transit companies. More recently, railway applications have also come on the scene, especially in Europe. In practice, the overall crew management problem is decomposed into two subproblems, called crew scheduling and crew rostering. In this talk, we give an outline of different ways of modeling the two subproblems and possible solution methods. Two main solution approaches are illustrated for real-world applications. In particular we discuss in some detail the solution techniques currently adopted at the Italian railway company, Ferrovie dello Stato SpA, for solving crew scheduling and rostering problems.
(joint work with Alberto Caprara, Paolo Toth, Daniele Vigo (DEIS, University of Bologna, Italy) and Pier Luigi Guida (FS-Ferrovie dello Stato SpA, Italy))

Thursday, November 11, Afternoon Session

Leo Kroon
Railway Crew Scheduling and Improvement of Punctuality

This presentation reports on the findings of a subproject of the project "Bestemming: Klant" ("Destination: Customer"). The aim of this project is to improve the quality and the punctuality of the railway services of NS Reizigers. This is (partly) to be achieved by improving the robustness and the stability of the underlying plans for the timetable, the rolling stock circulation, and the crew schedules. This presentation focuses on the crew scheduling aspect. New rules were developed for the assignment of trips to depots and for the required structures for the duties of train drivers and conductors. The consequences of these rules, in terms of the required depot capacities for drivers and conductors were analyzed by modeling the crew scheduling problems as large scale Set Covering Problems. These SCPs were solved by splitting them into smaller subproblems and by applying dynamic column generation, Lagrange relaxation and several powerful heuristics to each subproblem. In this presentation the results of the analysis are presented, as well as an evaluation of the applied approach.

Thomas Lindner
Train Schedule Optimization

For a set of train lines in a railroad network we generate train schedules with optimal departure and arrival times for each line at its stations. Here, certain realization costs of the schedule should be minimized subject to constraints derived from operational considerations as well as from marketing aspects.

We describe the train schedule problem in terms of a MIP-model. In order to sufficiently decrease the computation time for solving the MIP for real-world instances, we decompose the MIP into two parts: an optimization problem and a feasibility problem. The optimization part is solved as a smaller MIP adding some cutting planes. The feasibility problem is known as the *Periodic Event Scheduling Problem (PESP)* and can be solved using a modified version of the PESP algorithm suggested by Serafini and Ukovich.
We present computational results for several real-world instances.
(joint work with Uwe Zimmermann)

Marco Lübbecke
Optimal Engine Scheduling at Industrial In-Plant Railroads

In the practical background of this contribution we are concerned with industrial in-plant railroad companies, each of which is charged with the internal goods transportation of e.g. steel mills. *Transportation requests* have to be served, possibly in parallel, by a non homogeneous fleet of switching engines. Each request is characterized by an origin and a destination track, each attributed with the size of the load, a service duration, and a time window during which operations such as switching have to take place. Engines differ in power, technical equipment or driving personal and, as a consequence, only a subset of engines is admissible for each request. The objective is to construct a set of routes of *minimum cost* such that each request is served by exactly one admissible engine and time window and capacity constraints are obeyed. The cost of a route may be defined e.g. as the unproductive time (waiting, deadheading) of the respective engine. In the operations research literature the generic problem is known as the *Pickup and Delivery Problem with Time Windows* and many approaches have been proposed to solve variants of this—in a practical as well as the theoretical sense—hard combinatorial optimization problem exactly or, more often, approximately or heuristically. Additionally, in our special case of a railroad problem the combinatorial structure of each route is restricted to being the concatenation of simple *request patterns*, a state of affairs we refer to as pattern routing.
The fact that each feasible solution to our problem naturally partitions the set of requests (into a set of routes) suggests a *set partitioning formulation*, where each column is the incidence vector of a subset of requests to be served on an admissible engine. At most one such column has to be chosen for each engine. A prominent method to circumvent the obstacle of exponentially many columns is an iterative extension of a small but meaningful portion of the model, well known as *column generation*. For each column to be generated, a *pricing problem* has to be solved, in different stages of the generation process heuristically or exactly. In our case, the pricing belongs to the class of $\mathcal{NP}$-complete problems.
In this talk we present—besides a sketch of the above—a dynamic programming algorithm for the exact solution of the pricing problem which exploits the special structure of our problem and improves on existing algorithms. This algorithm is sped up by a lower bounding criterion which makes use of the dual variable information. We point out the great variety of choice of techniques when implementing a column generation code. The importance for the overall approach of fast heuristics for the pricing problem as well as sophisticated techniques for the interplay of exact and heuristic methods to solve (the *linear programming relaxation* of) our problem optimally is illustrated by computational results coming up from real-world data.
(joint work with Uwe Zimmermann)

Alberto Caprara
Train Timetabling

The train timetabling problem aims at determining a timetable for a set of trains which does not violate track capacity constraints and satisfies some operational constraints. In particular, we concentrate on the problem of a single, one-way track linking two major stations, with several intermediate stations in between. Each train connects two given stations along the track (possibly different from the two major stations) and may have to stop for a minimum time in some of the intermediate stations. Trains can overtake each other only in correspondence of an intermediate station, and a minimum interval between two consecutive departures and arrivals of trains in each station is specified.
On input, each train is assigned an ideal timetable, corresponding to a sequence of departure and arrival time instants for each station along the train path. In order to satisfy the track capacity constrains, one is allowed to slow down each train with respect to the ideal timetable, and/or to increase the stopping time intervals at the station, or even to cancel the train.
We propose a graph theoretic formulation for the train timetabling problem using a graph in which nodes correspond to departures/arrivals at a certain station at a given time instant. This formulation is used to derive an ILP model which is relaxed in a Lagrangean way. A novel feature of our model is that the variables in the relaxed constraints are associated only with nodes (and not with arcs) of the aforementioned graph. This allows a considerable speedup on the solution of the relaxation. This relaxation is embedded within a heuristic algorithm which makes extensive use of the dual information associated with the Lagrangean multipliers. We report extensive computational results on real-world instances provided from the Italian railways.
(joint work with M.Fischetti, P.Toth, and D.Vigo)

Stefan Voß
Building Reusable-Software Components for Heuristic Search—and their Application to Solve Real World Problems on a Container Terminal

In practice there is a great variety of discrete and combinatorial optimization problems. Since most of them are NP-hard, the modeling of the problem may be approximate, and the data are generally imprecise, heuristics are the primary way to tackle these problems. Furthermore, the use of heuristics generally meets the needs of decision makers to efficiently generate "satisfactory" solutions.
Though in practice there is a huge number of problems to be solved, the statement of Wolsey that "this profession [Operations Research] has presently more algorithms than applications" may still be regarded as valid. That is, in practice we need easy-to-use application systems that incorporate the results of basic research in the corresponding fields (No systems, no impact!). Therefore, we also have to deal with the issue of efficiently building such implementations to bridge the gap into practice, instead of just investigating and solving simplified problems by ad-hoc-approaches.
We review the goals, challenges and prospects concerning the reuse in the field of heuristic search. We present the current status of a heuristic optimization framework HOTFRAME, developed in Braunschweig, present some applications together with some motivation based on real-world problems on a container-terminal.

Thomas Winter
Stowage and Transport Optimization in Ship Planning

In container ship planning, several dispatch problems must be solved in order to serve the container vessels in time. For each vessel, the planning process starts two days before she enters the port. At that time, the current loading information is transmitted from the terminal visited before. Most of the export containers to be loaded arrive at the terminal in this two day period. For a large number of containers the concrete arrival time is not known due to traffic delays.
Based on such incomplete information on the arrival data and subject to the requirements provided by the ship owner, a preliminary stowage plan is prepared. This stowage plan specifies which container has to be loaded into which bay position.
Given that stowage plan, the containers are loaded in the following way. Each container is transported from its terminal position to a quay crane that moves it to the specified bay position. The transport is carried out by straddle carriers. In order to derive a good stowage plan, the planner should take into account both the loading and transportation process.
For this real-time planning problem, we present a new integrated planning approach that combines stowage and transportation planning. We model the just-in-time delivery of containers to the quay cranes by a mixed integer program and discuss some computational results for real-world data from a German container terminal. Moreover, we discuss some real-time heuristics and present computational results.
(joint work with D. Steenken and U. Zimmermann)

Thursday, November 11, Evening Session

George L. Nemhauser (Chair)
Jaques Desrosiers, Matteo Fischetti, Rolf Möhring, David Ryan, Tony Wren (Panel)
Panel Discussion: The Future of Transport Optimization Research

This discussion—sometimes controversial—revolved around the present and future role of optimization in traffic and transport.
Among the points discussed and opinions mentioned were:

- There is a clear need for optimization in traffic and transport. Students are looking for it, graduates have excellent professional opportunities, and companies (in particular the airline industry) have noticed the relevance of optimization. There is already a developing market for mathematical technology. This trend gets stronger as deregulation of hitherto monopolistic sectors gains ground.

- Many research groups have good networks to companies, authorities, and former graduates, and research projects are often financed by industrial funds.

- On the other hand, transport optimization is carried out very much by individuals or small groups. There is no coordination, neither in the community itself, nor at the interfaces to the engineering and social sciences. This is a disadvantage in an interdisciplinary environment and may account for a number of deficits.

- A deficit is that no science base for traffic and transport optimization has been established, see, e.g., the report on the NSF workshop “The Planning, Design, Management and Control of Transportation Systems”, which is available at

There is no common set of fundamentals, data bases, processes, and curricula.

- Another deficit is that the discipline is not visible. Optimization has difficulties in "marketing" itself as an important contributor. Technical and political aspects dominate the developments in traffic and transportation.
- This problem carries over to funding. Individuals and small groups have trouble in getting represented in the very large scale traffic and transportation research programs that national and international funding organizations set up.
- A result is that the impact of optimization on traffic and transportation is not as envisioned by the participants. In many areas, optimization technology is far from being or becoming the industry standard, the airline industry being a notable exception.

The discussion of the future had the "academic side" and the "business side" as its main topics:

- There is scientific as well as commercial interest in the area. Coexistence is possible, but there are serious potential conflicts. Companies do not want to disclose advantages to competitors, but this exchange is the essence of scientific work. Researchers that own or are attached to companies face this problem. The community must address this problem to stay on scientific grounds.
- A related danger are tendencies that transform traffic and transport optimization from a science into a discipline of algorithmic engineering. Research activities must concentrate on problems that nobody else can solve, and a line must be identified between true research and development efforts that should be carried out by commercial companies.
- This does not imply separation from engineers, practitioners, or companies at all. To the contrary, this network must be intensified to put much more mathematics into practice.
- New trends, such as supply chain management, vendor managed inventory, real time systems, and cooperative decision making, must be taken up faster. The community must not only react to industrial developments, it must participate in their creation. In the future, designing new systems will become more relevant than optimizing existing systems. Simulation models to anticipate transportation phenomena will become more important.
- On the scientific side, challenges and basic research goals must be identified. A science base for traffic and transport optimization must be established. Databases, software and problem libraries, and simulation environments must be made available to make comparisons possible, to ensure reproducibility of results, and to initiate more scientific competition. Curricula for transport optimization must be developed.

Gilbert Laporte
An Overview of Classical and Modern Heuristics for the Vehicle Routing Problem

The Vehicle Routing Problem consists of determining a set of least cost routes through n customers, using a fleet of identical vehicles based at a depot, while satisfying some side constraints. Over the past four decades, several algorithms have been proposed for this problem, but to this date no exact algorithm can consistently solve instances of more than 30 customers. Most research has concentrated on the development of heuristics. Classical heuristics employ methods based on savings, sweep procedures, insertion techniques, incomplete column generation, etc. Modern heuristics (or meta-heuristics) are based on simulated annealing, tabu search, genetic search and ant systems. In this talk, I will review the main heuristic ideas used for the solution of the vehicle routing problem and I will point out some methodological difficulties encountered while making computational comparisons.

Giovanni Rinaldi & Klaus Trümper
Logic, Learning and Traffic Control

We describe a logic programming compiler, a data mining tool, and use of these systems for traffic control. The key feature of the control approach is independent decision making at each intersection by a logic module. The first implementation of the control system in Italy has proved the approach to be superior to traditional traffic control schemes.

Hani Mahmassani
Hybrid Approaches for Dynamic Traffic Assignment: Models, Algorithms and Applications

The class of problems addressed involves the optimization of dynamic stochastic systems in which the behavior of human beings is a critical determinant of overall system performance. Vehicular traffic networks involve complex interactions among people and vehicles over space and time in a physical environment, possibly under real-time information provision. The complexity of these interactions has to date precluded analytical foundations that result in well-behaved mathematical optimization problems.
The principal dynamic assignment problem considered is that of optimally routing vehicles in a congested traffic network. A review of idealized instances when a central controller has full information on time-varying (origin-destination) trip desires over a future time horizon, and users follow the controller's instructions, is presented. A second instance where users reach a time-varying Wardrop User Equilibrium is also discussed. The instances are generalized to a problem in which multiple user classes are present in the network; each class is defined in terms of information availability, information supply strategy and behavioral response rules. Algorithms for these problems are presented, in which system performance and various related measures are evaluated using computer simulation of a network traffic process.
A rolling horizon procedure is proposed for the quasi real-time implementation of the above routing algorithm by the central controller. The scenario requires predictions of future time-varying origin-destination trip desires over the future horizon. The ability to predict such demands under rapidly changing conditions (e.g., traffic disruptions) is

limited, hence limited the overall procedure's ability to respond in a timely fashion to unforeseen events.
A decentralized approach, in which spatially distributed local controllers react to sensed conditions in the network is discussed, while sub-optimal under predictable traffic conditions, the approach is more effective than centralized predictive approaches under rapidly changing traffic.
Hybrid approaches are proposed to combine a centralized predictive approach with the ability to react through distributed reactive local control rules. A formulation is presented for a bi-level N-player Stackelberg game routing problem in which the central controller produces solutions consistent with the actions of the local controllers. A simulation-based algorithm implementation is presented, along with the results of computational experiments.
Several open problems remain for future developments, ranging from traffic modeling questions to considerations for fast real-time executions of the algorithmic procedures.

Friday, November 12, Afternoon Session

Tony Wren
Heuristics, Metaheuristics and Mathematics for Public Transport Driver Scheduling

The author has been involved since 1967 in the development of computer processes for the scheduling of bus and train drivers. During the early stages of this work many heuristics were developed, some formalising the processes of human schedulers, and some developed from first principles. Good results were achieved from time to time, but no approach was found to be consistently good over a wide range of scenarios. Subsequently, a set covering approach was developed in which heuristics reduced the search space before presentation to a specially developed Integer Linear Programming process. The consequent system was installed for London Transport buses in 1984, and is still in use by all of the current successor companies. Thereafter it was further developed and installed for about thirty other bus operating companies. In the 1990s, the mathematical components of the system have been improved using specialised column generation methods and refinements to the branch and bound process, so that much larger problems can be solved. The heuristics have also been replaced, so that the system can now deal with complex rail driver scheduling problems. The current version of the system is in use in two British bus companies, and has been applied to many large rail problems. Current research is directed at improving the robustness of the system so that yet more complex problems can be tackled in a single pass, and is also investigating new approaches to parts of the problem, using genetic algorithms, constraint programming and ant system simulation. Following a brief survey of the historical background, the talk outlines the current system and one of its applications, and explores the extent to which the basic mathematical processes can be assisted by heuristics, metaheuristics and constraint programming.

Stefan Irnich
A Column Generation Approach to the Mixed Direct and Hub Flight Problem

This talk presents a network design problem which has important applications in several areas of transportation. Freight has to be transported between a large number of

origins and destinations. In order to consolidate freight, it is first shipped to a terminal. Next, it is transported to another terminal where it is re-loaded and shipped to its destination. The focus here is on the design of the global transportation network, i.e. transportation between terminals.
The motivation for the model is an application where the terminals are airports and the freight is letter mail. There are three options for the design of this network:

- a network of direct flights
- a hub-and-spoke network
- or a mixed network with both direct and hub flights.

We propose a model based on a set partitioning formulation with side constraints. The model enables the use of column generation techniques. The master program can conveniently integrate a number of the difficult side constraints. For example, bounds on the maximum number of take- offs and landings at an airport and the maximum number of available aircraft of a certain type are a part of the master program. All other constraints are integrated into the description of a column, i.e. a feasible direct or hub flight. They determine the structure of the corresponding pricing problems which is a (so- called) combined clique-knapsack problem.
The column generation approach produces strong lower bounds. Small instances of the MFP can also be tackled by a combination of column generation and branch-and-bound (called branch-and-price) for producing integer solutions. Branching rules compatible with the pricing problem have been developed. Preliminary computational results are promising. (joint work with Tore Grünert and Hans-Jürgen Sebastian)

(Reporting: Ralf Borndörfer, Marco Lübbecke)

List of Email Addresses

Bachem, Achim
Ball, Michael O.
Barnhart, Cynthia
Bixby, Robert E.
Borndörfer, Ralf
Bussieck, Michael R.
Caprara, Alberto
Cominetti, Roberto
Crainic, Teodor Gabriel
Desrosiers, Jacques
Ewers, Hans-Jürgen
Fischetti, Matteo
Friesz, Terry L.
Grötschel, Martin
Irnich, Stefan
Jünger, Michael
Kleywegt, Anton
Kroon, Leo G.
Krumke, Sven O.
Laporte, Gilbert
Lauther, Ulrich
Lindner, Thomas
Löbel, Andreas
Lübbecke, Marco E.
Madsen, Oli B.G.
Mahmassani, Hani
Martin, Alexander
Mingozzi, Aristide
Möhring, Rolf Hermann
Nagel, Kai
Nemhauser, George L.
Powell, Warren B.
Rambau, Jörg
Rinaldi, Giovanni
Ryan, David M.
Savelsberg, Martin W.P.
Schrader, Rainer
Schrijver, Alexander
Simchi-Levi, David
Steenken, Dirk
Toth, Paolo
Truemper, Klaus
Voß, Stefan
Wedelin, Dag
Winter, Thomas
Wren, Anthony
Zimmermann, Uwe T.

Tagungsteilnehmer

Prof.Dr. Achim Bachem
Deutsche Forschungsanstalt
für Luft- und Raumfahrt e.V.
Porz-Wahnheide, Linder Höhe

51147 Köln

Prof.Dr. Michael O. Ball
Department of Finance
RHSmith School of Business
University of Maryland
YMH Building

College Park , MD 20742-1815
USA

Dr. Cynthia Barnhart
Department of Civil Engineering
Massachusetts Institute of
Technology

Cambridge , MA 02139
USA

Prof.Dr. Robert E. Bixby
Dept. of Mathematical Sciences
Rice University
P. O. Box 1892

Houston , TX 77251
USA

Ralf Borndörfer
Konrad-Zuse-Zentrum für
Informationstechnik Berlin (ZIB)
Takustr. 7

14195 Berlin

Dr. Michael Bussieck
GAMS Development Corporation
1217 Potomac Street NW

Washington DC 20007
USA

Prof.Dr. Alberto Caprara
DEIS
Universita di Bologna
Viale Risorgimento, 2

I-40136 Bologna

Prof.Dr. Roberto Cominetti
Depto. Ingenieria Matematica
Universidad de Chile
Casilla 170/3 Correo 3

Santiago
CHILE

Prof.Dr. Teodor Gabriel Crainic
Centre de Recherches de
Mathematiques
Universite de Montreal
C.P. 6128, Succ. Centre-Ville

Montreal P.Q. H3C 3J7
CANADA

Prof.Dr. Jacques Desrosiers
Ecole des Hautes; Etudes Commerc.
GERAD
3000 chemin de la Cote-St.
Catherine

Montreal , QC H3T 2A7
CANADA

Prof.Dr. Hans-Jürgen Ewers
Präsident
der Technischen Universität Berlin
Strasse des 17. Juni 135

10623 Berlin

Prof.Dr. Matteo Fischetti
Dipartimento di Elettronica e Informatica
Universita di Padova
Via Gradenigo 6/A

I-35131 Padova

Prof.Dr. Terry L. Friesz
Dept. of Systems Engineering and Operation Research
George Mason University

Fairfax , VA 22030
USA

Prof.Dr. Martin Grötschel
Konrad-Zuse-Zentrum für Informationstechnik Berlin (ZIB)
Takustr. 7

14195 Berlin

Stefan Irnich
Lehrstuhl für Unternehmensforschung
RWTH Aachen
Templergraben 64

52062 Aachen

Prof.Dr. Michael Jünger
Institut für Informatik
Universität zu Köln
Pohligstr. 1

50931 Köln

Prof.Dr. Anton J. Kleywegt
School of Industrial Engineering
Georgia Institute of Technology

Atlanta , GA 30332-0205
USA

Prof.Dr. Leo G. Kroon
Hoofdgebouw IV
Laan van Puntenburg 100
Postbus 2025

NL-3500 HA Utrecht

Dr. Sven Oliver Krumke
Konrad-Zuse-Zentrum für Informationstechnik Berlin (ZIB)
Takustr. 7

14195 Berlin

Prof.Dr. Gilbert Laporte
Centre de Recherche sur les transports
Univ. de Montreal
C.P. 6128, succ. Centre-Ville

Montreal , QC H3C 3J7
CANADA

Dr. Ulrich Lauther
SIEMENS AG
ZT SE 14
Otto-Hahn-Ring 6

81730 München

Thomas Lindner
Abteilung für Mathematische Optimierung
TU Braunschweig
Pockelsstr. 14

38106 Braunschweig

Dr. Andreas Löbel
Konrad-Zuse-Zentrum für
Informationstechnik Berlin (ZIB)
Takustr. 7

14195 Berlin

Marco E. Lübbecke
Abteilung für Mathematische
Optimierung
TU Braunschweig
Pockelsstr. 14

38106 Braunschweig

Prof.Dr. Oli B.G. Madsen
Department of Mathematical
Modelling
Technical University of Denmark
Building 321

DK-2800 Lyngby

Prof.Dr. Hani S. Mahmassani
Dept. of Civil Engineering
The Univ. of Texas at Austin
Ernest Cockrell Jr. Hall

Austin , TX 7812-1076
USA

Dr. Alexander Martin
Konrad-Zuse-Zentrum für
Informationstechnik Berlin (ZIB)
Takustr. 7

14195 Berlin

Prof.Dr. Aristide Mingozzi
Department of Mathematics
University of Bologna
Via Sacchi, 3

I-47023 Cesena

Prof.Dr. Rolf Hermann Möhring
Fachbereich Mathematik - FB 3
Technische Universität Berlin
MA 6-1
Straße des 17. Juni 136

10623 Berlin

Dr. Kai Nagel
Institute for Scientific Computing
ETH Zentrum/D-INFK

CH-8092 Zürich

Prof.Dr. George L. Nemhauser
Industrial and Systems Engineering
Georgia Institute of Technology

Atlanta , GA 30332-0205
USA

Prof.Dr. Warren Buckler Powell
Dept. of Civil Engineering and
Operations Research
Princeton University

Princeton , NJ 08544
USA

Jörg Rambau
Konrad-Zuse-Zentrum für
Informationstechnik Berlin (ZIB)
Takustr. 7

14195 Berlin

Dr. Giovanni Rinaldi
Istituto di Analisi dei Sistemi ed
Informatica
CNR
Viale Manzoni 30

I-00185 Roma

Prof.Dr. David M. Ryan
Dept. of Engineering Science
University of Auckland
private Bag 92019

Auckland
NEW ZEALAND

Prof.Dr. Paolo Toth
DEIS
Universita di Bologna
Viale Risorgimento, 2

I-40136 Bologna

Prof.Dr. Martin W.P. Savelsbergh
Industrial and Systems Engineering
Georgia Institute of Technology

Atlanta , GA 30332-0205
USA

Prof.Dr. Klaus Truemper
Computer Science Program MP 31
The University of Texas at Dallas
Box 83 06 88

Richardson , TX 75083-0688
USA

Prof.Dr. Rainer Schrader
Institut für Informatik
Universität zu Köln
Pohligstr. 1

50931 Köln

Prof.Dr. Stefan Voss
Abteilung Allgemeine BWL
Technische Universität Braunschweig
Abt-Jerusalem-Str. 7

38106 Braunschweig

Prof.Dr. Alexander Schrijver
CWI Amsterdam
Postbus 94079

NL-1090 GB Amsterdam

Prof.Dr. Dag Wedelin
Department of Computer Science
Chalmers University of Technology
and University of Göteborg

S-41296 Göteborg

Prof.Dr. David Simchi-Levi
Dept. of Industr. Engineering and
Management Science
Northwestern University

Evanston , IL 60208-3119
USA

Thomas Winter
Abteilung für Mathematische
Optimierung
TU Braunschweig
Pockelsstr. 14

38106 Braunschweig

Dirk Steenken
HHLA-Hamburger Hafen und
Lagerhaus AG
Postfach 11 14 06

20414 Hamburg

Prof.Dr. Anthony Wren
School of Computer Studies
University of Leeds

GB-Leeds LS2 9JT

Prof.Dr. Uwe Zimmermann
Abteilung für Mathematische
Optimierung
TU Braunschweig
Pockelsstr. 14

38106 Braunschweig